Energy, Environment, and Sustainability
Series Editor: Avinash Kumar Agarwal

Ram Krishna Upadhyay
Sunil Kumar Sharma
Vikram Kumar
Hardikk Valera *Editors*

Transportation Systems Technology and Integrated Management

International Society for Energy, Environment and Sustainability

Springer

Energy, Environment, and Sustainability

Series Editor

Avinash Kumar Agarwal, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

AIMS AND SCOPE

This books series publishes cutting edge monographs and professional books focused on all aspects of energy and environmental sustainability, especially as it relates to energy concerns. The Series is published in partnership with the International Society for Energy, Environment, and Sustainability. The books in these series are edited or authored by top researchers and professional across the globe. The series aims at publishing state-of-the-art research and development in areas including, but not limited to:

- Renewable Energy
- Alternative Fuels
- Engines and Locomotives
- Combustion and Propulsion
- Fossil Fuels
- Carbon Capture
- Control and Automation for Energy
- Environmental Pollution
- Waste Management
- Transportation Sustainability

Review Process

The proposal for each volume is reviewed by the main editor and/or the advisory board. The chapters in each volume are individually reviewed single blind by expert reviewers (at least four reviews per chapter) and the main editor.

Ethics Statement for this series can be found in the Springer standard guidelines here https://www.springer.com/us/authors-editors/journal-author/journal-author-helpdesk/before-you-start/before-you-start/1330#c14214

Ram Krishna Upadhyay · Sunil Kumar Sharma ·
Vikram Kumar · Hardikk Valera
Editors

Transportation Systems Technology and Integrated Management

Springer

Editors
Ram Krishna Upadhyay
School of Engineering and Applied Sciences
National Rail and Transportation Institute
Vadodara, Gujarat, India

Sunil Kumar Sharma
School of Engineering and Applied Sciences
National Rail and Transportation Institute
Vadodara, Gujarat, India

Vikram Kumar
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur, Uttar Pradesh, India

Hardikk Valera
Engine Research Laboratory
Indian Institute of Technology Kanpur
Kanpur, Uttar Pradesh, India

ISSN 2522-8366 ISSN 2522-8374 (electronic)
Energy, Environment, and Sustainability
ISBN 978-981-99-1516-3 ISBN 978-981-99-1517-0 (eBook)
https://doi.org/10.1007/978-981-99-1517-0

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Transportation systems technology deals with the practical uses of innovative transportation approach that combines with the latest state-of-the-art technology and policy changes. Without the implementation of both, modern mode of transportation is impossible. For an effective transport system, the changes that have been implemented in the past and the direction for future uses must be communicated effectively to impart the changes for better infrastructure, including transport system design and supply chain management. The integrated transport management system implies the way forward for a better methodology that needs to be employed for a better society cost-effectively.

The International Society for Energy, Environment, and Sustainability (ISEES) was founded at the Indian Institute of Technology Kanpur (IIT Kanpur), India, in January 2014 to spread knowledge/ awareness and catalyse research activities in the fields of energy, environment, sustainability, and combustion. Society's goal is to contribute to the development of clean, affordable, and secure energy resources and a sustainable environment for society and spread knowledge in the areas mentioned above, and create awareness about the environmental challenges the world is facing today. The unique way adopted by ISEES was to break the conventional silos of specialisations (engineering, science, environment, agriculture, biotechnology, materials, fuels, etc.) to tackle the problems related to energy, environment, and sustainability in a holistic manner. This is quite evident in the participation of experts from all fields to resolve these issues. The ISEES is involved in various activities, such as conducting workshops, seminars, and conferences, in the domains of its interests. The society also recognises the outstanding works of young scientists, professionals, and engineers for their contributions in these fields by conferring them awards under various categories.

Sixth International Conference on 'Sustainable Energy and Environmental Challenges' (VI-SEEC) was organised under the auspices of ISEES from 27–29 December 2021, in hybrid mode due to restrictions on travel because of the ongoing COVID-19 pandemic situation. This conference provided a platform for discussions between eminent scientists and engineers from various countries, including India, Spain, Austria, Australia, South Korea, Brazil, Mexico, USA, Malaysia, Japan, Hong Kong, China, the UK, Netherlands, Poland, Finland, Italy, Israel, Kenya, Turkey, and Saudi Arabia. At this conference, eminent international speakers presented their views on energy, combustion, emissions, and alternative energy resources for sustainable development and a cleaner environment. The conference presented two high-voltage plenary talks by Prof. Ashutosh Sharma, Secretary, DST and Dr. VK Saraswat, Honourable Member, NITI Ayog.

The conference included twelve technical panel discussions on energy and environmental sustainability topics. Each session had 6–7 eminent scientists who shared their opinion and discussed the trends for the future. The technical sessions at the conference included Fuels for Sustainable Transport, Challenges for Desalination and Wastewater Treatment and Possible Solutions, Engine Combustion Modelling, Simulation and Sprays, Bioenergy/biofuels, Coal Biomass Combustion for Power Generation, Microbial Processes and Products, Future of IC Engine Technology and Roadmap, Air Pollution and Climate Change: Sustainable Approaches, Sustainable Energy from Carbon Neutral Sources, Biological Waste Treatment, Combustion: Emerging Paradigm and Thermochemical Processes for Biomass. 500+ participants and speakers from around the world attended this three days conference.

This conference laid out the roadmap for technology development, opportunities, and challenges in energy, environment, and sustainability domains. All these topics are very relevant for the country and the world in the present context. We acknowledge the support from various agencies and organisations for conducting the Sixth ISEES conference (VI-SEEC), where these books germinated. We want to acknowledge our publishing partner Springer (Special thanks to Ms. Swati Mehershi).

The editors would like to express their sincere gratitude to many authors worldwide for submitting their high-quality work on time and revising it appropriately at short notice. We want to express our special gratitude to our prolific set of reviewers, Dr. Hari Krishna Gaddam, Dr. Santosh Kumar Mishra, Dr. Bipin Kumar Singh, Dr. Ravi Shankar Sinha, Dr. Abhilasha Saksena, Dr. Pradeep, Dr. Vikram Kumar, Dr. Sunil Kumar Sharma, Mr. Surya Pratap Singh, Mr. Abhay, Mr. Hardikk Valera, Mr. Utkarsha, who reviewed various chapters of this monograph and provided their valuable suggestions to improve the manuscripts.

The book aims to understand transportation ecosystems and management with its underlying technologies for futuristic freight and passenger movement. Chapters include recent results and focus on current trends in the transportation sector. The topics covered in this book range from current advances in transportation to essential technological aspects, including environment and energy, design of mobile aerial ropeways based on autonomous self-propelled chassis, highway soil performance, and repositioning of the rail system for competitiveness. In this book, different survey data from the large community have been gathered and illustrated to show the public's choices and preferences to understand the use case transportation policy. Further, these choices are integrated with management to generate a framework of the new policy that can serve the purpose of many in an economical way to design new facilities. The deep insight provided in the book, including design aspects, policy-making, describing the energy-efficient system, and the role of private trains on the effect of middle-income groups, is the backbone of this book, which is being highlighted by the working professionals in the consultation with transportation commodities including both public and private players. We hope the book will greatly interest the professionals and postgraduate students involved in policy-making, planning, infrastructure development, and managerial aspects in transport and environmental research.

Vadodara, India — Ram Krishna Upadhyay
Vadodara, India — Sunil Kumar Sharma
Kanpur, India — Vikram Kumar
Kanpur, India — Hardikk Valera

Contents

1 Introduction to Transportation Systems Technology and Integrated Management 1
Ram Krishna Upadhyay, Sunil Kumar Sharma, Vikram Kumar, and Hardikk Valera

2 Climate Change Adaptation Strategies for Road Transportation Infrastructure: A Systematic Review on Flooding Events 5
Victor Hugo Souza de Abreu, Thaís Guedes Máximo Monteiro, Adriano de Oliveira Vasconcelos, and Andrea Souza Santos

3 Examining Effects of Introduction of Private Trains on Middle-Income Groups 31
Saksham Gaur, Sankarshan Mukherjee, and Ram Krishna Upadhyay

4 Energy-Based Assessment of Commercial Adaptive Cruise Control Systems 87
Theocharis Apostolakis, Michail A. Makridis, Anastasios Kouvelas, and Konstantinos Ampountolas

5 Optimum Production-Ordering Policy for a Vendor Buyer Co-Ordinated System Subject to Production Disruption 109
Amit Kumar Mishra, Purushottam Kumar Singh, and Santosh Kumar Mishra

6 Opportunities and Challenges for the New Hydrogen Economy: Advances in Renewable Hydrogen 121
Laís Ferreira Crispino Proença, Alberto Coralli, Fabio Souza Toniolo, Gabriella Machado Darze, Gabriel dos Santos Ribeiro Heluey, Gabriele Freitas Martins, Ruan Carlos Vidal Rodrigues de Oliveira, Paulo Emílio Valadão de Miranda, and Andrea Souza Santos

7 Corrosion Protection Practices and Integrity Management Challenges in Oil and Gas Pipeline 141
Hemalata Jena, Suchismita Satpathy, Sanjukta Sahoo, Sasmita Sahu, and Bijaya Bijeta Nayak

8 Role of Technology on the Management of Transportation 163
Richa Verma and Bipin Kumar Singh

9 A Study of Public's Perception of Parking Problems in Vadodara 181
Anuj Tiwari, Himanshu Raj, and Ram Krishna Upadhyay

10 Performance of Highway Subgrade Soil Stabilized with Lime and Slag 215
Nivedita Panda, Sanjukta Sahoo, and Hemalata Jena

11 Repositioning the Nigerian Rail System for Global Competitiveness: Tackling the Noisome Peculiarities 231
Olorunfemi Ayodeji Olojede, Folaranmi Olufisayo Akinosun, Oluwatimilehin Gabriel Oluborode, Henry Afolabi, and Peter Bolaji Oladeji

12 Mobile Aerial Ropeways Based on Autonomous Self-propelled Chassis: Layout of Technological Equipment 253
Alexander V. Lagerev and Igor A. Lagerev

13 Sustainability and Safety Challenges in Mining Transportation by Railway in India 287
Suchismita Satapathy, Hemalata Jena, and Sasmita Sahu

14 Performance of Ribs in Double Pass Jet Solar Air Heater: A Review 303
Purushottam Kumar Singh and Santosh Kumar Mishra

15 Optimising Transit Networks Using Simulation-Based Techniques 317
Obiora A. Nnene, Mark H. P. Zuidgeest, and Johan W. Joubert

16 A Survey of Various 2,5-Furandicarboxylic Acid-Based Renewable Polyesters 347
Kartikeya Shukla, Karuppan Muthukumar, and Santosh Kumar Mishra

17 Recycling of Platinum Group Metals and Alternative Catalysts for Catalytic Converters 363
M. K. Shukla, Balendra V. S. Chauhan, Thallada Bhaskar, Atul Dhar, and Ajitanshu Vedratnam

18 Two-Wheeler Electric Vehicles Purchase Policy 399
Apoorva Kashyap, Anshuman Bajpai, and Ram Krishna Upadhyay

19 Adaptability of Management in Transportation Systems 443
Archana Santosh Mishra and Sandipkumar G. Prajapati

20 Comparison of Economic Viability of Electric and Internal Combustion Engine Vehicles Based on Total Cost of Ownership Analysis 455
Deepak Kumar, Gautam Kalghatgi, and Avinash Kumar Agarwal

About the Editors

Dr. Ram Krishna Upadhyay is currently working as Assistant Professor at the National Rail and Transportation Institute, Vadodara, established by the Ministry of Railway, Government of India. He received his Ph.D. and M.Tech. from the Indian Institute of Technology (ISM) Dhanbad in Mechanical & Mining Machinery Engineering with a broad specialization in Surface Engineering and Tribology. Before joining NRTI Vadodara, Dr. Upadhyay has worked as Postdoctoral Fellow at the Indian Institute of Technology (IIT) Kanpur for over three years. His research interests include lubrication and materials wear for industrial application, tribology of additive manufactured parts, and nanocomposites. He is a recipient of the SERB-ACS NPDF Best Poster Competition Award by the Science and Engineering Research Board, New Delhi, and the American Chemical Society, USA. He published several journal papers, book chapters, edited a book, and completed a project funded by the Science and Engineering Research Board, New Delhi.

Dr. Sunil Kumar Sharma is an Assistant Professor and the Assistant Program Director of the Engineering and Applied Science Department at the National Rail and Transportation Institute Vadodara, established by the Ministry of Railway, Government of India. He received his Ph.D. from the Indian Institute of Technology, Roorkee. He worked at the Non-destructive Evaluation and Structural Health Monitoring Laboratory at C. N. University, South Korea. His research interests are vehicle dynamics, contact mechanics, mechatronics, and real-time software-enabled control systems for high-speed rail vehicles. He published several research articles in national and international journals. Dr. Sharma is also among the top 2% of scientists in a global list compiled by Stanford University, USA.

Dr. Vikram Kumar is currently at Indian Institute of Technology (IIT) Kanpur where he also received his Ph.D. in Mechanical Engineering. His areas of research include polymer and composite coating, wear, friction and lubrication, IC engine tribology, alternative fuels, advanced low-temperature combustion, engine emissions measurement, and particulate characterization. Dr. Kumar has edited 1 book and authored 7 book chapters and 16 research articles in international journals and conferences. He has been awarded with 'ISEES Best Ph.D. Thesis Award' (2018) and 'Senior Research Associateship' under 'SCIR-POOL Scientist' (2018–2021). He is Lifetime Member of ISEES.

Mr. Hardikk Valera is pursuing Ph.D. from Indian Institute of Technology (IIT) Kanpur. He completed his M.Tech. and B.Tech. from NIT Jalandhar (India) and Ganpat University, respectively. His research interests include methanol-fueled SI engines, methanol-fueled CI engines, optical diagnostics, fuel spray characterization, and emission control from engines.

Chapter 1
Introduction to Transportation Systems Technology and Integrated Management

Ram Krishna Upadhyay, Sunil Kumar Sharma, Vikram Kumar, and Hardikk Valera

Abstract Transportation is considered a key element in the development of a city. Urbanisation will not be possible without proper mobility and well-integrated transportation. Effective and dependable mass transportation networks are critical for the world to maintain its rapid economic development. Services and industrial sectors, in particular, are concentrated around large metropolitan centres, necessitating robust and dependable urban transportation networks to transfer jobs and link from the manufacturing plants to the supply chain. The importance of urban and rural transportation stems from its role in poverty reduction by enhancing access to labour markets and raising wages in disadvantaged communities. Availability and urbanisation sustainability are essential for fostering the long-term economic development of a city's growth in the world. Therefore, they are inextricably linked in spatial distribution, urban stock, flow growth, and built structure unification. However, due to car-centric strategies implemented by subsequent city plans and initiatives, urban mobility has not led to optimal outcomes. In terms of policy and organisational consequences, urban migration is multifaceted. As a result, coherence in policy initiatives and linkages between systems is critical. Improved connectivity is not accomplished by constructing additional bridges, rail lines, or cars, nor by implementing impromptu spatial measures such as traffic control strategies to achieve delocalisation and decongestion in isolation. Countries like India and cities with dense populations and inadequate infrastructure have always struggled to provide congestion-free urban transportation. Part of the reason for this is the weak public transportation systems of such cities. Such inefficient public transportation systems have reduced people's trust in these services. These problems should be tackled by providing a sustainable transport system. This book aims to deliver an effective

R. K. Upadhyay (✉) · S. K. Sharma
National Rail and Transportation Institute, Vadodara, Gujarat 390004, India
e-mail: ram.upadhyay@gsv.ac.in

V. Kumar
Mechanical Engineering Department, Indian Institute of Technology Kanpur, Kanpur 208016, India

H. Valera
Engine Research Laboratory, Indian Institute of Technology Kanpur, Kanpur 208016, India

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_1

way of providing a sustainable transport system by reducing all the inefficiencies pertaining to the different modes of transport and by giving better policymaking strategies.

Keywords Transportation · Railways · Management aspect · Corrosion · Public parking · Road infrastructure

The rhythm of mobility has emerged as a dynamic accelerated central in developing countries, those becoming more urbanised with urban transportation networks serving as the urban form's skeleton. Even though cities and towns have elevated levels of public transport, getting to locations, events, and facilities are becoming impossible concerning convenience, expense, and time. In reality, current rates of metropolitan transportation are causing disasters characterised by solid concentrations of traffic, atmosphere emissions, traffic deaths, and asymmetry, inevitably contributing to an unfavourable connectivity crisis. The resolution of the problem lies in the development of transport technologies with reliable solutions that can be accommodated in the existing facilities. Transportation technology includes the latest automated transportation systems, such as integrated transport information systems, advanced public transportation systems, adaptive cruise control systems, automatic collision systems, adaptive cruise control, advanced traffic management system, and other intelligent transportation systems, including sensors and wireless technologies, helps to improve road safety, comfort, and fuel efficiency, as well as reduce the number of accidents, traffic congestion, and commuter waiting time by providing green extension. Integrating management in the transportation sector has immensely paved the way for futuristic modifications with better-applied technologies and cost-effective productions in the public transportation sector. All the issues and developing technologies related to the country's transportation system are addressed in the book for insightful information to the policymakers willing to address the challenges and help develop better infrastructure for a reliable and safe transport network.

The book chapter is a collection of integrated technologies of the transport system. Firstly, flooding events on the climate change strategies for road infrastructure are addressed for better adaption involving hard and soft adaptions due to the criticality of the flooding event for guiding land-use decisions and evaluating adaptation strategies. It helps in decision-making for required strategies, including public policy guidelines, to make road infrastructure more resilient against the impacts of flood events caused by climate threats such as heavy precipitation, sea-level rise, and storm surges. This could undoubtedly make the road infrastructure resilient. In another work, the issue of private trains for the middle-income group is covered through public opinion. Safety and security remain the most prioritised dimensions for people, customer service, and service efficiency, followed by onboard technological facilities. Vehicle automation is regarded as one of the most promising technologies in transportation networks. Adaptive cruise control (ACC) systems are the most reliable speed monitoring/adjusting technology. The energy demand and fuel consumption for human-driven and ACC-engaged vehicles in experiment-like running conditions with various vehicle specifications are included. It is found that the system is less energy-efficient, revealing a tendency for upstream energy propagation inside the platoon and abrupt speed, resilient acceleration may negatively affect the energy impact. Another important issue is greenhouse gas emissions. New clean forms of energy production using renewable sources are the best practical way to stop climate change. This can be accomplished by renewable hydrogen uses, which can be utilised in hydrogen-powered vehicles. Hydrogen is available in excess, which can be easily obtained and stored for further use by many different processes. However, its production process should be controlled better so the energy requirement should be minimised. Also, the requirement of transportation hurdles can be controlled due to its gaseous nature compared to the other liquid resources. The integration of management in the transportation sector is also discussed, including the companies' strategic goals that facilitate the users at a high level of contentment with their performance and the challenges associated with public, logistics, and goods transportation. The planning, procurement, and lifecycle management stages are important factors in optimising the supply chain system. The application of business processes in the sphere of transportation services is made possible by the modification of transport and logistics systems. It's a good idea to embrace innovations that can improve supply chain efficiencies, such as robotic process automation, artificial intelligence, drones, autonomous cars, and the Internet of things. These technologies are essential as vehicle growth in recent times is increasing exponentially, leading to high road congestion. The reason for this is the increase in the city's overall population of private vehicles/middle-range vehicles. This could be controlled by the changing in the rules. Policymakers should keep proper guidance and information system for parking prices in mind and shift towards a multilevel parking system to increase the supply. It may be helpful to increase the parking fees that may discourage people from using private vehicles and shifting to public transport. A design procedure is discussed based on the mathematical modelling of an autonomous self-propelled wheeled chassis of high-load capacity mobile transport and overloading equipment. It can be used to rapidly create logistics infrastructure for the sustainable development of hard-to-reach areas with complex natural terrain and rapid deployment during transport operations in man-made disasters. A transit network design problem (TNDP), which deals with finding efficient network routes among a set of alternatives that best satisfies the conflicting objectives of different network stakeholders, including passengers and operators, is studied to improve a network's operational efficiency using simulation-based techniques. The simulation models are helpful in the transit network design and thus evaluate the stochastic behaviour of different stakeholders on a network. A transit network design using a support tool helps policymakers develop effective policy decisions relevant to the transportation realities for sustainable development. The electric vehicle purchase policy is also discussed to adopt an innovative alternative fuel technology. The study uses a survey to investigate the factors influencing the purchase of traditional two-wheeler and factors that will prompt a younger generation to purchase a two-wheeler electric vehicle in the near future. Factor analysis is conducted on the Likert scale data obtained through a questionnaire survey to club the various variables into a few factors for easier interpretation. The study attempted to understand the growing and ever-changing landscape of electric vehicle adoption in India and its various government programmes. The factors influencing the purchase of traditional two-wheelers were price, characteristics, and the vehicle's economic value. The factors influencing the adoption of electric two-wheelers were pricing, vehicle characteristics, and social contribution. In addition, the economic comparison between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) based on the total cost of ownership is reviewed based on economic sustainability. It is suggested that the cost of electric vehicles should be reduced significantly to make an environment-friendly sustainable transport system using electrification without letting an economic burden on the government.

The book contains various aspects of transportation, management, and policy-making to provide a better perspective towards a sustainable transportation system that can overcome present challenging issues. Particular topics covered in this book are as follows:

- Introduction to transportation technology and integrated management
- Climate change adaptation strategies for road transportation infrastructure: a systematic review on flooding events
- Examining effects of the introduction of private trains on middle-income groups
- Energy-based assessment of commercial adaptive cruise control systems
- Optimum production-ordering policy for a vendor buyer co-ordinated system subject to production disruption
- Opportunities and challenges for the new hydrogen economy: advances in renewable hydrogen
- Corrosion protection practices and integrity management challenges in oil and gas pipeline
- Role of technology in the management of transportation
- A study of the public's perception of parking problems in Vadodara
- Performance of highway subgrade soil stabilised with lime and slag
- Repositioning the Nigerian rail system for global competitiveness: tackling the noisome peculiarities
- Mobile aerial ropeways based on autonomous self-propelled chassis: layout of technological equipment
- Sustainability and safety challenges in mining transportation by railway in India
- Performance of ribs in double pass jet solar air heater: a review
- Optimising transit networks using simulation-based techniques
- A survey of various 2,5-furandicarboxylic acid-based renewable polyesters
- Recycling of platinum group metals and alternative catalysts for catalytic converters
- Two-wheeler electric vehicles purchase policy
- The adaptability of management in transportation systems
- Comparison of economic viability of electric and internal combustion engine vehicles based on total cost of ownership analysis.

Chapter 2
Climate Change Adaptation Strategies for Road Transportation Infrastructure: A Systematic Review on Flooding Events

Victor Hugo Souza de Abreu, Thaís Guedes Máximo Monteiro, Adriano de Oliveira Vasconcelos, and Andrea Souza Santos

Abstract During the last decades, the number of flooding events has increased significantly, due to the global trend of urbanization and climate change, becoming a recurring biophysical impact, resulting in major physical disruption to water and wastewater systems, life and economic losses, and damage to the critical infrastructure. For the road transportation sector, this reality is indisputable, as severe flooding events tend to severely damage the transportation infrastructure and reduce the network connectivity, increasing repair, maintenance, and construction costs. Thus, through a systematic literature review, with direct database searches and application of inclusion and qualification (quality and applicability) filters, a repository of 213 publications on adaptation strategies applied to reduce the impacts of flooding on road infrastructure is developed. Most of these studies have been published since 2014, due to the publication of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. It should also be noted that, of the overall total, only 47% of studies deal specifically with the road transportation sector (the remaining 53% cite the sector only as an example), thus demonstrating the urgency of further studies on the topic. It should also be noted that the climate risk assessment, involving the creation of current and future flood risk maps, is essential for determining the best climate change adaptation strategies for road transportation infrastructure. As flood damages and costs are largely and strictly site-specific, analyses are critical for guiding land use decisions and evaluating adaptation strategies that can be divided into hard adaptation (optimization or redesign of hydraulic components, installation of protective structures and optimization of environmental conditions) and soft adaptation (creation

V. H. S. de Abreu · A. S. Santos (✉)
Sustainable Transport Laboratory (LabTS), Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE), Federal University of Rio de Janeiro (UFRJ), Transport Engineering Program, Rio de Janeiro, Brazil
e-mail: andrea.santos@pet.coppe.ufrj.br

T. G. M. Monteiro
Environmental Postgraduate Course, COPPE-UFRJ, Rio de Janeiro, Brazil

A. de Oliveira Vasconcelos
Laboratory for Computational Methods in Engineering (LAMCE), COPPE/UFRJ, Civil Engineering Program, Rio de Janeiro, Brazil

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_2

of transportation-focused master plans and development of quantitative models and systems).

Keywords Climate change · Impact · Flooding · Road infrastructure · Adaptation

2.1 Introduction

Flooding events have become a frequent biophysical impact in recent years, constituting one of the most severe and potentially devastating natural disasters, especially in the urban context due to impervious surfaces [1–7]. This biophysical impact ends up by causing not only major physical disruption to water, but also significant life and economic losses [8–10], and thus, well-planned decision making is necessary to reduce damages to infrastructure [11], such as electric, road and rail and sewage networks [12]. It is estimated that the larger the area affected by flooding, the greater the damage to the infrastructure and the disruption of its services, resulting in increased operational and maintenance costs [7, 13–15]. Impacts range from completely destroyed bridges and sewage systems to severely damaged schools and hospitals [16].

Specifically in relation to the transportation sector and its infrastructure, which underpins economic activities by enabling the movement of goods and people [17], depending on severity, floods can cause lane closures and reduced system capacity, leading to bottlenecks and congestion [14, 15]. Severe flooding events can damage transportation infrastructure—loss of its useful life—and reduce network connectivity, as well as increase repair, maintenance, and construction costs [18]. The cost of disruption due to flooding has been estimated at £100,000 at peak times for each major road affected in the UK—tangible effects [19], not to mention the incalculable cost of flood-related deaths as a result of vehicles being driven over flooded roads—intangible effects [20].

To make this situation worse, the number and severity of flood damage in urban areas will continue to increase in the coming decades due to the global trend of urbanization and climate change [7, 10, 21]. To have an idea, the expected annual damage from surface water flooding in UK, for example, may increase by 135% by 2080 under the future climate scenario [22]. The limited and in some cases insufficient adaptive capacity of the road infrastructure to withstand extreme hydrological events may to some extent be due to knowledge and methodological gaps regarding adequate adaptation to climate change [23].

Thus, implementing adaptation measures while considering climate risk analysis under a variety of future scenarios is crucial for establishing a long-term sustainable urban drainage system [24]. Thus, this paper conducts a relevant and current systematic investigation with a bibliometric approach with a focus on studies published in the last decade. Comprehensively, a review is performed to conduct this state-of-the-art research with emphasis on the impacts of flooding events resulting from climate change on the road infrastructure and climate risk assessment, as well as the corresponding climate change adaptation strategies and planning issues, with a focus on increasing awareness and knowledge as a basis for effective actions. Following this introduction section, Sect. 2.2 indicates the methodological procedure used to conduct this state-of-the-art research. Section 2.3 presents the research results with respect to biometric analyses and Sect. 2.4 with respect to systematic analyses—critically analyzing the selected studies. Finally, Sect. 2.5 concludes this paper and presents some suggestions for next research directions.

2.2 Methodological Procedure

With the growing increase in climate threats and biophysical impacts resulting from climate change, the need for studies on the subject has become even more urgent [14, 15]]. Thus, systematic reviews provide a range of extremely relevant results, preventing the limitation of conclusions with the reading of insufficient content or few studies. The reason is that, unlike simpler and more traditional reviews, systematic reviews aim to avoid biases that may appear in each phase from a rigorous method of (i) search and selection; (ii) evaluation of the relevance and validation of results; (iii) collection; (iv) synthesis; and (v) data interpretation [25]. In turn, bibliometric analysis, which is one of the main strategies used for the compilation and development of knowledge about scientific productions [26], is a quantitative–qualitative research method used in the analysis of sets of graphical descriptions of documents [27], offering convenient analysis methods due to the reference to codified knowledge, use of measurable data, and data availability [28] and providing information that assists researchers in identifying gaps to be explored in future research [29].

Thus, to obtain information about the impacts of climate change on the road transport infrastructure, with a focus on the biophysical impact of flooding, a systematic review with a bibliometric approach was developed to identify and analyze relevant studies (quality and applicability). It is worth noting that this research is based on the work of Abreu et al. [30], who sought to identify adaptation measures for various climate threats and their corresponding biophysical impacts. This review, which includes relevant studies preferably published in the last decade, allows researchers to identify emerging issues and associated themes, understand how these concerns and themes have evolved over time, and identify the challenges to be faced in the future. This paper also conducts a comprehensive review of state-of-the-art data on climate adaptation in the road transportation sector, with a focus on minimizing the impacts of flooding events. To this end, the systematic literature review consists of three phases, namely (i) systematic review protocol; (ii) direct and documentary searches; (iii) data processing; and (iv) developing the research repository and obtaining results.

In the first step, there is the definition of the most relevant keywords for the efficient conduction of the research, as well as the definition of the inclusion and qualification criteria, as summarized in Table 2.1. It is noteworthy that it was considered relevant to use combinations between some keywords directly related to climate change and

Table 2.1 Description of the research strategies

Criterion	Description
Database	*Web of Science* and *Scopus*
Topics	*Web of Science - TS = ('climate change' AND 'road infrastructure' AND 'adaptation' AND 'flood*') OR TS = ('climate change' AND 'highway infrastructure' AND 'adaptation' AND 'flood*')) OR TS = ('climate change' AND 'pavement' AND 'adaptation' AND 'flood*') OR TS = ('climate change' AND 'road infrastructure' AND 'adaptation' AND 'inundation') OR TS = ('climate change' AND 'highway infrastructure' AND 'adaptation' AND inundation)) OR TS = ('climate change' AND 'pavement' AND 'adaptation' AND inundation)* *Scopus - (TITLE-ABS- KEY ('climate AND change' AND 'road AND infrastructure' AND 'adaptation' AND 'flood*') OR TITLE-ABS-KEY ('climate AND change' AND 'highway AND infrastructure' AND 'adaptation' AND 'flood*') OR TITLE-ABS-KEY ('climate AND change' AND 'pavement' AND 'adaptation' AND 'flood*') OR TITLE-ABS- KEY ('climate AND change' AND 'road AND infrastructure' AND 'adaptation' AND 'inundation') OR TITLE-ABS- KEY ('climate AND change' AND 'highway AND infrastructure' AND 'adaptation' AND 'inundation') OR TITLE-ABS-KEY ('climate AND change' AND 'pavement' AND 'adaptation' AND 'inundation'))*
Search Method	Direct Search
Inclusion	I1: Time of coverage: all years in the database (1945–2021), although special focus was given to the most current studies—last ten years (2011–2022); I2: Source Relevance
Qualification	Q1: Are the study objectives clearly identified? Q2: Does the research present a well-reasoned literature review? Q3: Do the research methods support the study objectives? Q4: Does the study present technical innovation? Q5: Are the contributions discussed? Q6: Are limitations explicitly stated? and Q7: Are the results and conclusions consistent with pre-established objectives?
Search Date	January 02, 2022, at 7:00 pm

other keywords directly related to road transport. The choice of keywords and their combinations considered a brainstorming process to choose the most relevant terms and, subsequently, a team composed of academicians and professionals in the transportation area refined these keywords to provide a solid validation, according to the same as that established by Wang et al. [31]. It should be noted that both TS and TITLE-ABS-KEY indicate the keywords that will be searched in the title, abstract, and keywords of included studies, respectively, in the Web of Science and Scopus databases.

In the second step, searches are conducted in two main databases: (i) Scopus and (ii) Web of Science. In addition, documentary searches were carried out in important databases of scientific bodies and initiatives that deal with climate change such as the IPCC—Intergovernmental Panel on Climate Change, the National Research Council and the World Bank Group. This type of research was considered more adequate to the context of the development of lists of adaptation measures (Hard adaptation and Soft adaptation) applied to floods. At this stage, the initial research repository consisted of 514 studies.

Step 3 consisted of data processing, which consists of consolidating and organizing data to produce technical information necessary for the efficient conduct of the research. Since different databases can provide the same studies, the EndNote bibliographic management software was used to organize data and remove duplicate content. This step provided the necessary research repository for subsequent bibliometric and systematic analyses, finally considering the biophysical impacts of flooding. In it, 188 duplicate studies and 113 studies that did not meet the inclusion and qualification criteria (quality and applicability) were excluded, so the final research repository consisted of 213 studies.

Finally, Step 4 consisted of the development of the research report and the obtaining of results, expressed here as an article containing the knowledge produced from the research analyses. It is noteworthy that, to perform bibliographic and systematic analyses, several other computer programs were used, such as Excel for the creation of simpler graphs like the evolution of publications and citations per year, VOSviewer for the generation of interconnection maps between keywords, Tableau for the creation of maps of publications per country under investigation, among others.

2.3 Bibliometric Analysis

With the creation of the research repository, it was possible to conduct several bibliographic analyses, as exposed throughout this section and, that way, we sought to evaluate studies according to their year of publication. Thus, according to Fig. 2.1, after the publication of the Fifth Assessment Report [32], the number of publications grew steeply, peaking in 2020. To have an idea, the sum of studies until 2013 corresponds to approximately 14% of all publications, and the years 2020 and 2021 alone accounted for 13% and 12% of publications, respectively. All this indicates that

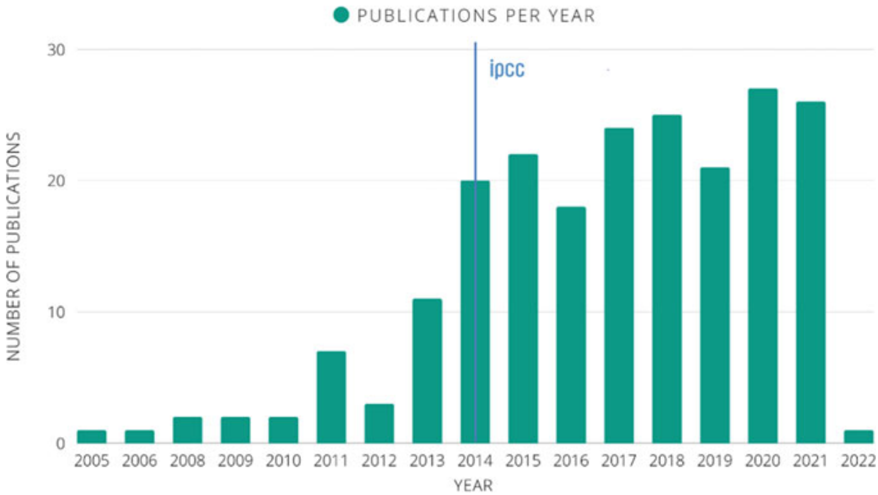


Fig. 2.1 Evolution of publications by year

the topic has become more popular in recent years and is likely of growing further with new IPCC publications, forecast for the year 2022. It is noteworthy that similar results were also found by Abreu et al. [30], who conducted a more comprehensive systematic review, considering impacts not only from flooding events but also from soil and rock slides, erosion, fires, and direct impacts from high temperatures.

Subsequently, it was possible to verify which are the main sources of publication of studies, as identified in Fig. 2.2, which shows that a large part of the studies—approximately 70%—consists of articles (many of them published in large journals with blind peer-review process, which gives greater relevance to the process), followed by reviews and conference proceedings, with global reach. This indicates a wide range of scientific exploration in the area under investigation.

Another interesting analysis is to find out which journals publish most studies on the theme, as well as their impact factor, according to Table 2.2. This analysis allows directing submission efforts to journals aligned with the scope of studies, so that researchers do not waste unnecessary time submitting their studies to journals that are not interested in the subject being investigated.

Table 2.2 shows that the journals that most stand out in terms of number of publications are Journal of Infrastructure Systems, Sustainability (Switzerland) and Climatic Change. In addition, when ordering them by Impact Factor, Science of the Total Environment, Transportation Research Part D: Transport and Environment, and Climatic Change stand out, all with IF greater than 4.7, demonstrating that the subject is covered in important journals.

Special emphasis can also be given to studies most cited in the Research Repository, as presented in Table 2.3. Sometimes, many citations of a scientific publication may prove to be an indicator of innovation (a new idea, method, discovery, etc.), which should be further investigated by those interested in working on the subject

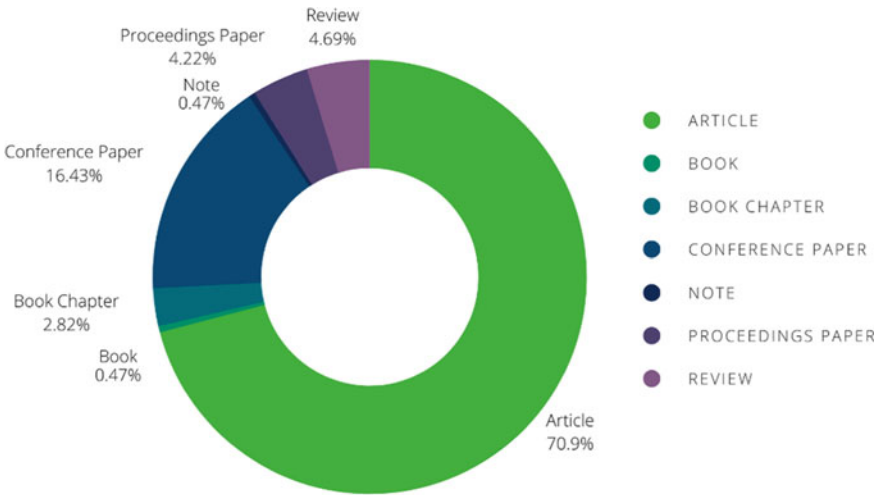


Fig. 2.2 Publications by type of document

Table 2.2 Publications by journal

Journal	Publications (%)	Impact factor (2020)
Journal of Infrastructure Systems	4.4	2.411
Sustainability (Switzerland)	4.4	3.251
Climatic Change	3.4	4.743
International Journal of Disaster Risk Reduction	3.0	4.320
Transportation Research Record	3.0	1.560
Transport Policy	2.0	4.674
Regional Environmental Change	1.5	3.678
Science of the Total Environment	1.5	7.963
Transportation Research Part D: Transport and Environment	1.5	5.495
Water (Switzerland)	1.5	3.103

[33]. In this regard, based on citations from the Web of Science database, it is identified that the most cited studies are Zahmatkesh et al. [34], Dong et al. [24] and Mei et al. [35], all with more than 95 citations. In addition, it was also possible to identify the average number of citations per year (CpY), where top ranked studies are Mei et al. [35], Dong et al. [24] and Argyroudis et al. [36], respectively.

The possibility of creating a network of interconnection between keywords, according to Fig. 2.3, is also worth mentioning. In this figure, it is possible to highlight very recurrent and even intuitive keywords, due to the search topics considered (see Table 2.1) such as “Climate Change,” “Sustainability,” and “Climate change adaptation” and “Roads and Streets."

Table 2.3 Most cited studies

Reference	Title	Biophysical Impact	Journal	Total citation	CpY
Zahmatkesh et al. [34]	Low-impact development practices to mitigate climate change effects on urban storm water runoff: Case study of New York City	Flood, mostly	Journal of Irrigation and Drainage Engineering	117	16.7
Dong et al. [24]	Enhancing future resilience in urban drainage system: Green versus gray infrastructure	Flood, mostly	Water Research	97	19.4
Mei et al. [35]	Integrated assessments of green infrastructure for flood mitigation to support robust decision making for sponge city construction in an urbanized watershed	Flood	Science Of The Total Environment	96	24.0
Selva et al. [37]	Roadless and low-traffic areas as conservation targets in Europe	Flood/soil and rock displacement/forest fires	Environmental Management	94	8.5
Charlesworth [38]	A review of the adaptation and mitigation of global climate change using sustainable drainage in cities	Flood/high temperatures	Journal of Water and Climate Change	82	6.8
Sterr [39]	Assessment Of Vulnerability And Adaptation To Sea-Level Rise For The Coastal Zone Of Germany	Flood/erosion	Journal Of Coastal Research	81	5.8

(continued)

Table 2.3 (continued)

Reference	Title	Biophysical Impact	Journal	Total citation	CpY
Neumann et al. [42]	Climate change risks to US infrastructure: impacts on roads, bridges, coastal development, and urban drainage	Flood/erosion	Climatic Change	79	11.3
Chinowsky et al. [40]	Assessment of climate change adaptation costs for the US Road network	Flood/erosion	Global Environmental Change	57	6.3
Argyroudis et al. [36]	Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience	Flood/earthquake/soil and rock movement/erosion	Reliability Engineering & System Safety	51	17.0
Pregnolato et al. [8]	Impact of climate change on disruption to Urban transport networks from pluvial flooding	Flood	Journal of Infrastructure Systems	51	10.2

The presence of other interesting keywords such as "Risk Assessment," "Vulnerability Assessment," "Deterioration," and "Cost-effectiveness" should also be highlighted. It is also noteworthy that this network presents 1,606 items, 36 clusters, 28,943 links with total size of 32,764. In addition, it is also possible to rank the main keywords, as shown in Table 2.4.

2.4 Systematic Analysis

Subsequently, with a thorough reading of studies included in the research repository, systematic analyses can be performed, which allow for the effective and continuous assimilation of this large volume of available information in vast areas of knowledge through a rigorous methodology by searching for results [41]. In the first systematic analysis, it was observed that not all studies included in the database present road transport as the focus of their research, many of them (about 53%) deal with critical

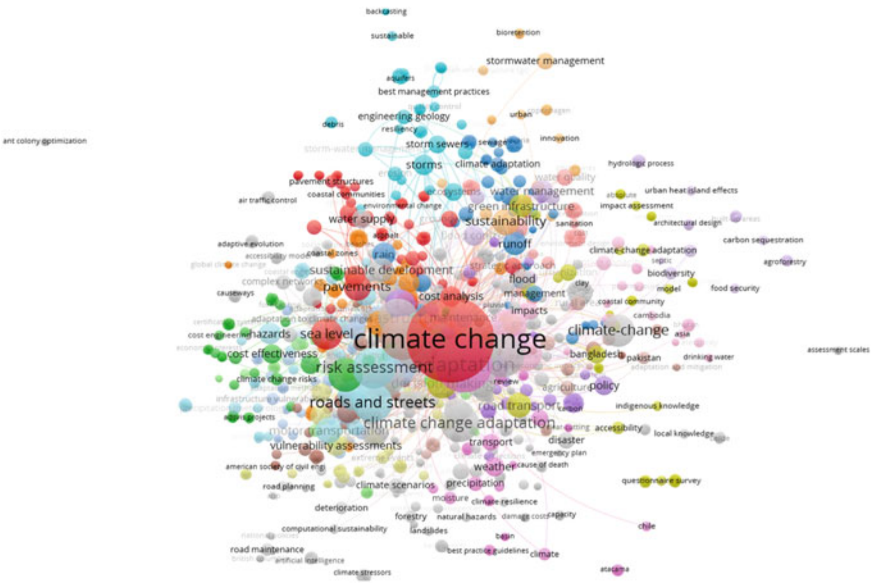


Fig. 2.3 Interlinking network between keywords

Table 2.4 Keyword ranking

Keyword	Number of occurrences
Climate Change	134
Adaptation	58
Floods	36
Flooding	33
Adaptive Management	30
Risk Assessment	32
Roads and Streets	28
Infrastructure	28
Climate change adaptation	26
Vulnerability	26
Transportation	24
Resilience	23
Climate effect	21
Climate models	21
Sea Level	18
Decision Making	16
Adaptation strategies	16

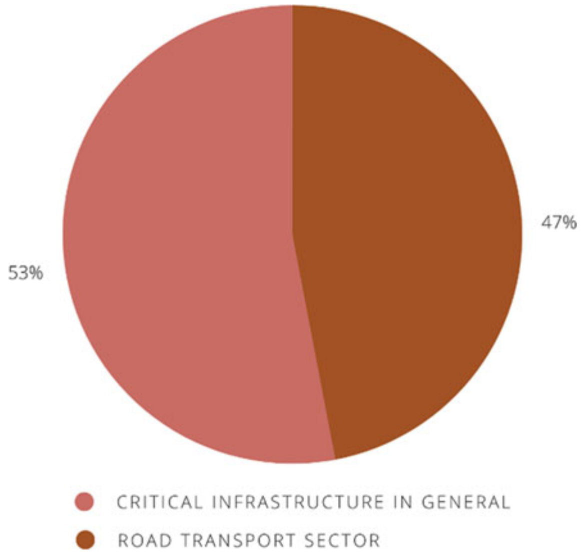


Fig. 2.4 Publications by focus

infrastructure in general and bring some reflections on the road sector, as can be seen in Fig. 2.4, also showing the scarcity of relevant studies on the sector.

Another interesting analysis is to verify which regions have been the focus of studies, especially case studies, on the theme, as expressed in Fig. 2.5. It should be noted that this analysis is different from that, which seeks to investigate the countries of educational institutions in which studies included in the research repository were carried out, because researchers from a given country may investigate a problem present in another country with higher degree of vulnerability and exposure to climate threats. In this regard, there is significant highlight for countries such as the USA (e.g., Chinowsky et al. [40]; Zahmatkesh et al. [34]; Neumann et al. [42]), with 38 publications (18% of the total), Canada (e.g., Denich and Zaghal [43]; Picketts et al. [44]; Abkowitz et al. [45]), with 17 publications (8% of the total), and the UK (e.g., Arkell and Darch [46]), with 15 publications (7% of the total). Together these three countries account for 33% of the publications.

It is also noteworthy that although the three countries above represent the developed North, a continuous effort to investigate the topic in developing countries of the South has been observed, with studies published in African countries (e.g., Arndt et al. [47]; Le Roux et al. [48]; Njogu [13]) and Asian countries (e.g., Chinowsky et al. [49]; Mukesh and Katpatal [7]) being increasingly frequent. This is necessary because many of developing countries react (significant spending in the recovery phase) rather than being proactive in managing the effects of flooding events on the infrastructure, being clearly demonstrated by the inadequate level of preparedness experienced before, during, and after flood events. To make this situation worse, existing literature indicates that the increase in flood events is further constraining

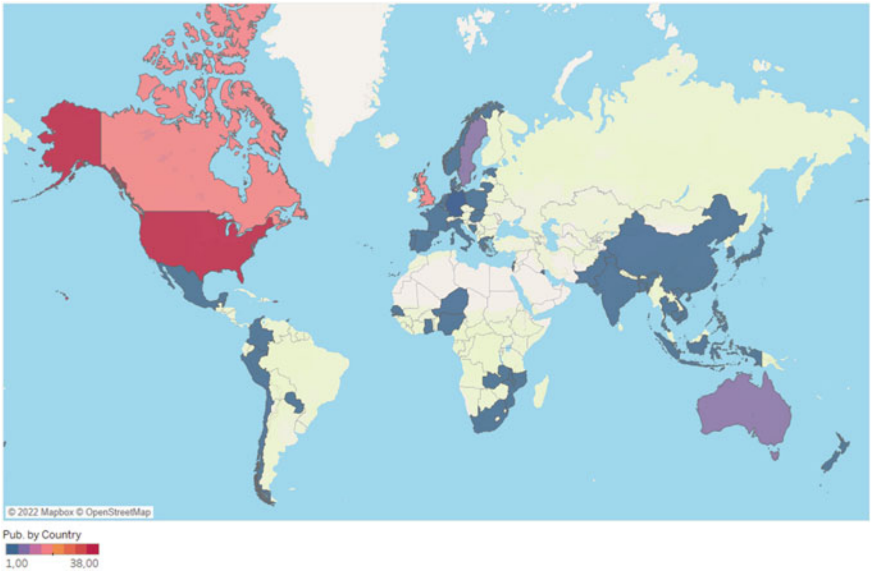


Fig. 2.5 Division of studies by country under analysis

national budgets as countries struggle to allocate more resources in response to natural disasters [13].

It should also be noted that for the construction of the map presented in Fig. 2.5, the federal level (representing which country is being investigated) was considered; i.e., even if the climate risk was specifically assessed for a given city (municipal level), the study was considered as belonging to that country. In this context, Fig. 2.6 seeks to determine which jurisdiction levels (local, municipal, state, federal, regional, or continental), studies were aimed at. It is emphasized that due to the specific and pervasive nature of climate change impacts, adaptation measures need to be taken at all levels, from local to regional to national [32]. Thus, it was observed that, although the federal level presents higher proportion of studies (27%), there is a certain balance among scopes, including strong participation of state, municipal, and local levels. Also on this subject, it is noteworthy that countries with continental dimensions such as the USA and Canada usually conduct analyses in specific cities or even neighborhoods and communities (local analyses) (e.g., Porter et al. [50]). Local communities, especially in developing countries, play a critical role in flood response and recovery (resilience) [13].

Global climate change is believed to induce transformation in the spatiotemporal rainfall distribution and magnitudes [51]. Thus, increased frequencies and patterns of high-intensity precipitation are predicted [6, 21, 52–56], which, as presented in Fig. 2.7, is the most ascertained climate threat in flood studies. Heavy rainfall generally causes surface flows that result in drainage systems that exceed their capacity and thus increase the likelihood of being blocked by Debris [13]. Subsequently, there are

Fig. 2.6 Publications by scope

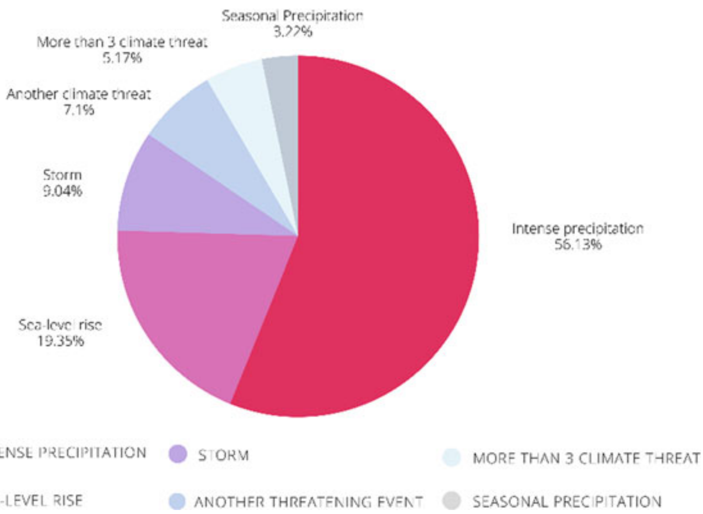


Fig. 2.7 Publications by type of climate threat

sea-level rise in coastal areas (e.g., Dasgupta et al. [57]; Heberger et al. [58]; Sadler et al. [59]), storm surges (e.g., Heberger et al. [58]; Bollinger et al. [60]; Sadler et al. [59]), and seasonal precipitation. It is also noteworthy that climate threats with less recurrence were grouped into another climate threat category, which corresponds to cyclone; freeze/thaw cycles; hurricane; typhoon; and tsunami.

Planning the impact of flooding events on the infrastructure is essential in building resilient road transport infrastructure. An important first step in adapting to increased flood risk is to identify the infrastructure most vulnerable to flooding—through, for example, creating a flood vulnerability map (taking into account aspects related to sensitivity and adaptive capacity)—so that physical and economic resources can be prioritized [4, 61]. These vulnerability maps combined with climate threat and exposure maps to perform climate risk assessment, which should also involve climate projections, must be developed considering relevant and standardized data so that the analyses expressed on them correspond as closely as possible to reality. Risk analysis serves as an important screening tool to help stakeholders better understand where to focus their resources when considering potential adaptation measures and as a catalyst to facilitate a more proactive approach to increase transportation resilience to extreme weather events [45]. In particular, road authorities and environmental managers need useful data and combinations of climate risk analysis methods to identify and assess the most critical road sections [62, 63]. In addition, it is necessary to develop public policies (through laws, decrees, etc.) that support increased resilience of road infrastructure, including the need for a review of construction and operating standards.

However, there are still few studies that have used data-driven approaches with Geographic Information System (GIS) mapping—including critical asset location intelligence system—and integration of various physical catchment features to assess flood risks at large scales [63–65]. Since flood damages and costs are highly site-specific, regional analyses are critical for guiding land use decisions and evaluating adaptation strategies [58]. Thus, policymakers need to know the factors that contribute to increased exposure, vulnerability, and eventually flood risk in a given geographic area [13]. Figure 2.8 shows that the keyword "Risk Assessment" has 32 recurrences in the database (15% of the total), 15 clusters, and 433 links/connections, being connected to other keywords such as “Risk Perception,” “Cost-Effectiveness,” and “Climate Change Adaptation.”

Response to impacts can be thought of not only in terms of actions or reactions to flooding events (evacuation, sheltering, road closures, sending rescue teams, etc.), but also the long-term adaptation strategies that may require protection, accommodation, or removal from risk areas [66]. Whenever and wherever any of these types of floods occur, long-term planning and adaptation, preparedness, and response time are critical factors in reducing overall impacts [4]. In dealing with climate change impacts, adaptation strategies focused on long-term perspective tend to be more effective or cost-efficient than reactive or ad hoc responses aimed at achieving a temporary goal [67].

It is undeniable that the gray infrastructure, which usually refers to centralized and human-engineered water management approaches, including pipes, pumps, ditches, detention and drainage ponds, and sewage systems [10], is needed to deal, especially, with episodes of intense precipitation [68]; however, simply continuing to increase the gray infrastructure capacity, a practice that has lasted for centuries, is considered unsustainable due to pressures associated with climate change and ongoing urbanization [69]. As an alternative to traditional gray infrastructure, green infrastructure has been applied in many countries to mitigate urban flooding since the 1990s [10, 35, 70].

During intense precipitation and storm events, for example, green infrastructure can process water body by infiltration, evapotranspiration, or runoff reuse, thereby

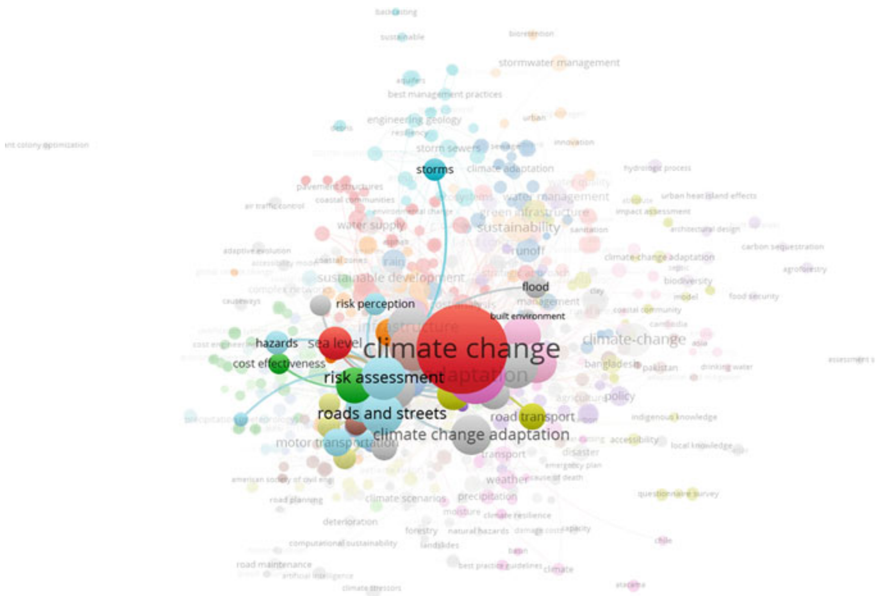


Fig. 2.8 Linking network with the keyword "Risk Assessment"

relieving pressure on the aging or undersized sewer system, avoiding combined sewer overflows and the need for energy-intensive floodwater pumping [71, 72]. In this regard, green infrastructure (green roofs, permeable paving surfaces, storage tanks, etc.) has become increasingly important for urban storm water management due to the effects of climate change and urbanization [35, 73].

However, despite the great effectiveness of the urban green infrastructure in alleviating storm water runoff, there is comparatively little research for planners and designers to determine an appropriate strategy for green infrastructure planning [10]. To minimize this situation, there is also the possibility of using blue-green infrastructure, which is commonly incorporated into sustainable drainage systems [74]. Blue-green refers to infrastructure aimed at restoring the naturally oriented water cycle while contributing to convenience, bringing together water management and green infrastructure [75]. All these structural modifications can be called hard adaptation, according to examples listed in Table 2.5.

Traditionally, solutions have been mainly focused on technical and engineering responses, but the last decades suggest holistic approaches on the best ways to create resilience during infrastructure planning and implementation [13, 30]. Thus, in addition to structural adaptations (gray infrastructure, green infrastructure, and blue-green infrastructure) also called hard adaptation—there are also soft adaptations such as policies, land use allocations, education, and social engagement. These adaptations, which can in many cases also be applied to other biophysical impacts such as soil and rock displacement, erosion, and high temperatures, involve change in behavior,

Table 2.5 Adaptation in road infrastructure—hard adaptation—in the face of flooding

Hard adaptation	Adaptation measures	References
Optimization or redesign of components	Increasing the capacity of the storm water drainage system	Zimmerman and Faris [76]; ADB [77]; Nazarnia et al. [78]
	Increase the number of stations or pumping capacity on highways	Nazarnia et al. [78]; SUTP [79]
	Improve maintenance of drains and culverts	Chapman [80]
	Replacement of impermeable road surface with permeable material in vulnerable areas—Installation of permeable paving	Pregnolato et al. [8], Vajjarapu et al. [81]
	Identification of storm water retention areas to divert excess storm water	Nazarnia et al. [78]
	Increase and protect signage and other electrical equipment	SUTP [79]
	Increase redundancy in electrical systems	SUTP [79]
	Upgrade the tunnel lining to prevent groundwater infiltration	SUTP [79]
	Construction of redundant infrastructure	Vajjarapu et al. [82]; SUTP [79]
	Elevate the road infrastructure	SUTP [79]
	Redesign or relocate road facilities	ADB [77]
	Build roads with thicker base and or subbase, changing road surface materials, or implementing policies to reduce vehicle miles traveled and road stress	Chinowsky et al. [40]
	Installation of WellPoint dewatering technology for permanent use	Nazarnia et al. [78]
	Installation of hard protection to provide a barricade against water ingress	ADB [77]; Nazarnia et al. [78]
	Installation of soft protection that includes natural sedimentation barriers and forests, and wetlands to create a buffer zone	DTTAS [83]; Nazarnia et al. [78]

(continued)

Table 2.5 (continued)

Hard adaptation	Adaptation measures	References
Installation or improvement of protective structures	Improve flood defenses	Chapman [80]
	Use of mobile barriers to prevent water from entering tunnels and underground transit systems	SUTP [79]
	Create accommodations related to reducing the severity of damage, such as raising and modifying infrastructure to reduce the impact of flooding	Nazarnia et al.[78]
Optimization of environmental conditions	Modification of drainage patterns	Bollinger et al. [60]
	Alteration of subsoil composition	Bollinger et al. [60]
	Increase the use of vegetation	Bollinger et al. [60]; DTTAS [83]

regulation, or management system [83]. Thus, a list of possible adaptation measures suitable for this context is presented in Table 2.6.

It is also noteworthy that climate change needs to be integrated into the spatial and community planning process to empower communities to adapt to them. Therefore, if planners have adequate knowledge about climate change and if they guide the participatory and collaborative planning process (thus reflecting local knowledge and suggestions), it is possible to consider climate change adaptations in the context of spatial and community planning [73].

Furthermore, it is important to consider the cascading effects associated with flooding events on the critical infrastructure such as the water supply, civil construction and agriculture sectors, because infrastructure exists as large-scale interconnected networks, which can lead to the propagation of faults, so that impacts extend far beyond flooded areas and/or flooding periods [13]. Thus, studies focused on identifying: (i) common impact metrics; (ii) elements vulnerable and exposed to flooding; (iii) similarities and differences of methodological aspects between different networks; and (iv) risks due to systemic interdependence should be developed [86]. In addition, computational models that investigate the impacts of direct and indirect connections between infrastructure systems, explore their relative importance in the network, and prioritize the associated risks for more efficient resource allocation should also be developed [87].

Table 2.6 Non-structural adaptation—soft adaptation—in the face of flooding

Soft adaptation	Adaptation measures	References
Master plans to control the form of urban development with focus on the transportation sector	Incorporate adaptation clauses into national investment in transportation infrastructure	DTTAS [83]
	Development of climate-sensitive policies, legislation, and development plans that reference resilience to protect infrastructure from known and anticipated climate risks	NJOGU [13]
	Land use planning	Chapman [80]; Nazarnia et al. [78]
	Periodic review of risk maps	ADB [77]; Chapman [80]
	More frequent and enhanced inspection of affected sites	URS [84]; SUTP [79]
	Prioritization of remedial works for sites assessed as most at risk of service interruption failures	URS [84]
	Improve integrated spatial planning in relation to road alignments to ensure that adjacent critical ecosystems, which serve as buffers against flooding, are maintained and protected	ADB [77]
	Increase resilience in the asset renewal phase	URS [84]; SUTP [79]
	Special attention to adaptation in critical evacuation routes	Nazarnia et al. [78]
	Improve weather forecasting capability and implement early warning systems	SUTP [79]
	Banning development in flood zones, recognizing the inherent cost of building in flood-prone areas	Vajjarapu et al. [82], Nazarnia et al. [78]
	Relocation, or even abandonment, of critical roads located in flood zones	Löwe et al. [85] and Nazarnia et al. [78]
	Enhance adaptive capacity in scalable, modifiable, and widely diverse ways	Zimmerman and Faris [76]

(continued)

Table 2.6 (continued)

Soft adaptation	Adaptation measures	References
	Assess the ability of the infrastructure to withstand the most extreme floods predicted as a result of climate change	URS [84]
	Conduct a mid-term review of statutory critical infrastructure adaptation plans with possible input from relevant stakeholders	DTTAS [83]
	Redirect priority passenger and freight traffic routes	Nazarnia et al. [78]
	Improve climate risk management by identifying critical infrastructure	Zimmerman and Faris [76]
	Encourage the use of new technologies, such as sustainable drainage systems, which will reduce existing and future flood risks	URS [84]
	Identify the location and functional strength of interdependencies between sectors	Zimmerman and Faris [76]
	Stakeholder participation, engagement and support—encouraging stakeholder involvement with climate adaptation needs and building resilience	Bollinger et al. [60]; DTTAS [83]; SUTP [79]; NJOGU [13]
	Creation of dynamic adaptation approaches, avoiding the predominance of solutions locked into single pathways or irreversible action courses	Zimmerman and Faris [76]; SUTP [79]
	Dissemination of Progress Report on Implementation of Transportation adaptation measures to representatives or advocates of accessibility and other interested sectors	DTTAS [83]
	Increase public awareness and capacity to act in flood situations	Zimmerman and Faris [76]

(continued)

Table 2.6 (continued)

Soft adaptation	Adaptation measures	References
	Disseminate geospatially distributed impact maps to transportation stakeholders	DTTAS [83]
	Develop appropriate monitoring indicators to assess the effectiveness of adaptation measures	DTTAS [83]
	Strengthen sectoral adaptation responses, ensuring that climate resilience is considered in assessment guidance	DTTAS [83]
	Effective integration with other sectors in the planning and development process	DTTAS [83]
Development of quantitative models	Review the effectiveness of current quantitative data collection procedures for the impacts of extreme weather events and long-term climate change with the aim of developing a cross-sectoral reporting mechanism	DTTAS [83]
	Ensure sectoral understanding of up-to-date climate information, including observational summary of long-term climate modeling results	DTTAS [83]
	Develop modeling and simulation techniques to represent and analyze the complex sets of interactions triggered by climate threats	Bollinger et al. [60]

2.5 Final Considerations

This study sought to review studies on the impacts of floods caused by climate change on the road infrastructure based on critical dimensions such as climate risk assessment, asset management, and other issues during the adaptation planning implementation. The review served to demonstrate the urgency for studies focusing on this theme, which is still in the expansion phase, especially since 2014, with the publication of the AR5 [32], having aroused a growing interest from journals with international prestige.

It is also important to highlight the researchers' concern with the adaptations inherent to northern countries, highlighting the excessive cost of the process. In addition, it is noted that, although developed northern countries hold the largest amount of research on the impacts of floods, great effort of researchers to investigate existing problems in developing southern countries such as countries in Africa and Asia has been identified, which are among the worst affected.

The main adaptation measures that can be applied in the context of climate change-induced floods were also reviewed, separating them into hard adaptation (i.e., structural measures) and soft adaptation (i.e., more institutional and governmental measures). It is believed that this literature review will serve to guide decision makers on the best strategies needed, including public policy guidelines, to make road infrastructure more resilient to the impacts of flood events caused by climate threats such as heavy precipitation, sea-level rise, and storm surges.

Finally, it is believed that the present study provides: (i) intensive coverage of the existing literature on adaptations in the flooding context, both hard adaptation and soft adaptation; (ii) exploration of current gaps and challenges; and (iii) engineering and management perspective of directions to be useful to engineers, committee consultants, policymakers, and academicians for future studies.

However, limitations of this study include that we have not identified which adaptation measures represent combined mitigation and adaptation efforts specifically for flooding events. Furthermore, it is advisable that new systematic review studies be developed considering other biophysical impacts less studied in the literature such as erosion and fires. In addition, case studies should be developed that make use of climate risk assessment, using threat, exposure, and vulnerability (sensitivity and adaptive capacity) indicators, to identify the most vulnerable regions (hot spots), as well as the creation of prioritization methods for climate change adaptation strategies.

Acknowledgements The authors would like to thank the AdaptaVias Project, which is an effort undertaken by the Ministry of Infrastructure (Ministério da Infraestrutura—MInfra, in Portuguese), within the framework of the Memorandum of Understanding signed with the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH in Brazil, which is supported by the Ministry of Science, Technology and Innovations (Ministério da Ciência, Tecnologia e Inovações—MCTI, in Portuguese) and the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais—Inpe, in Portuguese). In addition, this work was supported by Carlos Chagas Filho Foundation for Research Support of the State of Rio de Janeiro, under grants #2021007191. This study was also financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

References

1. Wang, H., Mei, C., Liu, J.H., Shao, W.W.: A New Strategy for integrated urban water management in China: Sponge City. Sci. China Technol. Sci. **61**, 317–329 (2018). https://doi.org/10.1007/s11431-017-9170-5
2. Liu, L., Yang, D.Y., Frangopol, D.M.: Network-level risk-based framework for optimal bridge adaptation management considering scour and climate change. J. Infrastruct. Syst. **26**, 04019037 (2020). https://doi.org/10.1061/(asce)is.1943-555x.0000516
3. Liu, H., Wang, Y., Zhang, C., Chen, A.S., Fu, G.: Assessing real options in urban surface water flood risk management under climate change. Nat. Hazards **94**, 1–18 (2018). https://doi.org/10.1007/s11069-018-3349-1
4. Giovannettone, J., Copenhaver, T., Burns, M., Choquette, S.: A statistical approach to mapping flood susceptibility in the lower connecticut river valley region. Water Resour. Res. **54**, 7603–7618 (2018). https://doi.org/10.1029/2018WR023018
5. Diakakis, M., Boufidis, N., Salanova Grau, J.M., Andreadakis, E., Stamos, I.: A Systematic assessment of the effects of extreme flash floods on transportation infrastructure and circulation: the example of the 2017 Mandra flood. Int. J. Disaster Risk Reduct. **47**, 101542 (2020). https://doi.org/10.1016/j.ijdrr.2020.101542
6. Goumrasa, A., Guendouz, M., Guettouche, M.S., Belaroui, A.: Flood Hazard Susceptibility Assessment in Chiffa Wadi Watershed and along the First Section of Algeria North–South Highway Using GIS and AHP Method. Appl. Geomatics **13**, 565–585 (2021). https://doi.org/10.1007/s12518-021-00381-4
7. Mukesh, M.S., Katpatal, Y.B.: Impact of the change in topography caused by road construction on the flood vulnerability of mobility on road networks in Urban areas. ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng. **7**, 1–13 (2021). https://doi.org/10.1061/ajrua6.0001137.
8. Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S., Dawson, R.: Impact of climate change on disruption to Urban transport networks from Pluvial flooding. J. Infrastruct. Syst. **23**, 04017015 (2017). https://doi.org/10.1061/(asce)is.1943-555x.0000372
9. Szewrański, S., Chruściński, J., van Hoof, J., Kazak, J.K., Świader, M., Tokarczyk-Dorociak, K., Zmuda, R.: A location intelligence system for the assessment of pluvial flooding risk and the identification of stormwater pollutant sources from roads in suburbanised areas. Water (Switzerland) **10**, 1–16 (2018). https://doi.org/10.3390/w10060746
10. Li, L., Uyttenhove, P., Van Eetvelde, V.: Planning green infrastructure to Mitigate Urban surface water flooding risk – a methodology to identify priority areas applied in the city of Ghent. Landsc. Urban Plan. **194**, 103703 (2020). https://doi.org/10.1016/j.landurbplan.2019.103703
11. Meyer, M., Flood, M., Keller, J., Lennon, J., McVoy, G., Dorney, C., Leonard, K., Hyman, R., Smith, J.: Strategic issues facing transportation, volume 2: climate change, extreme weather events, and the highway system: practitioner's guide and research report, vol. 2 (2014); ISBN 9780309283786
12. Espada, R. Jr., Apan, A., McDougall, K.: Vulnerability assessment and interdependency analysis of critical infrastructures for climate adaptation and flood mitigation, vol. 6; ISBN 0120140004 (2015)
13. Njogu, H.W.: Effects of floods on infrastructure users in Kenya. J. Flood Risk Manag. **14**, 1–10 (2021). https://doi.org/10.1111/jfr3.12746
14. Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (eds.): IPCC, 2022: climate change 2022: mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press. Cambridge (2022). https://doi.org/10.1017/9781009157926.
15. Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., B.R. (eds): IPCC, 2022: climate change 2022: impacts, adaptation, and vulnerability. In: Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge Univ. Press. (2022)

16. Koks, E., Van Ginkel, K., Van Marle, M., Lemnitzer, A.: Brief communication: critical infrastructure impacts of the 2021 mid-July Western European flood event. Nat. Hazards Earth Syst. Sci. Discuss. [preprint, Rev., 1–11.
17. Pregnolato, M.; Ford, A.; Wilkinson, S.M.; Dawson, R.J. The Impact of Flooding on Road Transport: A Depth-Disruption Function. *Transp. Res. Part D Transp. Environ.* **2017**, *55*, 67–81, doi:https://doi.org/10.1016/j.trd.2017.06.020. https://doi.org/10.1016/j.trd.2017.06.020
18. Kim, K.; Pant, P.; Yamashita, E. Integrating Travel Demand Modeling and Flood Hazard Risk Analysis for Evacuation and Sheltering. *Int. J. Disaster Risk Reduct.* **2018**, *31*, 1177–1186. https://doi.org/10.1016/j.ijdrr.2017.10.025
19. Hooper, E., Chapman, L., Quinn, A.: The Impact of Precipitation on Speed-Flow Relationships along a UK Motorway Corridor. Theor. Appl. Climatol. **117**, 303–316 (2014). https://doi.org/10.1007/s00704-013-0999-5
20. Fitzgerald, G., Du, W., Jamal, A., Clark, M., Hou, X.Y.: Flood Fatalities in Contemporary Australia (1997–2008): Disaster Medicine. EMA - Emerg. Med. Australas. **22**, 180–186 (2010). https://doi.org/10.1111/j.1742-6723.2010.01284.x
21. Kermanshah, A., Derrible, S., Berkelhammer, M.: Using Climate Models to Estimate Urban Vulnerability to Flash Floods. J. Appl. Meteorol. Climatol. **56**, 2637–2650 (2017). https://doi.org/10.1175/JAMC-D-17-0083.1
22. Sayers, P..; Horritt, M.S.; Penning-Rowsell, E.; McKenzie, A. Climate Change Risk Assessment 2017 Projections of Future Flood Risk in the UK Project A: Report Prepared for the Committee on Climate Change, UK. **2017**, 126.
23. Kalantari, Z., Folkeson, L.: Road Drainage in Sweden: Current Practice and Suggestions for Adaptation to Climate Change. J. Infrastruct. Syst. **19**, 147–156 (2013). https://doi.org/10.1061/(asce)is.1943-555x.0000119
24. Dong, X., Guo, H., Zeng, S.: Enhancing Future Resilience in Urban Drainage System: Green versus Grey Infrastructure. Water Res. **124**, 280–289 (2017). https://doi.org/10.1016/j.watres.2017.07.038
25. Galvão, C.M., Sawada, N.O., Trevizan, M.A.: Revisão Sistemática: Recurso Que Proporciona a Incorporação Das Evidências Na Prática Da Enfermagem. Rev. Lat. Am. Enfermagem **12**, 549–556 (2004). https://doi.org/10.1590/s0104-11692004000300014
26. Zupic, I., Čater, T.: Bibliometric Methods in Management and Organization. Organ. Res. Methods **18**, 429–472 (2015). https://doi.org/10.1177/1094428114562629
27. Bajdor, P.; Starostka-Patyk, M. Smart City: A Bibliometric Analysis of Conceptual Dimensions and Areas. *Energies* **2021**, *14*, doi:https://doi.org/10.3390/en14144288.
28. Tijssen, R.J.W. *Handbook of Quantitative Science and Technology Research*; 2005; ISBN 1402027559.
29. Daim, T.U., Rueda, G., Martin, H., Gerdsri, P.: Forecasting Emerging Technologies: Use of Bibliometrics and Patent Analysis. Technol. Forecast. Soc. Change **73**, 981–1012 (2006). https://doi.org/10.1016/j.techfore.2006.04.004
30. Abreu, V. H. S., Santos, A. S., Monteiro, T.G.M. Climate Change Impacts on the Road Transport Infrastructure: A Systematic Review on Adaptation Measures. *Sustainability* **2022**.
31. Wang, T., Qu, Z., Yang, Z., Nichol, T., Clarke, G., Ge, Y.E.: Climate Change Research on Transportation Systems: Climate Risks, Adaptation and Planning. Transp. Res. Part D Transp. Environ. **88**, 102553 (2020). https://doi.org/10.1016/j.trd.2020.102553
32. IPCC *Climate Change 2014 Part A: Global and Sectoral Aspects*; 2014; ISBN 9781107641655.
33. Nowak, P.; Mickiewicza, U.A.; Pedago-, W. Uki . Podej ś Cie Bibliometryczne i Webometryczne , Pozna Ń : **2009**, *13*, 235–240.
34. Zahmatkesh, Z., Burian, S.J., Karamouz, M., Tavakol-Davani, H., Goharian, E.: Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City. J. Irrig. Drain. Eng. **141**, 04014043 (2015). https://doi.org/10.1061/(asce)ir.1943-4774.0000770
35. Mei, C., Liu, J., Wang, H., Yang, Z., Ding, X., Shao, W.: Integrated Assessments of Green Infrastructure for Flood Mitigation to Support Robust Decision-Making for Sponge City Construction in an Urbanized Watershed. Sci. Total Environ. **639**, 1394–1407 (2018). https://doi.org/10.1016/j.scitotenv.2018.05.199

36. Argyroudis, S.A., Mitoulis, S., Winter, M.G., Kaynia, A.M.: Fragility of Transport Assets Exposed to Multiple Hazards: State-of-the-Art Review toward Infrastructural Resilience. Reliab. Eng. Syst. Saf. **191**, 106567 (2019). https://doi.org/10.1016/j.ress.2019.106567
37. Selva, N., Kreft, S., Kati, V., Schluck, M., Jonsson, B.G., Mihok, B., Okarma, H., Ibisch, P.L.: Roadless and Low-Traffic Areas as Conservation Targets in Europe. Environ. Manage. **48**, 865–877 (2011). https://doi.org/10.1007/s00267-011-9751-z
38. Charlesworth, S.M.: A Review of the Adaptation and Mitigation of Global Climate Change Using Sustainable Drainage in Cities. J. Water Clim. Chang. **1**, 165–180 (2010). https://doi.org/10.2166/wcc.2010.035
39. Sterr, H.: Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany. J. Coast. Res. **24**, 380–393 (2008). https://doi.org/10.2112/07A-0011.1
40. Chinowsky, P.S.; Price, J.C.; Neumann, J.E. Assessment of Climate Change Adaptation Costs for the U.S. Road Network. *Glob. Environ. Chang.* **2013**, *23*, 764–773, doi:https://doi.org/10.1016/j.gloenvcha.2013.03.004.
41. Van Noorden, R. Global Scientific Output Doubles Every Nine Years : News Blog. *Newsblog Nat. brings you Break. News from World Sci.* **2014**, post.
42. Neumann, J.E., Price, J., Chinowsky, P., Wright, L., Ludwig, L., Streeter, R., Jones, R., Smith, J.B., Perkins, W., Jantarasami, L., et al.: Climate Change Risks to US Infrastructure: Impacts on Roads, Bridges, Coastal Development, and Urban Drainage. Clim. Change **131**, 97–109 (2015). https://doi.org/10.1007/s10584-013-1037-4
43. Denich, C., Zaghal, A.: Designing for Environmental and Infrastructure Sustainability: Ontario Case Studies for Retrofits and New Developments. J. Green Build. **9**, 40–59 (2014). https://doi.org/10.3992/1943-4618-9.1.40
44. Picketts, I.M., Andrey, J., Matthews, L., Déry, S.J., Tighe, S.: Climate Change Adaptation Strategies for Transportation Infrastructure in Prince George Canada. Reg. Environ. Chang. **16**, 1109–1120 (2016). https://doi.org/10.1007/s10113-015-0828-8
45. Abkowitz, M., Jones, A., Dundon, L., Camp, J.: Performing A Regional Transportation Asset Extreme Weather Vulnerability Assessment. Transp. Res. Procedia **25**, 4422–4437 (2017). https://doi.org/10.1016/j.trpro.2017.05.344
46. Arkell, B.P., Darch, G.J.C.: Impact of Climate Change on London's Transport Network. Proc. Inst. Civ. Eng. Munic. Eng. **159**, 231–237 (2006). https://doi.org/10.1680/muen.2006.159.4.231
47. Arndt, C., Strzepeck, K., Tarp, F., Thurlow, J., Fant, C., Wright, L.: Adapting to Climate Change: An Integrated Biophysical and Economic Assessment for Mozambique. Sustain. Sci. **6**, 7–20 (2011). https://doi.org/10.1007/s11625-010-0118-9
48. le Roux, A., Khuluse-Makhanya, S., Arnold, K., Engelbrecht, F., Paige-Green, P., Verhaeghe, B.: A Framework for Assessing the Risks and Impacts of Rural Access Roads to a Changing Climate. Int. J. Disaster Risk Reduct. **38**, 101175 (2019). https://doi.org/10.1016/j.ijdrr.2019.101175
49. Chinowsky, P.S., Schweikert, A.E., Strzepek, N., Strzepek, K.: Road Infrastructure and Climate Change in Vietnam. Sustain. **7**, 5452–5470 (2015). https://doi.org/10.3390/su7055452
50. Porter, J.R.; Shu, E.; Amodeo, M.; Hsieh, H.; Chu, Z.; Freeman, N. Community Flood Impacts and Infrastructure: Examining National Flood Impacts Using a High Precision Assessment Tool in the United States. *Water (Switzerland)* **2021**, *13*, doi:https://doi.org/10.3390/w13213125.
51. Apel, H.; Martínez Trepat, O.; Nghia Hung, N.; Thi Chinh, D.; Merz, B.; Viet Dung, N. Combined Fluvial and Pluvial Urban Flood Hazard Analysis: Concept Development and Application to Can Tho City, Mekong Delta, Vietnam. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 941–961. https://doi.org/10.5194/nhess-16-941-2016
52. Lu, D., Tighe, S.L., Xie, W.C.: Pavement Risk Assessment for Future Extreme Precipitation Events under Climate Change. Transp. Res. Rec. **2672**, 122–131 (2018). https://doi.org/10.1177/0361198118781657
53. Vajjarapu, H., Verma, A.: Composite Adaptability Index to Evaluate Climate Change Adaptation Policies for Urban Transport. Int. J. Disaster Risk Reduct. **58**, 102205 (2021). https://doi.org/10.1016/j.ijdrr.2021.102205

54. Pregnolato, M., Ford, A., Dawson, R.: Disruption and adaptation of urban transport networks from flooding. E3S Web Conf. **7**, 1–8 (2016). https://doi.org/10.1051/e3sconf/20160707006
55. Olsen, A.S.; Zhou, Q.; Linde, J.J.; Arnbjerg-Nielsen, K. Comparing Methods of Calculating Expected Annual Damage in Urban Pluvial Flood Risk Assessments. *Water (Switzerland)* **2015**, *7*, 255–270. https://doi.org/10.3390/w7010255
56. Keller, S., Atzl, A.: Mapping natural hazard impacts on road infrastructure—the extreme precipitation in Baden-Württemberg, Germany, June 2013. Int. J. Disaster Risk Sci. **5**, 227–241 (2014). https://doi.org/10.1007/s13753-014-0026-1
57. Dasgupta, S.; Huq, M.; Khan, Z.H.; Masud, M.S.; Ahmed, M.M.Z.; Mukherjee, N.; Pandey, K. Climate Proofing Infrastructure in Bangladesh: The Incremental Cost of Limiting Future Flood Damage. *J. Environ. Dev.* **2011**, *20*, 167–190. https://doi.org/10.1177/1070496511408401
58. Heberger, M.; Cooley, H.; Herrera, P.; Gleick, P.H.; Moore, E. Potential Impacts of Increased Coastal Flooding in California Due to Sea-Level Rise. *Clim. Change* **2011**, *109*, 229–249. https://doi.org/10.1007/s10584-011-0308-1
59. Sadler, J.M.; Haselden, N.; Mellon, K.; Hackel, A.; Son, V.; Mayfield, J.; Blase, A.; Goodall, J.L. Impact of Sea-Level Rise on Roadway Flooding in the Hampton Roads Region, Virginia. *J. Infrastruct. Syst.* **2017**, *23*, 1–7. https://doi.org/10.1061/(asce)is.1943-555x.0000397
60. Bollinger, L.A.; Bogmans, C.W.J.; Chappin, E.J.L.; Dijkema, G.P.J.; Huibregtse, J.N.; Maas, N.; Schenk, T.; Snelder, M.; van Thienen, P.; de Wit, S.; et al. Climate Adaptation of Interconnected Infrastructures: A Framework for Supporting Governance. *Reg. Environ. Chang.* **2014**, *14*, 919–931. https://doi.org/10.1007/s10113-013-0428-4
61. Lambert, J.H., Wu, Y.-J., You, H., Clarens, A., Smith, B.: Climate change influence on priority setting for transportation infrastructure assets. J. Infrastruct. Syst. **19**, 36–46 (2013). https://doi.org/10.1061/(asce)is.1943-555x.0000094
62. Poussin, J.K., Botzen, W.J.W., Aerts, J.C.J.H.: Stimulating flood damage mitigation through insurance: an assessment of the French catnat system. Environ. Hazards **12**, 258–277 (2013). https://doi.org/10.1080/17477891.2013.832650
63. Kalantari, Z., Cavalli, M., Cantone, C., Crema, S., Destouni, G.: Flood probability quantification for road infrastructure: data-driven spatial-statistical approach and case study applications. Sci. Total Environ. **581–582**, 386–398 (2017). https://doi.org/10.1016/j.scitotenv.2016.12.147
64. Michielsen, A., Kalantari, Z., Lyon, S.W., Liljegren, E.: Predicting and communicating flood risk of transport infrastructure based on watershed characteristics. J. Environ. Manage. **182**, 505–518 (2016). https://doi.org/10.1016/j.jenvman.2016.07.051
65. Cantone, C.: Modelling sediment connectivity in Swedish catchments and application for Flood prediction of roads (2016)
66. Schmidt, N., Meyer, M.D.: Incorporating climate change considerations into transportation planning. Transp. Res. Rec. 66–73 (2009). https://doi.org/10.3141/2119-09
67. Adger, W.N., Arnell, N.W., Tompkins, E.L.: Successful adaptation to climate change across scales. Glob. Environ. Chang. **15**, 77–86 (2005). https://doi.org/10.1016/j.gloenvcha.2004.12.005
68. Pochwat, K., Słyś, D., Kordana, S.: The Temporal variability of a rainfall synthetic hyetograph for the dimensioning of stormwater retention tanks in small urban catchments. J. Hydrol. **549**, 501–511 (2017). https://doi.org/10.1016/j.jhydrol.2017.04.026
69. Hanak, E., Lund, J.R.: Adapting California's water management to climate change. Clim. Change **111**, 17–44 (2012). https://doi.org/10.1007/s10584-011-0241-3
70. Sharifi, A.: Co-benefits and synergies between urban climate change mitigation and adaptation measures: a literature review. Sci. Total Environ. **750** (2021). https://doi.org/10.1016/j.scitotenv.2020.141642
71. Copeland, C.: Green Infrastructure and Issues in Managing Urban Stormwater. Sel. Issues Water Resour. Manag., 79–113 (2013)
72. Grafakos, S., Trigg, K., Landauer, M., Chelleri, L., Dhakal, S.: Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities. Clim. Change **154**, 87–106 (2019). https://doi.org/10.1007/s10584-019-02394-w

73. Kim, D., Kang, J.E.: Integrating climate change adaptation into community planning using a participatory process: the case of Saebat Maeul Community in Busan, Korea. Environ. Plan. B Urban Anal. City Sci. **6**, 45, 669–690 (2016). https://doi.org/10.1177/0265813516683188
74. Kapetas, L., Fenner, R.: Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. **378** (2020). https://doi.org/10.1098/rsta.2019.0204
75. Arthur, S., Vladimir Krivtsov, D.A.: Blue-green infrastructure – perspectives on water quality benefits, ISBN 9780860177999 (2019)
76. Zimmerman, R., Faris, C.: Chapter 4: infrastructure impacts and adaptation challenges. Ann. N. Y. Acad. Sci. **1196**, 42–51 (2010)
77. Briefing, S.: Impacts, C.C. TRANSPORT (Roads). ADB (2012)
78. Nazarnia, H., Nazarnia, M., Sarmasti, H., Wills, W.O.: A systematic review of civil and environmental infrastructures for coastal adaptation to sea level rise. Civ. Eng. J. **6**, 1375–1399 (2020). https://doi.org/10.28991/cej-2020-03091555
79. Doogie, B.: Nick Pyatt of climate sense SUTP: adapting urban transport to climate change. Sustain. Transp. A Sourceb. Policy-makers Dev. Cities **70** (2021)
80. Chapman, L.: A climate change report card for infrastructure working technical paper transport : road transport (Inc . Cycling and Walking) Dr. Lee Chapman reader in climate resilience school of geography. Earth Environ. Sci. Univ. Birm., 1–20 (2019)
81. Vajjarapu, H., Verma, A., Gulzar, S.: Adaptation policy framework for climate change impacts on transportation sector in developing countries. Transp. Dev. Econ. 5 (2019). https://doi.org/10.1007/s40890-019-0071-y.
82. Vajjarapu, H., Verma, A., Hemanthini, A.R.: Evaluating mitigation and adaptation policies for transport sector using GIS—case study of Bangalore. Geospatial Infrastruct. Appl. Technol. India Case Stud. 235–255 (2018)
83. DTTAS Climate Change Sectoral Adaptation Plan for Transport Sector in Ireland, 112 (2019)
84. Urs Adapting Energy: Transport and water infrastructure to the long-term impacts of climate change summary report adapting energy, transport and water infrastructure to the long-term impacts of climate change summary report. Transport, 114 (2010)
85. Löwe, R., Urich, C., Sto. Domingo, N., Mark, O., Deletic, A., Arnbjerg-Nielsen, K.: Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations – a new generation of urban planning tools. J. Hydrol. **550**, 355–367 (2017). https://doi.org/10.1016/j.jhydrol.2017.05.009.
86. Arrighi, C., Pregnolato, M., Castelli, F.: Indirect flood impacts and cascade risk across interdependent linear infrastructures. Nat. Hazards Earth Syst. Sci. **21**, 1955–1969 (2021). https://doi.org/10.5194/nhess-21-1955-2021
87. Najafi, M.R., Zhang, Y., Martyn, N.: A flood risk assessment framework for interdependent infrastructure systems in coastal environments. Sustain. Cities Soc. **64**, 102516 (2021). https://doi.org/10.1016/j.scs.2020.102516

Chapter 3
Examining Effects of Introduction of Private Trains on Middle-Income Groups

Saksham Gaur, Sankarshan Mukherjee, and Ram Krishna Upadhyay

Abstract The work aims to study the priority level of certain dimensions of railway services and the quality of services (expected in Private Trains) from the perspective of the passengers and their impact on the passenger's choice of Private Trains as their preferred mode of travel for mid-length (>400 km) journeys. Only policy research has been done on the privatization of Indian Railways and its consequences; this work can be seen as a continuation of those studies as it will uncover the perceived and desired priority level of important railway service dimensions expected on Private Trains. Although this is the main deliverable of this research, special attention is also given to tapping the passenger's current satisfaction level of services in Indian Railways. Additionally, the passenger response to Railways' privatization worldwide has been studied. Within India itself, case studies of asset monetization of Indian Railways and public–private partnership (PPP) projects of governments and their outcomes have been discussed. An online survey was conducted to assess respondent's current satisfaction levels with Indian railway services on a scale of 1 to 5. Respondents were asked to rate the perceived importance of several mentioned dimensions to be included in Private Trains in a separate section dedicated to them. Statistical analysis was done using Microsoft Excel and Statistical Package for the Social Sciences (SPSS). The findings of this study were consistent with the observed trend in other privatized sectors. People are dissatisfied with the current technological facilities, complaint handling, enquiry systems, etc. While the high-income group prefers to shift to low-cost carriers with increased train ticket prices, the middle- and lower-income groups can be retained if the price increase is supported with value addition in customer service and service efficiency. Safety and security remain the most prioritized dimensions, followed by on-board technological facilities. Liberalized government monopoly markets have seen customers associating increased importance on customer services/hospitality/customer relations.

Keywords Railways · Privatization · Private Trains · Service dimensions · PPP

S. Gaur · S. Mukherjee · R. K. Upadhyay (✉)
School of Engineering and Applied Sciences, National Rail and Transportation Institute, Vadodara, Gujarat, India
e-mail: ram.upadhyay@gsv.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_3

3.1 Introduction and Literature Review

3.1.1 Theory of Privatization

Privatization is the act of connecting with the private area in a few parts of the capacities and obligations of government tasks. Eventually, governments should choose if securing an ideal help is best done through their own public offices or, on the other hand, assuming that it ought to be bought from private sellers at a cost directed by the market. This basic inquiry of 'makes or purchase' is the actual pith of privatization strategy and cycle. Showing up at a solution to that enquiry, notwithstanding, is just about as intricate and different as the administration governments give and the public that they serve [1].

While essentially all governments at any level look for some type of administration from private specialist co-ops, regardless of whether for-benefit, the genuine extent of privatization is generally misconstrued. Therefore, political talk with respect to privatization has embraced a short-sighted, argumentative, and frequently incorrect comprehension of the benefits and execution of the training. The beyond twenty years have seen various occurrences of hardliner discussions over privatization which embrace general philosophies either in favor or went against to privatization all in all. This has prompted a heap of privatization recommendations that have neglected to help the governments authorizing them, and, in specific cases, has even hurt the legislators, labor force, residents, and administration beneficiaries simultaneously [1].

While these disappointments have persuaded some to think that privatization is innately risky and ought to in this way be kept away from, others keep on supporting any work to move a public support of the private area to restrict the size and job of government. The truth of the matter is that privatization is seldom powerful, or even conceivable, when either worldview is utilized to look at it merits. By and by, privatization is best when used to guarantee that government, considering its requirements, abilities, and restrictions, endeavors to find the most ideal solution to the 'make or purchase' question. This paper will, in four unmistakable parts, look to inspect nature of privatization in both practice and hypothesis, with specific consideration toward monetary effect, effectiveness, and nature of administration [1].

The fundamental 'make or purchase' privatization question expects governments to assess whether they accept there is more prominent advantage in paying to make service arrangement inside open offices or then again on the off chance that buying those services from the private sector is more valuable. A definitive choice will rely upon both political and sober-minded factors [1].

The significant contemplations require an exhaustive appraisal to decide the genuine expense of offering types of assistance, which incorporates the nature of service, monetary circumstances, and proficiency of the choices accessible to the public director. This part will inspect speculations that endeavor to characterize central point affecting this cycle including how service quality can be tended to, the job that political belief system and ulterior thought processes can play and the association between privatization, contest, and effectiveness that make privatization fit for further developing the norm [1].

Forms of Privatization

Contracting The most widely recognized type of privatization in both discussion and practically speaking, contracting alludes to when an administration goes into concurrences with private merchants (either for-benefit or not-for-benefit) to give government services. The public authority giving the agreement can set the principles of administration and terms of the understanding. However, the help arrangement's administration is the assistance provider's obligation, to put it plainly, and public finances pay private sellers to offer public types of assistance. The term contracting-out alludes to the most common way of giving agreements for administrations that are at present being conveyed by open offices or representatives. Contracting-out is a significant focal point of numerous privatization programs and their guideline [1].

Vouchers. Vouchers are given to individual public assistance beneficiaries and involved by those people to get the administrations for which they qualify. The specialist organization gets the voucher in lieu of all or part of the expense of the help when delivered and gets the rest of the public authority. This permits the public authority to set the principles of administration, by controlling what administrations they will dispatch installments for while permitting the assistance beneficiaries to pick the supplier that they like in the open market. Areas where vouchers have been used incorporate food stamp programs, transportation, day care, and elective training projects, for example, contract schools [1].

Public–Private Associations. Partnerships between open offices and private help merchants have seen outstanding development as of late. Public–private organizations allude to regions where public offices and private specialist co-ops share the obligation regarding giving taxpayer-driven organizations. These associations are especially successful when government organizations face circumstances where their abilities or labor are abruptly or briefly overpowered by unexpected interest. Organizations and private area project workers decide a manner by which the two bodies can cooperate to accomplish the equivalent goal [1].

Franchises. The state gives a private seller honor to go about as a neighborhood restraining infrastructure inside a given region. Customers should pick if they wish to buy administration or not yet can't pick between numerous sellers offering services. Unmistakable instances of establishments incorporate cost assortment and visiting nurses [1].

Subsidies and Grants. The government goes into a concurrence with a private seller wherein they somewhat support or finance that gathering to counterbalance the costs of offering a specific assistance or services. These permit governments to empower the creation and development of specific private help businesses as well as where, when, and how they would like that industry to advance [1].

Asset Monetization. Governments sell or 'money out' resources—which could incorporate infrastructural gear, land, or other legislative center merchandise to private organizations to recover a bonus gain and further grow their expense base coming about in expanded revenues. This is especially successful when the government possesses land that is sought after or on the other hand assuming it claims framework, for example, large equipment recently used to offer types of assistance currently being contracted [1].

Volunteerism. A government depends on volunteer work, normally through a non-benefit association, to give work escalated public services. Prominent instances of volunteerism privatization are seen in AmeriCorps and City Year programs, where volunteers are depended on for errands going from the support of state backwoods to instructing in state-funded schools where that are encountering staffing or spending plan deficiencies [1].

Donations from Private Contributors. Governments depend on private contributors to give assets to help with offering public types of assistance. Assets could go from monetary help, to workforce, offices, or even equipment [1].

Administration Shedding. Governments significantly lessen or totally quit offering administrations to permit private area organizations the amazing chance to start offering them with private resources [1].

Deregulating the Economy. Governments quit directing administrations they hoard to permit private organizations to start offering similar administrations to support rivalry between the two sectors [1].

3.1.2 Privatization in India

A critical balance of payments crisis that occurred in the year 1991 was the immediate cause of India's economic reforms 1991 [1]. India's balance of payments crisis first surfaced in late 1990, when foreign exchange reserves began to decline [2]. India had to request IMF for loans and accept the terms and conditions of IMF which led it to de-license industry and imports [3].

India's reform plan, which began in July 1991, was a blend of macroeconomic stabilization and structural change. It was guided by both, short- and long-term goals [1]. In the short term, stabilization was required to restore the balance of payments equilibrium and contain inflation. Simultaneously, modifying the structure of institutions through reforms was equally crucial from a long-term viewpoint [3, 4].

The Industrial Policy of 1991 included major changes from the early policy of 1956.

The IPR of 1956 has been dubbed India's 'Economic Constitution.' The Resolution emphasized the growth of heavy and machine-building industries, the expansion of the public sector, the construction of a large and growing cooperative sector, and support of ownership and management diffusion in the private sector.

The division of the entire industrial sector into three schedules, as follows, was the most distinguishing aspect of the IPR, 1956:

- Schedule A—17 industries, under the exclusive ownership of the state.

- Schedule B—12 industries, state-owned, although private enterprise would be required to augment the government's efforts in these areas.
- Schedule C—Industries, under the private sector's initiative and enterprise, state-controlled through a system of licenses [5].

Foreign investment policy: Foreign investments including FDI and FPI were allowed. Similarly, loan capital was also introduced in the country to attract foreign capital [6].

Automatic approval was granted for foreign technology agreements in high-priority industries up to a lump sum payment of Rs. 1 crore, a 5% royalty for domestic sales and an 8% royalty for exports, with a total payment of 8% of sales over a ten-year period from the date of the agreement or seven years from the start of production [7]. In addition, the government made it easier to hire foreign technicians.

The Monopoly and Restricted Trade Practices Act was repealed as part of the New Industrial Policy of 1991. The Competition Commission was established in 2010 to operate as a watchdog in the economy, regulating competitive behaviors [8].

3.1.3 Privatization of Other Sectors in India

3.1.3.1 Iron and Steel Industry

On the back of several measures taken by the Indian government, the Indian steel industry has seen consistent expansion. The steel industry in India has been placed on the world map due to rising demand from various industries such as infrastructure, real estate, and automobiles.

1. The industry was removed from the list of public sector-only industries and was also exempted from mandatory licensing requirements, with the exception of a few regions.
2. The business was added to a list of 'high-priority' industries that will receive automatic clearance for up to 51% foreign equity participation. This threshold has recently been raised to 100%.
3. Steel pricing and distribution were deregulated in January 1992.
4. The trade policy was liberalized, allowing for unlimited import and export.
5. The Steel Development Fund levy was abolished in April 1994, giving key manufacturers more freedom in responding to market conditions.

A large number of new steel facilities have been built in the country as a result of large foreign investments and cutting-edge technologies [9, 10].

3.1.3.2 Airline Industry in India

India had nine air transport companies transporting both freight and passengers, shortly after independence. Then all aviation assets were nationalized by the Indian government in 1953 [11]. The reform process in India began in 1986 as a direct result of tourism industry complaints about insufficient capacity on some critical routes. By allowing private sector flights to operate as 'air taxis,' the Minister of Tourism and Civil Aviation took the first step [12]. In 1989, the government stated that it would introduce an 'open skies' policy, which would gradually loosen restrictions on air taxi companies and eventually allow them to conduct scheduled services. The result was the rapid awarding of five new licenses, but the largest of them had to stop operating after only five months. By the year 1991, the policy had been deemed a failure [13].

One of the most significant policy changes was the permission for air taxis to seek up to 40% of their equity financing from foreigners. Jet Airways, which was also funded by a tourism group, chose this option in 1993, with Kuwait Airways contributing 20% and Gulf Air contributing 20% [11]. By the end of 1993, 17 air taxi operators had been granted licenses, another 20 had received preliminary approval, and 54 routes were being served by new entrants [13]. Losses in traffic damaged Indian Airlines and Vayudoot, but they also suffered when pilots and engineers fled to the new carriers.

Government Initiatives to Promote Aviation [11].

- FDI in Domestic Airlines (Air Transport Services) has increased from 40 to 49%. NRIs and PIOs are eligible for 100% FDI.
- Private service providers with five years of domestic experience and a fleet of twenty aircraft have been granted permission to fly on international routes.
- To ensure that the aviation industry maintains worldwide standards and advances, the aircraft rules were updated.

Following liberalization, both the domestic and international passenger sectors of the aviation industry have experienced extraordinary growth [11, 14].

- The entry of private players has improved competition, resulting in greater customer service.
- The entry of low-cost carriers like Indigo, Spice Jet, and Go First altered the aviation industry's landscape. In both urban and rural India, the number of first-time flyers has risen considerably.
- Indian Airlines and Air India's hegemony over Indian skies came to an end.

3.1.3.3 Life Insurance Industry in India

Following the recommendations of the Malhotra Committee report, the Insurance Regulatory and Development Authority (IRDA) was established as a statutory body in April 2000 to promote competition, improve customer satisfaction through increased consumer choice and lower premiums, and, most importantly, ensure the financial stability of the insurance market. The market was first opened by the IRDA in August of 2000. Foreign corporations were allowed to own up to 26% of the company [15].

In December 2000, the General Insurance Corporation of India's subsidiaries were restructured as independent corporations, following the liberalization of the life insurance sector. The GIC has been renamed a national reinsurer. In July 2002, the four subsidiaries were de-linked from GIC by a bill enacted by Parliament [15].

There are currently 33 general insurance firms functioning in India, including the ECGC and the Agriculture Insurance Corporation of India, as well as 24 life insurance companies [15].

3.1.3.4 Banking Industry in India

For at least two reasons, there was little effective competition in the Indian banking system before the 1991 reforms. First, the RBI's comprehensive prescriptions, such as those governing interest rate settings, hampered the ability of banks to differentiate themselves in the marketplace. Second, India imposed strict entry barriers for new banks, effectively shielding incumbent banks from competition. Since the beginning of the 1990s, competition has expanded dramatically as entrance restrictions have been lowered [16]. Between 1994 and 2000, seven new private banks entered the market. Since 1994, around 20 foreign banks have opened offices in India [17]. By March 2004, the new private sector banks and foreign banks had taken about 20% of the market [17].

The Indian banking system has benefited from enhanced technology, specialized skills, better risk management techniques, and greater portfolio diversification because of deregulating entrance criteria and establishing new bank operations.

At present, there are about 12 public sector banks and 21 private sector banks in India [18].

3.1.4 Public–Private Partnerships in Indian Railways

The PPP model has been changed by Indian Railways (IR) throughout time. Until December 2012, the Nongovernment Railway Model was the only one that could be used for Rail-Port Connectivity projects.

The following five models are permitted under PPP policy [19].

1. Revenue-sharing model for non-government lines
2. Revenue-sharing joint ventures model
3. Developed an own-operate-and-transfer revenue-sharing model
4. Fixed-fee recovery model with annuities
5. Discount on freight moving on the line under a customer-funded model
6. Asset Creation through Foreign Direct Investment (FDI).

Examples of these models in the context of Indian Railways are mentioned in Table 3.1.

3.1.5 Privatization of Railways in Other Countries

Argentina: Under President Juan Perón, the South American country nationalized its rail network in 1948. It was privatized again in the 1990s under President Carlos Menem's neoliberal reforms, this time through agreements with state-owned infrastructure. However, after a period of severe deterioration, most rail routes were returned to state control in 2015 [20].

France: In 1878, the government established the Chemin de fer de l'État by taking over many small rail firms. After Chemin de fer de l'État amalgamated with Chemins de Fer de l'Ouest in 1938, the state acquired 51 percent of the company. In 1982, the government took control of the newly established SNCF (a merger of five major Railways). SNCF Reseau and SNCF Mobilities are in charge of the infrastructure and operating passenger and freight services, respectively. There is some reorganization going on right now (e.g., station infrastructure being bought into SNCF Reseau) [20].

Ireland: In 1945, the Great Southern Railways and the Dublin United Transport Company merged to form the Irish Córas Iompair Éireann. It was a private limited corporation until 1950, when it was nationalized. In 1953, the final private rail line, the Great Northern Railway, was combined and nationalized. Ireland and Northern Ireland are now sharing the assets (the UK) [21].

Italy: Before being nationalized in 1905, Italian Railways were consolidated and assigned to five regional concessionaires. Ferrovie dello Stato competes against Nuovo Trasporto Viaggiatori, which is partially controlled by SNCF and other private investors. Ferrovie dello Stato Italiane (FSI), which includes Trenitalia (the primary train service provider) and Rete Ferroviaria Italiana (RFI, the infrastructure manager), as well as other subsidiaries that manage stations and offer technical services, provides the Italian rail service. While the infrastructure and train operations are nominally separate, they work closely together in practice [22].

Japan: The Railway Nationalization Act of 1906 placed the majority of Japan's private rail network under government administration, and private companies were only allowed to provide local and regional services until 1907. The privatization of Japan's National Railways began in the 1980s and is now ongoing under the supervision of the government and the private JR Group [23].

United Kingdom: Because of World War I, the Railways were nationalized in 1914, but were returned to private ownership in 1921. The Railways Act of 1921 also ordered 120 businesses to consolidate into four—the Great Western Railway, the Southern Railway, the London and Northeastern Railway, and the London, Midland, and Scottish Railway—a process that took until 1923 to complete. British Railways was nationalized in 1948 and then privatized between 1994 and 1997 as a contract-based service provider, with over 100 businesses taking over. Railtrack declared bankruptcy in 2001 and was re-established as Network Rail, a private corporation with

Table 3.1 Comparison of different PPP models—types, roles of stakeholders, and example projects [19]

Model	Period of CA	Private party—role	MOR—role	Revenue	Example
NGR	No concession No transfer of rail system to IR	Finance, land acquisition, construction, O&M, traffic risk, etc.	Train operations, provision of reserved services	IR pays track access charge to NGR in perpetuity	1. Mundra—NGR with 3% of Apportioned Revenue + 60% of rest Revenue sharing with IR. The private party gets Rest 40% 2. Dhamra—NGR with 5% of A/Revenue + 30% of the rest of Rev. Sharing with IR, and 70% for Private Party
SPV	The concession duration is determined by the PPP's actual model	Finance, land acquisition, construction, O&M, traffic risk	Train operations, provision of reserved services	Track access charges or commission charges are paid by IR	1. RVNL as Govt. shareholder Hassan-Mangalore for GC of 293 km line in Karnataka Dahej-Baruch for GC of 52 km line in Gujarat Krishnapattnam Port connectivity in Andhra Pradesh d. Angul-Sukinda new line as alternate route in Orissa 2. IRCON 51%: RLDA 49%—SPV of Indian railway station development corporation (IRSDC)

(continued)

Table 3.1 (continued)

Model	Period of CA	Private party—role	MOR—role	Revenue	Example
JV	30 years	Finance, land (in the name of IR), Construction, O&M, Traffic Risk, etc.	Train operations, provision of reserved services	JV receives payment from IR for the track access charge	1. PRCL (Pipapav Rrail)—JV with 70% revenue share for Railways—30% for private party 2. IRCON, SECL & Govt. of Chhattisgarh—two rail corridors of 230 km in Chhattisgarh 3. RITES, PCM & Shapoorji—130 km Bhuj-Nalia new line in Gujarat
BOT	25 years subject to actual traffic materialization	Construction, O&M along with performance security to meet KPIs	Provide ROW. All sanctions may Provide VGF	IR pays TAC to the BOT operator. Also gives assurance of 80% of TAC in the loss of revenue	1. Kutch railway for GC of 300 km line from Palanpur to Gandhidham in Gujarat, for 32 years. Started operation in December 2006 2. Jaigarh Digni Rail Limited construction of Digni-Jaigarh port railway line in the length of 33.70 km in Ratnagiri—for 30 years under DBFOT 3. Haridaspur-Paradip port new line connecting port (for 30 years with RVNL) under BOOT model construction finished on 31.12.2016

(continued)

Table 3.1 (continued)

Model	Period of CA	Private party—role	MOR—role	Revenue	Example
User funded	Based on traffic volume	Funding for the last mile railway line	Construction, O&M	7% rebate on freight charges to the developer for a specific period	1. NTPC funded Hotgi-Kudgi (134 km) doubling project for 946 crores (2016)
BOT annuity	Till the cost recovery	Funding and construction	Land acquisition and O&M services	Annuity payment through competitive bidding	Projects have been identified for the same. Those are developing the third line between 1. Nagpur—Wardha 2. Kazipet—Balharsha 3. Bhadrak—Nergundi
FDI	100% FDI is allowed in Railways	The concessionaire will have complete freedom to form an SPV and attract FDI	Assessment of technical and financial viability	IR to pay the cost of services/products based on competitive bidding	MOR (26%)—Alstom (74%) JV at Madhepura, Bihar—manufacturing & supply of 800 electric locomotives over 11 years (20,000 Cr) in 2015 MOR (26%)—GE (74%) JV at Marhowra, Bihar—manufacturing & supply of 1000 diesel locomotives over 11 years (10,000 Cr) in 2015

no formal owner but functionally controlled by the government due to its constitution and finance [23].

Northern Ireland's Railways were nationalized in the 1940s and, unlike British Rail, remain state-owned.

3.1.6 Indian Railways and Privatization

The privatization of railways and future advancement in Europe considering the quantitative materials contains three distinct nations like USA, UK, and Sweden. This investigation discovered that liberation of strategies has gotten positive execution long haul as well as momentary viewpoint in every one of the areas except for UK which gives adverse consequences in transient way [24].

The investigation discovered that in cutthroat areas privatization has been a reverberating progress in working on firm execution. The review infers that developing worries of privatization ought to be switched in occasionally founded on its requirements [25].

Most of the privatization programs start with an incomplete way, so it won't influence the firm and furthermore observed that halfway privatization fundamentally affects company's business, benefit, and efficiency [26].

Advancement could limit the optional parts inside the direction and work on in money saving advantage strategies. It likewise expands the productivity objectives of the association. At long last, it presumes that advancement assists with expanding straightforwardness, better friendly adequacy both for ecological and for redistributive objectives [27].

Privatization should be guaranteeing the obligation of the occasion of security issues and defers influencing last clients; furthermore, they observed that all there is to it private or public areas should have fitting controls set up. This can be wiped out the issues looked by rail track in the radiance of the Hatfield crash. In view of the past examinations, it is perceived that most of the investigations have estimated the connection among privatization and company's worth in and all over the planet. Nevertheless, the investigations are needed to investigate the possibilities and outcomes of privatization in unambiguous. Subsequently, the current review attempts to investigate the possibilities and outcomes of privatization of Indian railways [28].

3.1.7 Asset Monetization of Indian Railways

The government likewise to some extent began privatization into the railways by giving re-appropriating administrations like housekeeping, cooking, and keeping up with the stations in the chosen regions. In any case, this support of private areas in railways in wide public discussion as this privatization would be the right advance. In this situation, railways in India moving toward privatization of a portion of the stations by open private activities. Under this undertaking, chosen stations might provide for private worry for modernization. The modernization remembers building shopping centers for the station, film corridors, inns as well as super specialty medical clinics in the railway premises. This plan of action guarantees to the improvement work, for example, reconstructing premises in the railway stations for next 15 years with next to no venture from government. Consequently, the concerned private area might be conceded the renting a valuable open door for the created business properties for an additional 50 years. This renting opportunity incorporates station upkeep, stopping charges, food counters at stations, sitting areas, and so forth. The redoing of the railway stations is intended to different stages. In starter stage, the responsibility had given to Indian Railway Station Development Corporation (IRSDC) for redoing the stations and its offices. In this association, the redoing of work of Habibganj Railway Station has previously begun by Bansal Group for which they have acquired 400 crores as advance to give the facilities like power, station charges and upkeep, waiting halls, food counters, sitting areas, and so on. In the following stage, the accompanying 23 railway stations have been observed which will be leased, for example, 'Kanpur Central, Allahabad, Lokmanya Tilak, Pune, Thane, Visakhapatnam, Howrah, Kamakhya, Faridabad, Jammu Tawi, Udaipur City, Secundrabad, Vijayawada, Ranchi, Chennai Central, Kozhikode, Yesvantpur, Bangalore Cantt, Bhopal, Mumbai Central, Bandra Terminus, Borivali, and Indore stations.' This patching up works will be done under unfamiliar direct speculation, some of the global organizations like 'Malaysia's state possessed Construction Industry Development Board (CIDB),' numerous Korean and Japanese organizations given their appearance of interest. During 2014, the nation permitted 100 percent FDI in railway framework advancement, through this a portion of the unfamiliar organizations previously settled two rail crazy manufacturing plants in Bihar with the venture of Rs.3500 crores. Indian railways conveyed 2.3 crore individuals and 3 million tons of products consistently. Most of the Indian populace depend on public transport rather than private vehicles. Railways are the most doable vehicle for every one of the areas of the public, which likewise associate topographically unique populace in every day. Indian Railways interfacing every one of the pieces of the nation particularly associate with distant region which runs 12,617 trains to convey the two travelers along with cargo. The idea of privatization might influence availability of these far-off regions because of monetary position. Typically, private area likes to run their administrations from productive course nor the non-beneficial courses. Notwithstanding, this multitude of exercises of privatization is a cross-country banter whether privatization would without a doubt the right advance. The exactness can be decided by concentrating on the possibilities and results of privatization in Indian railways. India's most memorable private worked train Tejas Express effectively sent off on fourth of October 2019 from New Delhi to Lucknow in charged by Indian Railways Catering and Tourism Corporation Limited, which covers 512 km in 6 h and 30 min. Therefore, the government of India has chosen to give endorsement for 150 additional private worked trains and courses which were cleared by open private organization examination panel (PPPAC) was considered as new achievement for Indian Railways. The accompanying courses intended to give private operated trains in India: 'Mumbai-Kolkata, Mumbai-Chennai, Mumbai-Guwahati, New Delhi Mumbai, Thiruvananthapuram-Guwahati, New Delhi-Kolkata, New Delhi-Bengaluru, New Delhi-Chennai, Kolkata-Chennai, Chennai-Jodhpur, Mumbai-Varanasi, Mumbai-Pune, Mumbai-Lucknow, Mumbai-Nagpur, Nagpur-Pune, Secunderabad-Visakhapatnam, Patna, Bengaluru, Pune-Patna, Chennai-Coimbatore, Chennai-Secunderabad, Surat-Varanasi, and Bhubaneswar-Kolkata.' Aside from these, a portion of different courses associating non-metro urban areas, for example, 'Allahabad, Amritsar, Chandigarh, Katra, Gorakhpur, Chhapra and Bhagalpur, Gorakhpur-Lucknow, Kota-Jaipur, Chandigarh-Lucknow, Visakhapatnam-Tirupati, and Nagpur-Pune' have additionally come under the thought to give private operated trains. For the most part, there will be 35 courses associating with New Delhi, 26 courses interfacing with Mumbai, 12 courses interfacing with Kolkata, 11 courses associating with Chennai, and 8 courses interfacing with Bengaluru under the privatization.

3.2 Results Obtained

3.2.1 Research Design

The research is descriptive, using surveys, content analysis, and some historical data. It is a combination of both qualitative and quantitative approaches with detailed discussion and case studies. The quantitative part starts when we start analyzing the result of the survey. The survey took place around early April in online format using Google Forms. 267 people responded to it. Statistical analysis was done using Microsoft Excel and SPSS for understanding the impact of introduction of Private Trains on middle-income groups. The survey is created to capture data from each socio-demographic group. For this, several questions like age, gender, household income, travel details were asked accompanied with questions about train travel details such as nature of travel, class of travel, frequency of travel, nature of ticket, and mode of ticket booking.

The survey/questionnaire also aimed to analyze current satisfaction level of respondents vis-à-vis the services provided by Indian railways on a scale of 1 to 5. The obtained data was analyzed to examine if there is a need to improve the services provided. A separate section is dedicated to Private Trains. Respondents were asked to rate the perceived importance of various listed factors to be included in Private Trains. Literature review helped in listing the factors. Data obtained was analyzed in MS Excel to obtain charts of all the factors. Mean rating for all the factors was calculated. Collected data was also put to factor analysis using IBM SPSS Statistics Software, and the results are published.

The survey also aimed to examine reasons for people not using Indian Railways, and the results of the same have been included in Appendix. After the survey about Private Trains, people were asked to choose their desired mode of travel after the introduction of Private Trains. Results of people who did not choose to travel by Private Trains are included in Appendix.

After both qualitative and quantitative analyses using MS Excel and IBM SPSS, conclusions of the obtained results were made and are included at last. Research Limitations have also been included while recommending possible future research on the chosen topic.

3.2.2 Details of Questionnaire

Section 1 contains the basic information about Private Trains and appealed to the respondent to fill the questionnaire honestly. The respondents were asked to only fill their name in the first section.

Section 2 asks the personal details of respondents and aimed to investigate the importance of listed factors on a scale of 1 to 5 to make the Mode Choice for their journey. The second section bifurcates the questionnaire based on the choice people make over the fact that if they travel by train or not.

Section 3 aims to collect responses for the satisfaction level of respondents with various listed services provided by Indian Railways on a Likert scale (1 to 5). The respondents who do not travel by train (according to their responses) are directed to Section 4, which aims to investigate into the reasons of people not choosing Indian Railways over other modes of travel. At the end of both third and fourth sections, respondents were asked to make the choice if they know about Private Trains and are willing to travel by them.

Section 5 takes responses of respondents who know about the introduction of Private Trains and investigates the desirability of listed factors on a scale of 1 to 5. Respondents who do not know about Private Trains are given a brief introduction of the same in Section-6 and their expected importance of the factors listed in Section-5 of the questionnaire was taken on a scale of 1 to 5. The factors listed in Section-5 and Section-6 were same in text. The listed factors aimed to examine the desirability of them by the current users of Indian Railways and the perception of respondents who do not use trains toward them. At the end of both the sections, respondents were asked to choose their desired mode of travel after the introduction of Private Trains. This question aimed to examine the estimated number of users who are willing to use the Private Trains after their introduction.

The questionnaire ends for the people who choose Trains/Private Trains as their desired mode of travel. However, the respondents who choose another mode of travel over trains are taken to Section-7.

Section-7 aims to examine the reasons due to which people are not willing to travel in Private Trains based on the listed factors. Respondents were asked to indicate their agreement level on a scale of 1 to 5.

Figure 3.1 shows the flowchart of questionnaire for an easier understanding.

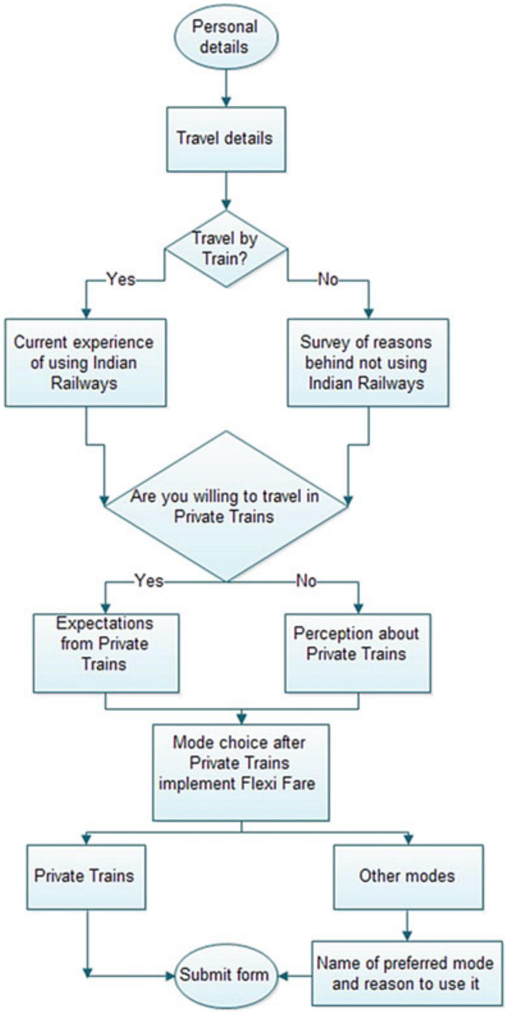


Fig. 3.1 Flowchart of questionnaire

3.2.3 Sample Characteristics

The sample consisted of 267 respondents who were given an online questionnaire to fill. Maximum of 122 respondents was of 20 years or less of age while a similar number (116) of respondents were between the age of 21 and 30. 29 respondents belonged to the age group of 31–40.

223 of the respondents were students while 29 were employed. 3 and 5 respondents were homemakers and self-employed, respectively. 7 of the respondents identified as not employed.

Majority of respondents (76) fall into the income category of 30,000–60,000 followed by the slab of 15,000–30,000 (73). 64 respondents were of the income category of 60,000–100,000 while 48 and 6 respondents come from families earning < 15,000 and 100,000 < , respectively.

Size of the families was 2–4 for a maximum of 149 respondents while 110 had five or more members in their families. 8 people identified as single persons.

When asked about the frequency of using trains to travel most respondents (93) responded that they use the trains half-yearly, followed by 76 respondents who make a yearly train journey. 68 respondents use trains once every month while 3 respondents travel weekly. 27 respondents prefer other modes over trains.

Personal and leisure trips are the purpose of travel for a maximum of 93 respondents followed by 61 respondents who take the train trips for educational purposes. 26 and 23 respondents use trains for making official and pilgrimage trips, respectively. 37 respondents use trains for reasons not listed in the questionnaire.

Maximum number (74) of respondents make train trips for the average distance of 500–1000 km followed by a similar number of 74 respondents who choose trains to travel 200–500 km. 22 people make journeys with distances under 200 km while 69 respondents choose trains for journeys of distances longer than 1000 km.

A maximum of 95 respondents choose to travel in AC 3 Tier for their train journey followed by 71 respondents who choose to travel in Sleeper Class. 45 respondents choose to travel in AC 2 Tier while 4 travel in AC First Class. 7 and 11 respondents choose to travel in General compartments and Second Seating, respectively.

When asked about the nature of ticket booking, a maximum of 209 respondents identified themselves as Reserved Ticket Holder while 22 respondents were Unreserved Ticket Holder. 9 respondents identified themselves as Seasonal Ticket/Pass Holder.

200 respondents book their tickets from the main IRCTC Website while 29 book them by physically going to the railway station reservation counters. 4 respondents identified that they use third-party booking sites to book their train tickets.

Majority of respondents (229) sponsor their trips themselves or get it sponsored by their family while organization/employer sponsors the train journey of 11 respondents.

When asked about their preferred mode of travel apart from using trains, 99 respondents chose Bus as their alternative mode of travel while 77 chose Airlines/LCC as their preferred alternative mode. 59 people chose the option of using Car/Taxi as their alternative mode while 5 respondents have other options.

Figure 3.2 shows the sample characteristics in tabular form.

3.2.4 Results for Current Satisfaction of Users of Indian Railways

To examine the feasibility of the endeavor to roll out Private Trains by Indian Railways, we tried to examine the current satisfaction levels of the respondents with the Indian Railways. 25 factors were used to analyze the satisfaction levels of various

		No of Respondents	% of Total Respondents
Age	<=20	122	45.69%
	21-30	116	43.45%
	31-40	29	10.86%
Qualifications	Pursuing Graduation	164	61.42%
	Postgraduate and above	18	6.74%
	Matriculation (10th)	2	0.75%
	Higher Secondary (12th)	23	8.61%
	Graduate/Diploma	60	22.47%
Profession	Student	223	83.52%
	Employed	29	10.86%
	Home Maker	3	1.12%
	Self-Employed	5	1.87%
	Not Employed	7	2.62%
Income Level	<15000	48	17.98%
	15000-30000	73	27.34%
	30000-60000	76	28.46%
	60000-100000	64	23.97%
	100000<	6	2.25%
Size of Family	1	8	3.00%
	2-4	149	55.81%
	5 or more	110	41.20%
Frequency of Travel	Weekly	3	1.12%
	Monthly	68	25.47%
	Half-Yearly	93	34.83%
	Yearly	76	28.46%
	Other Modes	27	10.11%
Purpose of Travel	Official	26	10.83%
	Educational	61	25.42%
	Personal	93	38.75%
	Tour and Pilgrimage	23	9.58%
	Others	37	15.42%
Approximate Distance of Travel	0-200	22	9.17%
	200-500	74	30.83%
	500-1000	75	31.25%
	1000<	69	28.75%
Class of Travel	1A-AC First Class	4	1.67%
	2A-AC 2 Tier	45	18.75%
	2S-Second Seating	7	2.92%
	3A-AC 3 Tier	95	39.58%

Fig. 3.2 Sample characteristics

services provided by Indian Railways inside and outside the trains. Respondents were asked to rate their satisfaction level of a scale of 1 to 5; 1 being Not Satisfied at All and 5 being Perfect!

The graphs obtained of the responses are shared below along with observations.

1. **Safety and Security During the Journey**

Maximum respondents (81) rated 3 to the factor of Safety and Security indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (55) given the satisfaction rating of 5 to the factor showing they find the service to be perfect. 12 respondents are found to be extremely dissatisfied with the service while 44 respondents and 48 respondents were found out to be Moderately Dissatisfied and Moderately Satisfied, respectively.

Figure 3.3 shows results for mean satisfaction rating for Factor 1: Safety and Security During the Journey.

2. **Cleanliness and Sanitation on the Train**

A major number of respondents feel there is a scope of improvement in the said service. 72 respondents are satisfied with the service while 35 respondents are highly dissatisfied. Highly Satisfied and Perfect scores are given by 20 and 24 respondents, respectively.

Figure 3.4 shows results for mean satisfaction rating for Factor 2: Cleanliness and Sanitation on the Train.

3. **Updated and Accurate Information About the Status of the Trains**

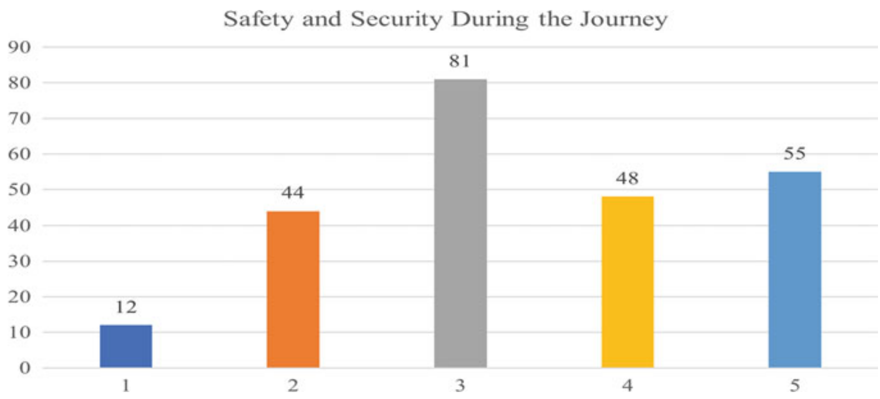


Fig. 3.3 Satisfaction rating for Factor 1

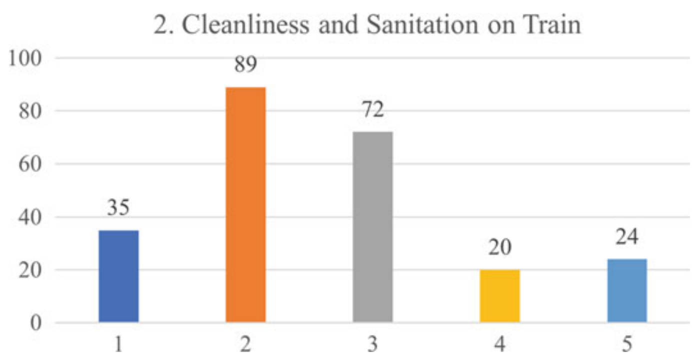


Fig. 3.4 Satisfaction rating for Factor 2

Maximum respondents (81) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (55) given the satisfaction rating of 5 to the factor showing they find the service to be perfect. 12 respondents are found to be extremely dissatisfied with the service while 44 respondents and 48 respondents were found out to be Moderately Dissatisfied and Moderately Satisfied, respectively.

Figure 3.5 shows results for mean satisfaction rating for Factor 3: Updated and Accurate Information about the Status of the Trains.

4. **Catering Facility on the Train**

Maximum respondents (93) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (86) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 27 respondents are found to be extremely dissatisfied with the service while 20 respondents and 14 respondents were satisfied with the service.

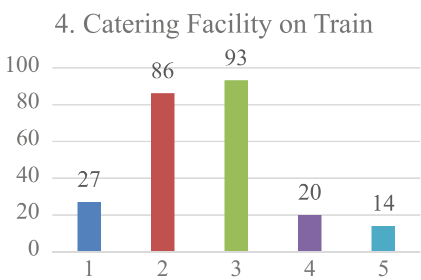
Figure 3.6 shows results for mean satisfaction rating for Factor 4: Catering Facility on Train.

5. **Trustworthy Employees**

Maximum respondents (125) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (61) given

Fig. 3.5 Satisfaction rating for Factor 3

Fig. 3.6 Satisfaction rating for Factor 4



the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 16 respondents are found to be extremely dissatisfied with the service while 22 respondents and 16 respondents were satisfied with the service.

Figure 3.7 shows results for mean satisfaction rating for Factor 5.

6. **Prompt Service**

Maximum respondents (105) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (90) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 5 respondents are found to be extremely dissatisfied with the service while 25 respondents and 14 respondents were satisfied with the service.

Figure 3.8 shows results of satisfaction rating for Factor 6.

7. **Speed of Train/Lesser Duration of Journey**

Maximum respondents (98) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (61) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 16 respondents are found to be extremely dissatisfied with the service while 22 respondents and 16 respondents were satisfied with the service.

Figure 3.9 shows results of satisfaction rating for Factor 7.

8. **Knowledgeable and Informed Employees**

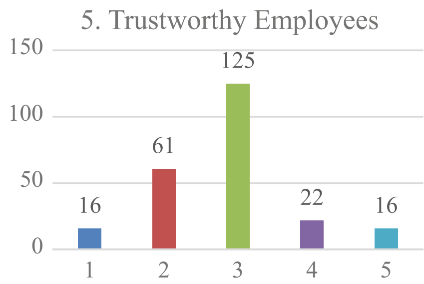


Fig. 3.7 Satisfaction rating for Factor 5

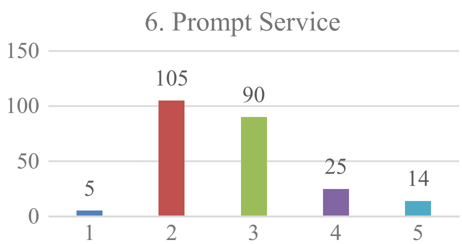
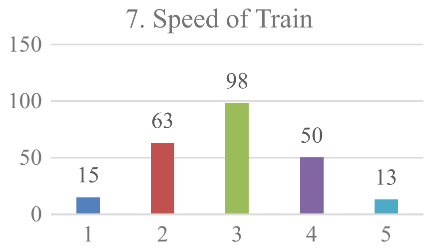


Fig. 3.8 Satisfaction rating for Factor 6

Fig. 3.9 Satisfaction rating for Factor 7



Maximum respondents (108) rated 3 to the factor of that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (75) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 12 respondents are found to be extremely dissatisfied with the service while 27 respondents and 16 respondents were satisfied with the service.

Figure 3.10 shows results of satisfaction rating for Factor 8.

9. **Friendly/Polite/Helpful Employees**

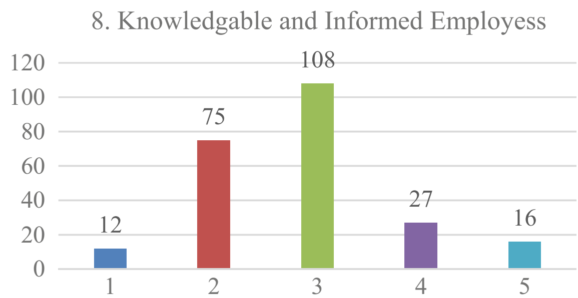
Maximum respondents (95) rated 3 to the factor indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (80) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 9 respondents are found to be extremely dissatisfied with the service while 35 respondents and 19 respondents were satisfied with the service.

Figure 3.11 shows results of satisfaction rating for Factor 9.

10. **Announcements on Platforms**

Maximum respondents (90) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (82) given the satisfaction rating of 4 to the factor showing they are satisfied with the service. 0 respondents are found to be extremely dissatisfied with the service while 38 respondents and 29 respondents were dissatisfied and extremely satisfied with the service, respectively.

Fig. 3.10 Satisfaction rating for Factor 8



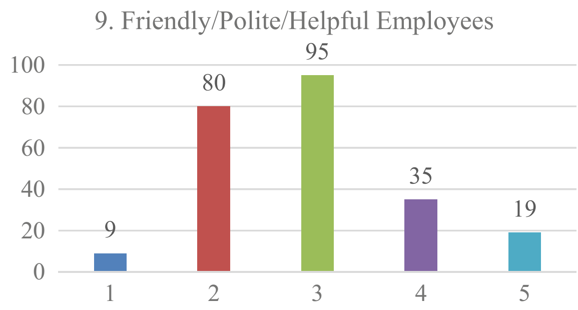


Fig. 3.11 Satisfaction rating for Factor 9

Figure 3.12 shows results of satisfaction rating for Factor 10.

11. **Cleanliness on Platform**

Maximum respondents (82) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (61) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 40 respondents are found to be extremely dissatisfied with the service while 31 respondents and 26 respondents were satisfied with the service.

Figure 3.13 shows results of satisfaction rating for Factor 11.

12. **Coach Maintenance**

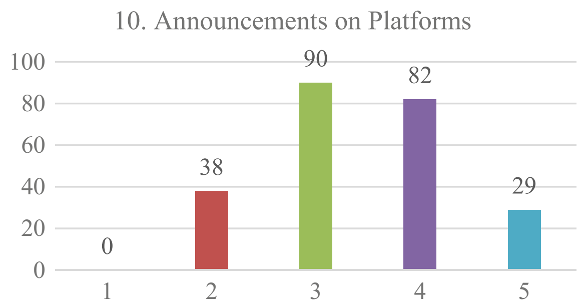


Fig. 3.12 Satisfaction rating for Factor 10

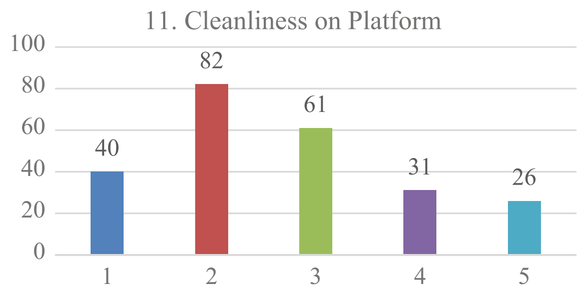


Fig. 3.13 Satisfaction rating for Factor 11

Maximum respondents (104) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (97) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 12 respondents are found to be extremely dissatisfied with the service while 10 respondents and 17 respondents were satisfied with the service.

Figure 3.14 shows results of satisfaction rating for Factor 12.

13. **Number of Trains on a Route**

Maximum respondents (106) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (79) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 4 respondents are found to be extremely dissatisfied with the service while 36 respondents and 15 respondents were satisfied with the service.

Figure 3.15 shows results of satisfaction rating for Factor 13.

14. **Timing of Trains**

Maximum respondents (97) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (67) given the satisfaction rating of 2 to the factor showing they find that there is a scope of

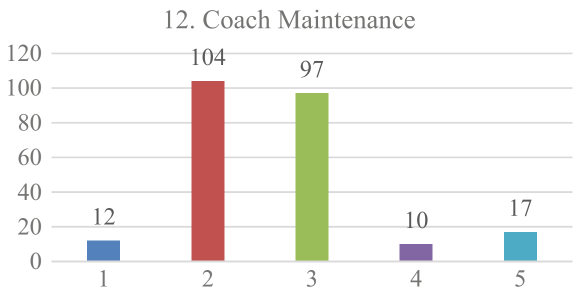


Fig. 3.14 Satisfaction rating for Factor 12

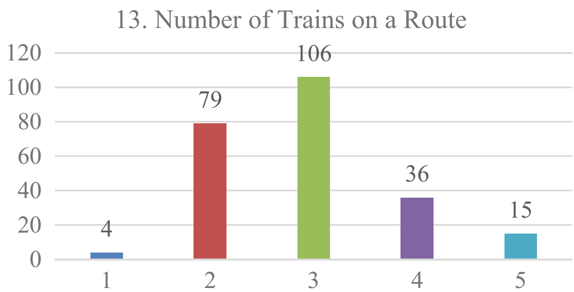


Fig. 3.15 Satisfaction rating for Factor 13

improvement in the service. 12 respondents are found to be extremely dissatisfied with the service while 41 respondents and 23 respondents were satisfied with the service.

Figure 3.16 shows results of satisfaction rating for Factor 14.

15. **Efficiency in Station Management**

Maximum respondents (94) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (76) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 13 respondents are found to be extremely dissatisfied with the service while 41 respondents and 16 respondents were satisfied with the service.

Figure 3.17 shows results of satisfaction rating for Factor 15.

16. **Availability of Coach Attendant/Helper on Train**

Maximum respondents (108) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (80) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 26 respondents are found to be extremely dissatisfied with the service while 16 respondents and 9 respondents were satisfied with the service.

Figure 3.18 shows results of satisfaction rating for Factor 16.

Fig. 3.16 Satisfaction rating for Factor 14

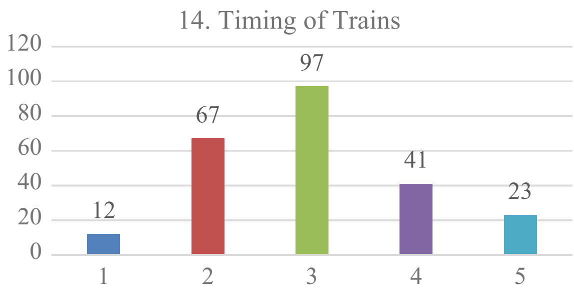


Fig. 3.17 Satisfaction rating for Factor 15

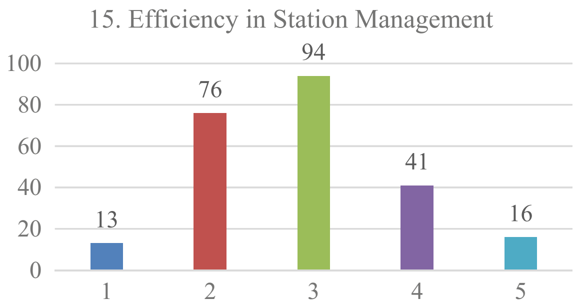
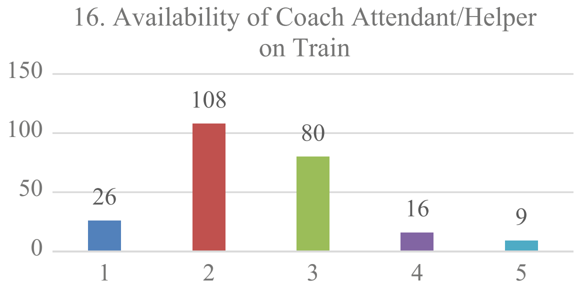


Fig. 3.18 Satisfaction rating for Factor 16



17. **Other Services like Bedding and Blanket Available on the Train**

Maximum respondents (93) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (91) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 34 respondents are found to be extremely dissatisfied with the service while 13 respondents and 9 respondents were satisfied with the service.

Figure 3.19 shows results of satisfaction rating for Factor 17.

18. **Complaint Handling System**

Maximum respondents (96) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (76) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 35 respondents are found to be extremely dissatisfied with the service while 20 respondents and 13 respondents were satisfied with the service.

Figure 3.20 shows results of satisfaction rating for Factor 18.

19. **Waiting Room Facility on the Platform**

Maximum respondents (106) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (58) given

Fig. 3.19 Satisfaction rating for Factor 17

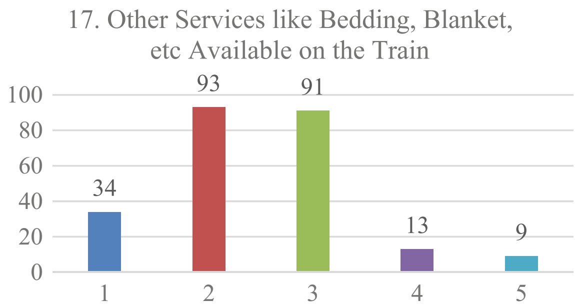
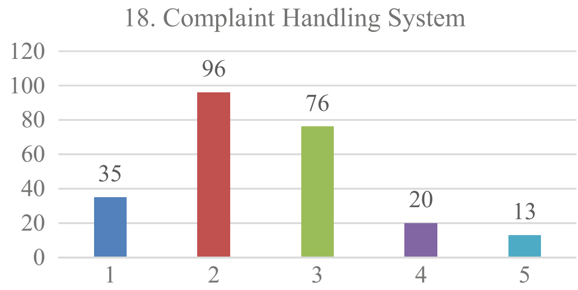


Fig. 3.20 Satisfaction rating for Factor 18



the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 23 respondents are found to be extremely dissatisfied with the service while 37 respondents and 16 respondents were satisfied with the service.

Figure 3.21 results of satisfaction rating for Factor 19.

20. **Ticket Availability Through Multi-channels**

Maximum respondents (85) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (57) given the satisfaction rating of 4 to the factor showing they are satisfied with the service. 20 respondents are found to be extremely dissatisfied with the service while 20 respondents and 25 respondents were dissatisfied and extremely satisfied with the service respectively.

Figure 3.22 shows results of satisfaction rating for Factor 20.

21. **Medical Facility on Train**

Maximum respondents (129) rated 2 to the factor indicating that they find that there is a scope of improvement in the service. Many respondents (52) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 37 respondents are found to be extremely dissatisfied with the service while 13 respondents and 9 respondents were satisfied with the service.

Figure 3.23 shows results of satisfaction rating for Factor 21.

Fig. 3.21 Satisfaction rating for Factor 19

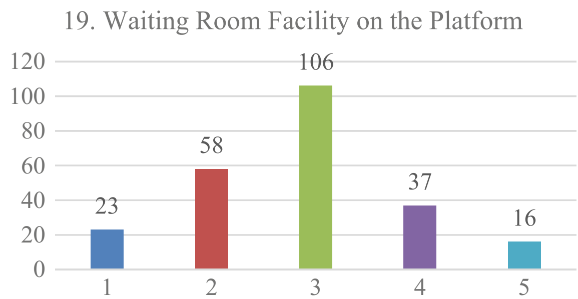


Fig. 3.22 Satisfaction rating for Factor 20

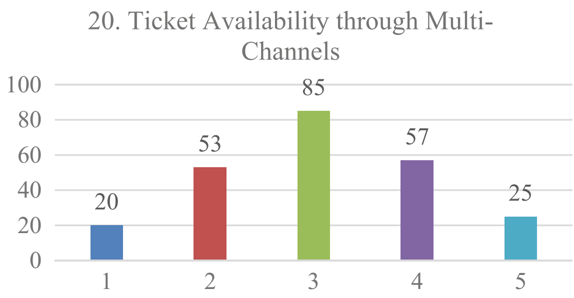
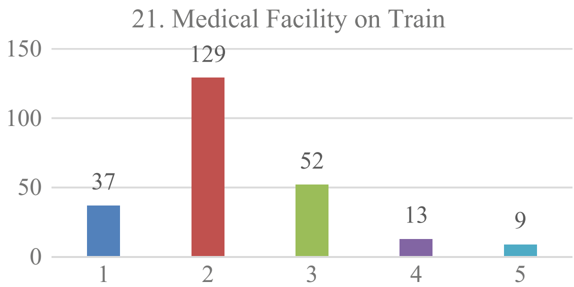


Fig. 3.23 Satisfaction rating for Factor 21



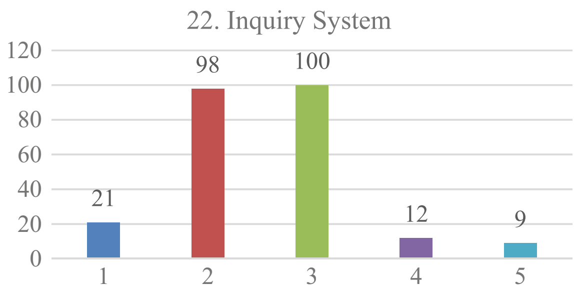
22. **Inquiry System**

Maximum respondents (100) rated 3 to the factor indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (98) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 21 respondents are found to be extremely dissatisfied with the service while 12 respondents and 9 respondents were satisfied with the service.

Figure 3.24 shows results of satisfaction rating for Factor 22.

23. **Wi-Fi and Entertainment Systems on Train**

Fig. 3.24 Satisfaction rating for Factor 22



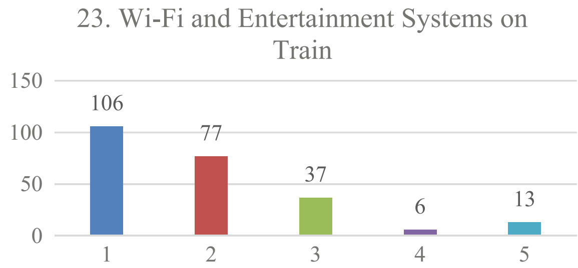


Fig. 3.25 Satisfaction rating for Factor 23

Maximum respondents (106) rated 1 to the factor indicating that they feel Highly Dissatisfied with the service and are neither satisfied nor dissatisfied. Many respondents (61) given the satisfaction rating of 2 to the factor showing they find that there is a scope of improvement in the service. 16 respondents are found to be extremely dissatisfied with the service while 22 respondents and 16 respondents were satisfied with the service.

Figure 3.25 shows results of satisfaction rating for Factor 23.

24. **Modern Coaches (Comfort, Look, Aesthetics)**

Maximum respondents (88) rated 2 to the factor of indicating that they find that there is a scope of improvement in the service. Many respondents (74) given the satisfaction rating of 3 to the factor showing that they feel Neutral about the service and are neither satisfied nor dissatisfied. 25 respondents are found to be extremely dissatisfied with the service while 37 respondents and 15 respondents were satisfied with the service.

Figure 3.26 shows results of satisfaction rating for Factor 24.

25. **Air-Conditioning and Lighting Facilities on the Train**

Maximum respondents (90) rated 3 to the factor of indicating that feel Neutral about the service and are neither satisfied nor dissatisfied. Many respondents (82) given the satisfaction rating of 4 to the factor showing they are satisfied with the service.

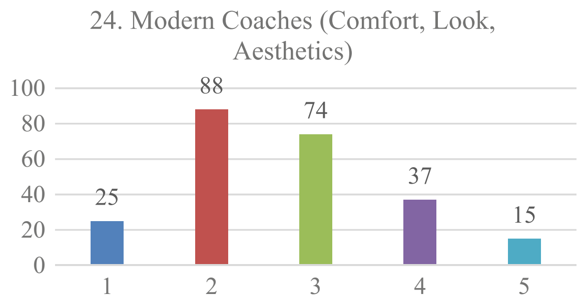


Fig. 3.26 Satisfaction rating for Factor 24

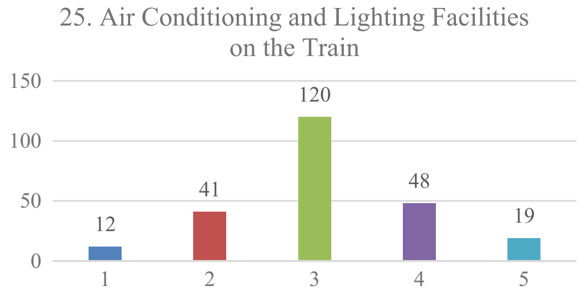


Fig. 3.27 Satisfaction rating for Factor 25

12 respondents are found to be extremely dissatisfied with the service while 41 respondents and 48 respondents were dissatisfied and extremely satisfied with the service, respectively.

Figure 3.27 shows results of satisfaction rating for Factor 25.

3.2.5 Results for Perception about Private Trains

To examine the feasibility of the endeavor to roll out Private Trains by Indian Railways we tried to examine the importance of factors to be rolled out in Private Trains as perceived by respondents. The idea was to estimate the perceived importance and judging if the factors are needed by the public. Respondents were asked to rate their perceived importance of 25 listed factors on a scale of 1 to 5. 1 being Not Important at all and 5 being Extremely Important. The results of the same are obtained in forms of graphs.

The obtained results are published herewith along with the observations.

1. **Seating Arrangements, Sanitation, AC, and Lighting Facility inside the Train**

A maximum of 140 respondents feel that the listed factor is Essential in Private Trains and must be included. 84 respondents feel that the factor is moderately essential while 31, 8, and 4 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.28 shows perceived importance rating for Factor 1.

2. **Catering Service, RO Water Filters, Tea/Coffee Vending Machines Inside the Train**

A maximum of 108 respondents find the listed factor to be Moderately Important. A similar number of respondents (102) found out the factor to be essential. 38, 13, and 6 respondents found the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

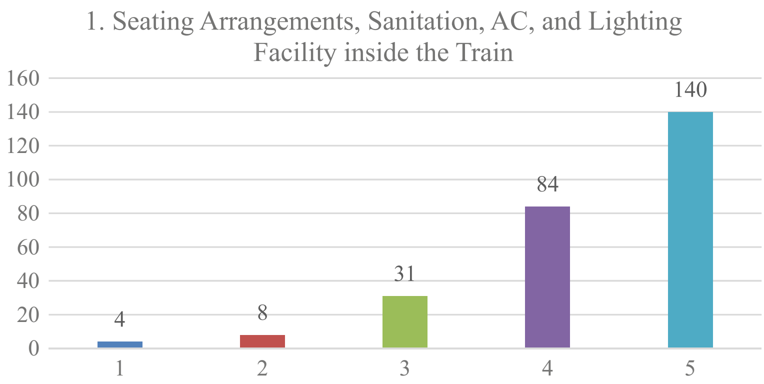


Fig. 3.28 Importance rating for Factor 1

Figure 3.29 shows perceived importance rating for Factor 2.

3. **Medical Facility Inside the Train**

A maximum of 124 respondents feel that the listed factor is Essential in Private Trains and must be included. 87 respondents feel that the factor is moderately essential while 39, 9, and 8 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.30 shows perceived importance rating for Factor 3.

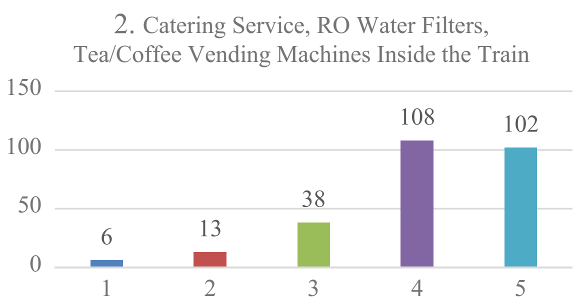
4. **Availability of Tickets through Multiple Channels**

A maximum of 122 respondents feel that the listed factor is Essential in Private Trains and must be included. 96 respondents feel that the factor is moderately essential while 38, 7, and 4 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.31 shows perceived importance rating for Factor 4.

5. **On-Board Wi-Fi Facilities**

Fig. 3.29 Importance rating for Factor 2



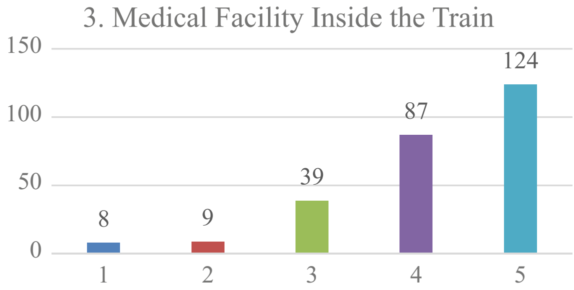


Fig. 3.30 Importance rating for Factor 3

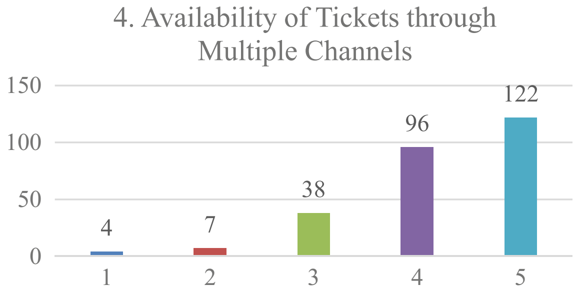


Fig. 3.31 Importance rating for Factor 4

A maximum of 114 respondents feel that the listed factor is Essential in Private Trains and must be included. 87 respondents feel that the factor is moderately essential while 48, 11, and 7 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.32 shows perceived importance rating for Factor 5.

6. **Automated Doors**

A maximum of 90 respondents find the listed factor to be Moderately Important. 66 respondents found out the factor to be Essential and feel that it cannot be avoided

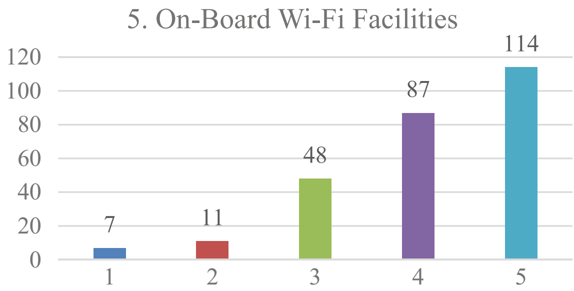


Fig. 3.32 Importance rating for Factor 5

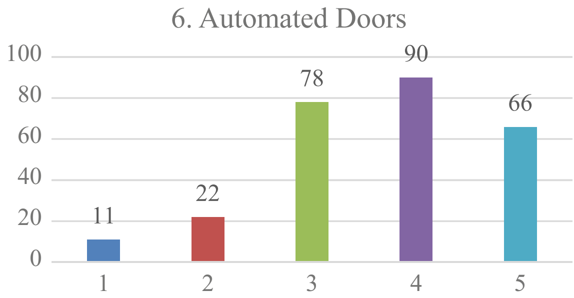


Fig. 3.33 Importance rating for Factor 6

in Private Trains. 78, 22, and 11 respondents found the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.33 shows perceived importance rating for Factor 6.

7. **Safety and Security During the Journey**

A maximum of 194 respondents feel that the listed factor is Essential in Private Trains and must be included. 40 respondents feel that the factor is moderately essential while 29, 2, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.34 shows perceived importance rating for Factor 7.

8. **Frequency of Train Schedule**

A maximum of 111 respondents find the listed factor to be Moderately Important. A similar number of respondents (104) found out the factor to be essential. 43, 7, and 2 respondents found the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.35 shows perceived importance rating for Factor 8.

9. **Timeliness of Trains**

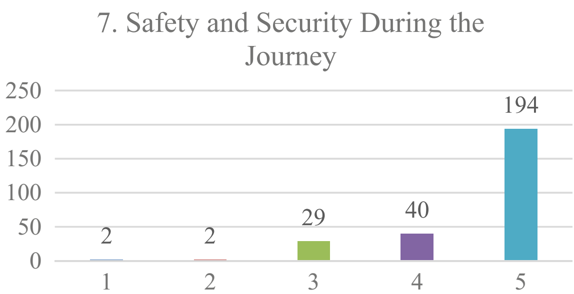


Fig. 3.34 Importance rating for Factor 7

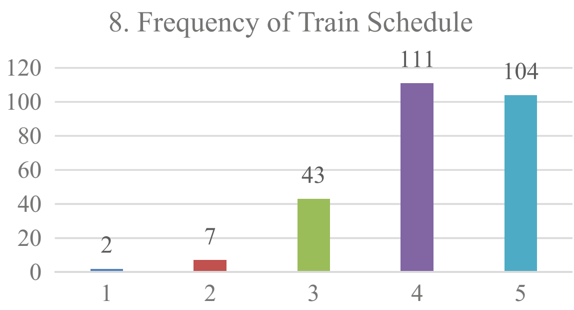


Fig. 3.35 Importance rating for Factor 8

A maximum of 130 respondents feel that the listed factor is Essential in Private Trains and must be included. 91 respondents feel that the factor is moderately essential while 37, 7, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.36 shows perceived importance rating for Factor 9.

10. **Accurate Information of Arrival and Departure of Train**

A maximum of 151 respondents feel that the listed factor is Essential in Private Trains and must be included. 79 respondents feel that the factor is moderately essential while 33, 2, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.37 shows perceived importance rating for Factor 10.

11. **Timely Provision of Complaint Redressal**

A maximum of 138 respondents feel that the listed factor is Essential in Private Trains and must be included. 77 respondents feel that the factor is moderately essential while 42, 8, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.38 shows perceived importance rating for Factor 11.

12. **Dynamic Pricing**

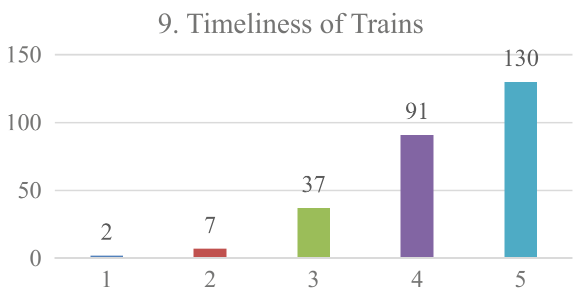


Fig. 3.36 Importance rating for Factor 9

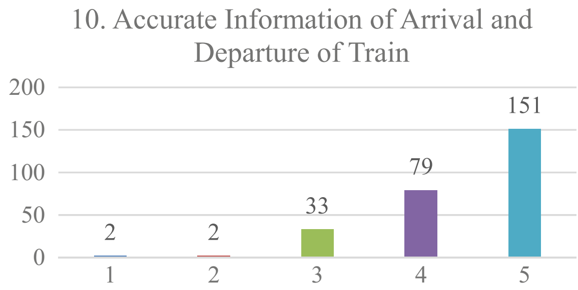


Fig. 3.37 Importance rating for Factor 10

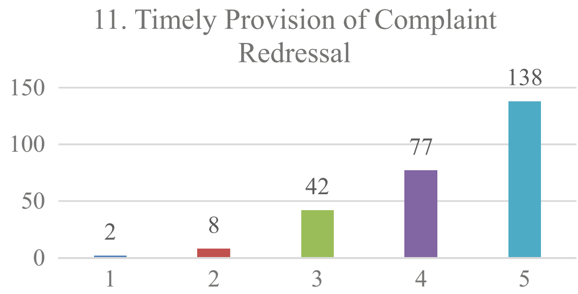


Fig. 3.38 Importance rating for Factor 11

A maximum of 88 respondents feel that the listed factor is Essential in Private Trains and must be included. 70 respondents feel that the factor is moderately essential. Exactly same (70) number of respondents find the factor to be Neutral while 28 and 11 respondents find the factor to be Slightly Important and Not Important at all, respectively.

Figure 3.39 shows perceived importance rating for Factor 12.

13. **Ease of Communication with On-board Staff**

A maximum of 102 respondents find the listed factor to be Moderately Important. A similar number of respondents (100) found out the factor to be essential. 51, 10, and 4 respondents found the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

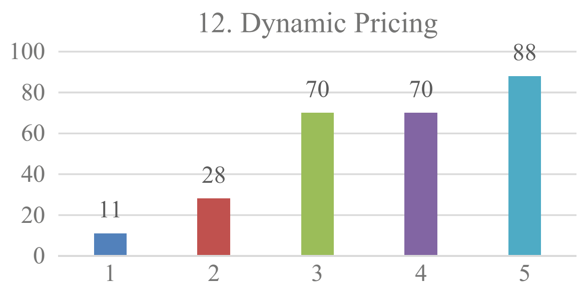


Fig. 3.39 Importance rating for Factor 12

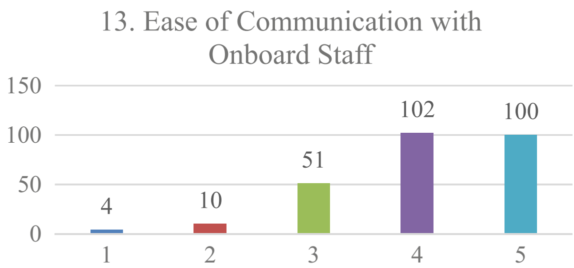


Fig. 3.40 Importance rating for Factor 13

Figure 3.40 shows perceived importance rating for Factor 13.

14. **Knowledge Staff to Answer Questions**

A maximum of 117 respondents feel that the listed factor is Essential in Private Trains and must be included. 99 respondents feel that the factor is moderately essential while 43, 6, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.41 shows perceived importance rating for Factor 14.

15. **Tatkal and Premium Tatkal Facility**

A maximum of 105 respondents feel that the listed factor is Essential in Private Trains and must be included. 98 respondents feel that the factor is moderately essential while 59, 3, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.42 shows perceived importance rating for Factor 15.

16. **Refund on Train Delay**

A maximum of 144 respondents feel that the listed factor is Essential in Private Trains and must be included. 77 respondents feel that the factor is moderately essential while 39, 5, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

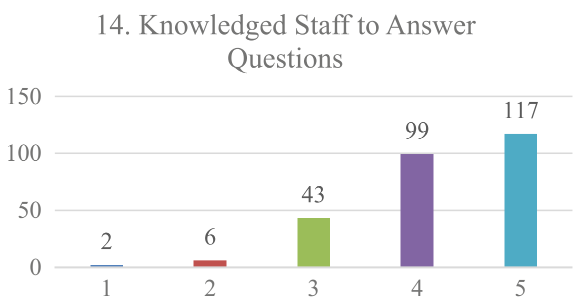


Fig. 3.41 Importance rating for Factor 14

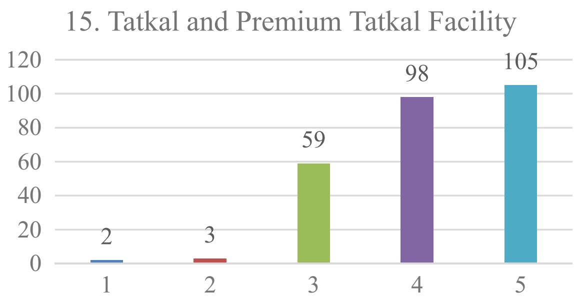


Fig. 3.42 Importance rating for Factor 15

Figure 3.43 shows perceived importance rating for Factor 16.

17. **The Willingness of Staff to Resolve Problems**

A maximum of 114 respondents feel that the listed factor is Essential in Private Trains and must be included. 100 respondents feel that the factor is moderately essential while 46, 9, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.44 shows perceived importance rating for Factor 17.

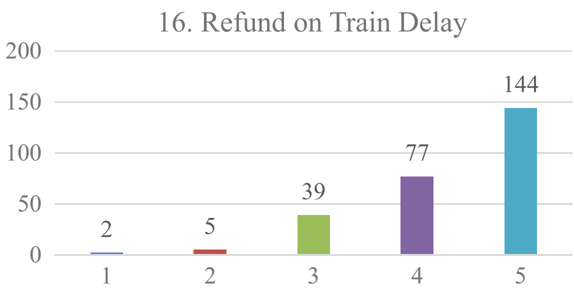


Fig. 3.43 Importance rating for Factor 16

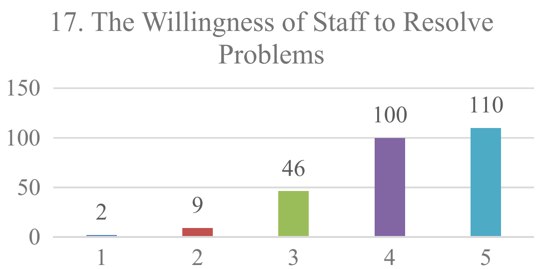


Fig. 3.44 Importance rating for Factor 17

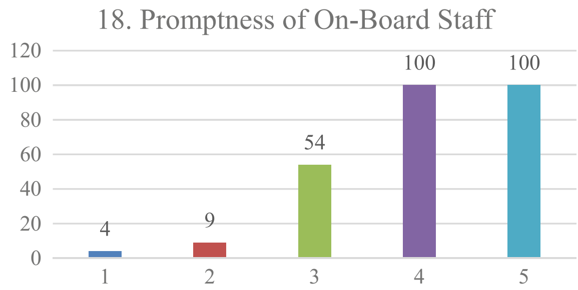


Fig. 3.45 Importance rating for Factor 18

18. **Promptness of On-Board Staff**

An equal of 100 respondents feel that the listed factor is Essential in Private Trains and must be included. 54 respondents feel that the factor is Neutral while 9 and 4 respondents find the factor to be, Slightly Important and Not Important at all, respectively.

Figure 3.45 shows perceived importance rating for Factor 18.

19. **Helpfulness of Coach Attendant**

A maximum of 101 respondents feel that the listed factor is Essential in Private Trains and must be included. 92 respondents feel that the factor is moderately essential while 64, 6, and 4 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.46 shows perceived importance rating for Factor 19.

20. **Response Time to Complaints**

A maximum of 138 respondents feel that the listed factor is Essential in Private Trains and must be included. 76 respondents feel that the factor is moderately essential while 49, 2, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.47 shows perceived importance rating for Factor 20.

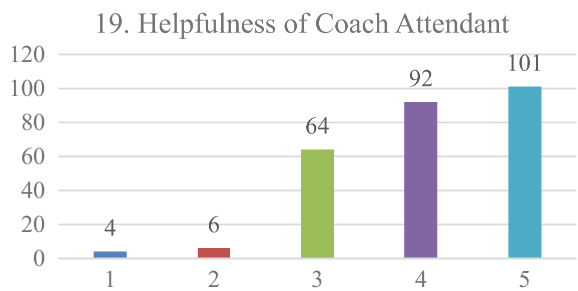


Fig. 3.46 Importance rating for Factor 19

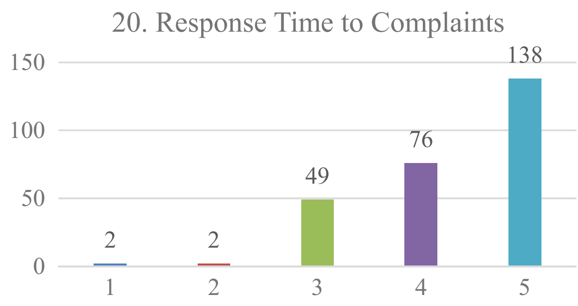


Fig. 3.47 Importance rating for Factor 20

21. **Online Complaint Lodging Facility**

A maximum of 140 respondents feel that the listed factor is Essential in Private Trains and must be included. 87 respondents feel that the factor is Moderately Essential while 48, 11, and 7 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.48 shows perceived importance rating for Factor 21.

22. **Availability of Coach Attendants on the Train**

A maximum of 119 respondents find the listed factor to be Moderately Important. 87 respondents found out the factor to be Essential and feel that it cannot be avoided in Private Trains. 50, 6, and 5 respondents found the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.49 shows perceived importance rating for Factor 22.

23. **Personalized Response to Complaints**

A maximum of 101 respondents feel that the listed factor is Essential in Private Trains and must be included. 100 respondents feel that the factor is Moderately Essential while 54, 8, and 4 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.50 shows perceived importance rating for Factor 23.

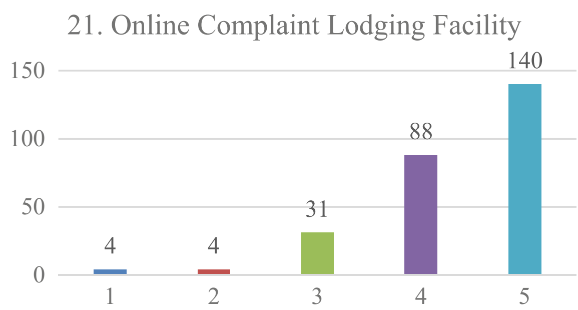


Fig. 3.48 Importance rating for Factor 21

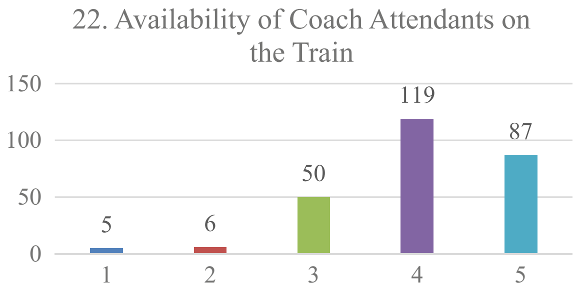


Fig. 3.49 Importance rating for Factor 22

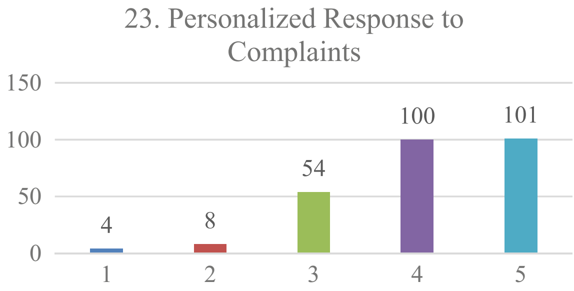


Fig. 3.50 Importance rating for Factor 23

24. **Last-Mile Connectivity provided by Railways**

A maximum of 103 respondents feel that the listed factor is Essential in Private Trains and must be included. 92 respondents feel that the factor is moderately essential while 59, 11, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.51 shows perceived importance rating for Factor 24.

25. **Politeness of Employees**

A maximum of 108 respondents feel that the listed factor is Essential in Private Trains and must be included. 97 respondents feel that the factor is Moderately Essential

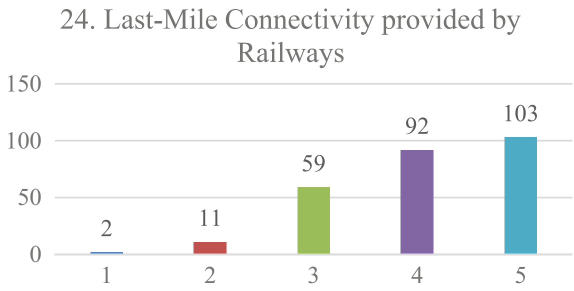


Fig. 3.51 Importance rating for Factor 24

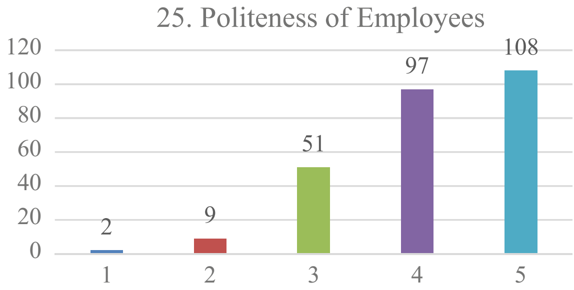


Fig. 3.52 Importance rating for Factor 25

while 51, 9, and 2 respondents find the factor to be Neutral, Slightly Important, and Not Important at all, respectively.

Figure 3.52 shows perceived importance rating for Factor 25.

3.2.6 Results obtained from Factor Analysis of obtained data

The current study aims to propose a hierarchical framework of the primary dimensions of perceived/desired Priority Levels of Various Services in Private Trains, that influence the perceived quality of railway services and, as a result, customer satisfaction.

The nonparametric Kendall's W test was used to rank the primary dimensions of perceived/desired priority levels in a hierarchical order. Test statistics are shown in Table 3.2.

As indicated in Table 3.3, respondents assign varying relative weights to the various elements of private train services, with safety during journey being regarded as the most important, followed by Accurate Information of Arrival and Departure of Train, and Dynamic Ticket Pricing being ranked as the least important.

The first stage in analyzing the effect of these dimensions on overall customer satisfaction coverage with Private Railway services was to reduce the number of statements to a smaller number of variables that could then be used for further analysis. This was done using factor analysis.

Table 3.2 Kendall's coefficient of concordance

Test Statistics	
N	267
Kendall's W[a]	0. 072
Chi-Square	461. 011
df	24
Asymp. Sig	<0.001

Table 3.3 Mean ranks of dimensions/variables of different railway services

Dimensions/variables	Mean rank
Safety and security during the journey	16.98
Accurate information of arrival and departure of train	15.04
Helpfulness of coach attendant	14.43
Online complaint lodging facility	14.42
Response time to complaints	14.36
Seating arrangements, sanitation, AC, and lighting facility inside the train	14.33
Timely provision of complaint redressal	14.18
Timeliness of trains	13.87
Availability of tickets through multiple channels	13.57
Medical facility inside the train	13.26
Knowledge staff to answer questions	13.23
The willingness of staff to resolve problems	12.67
Frequency of train schedule	12.65
Politeness of employees	12.64
Tatkal and Premium Tatkal Facility	12.63
On-board Wi-Fi facilities	12.47
Personalized response to complaints	12.31
Ease of communication with on-board staff	12.27
Last-mile connectivity provided by railways	12.26
Catering service, RO water filters, tea/coffee vending Machines inside the train	12.25
Availability of coach attendants on the train	12.12
Promptness of on-board Staff	11.99
Refund on train delay	11.69
Dynamic pricing	10.35
Automated doors	9.01

Verifying the Suitability of Factor Analysis

Kaiser–Meyer–Olkin (KMO) and Bartlett's test were used to determine whether factor analysis was appropriate for the collection of variables (dimensions).

The magnitude of observed correlation coefficients is compared to the magnitude of partial correlation coefficients using the KMO method. It is preferable to have a value greater than 0.5. The correlation of variables is measured using Bartlett's test. A probability of less than 0.05 is acceptable.

The following is the proposed hypothesis:

Ho: (Null Hypothesis): There is insignificant correlation between the variables.

H1: (Alternate Hypothesis): There is significant correlation between the variables.

Results of KMO and Bartlett's tests are shown in Table 3.4.

Table 3.4 KMO and Bartlett's test results

KMO and Bartlett's Test		
Kaiser–Meyer–Olkin measure of sampling adequacy		0. 915
Bartlett's test of sphericity	Approx. chi-square	5598. 237
	df	300
	Sig	0. 000

As shown in Table 3.4, the KMO value is greater than 0.5 and the significance level is 0.000 which shows that the KMO value is significant at 5 percent level of significance. Hence, the alternate hypothesis is accepted; i.e., there is significant correlation between the variables. It denotes that factor analysis is appropriate.

Finding the Number of Factors and the Variables Under Each Factor

The 25 statements used to measure consumers' perceptions of the priority levels of performance of the different elements of Private train services were subjected to factor analysis. Table 3.5 shows total variance explained by each dimension/variable an eigenvalue greater than 1, and a percentage of variance greater than 65% were used to determine the number of components to be considered.

The scree plot, in Fig. 3.53, shows the eigenvalues of the dimensions/variables in decreasing order.

The rotated component matrix, shown in Table 3.6, shows that the number of factors based on factor analysis is four. The variables in the factor were chosen based on the factor's highest loadings.

Factor 1-Passenger Support & Employee Behavior.

1. Timely Provision of Complaint Redressal.
2. Ease of Communication with On-board Staff.
3. Knowledge Staff to Answer Questions.
4. Helpfulness of Coach Attendant.
5. The Willingness of Staff to Resolve Problems.
6. Promptness of On-board Staff.
7. Response Time to Complaints.
8. Online Complaint Lodging Facility.
9. Availability of Coach Attendants on the Train.
10. Personalized Response to Complaints.
11. Last-mile Connectivity provided by Railways.
12. Politeness of Employees.

Factor 2-On-Board Train Amenities

1. Seating Arrangements, Sanitation, AC, and
2. Lighting Facility inside the Train.
3. Catering Service, RO Water Filters,
4. Tea/Coffee Vending Machines inside the train.

Table 3.5 Total variance explained by each dimension/variable

Component	Initial Eigenvalues			Extraction sums of squared loadings			Rotation Sums of Squared Loadings		
	Total	% Of Variance	Cumulative %	Total	% Of variance	Cumulative %	Total	% Of variance	Cumulative %
1	13.061	52.244	52.244	13.061	52.244	52.244	6.892	27.569	27.569
2	1.886	7.542	59.787	1.886	7.542	59.787	4.188	16.750	44.319
3	1.304	5.217	65.004	1.304	5.217	65.004	3.331	13.322	57.642
4	1.034	4.136	69.140	1.034	4.136	69.140	2.875	11.498	69.140
5	0.872	3.489	72.629						
6	0.771	3.083	75.712						
7	0.697	2.788	78.500						
8	0.568	2.273	80.773						
9	0.556	2.223	82.996						
10	0.502	2.008	85.004						
11	0.465	1.858	86.862						
12	0.439	1.757	88.619						
13	0.392	1.567	90.187						
14	0.337	1.347	91.534						
15	0.311	1.243	92.777						
16	0.287	1.149	93.925						
17	0.271	1.086	95.011						
18	0.252	1.007	96.018						
19	0.212	0.847	96.865						
20	0.182	0.726	97.591						

(continued)

Table 3.5 (continued)

Component	Initial Eigenvalues			Extraction sums of squared loadings			Rotation Sums of Squared Loadings		
	Total	% Of Variance	Cumulative %	Total	% Of variance	Cumulative %	Total	% Of variance	Cumulative %
21	0.165	0.660	98.251						
22	0.131	0.523	98.774						
23	0.117	0.466	99.241						
24	0.112	0.448	99.688						
25	0.078	0.312	100.000						

Extraction Method: Principal Component Analysis

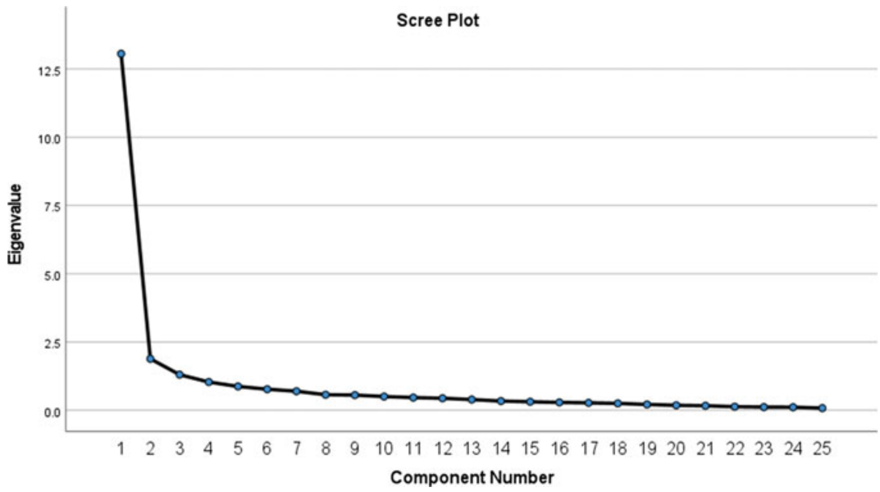


Fig. 3.53 Scree plot obtained after factor analysis

5. Medical Facility inside the Train.
6. On-Board Wi-Fi Facilities.
7. Automated Doors.

Factor 3-Train Operations & Services.

1. Availability of tickets through multiple channels.
2. Safety and Security During the Journey.
3. Timeliness of Trains.
4. Accurate Information of Arrival and Departure of Train.

Factor 4-Ticketing and Pricing

1. Dynamic Pricing.
2. Refund on Train Delay.
3. Tatkal and Premium Tatkal Facility.

The factors have been named based on their variable makeup. Table 3.7 shows the component transformation matrix.

Multiple Regression using the Independent Factors

To determine the impact of the factors identified above on determining overall customer satisfaction with Railways, regression analysis was performed using the four factor scores against each dimension as independent variables and overall customer satisfaction (as measured by the dimensions/variables w.r.t Private Trains) as the dependent variable.

First, normality tests were run on the dependent variable, and the results are shown in Table 3.8.

Table 3.6 Rotated component matrix obtained after factor analysis

Rotated component matrix[a]				
	Component			
	1	2	3	4
Seating arrangements, sanitation, AC, and lighting facility inside the train	0.264	**0.724**	0.104	0.307
Catering service, RO water filters, tea/coffee vending machines inside the train	0.264	**0.821**	0.102	0.126
Medical facility inside the train	0.221	**0.728**	0.194	0.190
Availability of tickets through multiple channels	0.013	0.487	0.134	**0.598**
On-board Wi-Fi facilities	0.224	**0.763**	0.256	0.220
Automated doors	0.225	**0.735**	0.135	-0.060
Safety and security during the journey	0.511	0.299	0.289	**0.527**
Frequency of train schedule	0.284	0.091	0.339	**0.741**
Timeliness of trains	0.557	0.140	0.038	**0.588**
Accurate information of arrival and departure of train	0.463	0.148	0.451	**0.556**
Timely provision of complaint redressal	**0.573**	0.297	0.354	0.417
Dynamic pricing	0.099	0.161	**0.672**	0.173
Ease of communication with on-board staff	**0.709**	0.178	0.296	0.167
Knowledge staff to answer questions	**0.641**	0.225	0.485	0.163
Tatkal and premium Tatkal facility	0.177	0.097	**0.654**	0.368
Helpfulness of coach attendant	**0.453**	0.279	0.408	0.365
The willingness of staff to resolve problems	**0.623**	0.376	0.457	0.150
Promptness of on-board staff	**0.552**	0.321	0.514	0.106
Refund on train delay	0.517	0.351	**0.591**	0.023
Response time to complaints	**0.647**	0.178	0.464	0.071
Online complaint lodging facility	**0.722**	0.235	0.413	0.221
Availability of coach attendants on the train Personalized response to complaints	**0.769**	0.280	0.026	0.122
	0.808	0.259	0.177	0.160
Last-mile connectivity provided by railways	**0.802**	0.172	0.043	0.250
Politeness of eployees	**0.679**	0.217	0.176	0.346
Extraction Method: principal component analysis Rotation Method: varimax with kaiser normalization				

[a]Rotation converged in 7 iterations

Table 3.7 Component transformation matrix for dimension reduction

Component Transformation Matrix				
Component	1	2	3	4
1	0.683	0.455	0.431	0.376
2	−0.452	0.876	−0.157	−0.060
3	−0.543	−0.159	0.397	0.723
4	−0.188	0.006	0.795	−0.576
Extraction Method: Principal Component Analysis Rotation Method: Varimax with Kaiser Normalization				

Table 3.8 Normality test results on dependent variable (Overall Customer Satisfaction)[a]

	Kolmogorov–Smirnov			Shapiro–Wilk		
	Statistic	df	Sig	Statistic	df	Sig
Overall customer satisfaction	0.256	267	<0.001	0.85	267	<0.001

[a] Lilliefors Significance Correction

The Shapiro–Wilk, as well as Kolmogorov–Smirnov test significance, came to be <0.001. Hence, our dependent variable is normally distributed. The histogram and the normal QQ, shown in Fig. 3.54 and Fig. 3.55, plot further confirm the normal distribution of the dependent variable.

Table 3.9 shows the descriptive statistics of the dependent variable and proves the absence of highly skewed variables/outliers in the data set and so a reliable multiple regression model can be fitted.

The value of R^2 was found to be 0.722, and the adjusted R^2 was 0.718, which shows that the model is a good fit. The significance of the F-value came out to be <0.001, indicating that the model is statistically significant at the 5% level of significance. Table 3.11 shows the ANOVA test results.

Table 3.12 shows the coefficients obtained after multiple regression analysis. As per the standardized beta values, it can be inferred that Factor 1, i.e., Passenger Support & Employee Behavior, has the maximum effect on the overall satisfaction of the customer while Factor 4, i.e., Ticketing and Pricing, has the least effect.

The histogram and QQ plot of the residuals obtained during MRA are shown in Fig. 3.56 and Fig. 3.57, respectively.

A regression equation can be developed to retrieve the value of the dependent variable based on the values obtained.

Overall Customer Satisfaction = 6.015(constant) + 0.719(Passenger Support & Employee Behavior) + 0.552*(On-Board Train Amenities) + 0.417*(Train Operations & Services) + 0.373*(Ticketing and Pricing).*

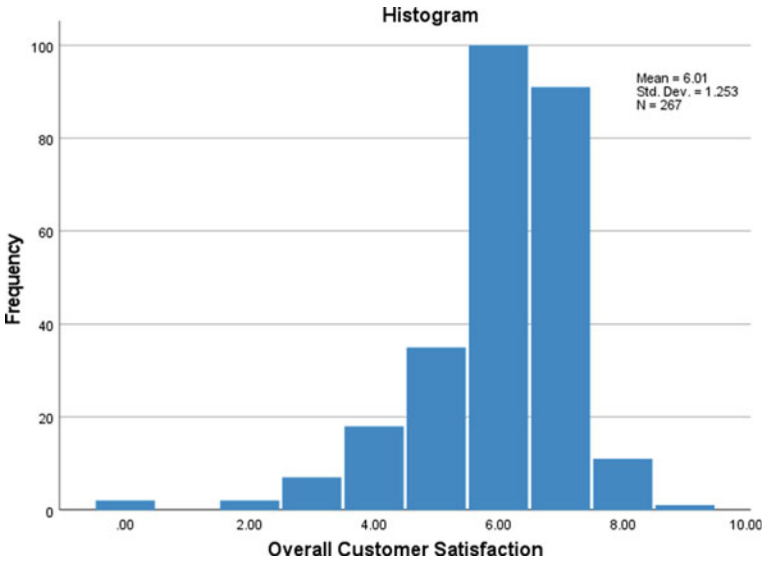


Fig. 3.54 Histogram showing distribution of the variable 'Overall Customer Satisfaction'

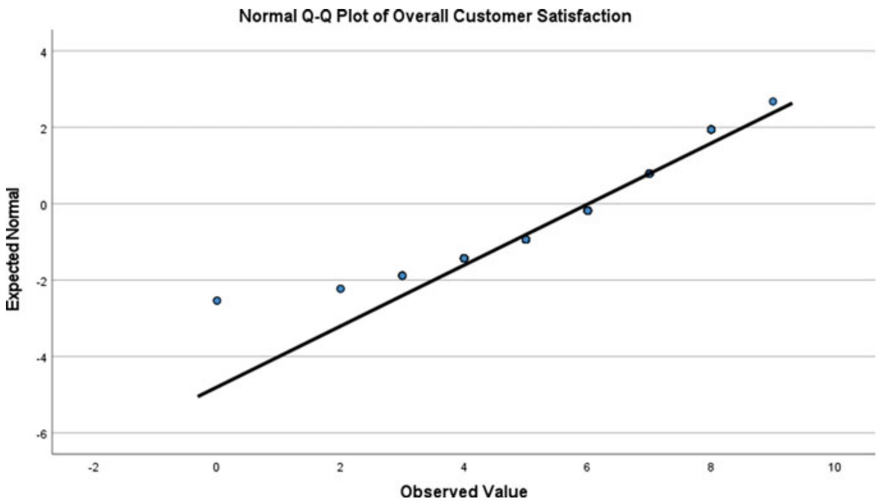


Fig. 3.55 Normal QQ plot of the dependent variable

Customers' satisfaction with Private Trains will grow when their contentment with each of these factors increases. As seen in Fig. 3.58, the model can also be represented graphically. The beta values of the respective variables indicate the projected increase/decrease in overall satisfaction with Private Trains for each unit rise or reduction in these factors.

Table 3.9 Descriptive statistics of the dependent variable

Descriptives				
			Statistic	Std. error
	Mean		6. 0150	0. 07671
Overall Customer Satisfaction	95% Confidence Interval for Mean	Lower Bound	5. 8639	
		Upper Bound	6. 1660	
	5% Trimmed Mean	6. 0972		
	Median	6. 0000		
	Variance	1. 571		
	Std. Deviation	1. 25348		
	Minimum	0. 00		
	Maximum	9. 00		
	Range	9. 00		
	Interquartile Range	1. 00		
	Skewness	−1.425	0. 149	
	Kurtosis	3. 797	0. 297	

Summary of multiple regression analysis is shown in Table 3.10.

Table 3.10 Model summary of MRA

Model Summary[b]				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0. 850[a]	0. 722	0. 718	0. 66571

[a] Predictors: (Constant), Ticketing and Pricing, Train Operations & Services, On-Board Train Amenities, Passenger Support & Employee Behavior
[b] Dependent Variable: Overall Customer Satisfaction

Table 3.11 ANOVA test results

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig
1	Regression	301. 829	4	75. 457	170. 267	<0.001[b]
	Residual	116. 111	262	0. 443		
	Total	417. 940	266			

[a] Dependent Variable: Overall Customer Satisfaction
[b] Predictors: (Constant), Ticketing and Pricing, Train Operations & Services, On-Board Train Amenities, Passenger Support & Employee Behavior

Factor 1-Passenger Support & Employee Behavior.
Factor 2-On-Board Train Amenities.
Factor 3-Train Operations & Services.

Table 3.12 Coefficients obtained after multiple regression of independent factors on the dependent variable

Coefficients[a]								
Model		Unstandardized coefficients		Standardized coefficients	t	Sig	Collinearity statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	6. 015	0. 041		147. 640	<0.001		
	Passenger Support & Employee Behavior	0. 719	0. 041	0. 573	17. 609	<0.001	1. 000	1. 000
	On-Board Train Amenities	0. 552	0. 041	0. 441	13. 528	<0.001	1. 000	1. 000
	Train Operations & Services	0. 417	0. 041	0. 333	10. 228	<0.001	1. 000	1. 000
	Ticketing and Pricing	0. 373	0. 041	0. 297	9. 131	<0.001	1. 000	1. 000

[a]Dependent Variable: Overall Customer Satisfaction

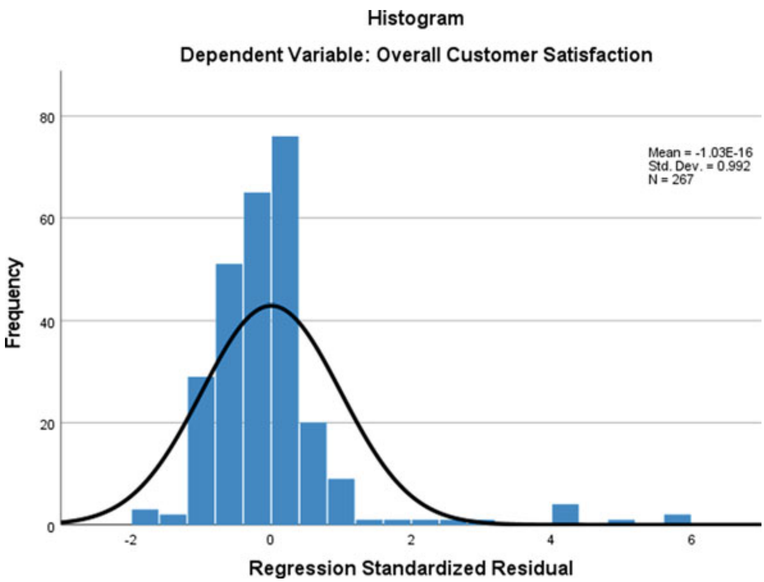


Fig. 3.56 Histogram of residuals after model fit

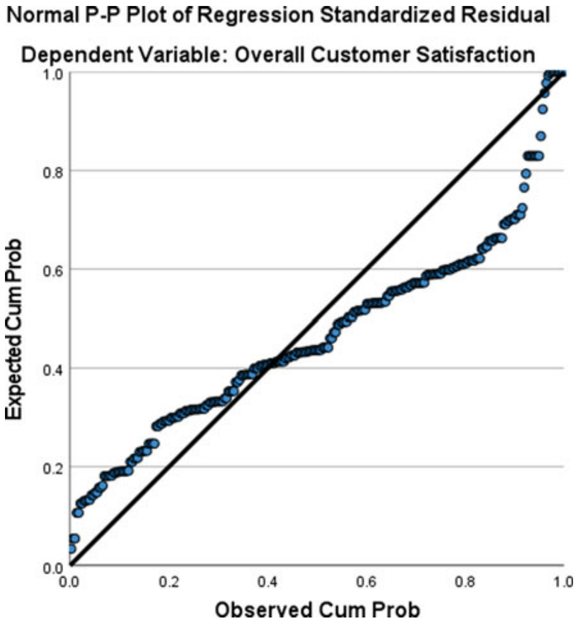


Fig. 3.57 Normal QQ plot of regression standardized residual

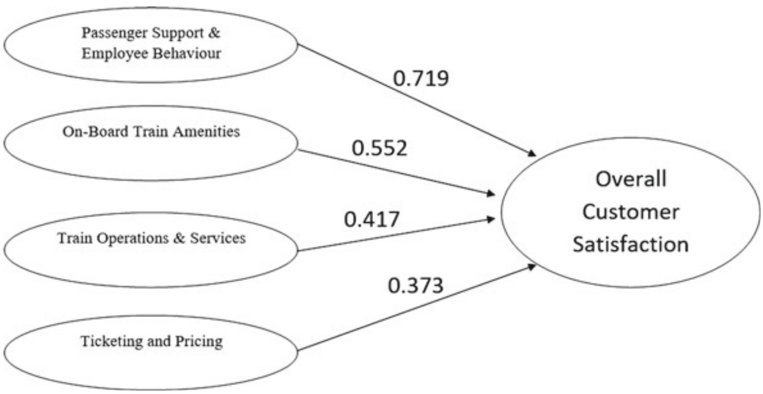


Fig. 3.58 Pictorial representation of the regression equation obtained

Factor 4-Ticketing and Pricing.

For example, overall satisfaction is expected to improve by 0.719 if perceived service quality of Passenger Support and Employee Behavior improves by one unit and all other variables remain constant.

3.3 Conclusions

Various responses from 267 respondents were recorded and analyzed by the means of an online survey/questionnaire. From the analysis of data obtained for Current Satisfaction of Customers from Indian Railways, we find out that the mean score of all the services is less than 3 indicating that the average satisfaction level of all the services is Neutral at best. Out of 5, the service of Safety and Security during the journey gets the highest average rating of 3.14 while the lowest mean rating is given to the service of Wi-Fi and Entertainment System inside the Trains. Since the average rating is not greater than 3, we conclude that there is a clear need of improvement in railway services.

Respondents were then told about the idea of Private Trains and were asked to rate their perceived importance of 25 listed services on a scale of 1 to 5. Descriptive analysis of obtained data showed that the service of Safety and Security during the Journey got the highest mean rating out of 5 while the lowest rated service came out to be Automated Doors.

Respondents who chose the last option (I prefer other modes over trains) in the question of Frequency of travel in Section-1 were asked to fill out a questionnaire where they would rate their agreement with various listed reasons of not using Indian Railways to travel on a scale of 1 to 5. The collected data was put into graphs (mentioned in Appendix-2) and was analyzed to reveal that most of the respondents do not use trains to travel because they feel that coaches of Indian railways are not modern enough as respondents have given it a mean rating of 3.32 out of 5. By this, we can conclude that Indian Railways need to work on the modernity of coaches by installing or adopting more services to modernize the travel. This is in coherence with the mean rating found for the satisfaction of customers with the service of On-board Wi-Fi and Entertainment Systems, i.e., 1.92 out of 5.

Therefore, the qualitative analysis of the data shows a clear case for improvement in existing services and introduction of Private Trains.

The primary concept of this study was that customer satisfaction with Private Trains services is greatly impacted by customer perceptions of their priority levels of several dimensions, which are categorized under a few parameters. The findings revealed that when the individuals' most important service aspects are of higher quality, they are more satisfied with Private Trains as a whole.

On the other side, respondents were less satisfied with Private Trains as a whole when they thought the performance of several parameters was bad. Because the dimensions stay relatively constant, these findings appear to be generalizable to practically all routes. Customers value safety and security throughout their journeys, and thus, the PTOs should pay greater attention to them. According to the suggested model of customer satisfaction, PTOs should pay close attention to each component of railway services to guarantee that consumers are satisfied—not just with the core service, but also with the overall service experience. Passenger assistance and employee behavior have been given the highest relative value by the respondents, as indicated in the suggested model of customer satisfaction. This means that employees' behavior—friendliness, politeness, collaboration, promptness, efficiency, knowledge level, trustworthiness, and so on—can significantly impact the satisfaction level of the customers. Within the restrictions imposed by regulatory requirements and skill requirements, PTOs should aim to hire employees for specialized jobs, educate them to efficiently manage clients, and enable speech, behavior, and performance monitoring systems. Following employee behavior, the next most important dimension was on-board train amenities, which included seating arrangements, sanitation, air-conditioning, and lighting inside the train, medical facilities inside the train, catering service, RO water filters, tea/coffee vending machines inside the train, automated doors, and on-board Wi-Fi. This means that, while tangible facilities are valuable to consumers, a focus on customer convenience and providing the necessary support for customer inquiries should be prioritized. These elements of the service environment serve as explicit or implicit signals that convey the service's image. First-time customers will attempt to deduce meanings and build perceptions based on these tactile indications.

These measurements assist clients in navigating the surroundings. When customers are unable to acquire precise information, they become disoriented, causing worry, and ambiguity about how to proceed in order to obtain the required service. Inexperienced clients may become frustrated and angry as a result of being lost in a complicated atmosphere. Customers make their first touch with railway services when they need to make reservations.

The third important dimension as per the model is train operations and services. Under this, we have timeliness of trains, the availability of ticket through multiple channels, security and safety during the journey, frequency, and headway of train schedules, availability of status information.

The fourth significant factor determining customer satisfaction is ticketing and pricing. This covers tatkal and premium tatkal services, dynamic pricing, and train delay refunds. Finally, while individuals often acquire opinions about specific features or dimensions of a service, it is the whole configuration of all of these factors that affect consumer responses and satisfaction with the service as a whole.

Consumers have a holistic perception of a service's performance, and consumer responses to the physical environment are influenced by ensemble effects or configurations. Services must be viewed as a whole, which means that no aspect of the design can be optimized separately. Depending on the priority assigned to them by the customers, all areas must be addressed.

This will ensure that customers are happy with the service, resulting in customer loyalty and repeat business.

3.4 Limitations and Future Scope of Research

A study with adequate representation of each socio-demographic group could provide additional insight into the use of Private Trains as a mode of transportation. The dimensions presented are not exhaustive, and real customer sentiment may not be accurately evaluated until Private Train Operations become more prevalent in India. Furthermore, actual pricing adjustments influenced by PTOs will be required to assess the likelihood of passengers switching to alternative means of transportation.

References

1. 1991: Economics Reforms. http://indiabefore91.in/1991-economic-reforms
2. Economic Reforms of 1991|Accessed April 25, 2022. https://www.encyclopedia.com/international/encyclopedias-almanacs-transcripts-and-maps/economic-reforms-1991
3. Ghosh, A.: India's pathway through financial crisis. Wayback Machine. Published Autumn 2007. Accessed April 25, 2022. https://web.archive.org/web/20111112080531, http://www.globaleconomicgovernance.org/wp-content/uploads/Ghosh%20-%20India.pdf
4. RBI Reports. 2020–21. Accessed April 25, 2022. https://rbidocs.rbi.org.in.
5. Current Industrial Licensing Policy in India. Published online October 17, 2015. https://www.gktoday.in/topic/current-industrial-licensing-policy-in-india/
6. Jose, T.: What are the features of New industrial policy of 1991? Published online October 6, 2016. Accessed April 25, 2022. https://www.indianeconomy.net/splclassroom/what-are-the-features-of-new-industrial-policy-of-1991/
7. Key Provisions of New Industrial Policy: Published online October 19, 2015 (1991)
8. Monopolies and restrictive trade practices act 1970. Published online September 14, 2011
9. Burange, L., Yamini, S.: The performance of Indian iron and steel industry and competitiveness of the firms. J. Indian Sch. Polit. Econ.. **20**, 449–495 (2008)
10. Development of Indian Steel Sector Since 1991. https://steel.gov.in/sites/default/files/DEVELOPMENT.pdf
11. Aviation in India - Aviation Industry in India, Air Travel in India. Accessed April 25, 2022. http://www.tradechakra.com/indian-economy/infrastructure/aviation.html
12. Hooper, P.: Liberalization of the airline industry in India. J. Air Transp. Manag. **3**(3), 115–123 (1997). https://doi.org/10.1016/S0969-6997(97)00019-7
13. Malik, H., Malik, P.: How to avoid repeating the mistakes of the past. The Avmark Aviation Economist 1. The Avmark Aviation Economist. Published online 1996 (1994)
14. Passenger air traffic each year | Statista. Accessed April 25, 2022. https://www.statista.com/statistics/564717/airline-industry-passenger-traffic-globally/
15. Kulkarni, L.: Liberalization of India's life insurance sector: an evaluation
16. Handbook on Indian Insurance Statistics. IRDA (2020)
17. Mohan, R.: Financial sector reforms in India: policies and performance analysis. In: Reserve Bank of India Bulletin (2004)
18. Bandyopadhyay, T.: Three decades of liberalization: Banking highs and lows. Published online February 7, 2021
19. Sitharamaraju, K., Beerelli, S.K., Saket, A.Y., Sundaravalli, N.: Public-private partnership (PPP) in Indian railways: models, framework, and policies. IIM A Working Paper. Published online December 2020
20. Privatization of Indian Railways – Part 4: International Experience of Rail Privatization. Published June 21, 2021. https://cgpi.org/21610
21. Fernandes, J.: Indian Railways privatization | A look at other countries that have taken this route. Published March 8, 2020. Accessed April 25, 2022. https://www.moneycontrol.com/news/economy/policy/indian-railways-privatisation-a-look-at-other-countries-that-have-taken-this-route-5498651.html
22. Mizutani, F., Nakamura, K.: Privatization of the Japan National Railway: overview of performance changes. International Journal of Transport Economics. **24**(1), 75–99 (1997)
23. Nash, C.A.: Rail privatization - the experience so far

24. Hilmola, O.P., Ujvari, S., Szekely, B.: Deregulation of railroads and future development scenarios in Europe: Analysis of the privatisation process taken place in the USA, the Sweden and UK. World Rev. Intermodal Transp. Res. **1**(2), 146–169 (2007)
25. Kikeri, S., Nellis, J.: An assessment of privatization. The World Bank Research Observer **19**(1), 87–118 (2004)
26. Ponti, M., Erba, S.: Railway liberalization from a public choice perspective. Transporti Europei **VII** (20–21), 38–46 (2002)
27. Ball, J., White, P.: Experience of national railway privatisation, and of vertical separation in metro system. Transporti Europe **VII**(20–21), 38–46 (2002)
28. Key Provisions of New Industrial Policy 1991: Accessed April 25, 2022 (2015). https://www.gktoday.in/topic/new-industrial-policy-1991

Chapter 4
Energy-Based Assessment of Commercial Adaptive Cruise Control Systems

Theocharis Apostolakis, Michail A. Makridis, Anastasios Kouvelas, and Konstantinos Ampountolas

Abstract Vehicle automation is regarded as one of the most promising technologies in transportation networks to alleviate congestion, improve safety and energy efficiency. Adaptive cruise control (ACC) systems, which serve as the first step of automation, are already standard equipment in many commercially available vehicles. Therefore, the observation-based assessment of such systems individually and in platoon formations is very appealing. The thematic focus of this study is laid on investigations into the impact of ACC systems on energy and fuel consumption inside the platoon. High-resolution data from two experimental car-following campaigns consisted of platoons with ACC-equipped vehicles are collected. Two driving modes are considered, human- and ACC-driven vehicles. Results are presented with four independent energy consumption models. The findings reveal that an upstream energy propagation was observed inside the platoon by the ACC participants, indicating that ACC systems are less efficient than human drivers. On the positive side, ACC systems do not generally fail inside a platoon, keeping steady time-gaps. They seem to operate based on a constant headway policy, and their performance is conditioned to the environment. ACC drivers in protected environments and campaigns might perform better but should be (ideally) tested in adverse environments.

Keywords Adaptive cruise control · Tractive energy consumption · Fuel consumption · Experimental campaigns · Driving behavior · Platoon

Th. Apostolakis (✉) · K. Ampountolas
Department of Mechanical Engineering, University of Thessaly, 38334 Volos, Greece
e-mail: tapostolakis@uth.gr

M. A. Makridis · A. Kouvelas
Institute for Transport Planning and Systems, ETH, Zürich, Switzerland

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_4

4.1 Introduction

The energy and environmental challenges facing humanity are further exacerbated by the rising transport of goods and people. The transport sector is heavily reliant on fossil fuels. As a result, transportation generates a large share of greenhouse gas (GHG) emissions around the world. However, the future of transportation networks is expected to be transformed radically, due to the recent advances in vehicle automation and communication systems. Vehicle automation comes with the promise to increase road safety, road capacity, and traffic flow that are currently limited due to heterogeneity in vehicle dynamics and human driving behaviors. Nowadays, many commercially available vehicles are equipped with advanced driver assistance systems (ADAS) that support the driver by taking over particular driving tasks.

Adaptive cruise control (ACC) systems, which are considered as the first step of driving automation (Level-1 of SAE levels of driving automation [1]), are already optional or standard equipment in many commercially available vehicles. Driving automation of Level-1 undertakes the steering or brake/acceleration task of the driver. Level-2 assumes a combination of multiple assistance functionalities, e.g., undertaking both steering and brake/acceleration tasks of the driver. The ACC system controls the longitudinal movement of the equipped vehicle by monitoring the speed and distance from the vehicle ahead constrained by a user-defined desired speed. ACC uses onboard sensors (right and left side on the front bumper), such as LiDAR, radar, or cameras to continuously detect the distance to the preceding vehicle. ACC can be enabled and disabled by the driver upon request. The driver activates ACC by setting the desired maximum speed and by selecting among different time-gap settings from the preceding vehicle. Then, ACC can automatically adjust the vehicle's speed by accelerating or decelerating it, to maintain a constant predefined headway with the vehicle in front or to reach the predefined desired speed. Moreover, a braking guard can warn about imminent collision and automatically start braking and disengage ACC. ACC disengagement occurs whether the headway between two vehicles is close to infinity or when a vehicle travels with the minimum ACC operating speed. The driving behavioral properties of ACC are considered to reduce heterogeneity, affecting traffic flow (negative or positive depending on the conditions) and affecting fuel consumption and emission pollutants.

The penetration rate of ACC-equipped vehicles on public roads is rapidly increasing, gaining traction among car manufacturers and consumers. However, the surging acceptance of such systems across the globe is escalating concerns on undesired properties of commercial ACC systems such as string instability, negative impact on-road capacity, safety concerns, energy demand, and fuel consumption [2–6].

Studies on the energy footprint of ACC-equipped vehicles are based on traffic simulation or empirical data obtained from experimental campaigns. For instance, a novel vehicular ACC system was proposed that can comprehensively address issues of tracking capability, fuel economy, and driver desired response [7]. Detailed simulations with a heavy-duty truck showed that the developed ACC system provides significant benefits in terms of fuel economy, achieving fuel savings of 5.9 and 2.2% during urban and highway driving scenarios, respectively.

A large-scale study with a fleet of 51 test vehicles over 62 days and 199,300 miles (driven by General Motor employees on their daily commutes) was conducted to analyze the GHG emissions benefit of ACC from a statistical perspective [8]. The results show that ACC driving could significantly reduce GHG emissions at low speeds, which, however, would hardly deliver a meaningful benefit for the whole journey because ACC utilization rates at low speeds were marginal and low-speed driving only covered a small portion of the total travel distance. Generally, the study reports a positive total GHG (directly correlated to fuel consumption) emissions benefit of the ACC systems.

An experimental campaign involving 10 commercially available ACC-equipped vehicles was presented [9]. The test campaign was executed in two different test tracks of the ZalaZONE proving ground, in Hungary. Results confirm the previous findings in terms of string instability of the ACC and highlight that in the present form, ACC systems may lead to higher energy consumption and introduce new safety risks when their penetration in the fleet increases.

Another field experiment was conducted with seven commercial SAE Level-2 equipped vehicles, driven as a platoon on public roads for a trip of almost 500 km [10]. The study concludes that SAE Level-2 systems are not suitable for driving as platoons of more than typically three to four vehicles, because of instabilities in the car-following behavior and hence, discomfort and large fuel consumption. Finally, another experiment was performed with ACC-equipped vehicles in real-world car-following scenarios from Ispra to Vicolungo and back, in Italy [11]. Two driving modes were adopted, with and without ACC systems enabled. The results show that from individual and platoon perspectives, ACC followers tend to have energy consumption higher than those of human counterparts, questioning the positive impact of ACC systems on fuel and energy consumption.

Experimental observations with partially or fully automated vehicles are scarce, but their number is expected to increase in the coming years due to the availability of heterogeneous, precise, and inexpensive sensors. Nevertheless, the energy demand of automated vehicles, as well as their commonalities and differences with human drivers are not widely discussed in the literature, which constitutes a gap that this work aims to fill. Toward this goal, the present chapter provides a comprehensive study of the energy impact of ACC systems under car-following conditions, based on empirical observations from two independent real-life experimental campaigns, with platoons of ACC-equipped vehicles, using two different data acquisition methods. Their energy impact is assessed by four state-of-the-art energy demand and fuel consumption models available in the literature. Both ACC- and human-driven vehicles are considered in the investigation to elaborate on the behavioral similarities and differences between these two driving modes. As a result, it expands the discussion from safety concerns and technological aspects of ACC systems and includes the effect of transportation on the environment under real circumstances.

The main findings of this work are as follows: (a) In both experimental campaigns, an upstream energy propagation was observed inside the platoon by the ACC participants, regarding both tractive energy and fuel consumption, indicating that ACC systems are less efficient; (b) ACC driving operation (strong accelerations, steep speeds) may negatively affect the energy impact of ACC systems; (c) ACC systems may lead to string instability failing to avoid an upstream energy amplification; and (d) road gradient changes could create string instabilities in the traffic flow and may negatively affect the energy impact of ACC systems.

Despite the above shortcomings of ACC, we highlight that ACC systems do not generally fail inside a platoon, and they drive very steady in equilibrium conditions. Especially on highways, commercially implemented ACC systems can be reliable, safe, comfortable (no need to press the pedal), and energy efficient in equilibrium conditions. To support the above arguments, we show that the time- and space-gaps of the ACC participants are smaller (in absolute values) and better distributed when compared to their human counterparts. This highlights the ability of the ACC drivers to keep constant time-gap policies. We also show that the more efficient ACC systems are regarding their functional specifications, the less energy efficient tend to be. Consequently, commercially implemented ACC systems must be optimized to realize a trade-off between functional specifications in terms of time-gap policies and safe and eco-driving instructions. This will ideally eliminate high energy levels and achieve the desired eco-driving and safety features of commercial ACC systems.

The rest of this chapter is organized as follows: Sect. 4.2 presents four independent energy and fuel consumption models. Two experimental car-following campaigns in Italy and Sweden are then presented, providing us with two large datasets, valuable for the assessment of the four models. Section 4.3 first analyzes the experimental data from the two test campaigns. Then, it assesses the energy footprint of ACC and human drivers as obtained from the application to the considered energy demand and fuel consumption models. Also, it offers a discussion around the similarities and differences between these two driving modes concerning several technical aspects. Specifically, ACC and human driving behaviors are compared with respect to the transient response of speed and acceleration profiles, traffic perturbation events, string stability, and time-gap policies. Finally, Sect. 4.4 summarizes the findings of this study and offers suggestions for future work.

4.2 Methodology

This section presents four independent energy and fuel consumption models. The first model concerns the tractive energy consumption [11, 12], ruling out the effect of the propulsion system (tractive power demand on the wheels). The other three models, namely VT-micro [13], VSP [14, 15], and ARRB [16], focus on the (instantaneous) fuel consumption.

4.2.1 Tractive Energy Consumption

Tractive energy consumption serves as a suitable indicator for the assessment of ACC driving behavior. This indicator considers only the tractive power demand on the wheels, without considering the powertrain dynamics and the regenerative braking power. Although it does not directly reflect the engine fuel consumption (which will be considered in Sect. 2.2) or the battery charge depletion, this metric can rule out the energy effect of heterogeneous propulsion systems in the traffic network [11].

The instantaneous tractive power (P_t, kW) required to move the engine at the defined velocity and surpass the aerodynamic and rolling resistances is given by [12]:

$$P_t = \begin{cases} \left(F_0 + F_1 v_e + F_2 v_e^2 + 1.03 m a_e + mg \cdot \sin\theta\right) v_e \cdot 10^{-3}, & P_t \geq 0 \\ 0, & P_t < 0 \end{cases}, \tag{4.1}$$

where F_0, F_1, and F_2 are road load coefficients that describe the relationship between overall resistances to motion and the vehicle speed, given in N, Ns/m, and Ns^2/m^2, respectively; m is the vehicle mass (kg); v_e and a_e are the ego vehicle's speed (m/s) and acceleration (m/s^2), respectively; θ is the road gradient (rad); g is the gravitational acceleration (9.81 m/s^2).

The terms inside the parentheses in Eq. 4.1 represent the resistance forces to vehicle motion and speed. The F_0, F_1, and F_2 coefficients are commonly used to characterize the road loads of vehicles, as mentioned above. They express the constant part of a vehicle's resistances (tire rolling resistances), the part that is proportional to velocity (partly tire rolling resistance, partly drivetrain losses), and the part that is proportional to the square of the vehicle's velocity (aerodynamic component) [17]. Consequently, the first two terms ($F_0 + F_1 v_e$) represent the rolling resistance force, the second one ($F_2 v_e^2$) the aerodynamic drag, the third term (1.03ma_e) is the force of inertia, where the factor of 1.03 is applied to correct the inertia of the vehicle which accounts for the vehicle mass and the inertia of its rotating components, and the last one (mg $\cdot$ sinθ) is related to the force due to gravity and roadway grade.

The vehicle's tractive energy consumption (E_t, kWh/100 km) results by integrating the instantaneous tractive power requirements (P_t, kW) at the wheels over time, without considering the negative power components from the regenerative braking, and dividing it by the distance covered which corresponds to the integration of the instantaneous speed over time [11]. Finally, a factor of 0.036 is applied to the denominator so that the results are available in the commonly used units mentioned above (kWh/100 km), as described by:

$$E_t = \frac{\int_0^T P_t dt}{0.036 \cdot \int_0^T v_e dt}, \tag{4.2}$$

where dt is the time interval (s) between consecutive measurement points and T denotes the total duration (s) of the travel period.

4.2.2 *Fuel Consumption*

The impact of ACC driving behavior on fuel consumption is assessed with three state-of-the-art vehicle fuel consumption models, namely VT-micro [13], VSP [15], and ARRB [16], focusing on instantaneous fuel consumption.

4.2.2.1 The VT-Micro Model

Virginia Tech (VT)-micro model is a microscopic dynamic emission and fuel consumption model [13]. The VT-micro model was developed from experimentation with numerous polynomial combinations of speed and acceleration profiles, on a second-by-second basis [18]. Specifically, linear, quadratic, cubic, and quartic speed and acceleration terms were tested using chassis dynamometer data, collected at the Oak Ridge National Laboratory (ORNL). The ORNL data consisted of nine normal-emitting vehicles, including six light-duty automobiles and three light-duty trucks. The raw data collected at the (ORNL) contained 1300–1600 individual vehicle data points, each collected every second during various driving cycles. Typically, vehicle acceleration values ranged from -1.5 to 3.7 m/s^2 at increments of 0.3 m/s^2, while vehicle speeds varied from 0 to 33.5 m/s at increments of 0.3 m/s [13].

Generally, two types of mathematical models were investigated, nonlinear regression models and artificial neural network models. For the purposes of this study, the instantaneous fuel consumption, $F(v_i, a_i)$ (L/s), of an individual vehicle, can be expressed as:

$$F(v_i, a_i) = \exp\left(\sum_{j_1=0}^{3}\sum_{j_2=0}^{3} K_{j_1 j_2}(v_i)^{j_1}(a_i)^{j_2}\right), \tag{4.3}$$

where v_i and a_i are the speed (m/s) and acceleration (m/s^2) of the vehicle at time i, respectively; j_1 and j_2 are the power indexes; $K_{j_1 j_2}$ are constant coefficients that can be found in Table 4.1 [19].

Table 4.1 Coefficients of the VT-micro model

$K_{j_1 j_2}$	$j_2 = 0$	$j_2 = 1$	$j_2 = 2$	$j_2 = 3$
$j_1 = 0$	−7.537	0.4438	0.1716	−0.0420
$j_1 = 1$	0.0973	0.0518	0.0029	−0.0071
$j_1 = 2$	−0.003	−7.42E−04	1.09E−04	1.16E−04
$j_1 = 3$	5.3E−05	6E−06	−1E−05	−6E−06

4.2.2.2 The VSP Model

The concept of vehicle specific power (VSP) is a formalism used in the evaluation of vehicle emissions. Vehicle specific power is defined as the instantaneous power per unit mass of the vehicle [14]. The instantaneous power generated by the engine is used to overcome the rolling resistance and aerodynamic drag and to increase the kinetic and potential energies of the vehicle [14], so VSP is described as:

$$\text{VSP} = \frac{\text{Power}}{\text{mass}} = \frac{\frac{d}{dt}\left(E_{\text{kinetic}} + E_{\text{potential}}\right) + F_{\text{rolling}} \cdot v + F_{\text{aerodynamic}} \cdot v}{m}, \quad (4.4)$$

where E_{kinetic} is the kinetic energy; $E_{\text{potential}}$ is the potential energy, F_{rolling} is the rolling resistance force; $F_{\text{aerodynamic}}$ is the aerodynamic resistance force; v is the vehicle speed; and m is the vehicle mass. More specifically, it equals the product of speed and an equivalent acceleration, which includes the effects of roadway grade and rolling resistance, plus a term for aerodynamic drag which is proportional to the cube of the instantaneous speed [14], as described by:

$$\text{VSP} = \frac{\text{Power}}{\text{mass}} = \frac{\frac{d}{dt}(\frac{1}{2}m \cdot (1+\varepsilon_i) \cdot v^2 + mgh) + C_R mg \cdot v + \frac{1}{2}\rho_a C_D A (v + v_w)^2 \cdot v}{m}, \quad (4.5)$$

and hence,

$$\text{VSP} = v \cdot (a \cdot (1+\varepsilon_i) + g \cdot \text{grade} + g \cdot C_R) + \frac{1}{2}\rho_a \frac{C_D \cdot A}{m}(v + v_w)^2 \cdot v, \quad (4.6)$$

where v, m as described above, given in m/s and kg, respectively; a is the vehicle acceleration (m/s^2); ε_i[1] is the "mass factor," which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain; h is the altitude of the vehicle; grade[2] [14]. However, for the purposes of this study, $\sin(\tan^{-1}(\text{grade}))$ was used.) is the vertical rise divided by the slope length; g is the gravitational acceleration (9.81 m/s^2); C_R[3] is the coefficient of rolling resistance (dimensionless); C_D is the drag coefficient (dimensionless); A is the frontal area of the vehicle; ρ_a is the ambient air density (1.207 kg/m^3 at 20 °C); v_w is the headwind into the vehicle. The last term of Eq. 4.6, the load due to aerodynamic drag, depends on the factor $(C_D \cdot A/m)$ which is different for each specific vehicle model. An estimate was done based on the bibliography and was set equal to 0.0005. Thus, the

[1] Typical values of ε_i for a manual transmission are 0.25 in 1st gear, 0.15 in 2nd gear, 0.10 in 3rd gear, 0.075 in 4th gear, etc. Finally, ε_i was set equal to 0.1 [14].

[2] Rigorously $\sin(\tan^{-1}(\text{grade}))$ should be used instead of grade, but the error of this approximation is small (less than 1% relative error for grades below 14%.

[3] The value of C_R depends on the road surface and tire type and pressure, with a small dependence on vehicle speed, with typical values ranging from 0.0085 to 0.016, so a value of 0.0135 has been used [14].

vehicle specific power, after calculations, is given in W/kg, as:

$$\mathrm{VSP} = v \cdot (1.1 \cdot a + 9.81 \cdot \mathrm{grade} + 0.132) + 3.02 \cdot 10^{-4}(v + v_w)^2 \cdot v. \quad (4.7)$$

For the purposes of this study, the following form was used:

$$\mathrm{VSP}_i = v_i \cdot (1.1a_i + 9.81g + 0.132) + 3.02 \cdot 10^{-4} v_i^3, \quad (4.8)$$

where VSP_i is the instantaneous vehicle specific power (W/kg); v_i and a_i are the speed (m/s) and acceleration (m/s^2) of the vehicle at time i, respectively;g denotes the road grade given as mentioned previously.

To perform the energy characterization of a vehicle, a portable laboratory was used to measure fuel consumption, pollutant emissions, and vehicle dynamics under on-road conditions of 14 conventional vehicles and 5 hybrid vehicles. For each second of driving, according to the power demand resulting from the vehicle specific power VSP_i mentioned above, the correspondent VSP mode was calculated. Using the data collected on-road, a general trend of fuel consumption as a function of VSP mode was observed, which was defined by 6 coefficients adjustable from vehicle to vehicle according to the certification inputs [15]. As a result, the instantaneous fuel consumption is expressed as a function of vehicle specific power, VSP_i (g/s), as:

$$F(v_i, a_i) = F(\mathrm{VSP}_i) = \begin{cases} f, & \text{if } \mathrm{VSP}_i < -10 \\ \alpha \mathrm{VSP}_i^2 + b\mathrm{VSP}_i + c, & \text{if } -10 \le \mathrm{VSP}_i \le 10 \\ m\mathrm{VSP}_i + d, & \text{if } \mathrm{VSP}_i > 10 \end{cases}, \quad (4.9)$$

where $\alpha = 1.98\mathrm{E}{-03}$, $b = 3.97\mathrm{E}{-02}$, $c = 2.01\mathrm{E}{-01}$, $d = 2.48\mathrm{E}{-03}$, $f = 2.48\mathrm{E}{-03}$, and $m = 7.93\mathrm{E}{-02}$ are coefficient values corresponding to one of the testing vehicles that were used [15]. To obtain the results in L/s, the instantaneous fuel consumption, $F(v_i, a_i)$ (g/s), is divided by the fuel density. For the purposes of this work, we assume only diesel vehicles, and hence, the oil density ρ is estimated around 850 g/L.

4.2.2.3 The ARRB Model

Australian road research board (ARRB) model is an instantaneous fuel consumption model suitable for determining the incremental effects on fuel consumption resulting from changes in traffic management [16]. The model relates fuel consumption to the fuel to maintain engine operation and to the energy consumed (word done) in providing tractive force to the vehicle.

A power-based model was proposed that could relate the instantaneous fuel consumption to the instantaneous power demand experienced by the vehicle, using a simple linear relation [20]. However, the validation of this power model was not sufficient for the use of the model in the detailed assessment of the impacts of proposed traffic management schemes. Using data collected from carefully controlled on-road acceleration, deceleration, and steady-speed fuel consumption tests, it was demonstrated that the power model gave adequate estimates of fuel consumption over trip segments of at least 60 s duration, as well as during cruise and slow-to-medium accelerations (mean errors generally less than 5%) [21]. On the other hand, during hard accelerations, fuel consumption was significantly underestimated, with mean errors of up to 20% depending on the acceleration and final speed [16]. Therefore, an extension (ARRB model) of the power model was presented, improving the accuracy of estimated fuel consumption, especially during hard accelerations [22].

For the purposes of this work, ARRB fuel consumption model can be expressed as the following simple polynomial function of instantaneous speed and acceleration, given in mL/s, as described by:

$$F(v_i, a_i) = \beta_1 + \beta_2 v_i + \beta_3 v_i^2 + \beta_4 v_i^3 + \gamma_1 v_i a_i + \gamma_2 v_i \left(\max(0, a_i)^2\right), \quad (4.10)$$

where v_i and a_i are the speed (m/s) and acceleration (m/s^2) of the vehicle at time i, respectively; $\beta_1 = 0.666$; $\beta_2 = 0.019$; $\beta_3 = 0.001$; $\beta_4 = 0.00005$; $\gamma_1 = 0.12$; $\gamma_2 = 0.058$. These parameters were calibrated using a Cortina test car, so that the model will accurately estimate the contribution of each energy component to fuel consumption [16].

4.2.2.4 Fuel Consumption Estimation

To obtain meaningful results from the fuel consumption models, the vehicle's fuel consumption, F_c (L/100 km), results by integrating the instantaneous fuel consumption, $F(v_i, a_i)$ (L/s), and dividing it by the distance covered which corresponds to the integration of the instantaneous speed over time. A factor of 10^{-5} is applied to the denominator so that the results are available in L/100 km, given by:

$$F_c = \frac{\int_0^T F(v_i, a_i)dt}{10^{-5} \cdot \int_0^T v dt}, \quad (4.11)$$

where $F(v_i, a_i)$ is the instantaneous fuel consumption of the various models, given in L/s; v is the instantaneous speed (m/s); dt is the time interval (s) between consecutive measurement points; T denotes the total duration (s) of the travel period.

4.2.3 Experimental Campaigns

4.2.3.1 Ispra-Vicolungo

The first campaign was conducted in the first quarter of 2019, involving three days of car-following testing, on a section of Autostrada A26[4] between Ispra and Vicolungo, in northern Italy. The testing was performed with five ACC-equipped vehicles of various brands and models, driving in a car-platoon formation, in a 124.6 km round trip. Tests were scheduled for non-peak hours to minimize interference from other road users, such as cut-in behaviors. This real-world experiment aimed to collect driving data under actual traffic conditions in real-world scenarios.

Data acquisition was performed in binary format from the U-blox M8 devices,[5] with one device installed per vehicle. The acquired data had approximately a sampling frequency of 3–5 Hz, so cubic splines interpolation was implemented to achieve a 10 Hz frequency. GNSS receivers were configured to collect signals from both GPS and Galileo,[6] with the ability to process up to 16 satellite signals, enabling a good performance. The average horizontal accuracy reported by the receivers was less than 50 cm. GNSS active antennas were mounted on the roof of the cars, to ensure maximum satellite visibility and avoid signal attenuations from the body of the vehicles. At each time instant, the geographic coordinates (latitude, longitude, and altitude) of the vehicles were recorded. These coordinates were then transformed into a local East, North, and Up (ENU) Cartesian reference frame. Also, outliers were filtered using typical moving average postprocessing; big noisy parts have been removed from the dataset. Additional antennas were positioned to the front bumper of each vehicle to estimate the inter-vehicle distances. First, the instantaneous inter-vehicle distances are calculated based on position data, and then, these measurements are corrected based on computing bumper-to-bumper distances, by subtracting the leader's antenna-back bumper distance and the follower's antenna-front bumper distance.

The leader was instructed to drive manually and perform occasional random decelerations and accelerations over the desired speed. The followers, whenever possible, were driving with ACC systems enabled, apart from the last day when manual driving situations were tested. Therefore, to investigate the impact of both driving behaviors, the last day of the experimental campaign was the most appropriate for the purposes of this work. Specifically, on the southbound (SB) route (from Ispra to Vicolungo) of the trip, all vehicles were operated by human drivers. On the contrary, on the northbound (NB) route, the followers adopted ACC driving to regulate the longitudinal speed and the inter-vehicle distance with the minimum distance setting selected, while the leader and the last follower, whose drivers were respectively the same during the trip, were always human-driven. Also, a fixed vehicle order was adopted during the whole trip. Table 4.2 summarizes some of the vehicle specifications.

---

[4] Autostrada A26 is a motorway in the northwestern Italian regions of Liguria and Piedmont.

[5] https://www.u-blox.com/en/product/evk-8evk-m8.

[6] The European Global Navigation Satellite System (GNSS) receiver.

Table 4.2 Vehicle specifications for Ispra-Vicolungo campaign

	Vehicles	Max power (kW)	Engine size (cc)	Top speed (km/h)	Model year
C1	Mitsubishi SpaceStar	59	1193	173	2018
C2	Ford S-Max	110	1997	196	2018
C3	Peugeot 3008 GT Line	130	1997	208	2018
C4	KIA Niro	77.2	1580	172	2019
C5	Mini Cooper	100	1499	210	2018

4.2.3.2 AstaZero Test Track

The second campaign was conducted in the second quarter of 2019, involving two days of car-following testing on the rural road of the AstaZero test track in Sweden. The testing was performed with five ACC-equipped vehicles, from four different makes (all different models), driving in a car-platoon formation. AstaZero's rural road is approximately 5.7 km long, half is designed for speeds around 70 km/h and a half for speeds around 90 km/h; however, its elevation profile is quite flat.

Trajectory data acquisition was performed with an inertial navigation system, the RT-Range S multiple target ADAS measurements solution by Oxford Technical Solutions Company, with a differential GNSS accuracy. The differential GNSS system ensures precision of 2 cm/s in the speed and 2 cm in the positioning measurements. This acquiring system provided a frequency of more than 100 Hz, so downsampling was applied to achieve a 10 Hz frequency, enough for capturing the vehicle dynamics in the platoon.

The experiments were organized in laps, containing five vehicles in a platoon formation. In all the tests, the leading vehicle was the same, and it was driven with the ACC system enabled to avoid noisy fluctuations around the desired speed due to manual maneuvers. In general, two different car-following patterns were applied for the following vehicles, a) car-platoon with constant speed, and b) car-platoon with the performance of perturbations (deceleration to a new desired speed) from an equilibrium point. For the second pattern, a radio-based communication between the drivers of the first and last vehicles ensured that the speed of the last vehicle was stable at the desired speed, and therefore, the car-platoon was close to an equilibrium state, before applying a new perturbation. Each perturbation was triggered by the driver by setting the desired speed of the ACC system to a new lower desired speed value. Consequently, the vehicle decelerates autonomously, and when the new desired speed is reached, the driver resets the desired speed to the previous setting. The duration of the perturbation is automatically adjusted based on the deceleration strategy applied by the controller. This procedure was selected to perform the different perturbations in a controlled way, and it resembles the way that vehicles with the ACC systems enabled behave on-road. For safety reasons, in each lap, the desired speeds were fixed to 13.9–16.7 m/s along the curves and to 25–27.8 m/s on the straight parts. Followers

Table 4.3 Vehicle specifications from AstaZero campaign

	Vehicles	Max power (kW)	Engine size (cc)	Top speed (km/h)	Model year
C1	Audi A8	210	2967	250	2018
C2	Audi A6	150	1968	246	2018
C3	BMW X5	195	2993	230	2018
C4	Mercedes A Class	165	1991	250	2019
C5	Tesla Model 3	150	–	210	2019

were driving with ACC enabled, with the minimum distance setting selected, apart from two laps where manual driving situations were tested. To investigate the impact of ACC driving behavior compared to the human one, the two most suitable parts of AstaZero's database were selected for the assessment. The first part included only human driving vehicles except the first one, while the second one involved only vehicles with the ACC systems enabled. In addition, the same five vehicles were used, in the same fixed order. Table 4.3 summarizes some of the vehicle specifications.

4.3 Results and Discussion

This section employs several data analysis techniques to present the obtained results from the application of four energy demand and fuel consumption models (see Sects. 2.1 and 2.2) to the two experimental car-following campaigns presented in Sect. 2.3. The impact of ACC on tractive energy and fuel consumption is assessed from individual and platoon perspectives. Vehicles in the same platoon are experiencing quite similar road and traffic conditions but with totally different specifications. To isolate the driving behavior as the only possible contributor to tractive energy and fuel consumption differences, a scaling technique is employed to normalize heterogeneous vehicle specifications and road and traffic conditions. Specifically, this heterogeneity is handled by assuming that the same default values for the vehicle's road load coefficients and mass, among the various energy and fuel consumption models, are used for the whole platoon (platoon normalization).

4.3.1 Ispra-Vicolungo

The first experimental campaign consisted of five vehicles in a platoon formation, and was divided into two trajectory paths, one going from Ispra to Vicolungo (southbound route) and another returning back (northbound route), using the same vehicles in a fixed order during the whole trip (third day of the experiments). On the southbound route, all vehicles in the platoon were operated by human drivers, while on the northbound route, the followers enabled the ACC systems. The first and the last vehicles were human-driven throughout the whole trip.

4.3.1.1 Energy Consumption

The tractive energy values of the vehicles sharing the same platoon are compared, provided that all vehicles share the same specifications as those of their leader (platoon normalization). Figure 4.1 presents the obtained results from the campaign in Italy. Figure 4.1i displays the tractive energy impact of human and ACC driving behavior inside the platoon. The figure reveals a tendency for upstream energy propagation in the platoon with ACC systems enabled (northbound route). Specifically, the tractive energy values of the ACC followers (C2, C3, and C4) tend to consecutively increase, in contrast to the tractive energy values that their human counterparts achieve in the southbound route. Therefore, ACC systems seem to be less energy efficient than human-driven vehicles from a platoon perspective.

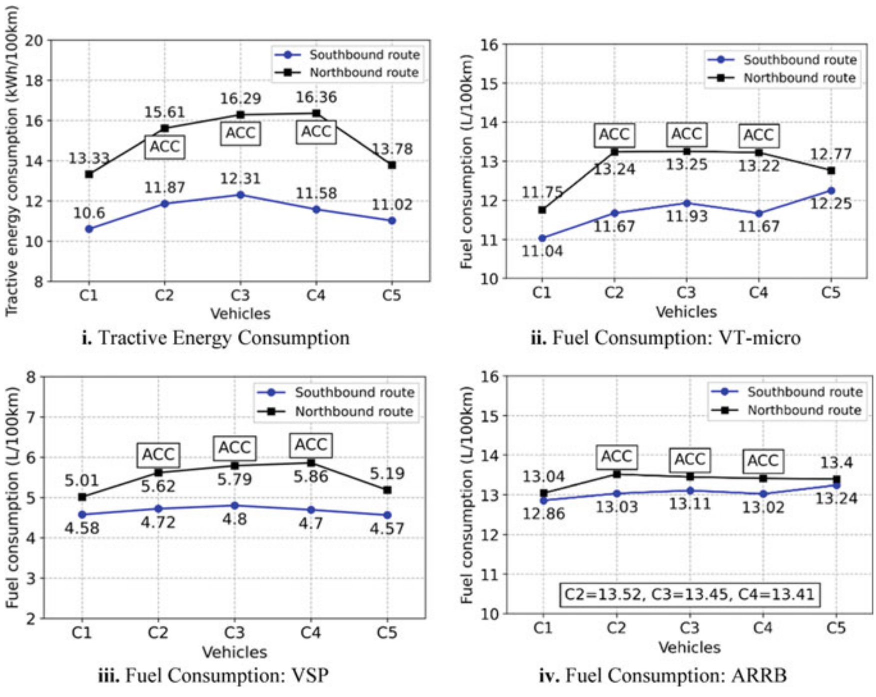


Fig. 4.1 Energy and fuel consumption models (Ispa-Vicolungo)

4.3.1.2 Fuel Consumption

The impact of ACC systems on fuel consumption inside the platoon is examined using the three independent fuel consumption models, as illustrated in Fig. 4.1. The results are given in (L/100 km). As can be seen, quite the same tendency is revealed among the various fuel consumption models, regarding the ACC driving behavior. More precisely, the findings of the VT-micro model reveal a strong fuel consumption amplification by the first ACC participant (C2) inside the platoon (northbound route), with the rest of them (C3, C4) maintaining the values on high levels relative to those that the human counterparts achieve in the southbound route. Additionally, the VSP model reveals quite similar results to the energy consumption model, regarding both ACC and human driving behaviors, showing the same exact tendency for fuel consumption propagation upstream of the platoon. On the contrary, the last human counterpart (C5) in the northbound route reveals a relatively downward value trend, in both VT-micro and VSP models, trying to absorb the fuel consumption propagations occurring upstream of the platoon from the ACC participants. The same behavior is also detected in the findings of tractive energy consumption, mentioned above. On the other hand, both driving modes seem to achieve very small value fluctuations showing almost flat fuel consumption profiles in the case of ARRB model, which seems to be a more conservative model. Finally, the value ranges among the three models seem to differ significantly, with the VSP model showing the largest deviations. Generally, ACC systems tend to increase fuel consumption inside the platoon in all three fuel consumption models and hence are less efficient compared to human-driven vehicles.

4.3.2 AstaZero

In this experimental campaign, a five-vehicle platoon was involved with the leading vehicle being always under ACC driving operation. Specifically, in the first phase, the following vehicles were operated by human drivers, while in the second one, all the vehicles adopted ACC driving. Finally, the same vehicles, in the same fixed order, were used in both parts.

4.3.2.1 Energy Consumption

Figure 4.2 presents the obtained results from the AstaZero test track. As can be seen in Fig. 4.2i, the tractive energy values are amplified upstream of the platoon when ACC systems are enabled, especially for the last participants (C3, C4, and C5). On the other hand, human-driven vehicles reveal a more constant behavior with very small variations in tractive energy values. Consequently, the present results verify the above findings from the first experimental campaign in Italy, proving that ACC systems end up being more “energy-hungry.”

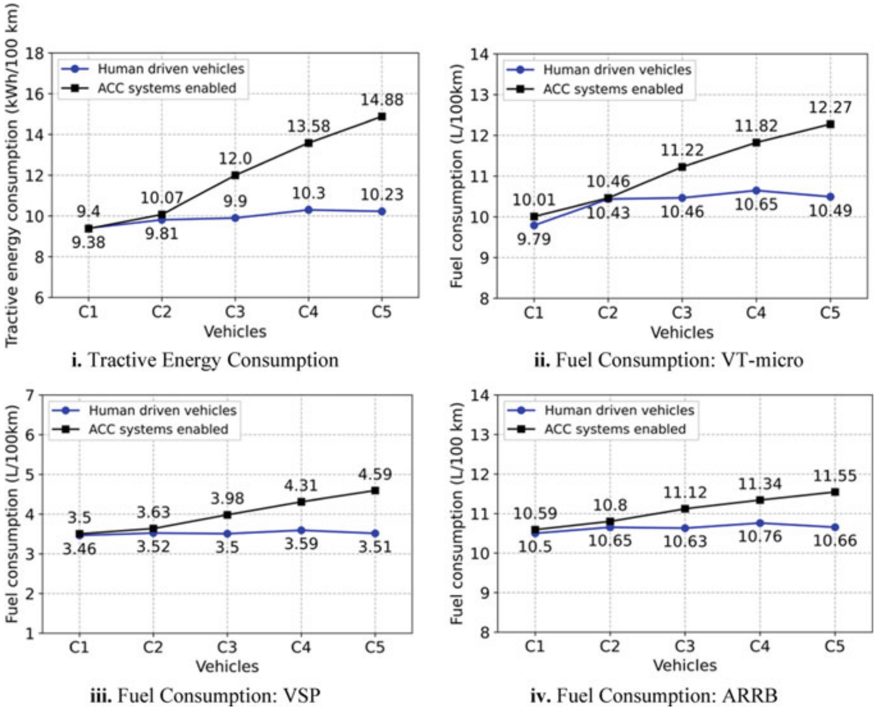


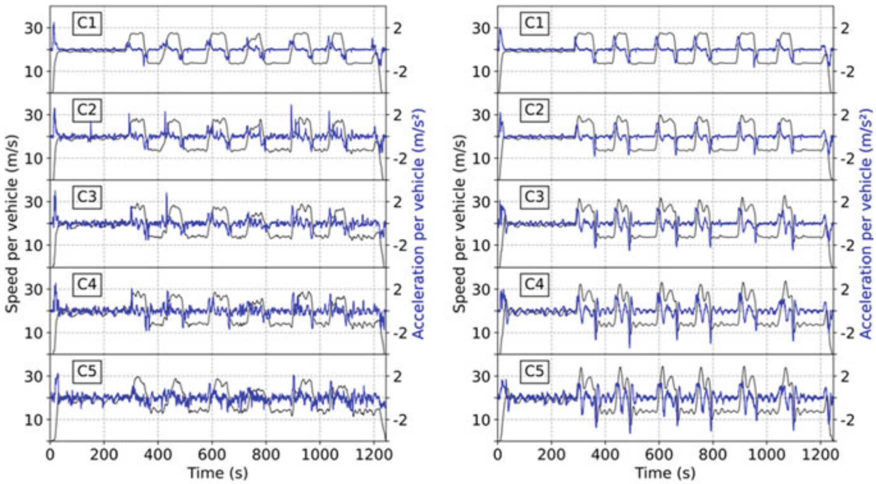
Fig. 4.2 Energy and fuel consumption models (AstaZero)

4.3.2.2 Fuel Consumption

In terms of fuel consumption, a clear upstream fuel consumption amplification by the ACC participants inside the platoon is detected among all three models, as shown in Fig. 4.2. On the contrary, the human counterparts seem to achieve very small value fluctuations showing a noticeably invariable behavior. The value ranges among the three fuel consumption models seem to differ again, with the VSP model showing quite unexpectedly small values. Eventually, the findings from both energy and fuel consumption models seem to be in total agreement with the above findings, indicating once again that the ACC systems turn out to be less energy efficient from a platoon perspective.

4.3.3 Discussion

Generally, the findings reveal that ACC participants cannot reduce fuel and energy consumption inside the platoon, tending to be more "energy-hungry" than human-driven vehicles and hence less energy efficient from a platoon perspective. Both



i. Human driven vehicles **ii.** ACC systems enabled

Fig. 4.3 Speed/acceleration profiles (AstaZero)

experimental campaigns investigated, using four independent energy and fuel consumption models, seem to agree with this statement.

As mentioned in Sect. 4.1, ACC systems can automatically adjust the vehicle's speed by accelerating or decelerating it, to maintain a constant predefined time-gap with the vehicle in front or to reach the predefined desired speed. Figure 4.3 illustrates the speed and acceleration profiles of each testing vehicle, separately, taken from the second experimental campaign that was held on the rural road of AstaZero test track. As shown in the second subfigure on the right, ACC systems operate in a stricter way than human drivers do. More specifically, ACC participants reveal strong and sharp accelerations with several peaks and variations in the speed profile, especially when moving upstream the platoon (C3, C4, and C5), while human counterparts reveal smaller fluctuations around the equilibrium points, regarding speed and acceleration.

As a result, the way that ACC systems operate under car-following situations seems to affect the energy impact of the ACC participants inside the platoon. All the models presented in Sect. 4.2 estimate energy demand and fuel consumption, mainly, as functions of speeds and accelerations. Hence, there are plenty of peaks and spikes appearing in both speed and acceleration profiles when ACC systems are enabled, which could possibly affect their energy impact. The findings seem to verify the above hypothesis that the steeper points and spikes appear in the speed and acceleration profiles the greater fuel and energy consumption is.

Additionally, in Fig. 4.4 are presented two random perturbation events from the AstaZero campaign, which occurred between the same speeds for both driving modes. As previously mentioned, the ACC participants reveal several peaks and steep variations in the speed profile (as well as in the acceleration profile), especially when moving upstream of the platoon, as illustrated in Fig. 4.3ii. In the left subfigure,

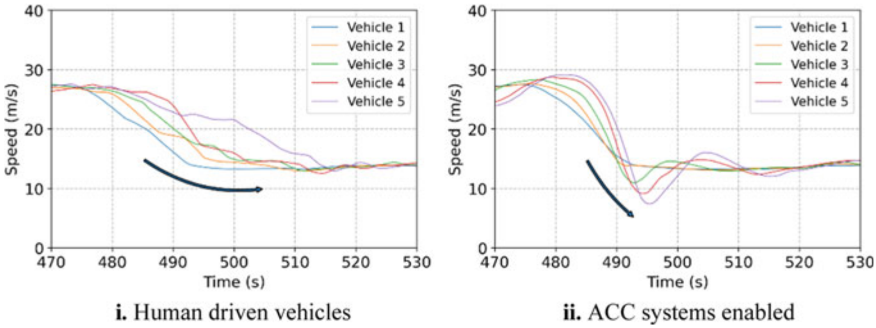


Fig. 4.4 Speed overshoots (AstaZero)

the speed variations of the leader are not amplified through the human participants. However, in the second subfigure, ACC followers significantly enlarge their leader's speed perturbation, revealing large speed overshoots amplified upstream the platoon. These black curved arrows indicate the stable car-following behavior of human drivers (Fig. 4.4i) and the string instability that ACC participants cause (Fig. 4.4ii).

String stability is achieved in a platoon when the last following vehicle dissolves the perturbation imposed by the leading vehicle [23]. In other words, string stability means any nonzero position, speed, and acceleration errors of an individual vehicle in a string do not amplify when they propagate upstream [24]. The string stability of a platoon of five ACC-equipped vehicles under several conditions in the AstaZero proving ground was investigated, and the results show that in all conditions, ACC systems led to string unstable platoons [25].

Therefore, this string instability that ACC systems reveal could negatively affect their energy impact. Without loss of generality, a correlation between string stability and energy and fuel consumption seems to exist, with speed overshoots propagating upstream being proportional to the upstream amplification of energy and fuel consumption inside the platoon. Of course, this relation should be studied across the complete operational domain and under all possible conditions, to obtain meaningful and solid results.

Also, as it was previously mentioned, the last human participant (C5) in the northbound route of the first experimental campaign revealed a relatively downward value trend among the various fuel and energy consumption models, trying to absorb the energy propagation that occurred upstream of the platoon. Figure 4.5 depicts a random perturbation event during real-world conditions in the motorway of Autostrada A26 in Italy. The findings reveal that the last follower (C5) absorbs the speed overshoots propagating upstream the platoon. A possible explanation could be that human drivers can detect decelerations occurring 2–3 vehicles downstream of the platoon and hence responding in a more polite way. Therefore, this tendency for absorbing the perturbations propagating upstream of the platoon could be related to the lower energy and fuel consumption values achieved by the last participant.

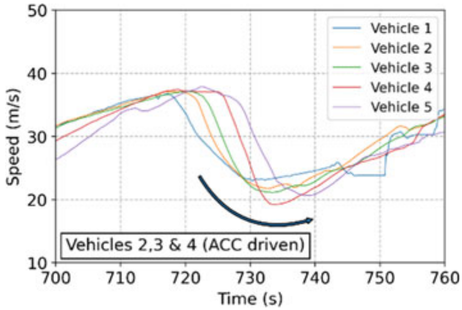


Fig. 4.5 Speed overshoots with ACC systems enabled (Ispra-Vicolungo)

In addition, it is worth mentioning that another possible cause of string instability inside a platoon with ACC participants could be the road gradient. Several altitude changes are observed in the elevation profile of the Autostrada A26 motorway in Italy, since it is located at the foot of the Alps Mountains, which could significantly affect the way that ACC controllers operate under car-following situations.

More specifically, if we assume a vehicle with an ACC system enabled, under steady-state conditions with a constant predefined speed, an altitude increase would require additional work from the controller to reach the predefined speed. In this effort, trying to counterbalance the impact of the road grade, the controller ends up overshooting. In a similar way, as the altitude decreases, the controller undershoots reaching a lower speed than the desired one. In both cases, oscillations are generated around the predefined speed directly affecting the followers (assume ACC participants). These oscillations propagating upstream of the platoon could lead to string instability and hence affect the energy impact of ACC systems as it was mentioned previously. Even for slight perturbations derived by variability in the road gradient, string instability can be observed, raising concerns about potential consequences in traffic flow as the penetration rate of ACC systems is rapidly increasing [25].

However, as it turns out, ACC systems do not generally fail inside a platoon. More precisely, Figs. 4.6 and 4.7 provide an estimation of time/space-gap distributions for both experimental campaigns. The computation of time-gaps between two vehicles inside the platoon was performed by dividing the obtained space-gaps (IVS) between two vehicles with the speed of the following vehicle. Space-gaps were already estimated and hence, available in the two experimental datasets. As can be seen (see Figs. 4.6 and 4.7), the time- and space-gaps are smaller (in absolute values) with ACC engaged and better distributed compared to human drivers. Provided that the time-gaps are more or less constant with ACC engaged, we conjecture that the commercial ACC system in the cars in Table 4.3 employs a constant time-gap policy. However, the core functionality (controller type and its parameters) is not publicly available, so any conclusions must be drawn with caution.

This positive result for the ACC drivers is attributed to the ACC controller. It highlights that commercial ACC controllers (despite the criticism to their negative impact concerning traffic flow and stability) deliver some improvements. Actually, the improvements to be expected from their design and controller synthesis (e.g.,

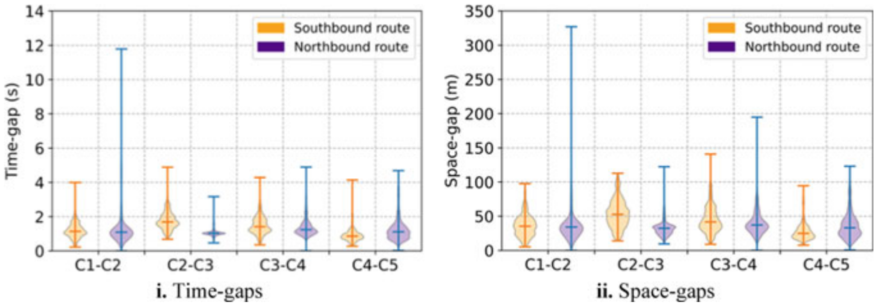


Fig. 4.6 Time-gap/space-gap distributions (Ispra-Vicolungo)

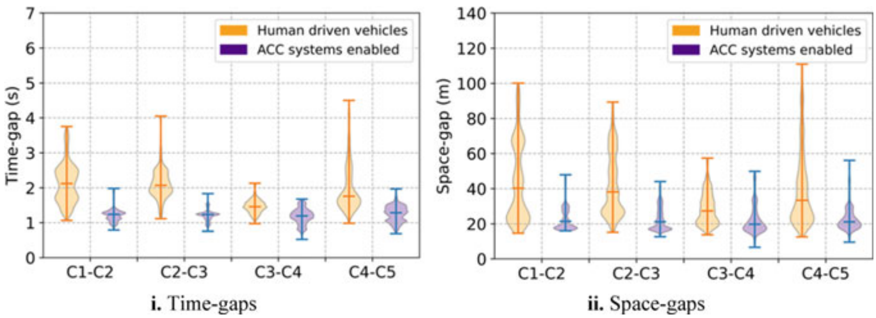


Fig. 4.7 Time-gap/space-gap distributions (AstaZero)

constant time-gap), i.e., to keep constant and safe space/time-gaps. However, it is well known that constant spacing (space-gap) policies lead to string unstable platoons of vehicles [26–28], while constant time-gap policies are string stable for ACC vehicles without inter-vehicle connectivity [2, 4, 5, 29].

Another observation is related to the comparison of the same graphs (Figs. 4.6 and 4.7) for the two different campaigns (one took place in a public motorway network and the other in a protected test environment). In the protected environment of AstaZero, it seems that the improvements for the space/time-gaps are more evident and higher compared to the campaign in Italy. This is attributed to: (a) the employed vehicles (characteristics/specifications), (b) the environment (protected in AstaZero, so no inference with other cars and mixed heterogeneous traffic, a public motorway in Italy with mixed traffic and more disturbances). These observations also underline that ACC drivers in protected environments and campaigns might perform better but can be (ideally) tested in adverse environments.

Therefore, as it was previously mentioned, in both experimental campaigns, an upstream energy propagation was observed inside the platoon by the ACC participants, regarding both energy and fuel consumption, indicating that ACC systems are less efficient. However, the ACC participants succeed in maintaining a constant predefined time-gap between two consecutive vehicles, which is part of the ACC logic and one of the requirements vehicle manufacturers need to fulfill. ACC distributions seem to be more accumulated around lower levels compared to human ones, especially in the AstaZero campaign, indicating that ACC systems are more efficient. It seems that the more efficient ACC systems are regarding their functional specifications, the less energy efficient tend to be. Consequently, a trade-off between time/space-gaps and fuel and energy consumption could exist, to eliminate high energy levels and achieve the desired safety, at the same time.

4.4 Conclusions and Outlook

This study assessed the energy impact of ACC systems under car-following conditions. The thematic focus was laid on investigations into energy demand and fuel consumption for human-driven and ACC-engaged vehicles in real-life experimental campaigns with a variety of vehicle specifications, propulsion systems, drivers, and road and traffic conditions. To this end, high-resolution empirical data from two experimental car-following campaigns were used. Then, energy demand and fuel consumption estimations were calculated by employing four independent models. The main findings of this study can be summarized as follows:

- ACC systems are less energy efficient, revealing a tendency for upstream energy propagation inside the platoon.
- Human counterparts adopt a more conservative and invariable energy behavior.
- ACC driving operation (strong accelerations, steep speeds, etc.) may negatively affect the energy impact of ACC systems under car-following conditions.
- ACC systems may lead to string instability failing to avoid an upstream energy amplification.
- Road gradient changes could create string instabilities in the traffic flow and may negatively affect the energy impact of ACC systems under car-following conditions.
- ACC systems succeed in delivering a constant time-gap policy, between two consecutive vehicles, at lower levels than human drivers do.

It should be noted that there is an agreement for both campaigns (one conducted in a public highway and the other in a protected test site) and for four independent models in terms of tractive energy and fuel consumption footprint (human drivers are more efficient compared to the ACC drivers), despite the different data acquisition methods employed and the differences in the design and execution of the experimental campaigns.

Finally, it should be highlighted that the more efficient ACC systems are regarding their functional specifications, the less energy efficient tend to be. Consequently, commercial ACC systems must be designed to realize a trade-off between functional specifications in terms of time/space-gaps and tractive energy and fuel consumption. This will ideally eliminate high energy levels and achieve the desired safety features of commercial ACC systems.

Further study should focus on:

- The trade-off between time/space-gaps and fuel and energy consumption of ACC systems driving in a car-platoon formation, toward a more complete picture of the fundamental relations between the several requirements vehicle manufacturers need to fulfill.
- The correlation between the leader's and the follower's driving profile (i.e., speed-acceleration), see, e.g., [11]. Such analysis would be useful to unveil how strong is the bond between the (free) leader and ego vehicles in a platoon (whose mission is to ensure safety and keep constant headways).
- The design and synthesis of ACC systems with safe and eco-driving instructions. However, this might lead ACC drivers to brake at longer safety margins for safety and energy savings toward eco-driving.

Finally, the results presented in this study and in the relevant literature might be biased toward the acquisition method used in different experimental campaigns. Thus, additional analysis for various energy and fuel consumption models using empirical data from other experimental campaigns employing different acquisition methods can be conducted to shed some light on the energy footprint of human and ACC drivers.

References

1. SAE International: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (2021)
2. Ioannou, P.A., Chien, C.C.: Autonomous intelligent cruise control. IEEE Trans. Veh. Technol. **42**, 657–672 (1993)
3. Swaroop, D.: String stability of interconnected systems: an application to platooning in automated highway systems (1997)
4. Swaroop, D., Hedrick, J.K.: String stability of interconnected systems. IEEE Trans. Autom. Control **41**, 349–357 (1996)
5. Liang, C.-Y., Peng, H.: Optimal adaptive cruise control with guaranteed string stability. Veh. Syst. Dyn. **32**, 313–330 (1999)
6. Shi, X., Yao, H., Liang, Z., Li, X.: An empirical study on fuel consumption of commercial automated vehicles. Transp. Res. Part D Transp. Environ. **106**, 103253 (2022)
7. Li, S., Li, K., Rajamani, R., Wang, J.: Model predictive multi-objective vehicular adaptive cruise control. IEEE Trans. Control Syst. Technol. **19**, 556–566 (2011)
8. Dvorkin, W., King, J., Gray, M., Jao, S.: Determining the Greenhouse Gas Emissions Benefit of an Adaptive Cruise Control System Using Real-World Driving Data, p. 9 (April 2019)
9. Ciuffo, B., Mattas, K., Makridis, M., Albano, G., Anesiadou, A., He, Y., Josvai, S., Komnos, D., Pataki, M., Vass, S., Szalay, Z.: Requiem on the positive effects of commercial adaptive cruise control on motorway traffic and recommendations for future automated driving systems. Transp. Res. Part C Emerg. Technol. **130**, 103305 (2021)
10. Knoop, V.L., Wang, M., Wilmink, I., Hoedemaeker, D.M., Maaskant, M., der Meer, E.-J.V.: Platoon of SAE Level-2 automated vehicles on public roads: setup, traffic interactions, and stability. Transp. Res. Rec. **2673**, 311–322 (2019)
11. He, Y., Makridis, M., Fontaras, G., Mattas, K., Xu, H., Ciuffo, B.: The energy impact of adaptive cruise control in real-world highway multiple-car-following scenarios. Eur. Transp. Res. Rev. **12** (December 2020)

12. Ehsani, M., Gao, Y., Gay, S.E., Emadi, A.: Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design, 3rd ed. CRC Press (2018)
13. Ahn, K.: Microscopic fuel consumption and emission modeling (1998)
14. Jiménez-Palacios, J.L.: Understanding and quantifying motor vehicle emissions with vehicle specific power and TILDAS remote sensing (1999)
15. Duarte, G.O., Gonçalves, G.A., Baptista, P.C., Farias, T.L.: Establishing bonds between vehicle certification data and real-world vehicle fuel consumption–a Vehicle Specific Power approach. Energy Convers. Manage. **92**, 251–265 (2015)
16. Akçelik, R., Biggs, D.C.: An energy-related model of instantaneous fuel consumption. Traffic Eng. Control **27**, 320–325 (1986)
17. Makridis, M., Fontaras, G., Ciuffo, B., Mattas, K.: MFC free-flow model: introducing vehicle dynamics in microsimulation. Transp. Res. Rec. **2673**, 762–777 (2019)
18. Rakha, H., Ahn, K., Trani, A.: Development of VT-Micro model for estimating hot stabilized light duty vehicle and truck emissions. Transp. Res. Part D Transp. Environ. **9**, 49–74 (2004)
19. Zegeye, S.K., Schutter, B.D., Hellendoorn, J., Breunesse, E.A., Hegyi, A.: Integrated macroscopic traffic flow, emission, and fuel consumption model for control purposes. Transp. Res. Part C Emerg. Technol, **31**, 158–171 (2013)
20. Post, K., Kent, J.H., Tomlin, J., Carruthers, N.: Fuel consumption and emission modelling by power demand and a comparison with other models. Transp. Res. Part A Gen. **18**, 191–213 (1984)
21. Akçelik, R., Biggs, D.C.: Validation of a power based model of car fuel consumption. Australian Road Research Board, Internal Report AIR 390-4 (1984)
22. Akçelik, R., Biggs, D.C.: Further work on modelling car fuel consumption. Australian Road Research Board, Internal Report AIR 390-10 (1985)
23. Monteil, J., Bouroche, M., Leith, D.J.: L_2 and L_∞ stability analysis of heterogeneous traffic with application to parameter optimization for the control of automated vehicles. IEEE Trans. Control Syst. Technol. **27**, 934–949 (2019)
24. Lei, C., van Eenennaam, E.M., Klein Wolterink, W., Ploeg, J., Karagiannis, G., Heijenk, G.: Evaluation of CACC string stability using SUMO, Simulink, and OMNeT++. EURASIP J. Wirel. Commun. Netw. **2012**, 1–12 (2012)
25. Makridis, M., Mattas, K., Ciuffo, B., Re, F., Kriston, A., Minarini, F., Rognelund, G.: Empirical study on the properties of adaptive cruise control systems and their impact on traffic flow and string stability. Transp. Res. Rec. **2674**, 471–484 (2020)
26. Seiler, P., Pant, A., Hedrick, K.: Disturbance propagation in vehicle strings. IEEE Trans. Autom. Control **49**, 1835–1842 (2004)
27. Jovanovic, M.R., Bamieh, B.: On the ill-posedness of certain vehicular platoon control problems. IEEE Trans. Autom. Control **50**, 1307–1321 (2005)
28. Middleton, R.H., Braslavsky, J.H.: String instability in classes of linear time invariant formation control with limited communication range. IEEE Trans. Autom. Control **55**, 1519–1530 (2010)
29. Rajamani, R., Zhu, C.: Semi-autonomous adaptive cruise control systems. IEEE Trans. Veh. Technol. **51**, 1186–1192 (2002)

Chapter 5
Optimum Production-Ordering Policy for a Vendor Buyer Co-Ordinated System Subject to Production Disruption

Amit Kumar Mishra, Purushottam Kumar Singh, and Santosh Kumar Mishra

Abstract In modern era with an increase in globalization, supply chain system becoming more complex and competitive in order to satisfies the demands of the customers. The rigorous research over the span of time on supply chain has made supply chain not only trendy but also more complex. In the recent past years, the scholars have found various key trends like JIT (just in time), outsourcing, global sourcing, etc. These concepts have increased the efficiency of the supply chain but simultaneously made the supply chain more vulnerable to risk and disruption. In this paper, a recovery model for two-stage co-ordinated serial supply chain having a vendor and buyer has been presented. The objective is to determine the optimum numbers of orders when disruption occurs. There is need of production policy for the system at disruption state. The consideration of some fine at vendor level in order to recover original schedule in place of the disruption is necessary. The model is solved on LINGO. The behaviour of the system with various cost parameters is also analysed.

Keywords Supply chain management · Recovery strategies · Recovery time window · Disruption · LINGO

5.1 Introduction

A supply chain is a well-defined network of various entities or facilities which convert finished goods from raw materials. Production and supply chain systems are key

A. K. Mishra
Department of Mechanical Engineering, BIT Sindri, Sindri 828123, India

P. K. Singh
Department of Mechanical Engineering, National Institute of Technology, Silchar 788010, India

S. K. Mishra (✉)
Department of Production Engineering, National Institute of Technology Trichy, Trichy 620015, India
e-mail: apsantoshmishra@gmail.com

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_5

factors in an organization. It is depending upon different numerous entities like size, type of the organization, produced product, the number of suppliers, buyers, etc. The main reason for the success of any organization, under different supply chain environment, is to assure the smooth functioning of each and every entity in the chain by managing risks and disruptions (both predictable and unpredictable) efficiently. According to Iris Heckmann et al. [6], if we talk about risk in terms of general environment, it means—Fear Or Adventure, while when we talk about in terms of supply chain, it stands for “something that needs to be avoid”. As a matter of fact, supply chain disruption can be defined as an event that breaks the flow of material in supply chain system, resulting in a sudden interruption in the flow of goods. Supply chain disruption may arise due to both internal as well as external reasons. Hence, disruption to the supply chain is costly, and sometimes, it is too much that can take a long time to overcome that loss. By looking all these factors, one can say that a proper response to all these factors must be pertinent at design phase of the system, so that whole system can be saved from being imbalanced and reduces both the financial loss and loss of their goodwill; hence, every organization must have some pertinent techniques to minimize the impact of disruption to their supply chain network.

The main aim of the disruption management is to execute the right strategies at the right time so that disrupted system will quickly return to their original state in order to minimize the various associated costs involved in disruption. The study of disruption risk occurring in supply chain has started at the recent past years. The scholars were mainly concentrated only on supply chain risk. They are not considering the part of disruption over the past. However, in present, numerous studies have been performed to develop models and strategies for managing both risk and disruption at various stages of supply chain systems. Before the review begins, it is good to introduce the basic non-disrupted system model given by Banerjee [1] because he gave the basic two-stage non-disrupted model idea and worked on it. Tomlin [16] examined the concept to derive optimal techniques for a single product producing company with unreliable and reliable suppliers, but reliable were the expensive ones. In his study, Tomlin also works on a special case when the system faces a single disruption. He discovers the options that a risk-neutral firm has like mitigation by carrying inventory, single sourcing from reliable supplier, or passive acceptance, etc. If the unreliable supplier has finite capacity or firm is risk averse, he shows that in this case, the mixed mitigation strategies will be optimum. Schmitt et al. [13] and Chen et al. [2] improve the work of Tomlin by considering the stochastic demand. Schmitt and Snyder [14] carried a study for comparison between single and multiple period setting for a system subjected to supply disruption and yield uncertainty. Earlier, it was done for single product and single period for conducting as seen in the work of Chopra and Sodhi [3]. Moinzadeh and Aggarwal et al. [7] consider a system with a constant production facility and deterministic demand rate with arbitrary disruption at facility. They coined the issues of unreliability and their impact on the system. They have considered the case when the disruption occurs in the system the excess demand in disruption period as back order, with numerical experimentation. They devise the result that the reduction in the setup cost will be more effective when our running production system is more reliable. They also devise that reduction in setup cost for the unreliable system will results in higher safety stock. Arreola et al. have worked on inventory management system for stochastic-demand systems. In their model, disruption occurs randomly in the product supply for a random duration and demands. The disruption period would be a mix of backorders and lost sales. They considered the case of the source of disruption in two forms, i.e. either process or market based. In the first case, the supply disruption may be in the form of machine breakdown, transportation disruption, or a strike. In the second form, the products are available, but the market situation is not accessible. It contains price fluctuation or higher price of the product that reduce the customer desire to purchase the product. Later Snyder [15] introduced a new simple and tightly approximated model for the advancement in Arreola work. Sodhi et al. proposed the various mitigation strategies which include supplier's redundancy and responsiveness. The consequences of production disruption can be mitigated by keeping extra inventory in the form of backup or increase the capacity of the system. Keeping the inventory with us is more attractive mitigation strategies, but it will be fruitful for the disruption shortage. If the disruption tends to be rare and long, then in such situation, the strategies like supply redundancy are more useful. Gallego [4] has schedule of production system when a single disruption happens. He has defined base stock policy with regards to the economic lot scheduling. A heuristic method has been proposed dealing with recovery of system when subjected to machine breakdown and other disturbances. Their main focus is to reduce inventory holding cost rather than abstain stock out cost. Recovery strategies for demand disruption have been done by Qi et al. [12] and Yang et al. [18]. The main revolution in disruption management strategies comes by the work of Xia et al. [17]. Xia et al. have proposed a general approach to the disruption management for a production inventory system. This was the first time when the concept of recovery time window was introduced by them. In their work, they also introduce the concept of fine for change in the schedule means if there is a deviation in scheduled production. They proposed the concept of fine either linear or quadratics. As a special case, they consider a short time window consists of one or two production cycle. The main purpose of their studies is to regain their system from disruption to original schedule as soon as possible at minimum disruption cost. They give various theorems for scheduled recovery. In past few decades, the demand disruption in supply chain system has long been main issues. Scant attention has been to disruption once the final plan for production prepared, but little change in original schedule due to disruption may cause considerable deviation in cost may observe. Hishamuddin et al. [5] give a disruption recovery model for single-stage production inventory system subjected to production disruption for a given period of time. They also develop a heuristic for solving their model. They include all the basic four costs in their system including loss of demand during the disruption period which would be a mix of back order and lost of sales.

In this study, the recovery model is based on a vendor and buyer. In most of the studies, the single-stage production inventory system is taken into consideration. A recovery model for a two-stage co-ordinated serial supply chain system subject to random production disruption occurs at vendor during a cycle is considered. The term recovery is defined for bringing back normal production by reducing the associated costs. The main objective of this model is to find out the new recovery plan, i.e. ordering and production quantities for vendor and buyer while minimizing the total expected cost in the recovery time window. A comparison is drawn between expected costs based on model with other possible strategies using numerical example. The model is considered as constrained nonlinear programming model solved on Lingo 10.

5.2 Production Disruption Model for a Vendor Buyer

In modern era with increase in competition in the market, everyone wants to make their supply chain more efficient and flexible by adopting several policies like outsourcing, global outsourcing, supply base reduction, etc. On the other hand, it also makes our supply chain more prone to disruption or risk. This disruption leads to losses in the supply chain. If right strategies at right time are not implemented it can result in huge losses to the supply chain. The losses are not avoidable. In this chapter, we carried out the work on mathematical modelling for two-stage co-ordinated serial supply chain consists of a vendor buyer subjected to production disruption at vendor during production up time. Whenever a disruption occurs, every system must adopt some strategies to cope with disruption while minimizing loss to their system. We work on this model in the same sense to find out the recovery strategies for vendor buyer, i.e. optimal ordering and production quantity in the further cycle so that we can recover our system from disruption as soon as possible while minimizing the cost.

In this study, the system having a vendor and buyer is considered, where the vendor has a production facility and follows the economic production quantity (EPQ) model while buyer follows economic order quantity (EOQ) model). The objective is to find out the optimal ordering and production policy for buyer and vendor when a disruption occurs at vendor facility. A single batch production product environment, deterministic, and constant demand rate is considered. In this study, the case of a lot of lot policy is proposed. The manufacturing lot size at vendor should be equal to ordering lot size for buyer in a given time frame. Recovery time window is defined as additional time to attain the original working condition. This concept of handling disruption comes under recovery strategies. Provision of safety stock has to be kept by the vendor which will be used at the occurrence of disruption. During disruption when the vendor is not able to fulfil the requirement of buyer due to insufficient production, the safety stock will be delivered as required by buyers. When safety stocks reach to zero, the unsatisfied demand became backorder and loss of sales. The inventory holding cost, setup cost, backorder and loss of sales cost, net cost incur by vendor due to disruption decide total recovery cost. The main objective of this model is to find out the new recovery plan, i.e. ordering and production quantities for vendor and buyer while minimizing the total expected cost in the recovery time window. There is also a need to consider the effect of various parameters on total cost.

The following assumptions have considered in the analysis of production disruption model

- Demand rate D should be less than production rate P.
- It is assumed that at second stage, the order is made only when the on-hand inventory becomes equal to zero.
- Disruption occurs only at once. There should not be any other disruption within recovery window.

Let us consider M_i is production lot sizes at vendor in cycle i during recovery window, S_i is order lot sizes at buyer in cycle during recovery window. P is production rate (units/year), D is demand rate (units/year), T_c is production cycle time for a normal cycle (Q/D), T_d is disruption time, C_{01} is setup cost for vendor, C_{h1} is holding cost/unit for vendor, C_b is backorder cost/unit for vendor, C_{L1} is loss of sales/unit for vendor, C_{02} is ordering cost for buyer, C_{h1} is holding cost/unit for buyer, C_{b2} is backorder cost/unit for buyer, C_{L2} is loss of sale cost/unit for buyer, S is safety stock at vendor, Q_b is backorder quantity (units), and Q_L is loss of sales (units). The original working condition is shown in Fig. 5.1.

The disrupted condition model is depicted in Fig. 5.2.

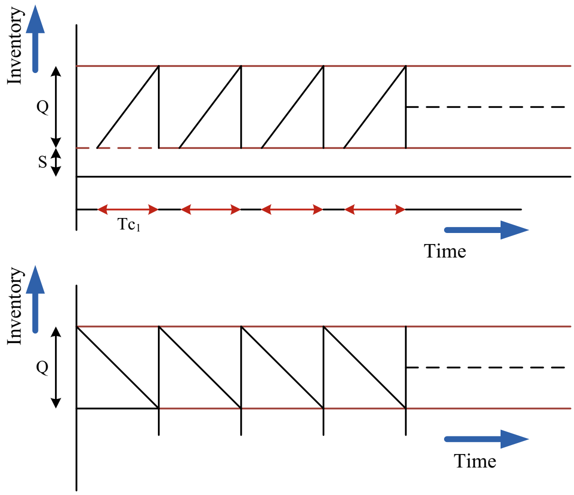


Fig. 5.1 Original working condition of the system

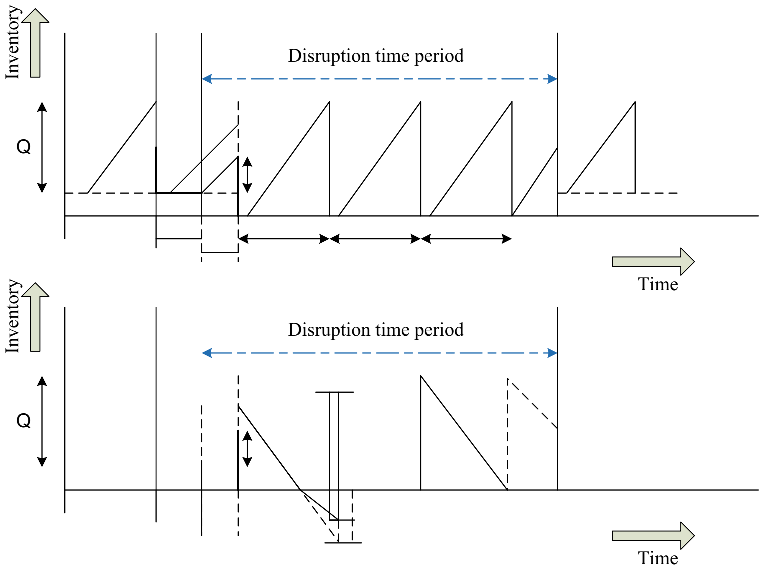


Fig. 5.2 Woking condition of disrupted system

5.3 Mathematical Formulation

The total recovery cost for each one is the summation of all the cost, i.e. inventory holding cost, setup cost, backorder and loss of sales cost, etc., and the overall total cost equation will be the addition of both (vendor and buyer) recovery cost equation. The recovery cost equation for the vendor and buyer is TC_1 and TC_2, respectively, where TC_3 is the recovery cost by combining of both recovery cost equation.

Holding cost for vendor =

$$H_{M1} = S(T_D + T_1) + \frac{1}{2}M_2T_2 + \frac{1}{2}M_3T_3 + \ldots + \frac{1}{2}(M_n + S)T_n$$

$$H_{M1} = S(T_D + T_1) + \frac{1}{2}\frac{(M_2^2)}{P} + \frac{1}{2}\frac{(M_3^2)}{P} + \ldots + \frac{1}{2}\frac{(M_n + S)^2}{P}$$

$$H_{M1} = ST_D + \left(S\frac{M_1}{P}\right) + \frac{1}{2}\frac{M_2^2}{P} + \frac{1}{2}\frac{M_3^2}{P} + \ldots + \frac{1}{2}\frac{(M_n + S)^2}{P}$$

$$H_{M1} = S\left(T_D + \frac{M_1}{P}\right) + \frac{1}{2P}\sum_{i=2}^{n-1} M_i^2 + \frac{1}{2P}(M_n + S)^2$$

$$H_{M1} = S\left(T_D + \frac{M_1}{P}\right) + \frac{1}{2P}\sum_{i=2}^{n-1} M_i^2 + \frac{1}{2P}(M_n + S)^2 \tag{5.1}$$

Holding cost for buyer

$$H_{M2} = \frac{1}{2}R_i T_1 + \frac{1}{2}(R_2 - Q_b)T_2 + \frac{1}{2}R_3 T_3 + \ldots n$$
$$H_{M2} = \frac{1}{2}R_i \frac{R_1}{D} + \frac{1}{2}\frac{(R_2 - Q_b)^2}{D} + \frac{1}{2}\frac{R_3^2}{D} + \frac{1}{2}\frac{R_4^2}{D} \ldots$$
$$H_{M2} = \frac{1}{2}D\left[R_1^2 + (R_2 - Q_b)^2\right] + \sum_{i=3}^{n} R_i^2 \tag{5.2}$$

Since

$$Q_b = [T_D D - Q_L]$$
$$Q_L = \left[NQ - \sum_{i=1}^{n} R_i\right]$$
$$Q_b = \left[T_D D - NQ + \sum_{i=1}^{N} R_i\right]$$
$$Q_b = \left[T_D D + \sum_{i=1}^{N} R_i - NQ\right] \tag{5.3}$$

Backorder cost for manufactures

$$X = C_{b1}\frac{1}{2}\left(Q_b T_1^{''}\right)$$
$$X = C_{b1}\frac{1}{2}[T_D D - Q_L]\left[\frac{R_2 - Q_b}{D} - \frac{R_1}{D}\right]$$
$$X = C_{b1}\frac{1}{2D}[T_D D - Q_L][(R_2 - Q_b) - R_1]$$
$$X = C_{b1}\frac{1}{2}\left[T_D D + \sum_{i=1}^{N} R_i - NQ\right]\left[R_2 - \left(T_D D + \sum_{i=1}^{N} R_i - NQ\right)\right]$$
$$X = C_b 1\frac{1}{2}\left[T_D D + \sum_{i=1}^{N} R_i - NQ\right]\left[NQ - T_D D - \sum_{i=1}^{N} R_i + R_2\right] \tag{5.4}$$

Lost of sales cost for vendors

$$Y = C_{L1} Q_L$$
$$Y = C_{L1}\left(NQ - \sum_{i=1}^{N} R_i\right) \tag{5.5}$$

Now

Backorder cost for buyer

$$Z = \left[\frac{C_{b2}}{2D}\right]\left[T_D D + \sum_{i=1}^{N} R_i - NQ\right]\left[NQ - T_D D - \sum_{i=1}^{N} R_i + R_2\right] \tag{5.6}$$

Lost of sales cost for buyer

$$A = C_{L2}\left(NQ - \sum_{i=1}^{N} R_i\right) \tag{5.7}$$

Objective function for optimal recovery plan for both vendor and buyer TC-

$$\begin{aligned}
&\text{Minimum TC}\left[\mathrm{M_{i,}R_i}\right] = \\
&C_{01} * N + C_{02} * N + S\left(T_D + \frac{M_1}{P}\right) \\
&+ \frac{1}{2P}\sum_{i=2}^{n-1} M_i^2 + \frac{1}{2P}(M_n + S)^2 \\
&+ \frac{1}{2D}\left[R_1^2 + (R_2 - Q_b)^2 + \sum_{i=3}^{n} R_i^2\right] \\
&+ C_{b1}\frac{1}{2}\left[T_D D + \sum_{N}^{N} R_i - Q\right]\left[NQ - T_D D - \sum_{i=1}^{N} R_i + R_2\right] \\
&+ C_{L1}\left(NQ - \sum_{i=1}^{N} R_i\right) + \left[\frac{C_{b2}}{2D}\right]\left[T_D D + \sum_{i=1}^{N} R_i - NQ\right]\left[NQ - T_D D - \sum_{i=1}^{N} R_i + R_2\right] \\
&+ C_{L2}\left(NQ - \sum_{i=1}^{N} R_i\right)
\end{aligned} \tag{5.8}$$

Fine for vendor due to deviation from original production schedule $= x\% C_{01}|\Delta q|$ (5.9)

It is subjected to following constraints:

- Time bound constraints for first cycle at vendor.
- Amount delivers to the buyer by considering the safety stock of vendor.
- Production capacity constrained at vendor.
- It is assumed that at the end of the recovery window, the ordering policy must resumed to its original as in normal cycle.
- It should be ensured that at end of recovery window, the original condition as in normal cycle at vendor (consideration of producing the safety stock as well).

$$M_1 \leq (T_c - T_d) * P \tag{5.10}$$

$$R_1 \leq M_1 + S \tag{5.11}$$

$$\sum_{i=1}^{N} M_i \leq N * P * T_c \tag{5.12}$$

$$\sum_{i=1}^{N} R_i \leq N * Q \tag{5.13}$$

$$\sum_{i=1}^{N} M_i \geq N * Q + S \tag{5.14}$$

5.4 Results and Discussion

An important feature of this work is to find out the optimal recovery window length which enables the system (vendor and buyer) to know time needed to recover from disruption. It is also useful in finding out the optimum production and ordering inventory with minimum recovery cost. So, whenever a disruption occurs in the system, it is required to find out the optimal recovery window length first. Formulation of data should be done in the form of equations. The equations are solved using LINGO to get the result. This concept is applied on a numerical problem, and finally that problem is solved on LINGO for different values of recovery window. The recovery strategy is compared with mitigation strategy to find out which one is better. The result obtained is plotted in graph.

5.4.1 Computational Experience

In this section, an experiment is conducted to demonstrate the applicability of this model. The mathematical model presented in the mathematical formation is solved on LINGO.

Figure 5.3 shows that as the number of recovery period increases, the cost of recovering the system from disruption will also increase. The recovery period N depends on the disruption time period. As the disruption time period increases, the cost to recover the system will also increase in the same fashion as shown in Fig. 5.4.

Fig. 5.3 Variation of total recovery cost with respect to number of recovery window

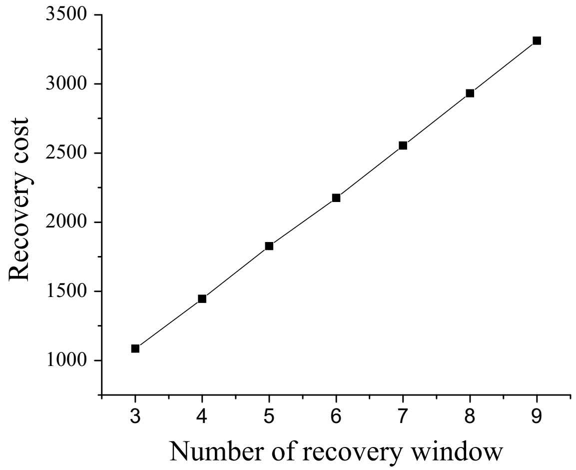
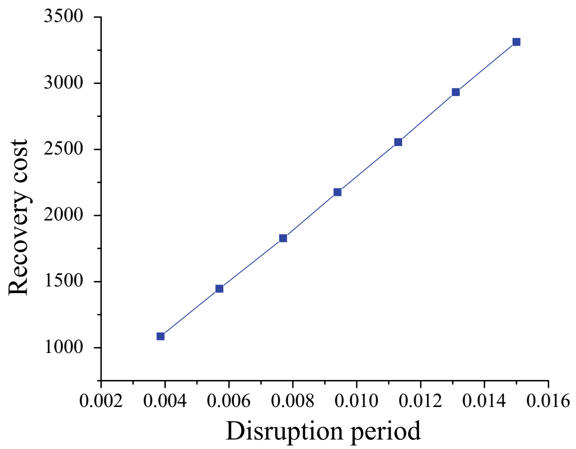


Fig. 5.4 Variation of recovery cost and disruption period



5.4.2 Recovery Strategies Versus Mitigation Strategies

The mitigation strategies dealing with disruption throughout the time may be costly to the system for long time. It works well on frequent and very short duration. The cost is found out first using recovery strategies and then compared with mitigation strategies. For better understanding, it has been implemented on 10 cycles with assumption that disruption occurs only once at a time and then it has been extended for two year and assume two disruptions. These two disruptions can be any combination of disruption time.

Figure 5.5 shows the variations of the cost for recovery strategies and mitigation strategies. We can easily quote from this graph that the cost associated with recovery strategies will be less as compared with the mitigation strategies.

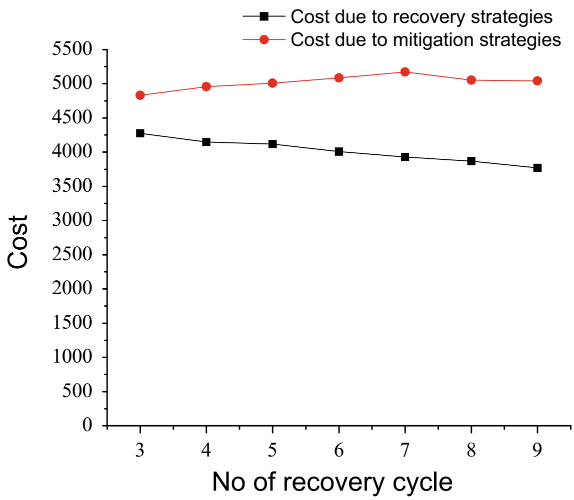


Fig. 5.5 Comparison between costs for 10-cycle consideration

5.5 Conclusions

In this work, we carried out our work for optimum ordering-production policy for a vendor buyer coordinated system subject to production disruption which is able to determine the optimal inventory policies for both member of the supply chain system so that the total cost associated with that could be minimum. The prepared model has been solved on software LINGO. After solving, we can conclude that the recovery cost will increase constantly with disruption time. The recovery strategies are better than mitigation strategies in terms of the cost for recovery from disruption. The aforementioned model can be very helpful in the manufacturing sector where a manager can use the same concept, develop their objective function as described above, apply their constraints, solve the model in accordance with the needs to deal with disruptions, and then get a effective cost recovery plan to increase productivity and profitability with the least amount of disruption to their system.

References

1. Banerjee, A.: A joint economic-lot-size model for purchaser and vendor. Decis. Sci. **17**, 292–311 (1986)
2. Chen, J., Zhao, X., Zhou, Y.: A periodic review inventory system with a capacitated backup supplier for mitigating supply disruptions. Eur. J. Oper. Res. **219**, 312–323 (2012)
3. Chopra, S., Sodhi, M.S.: Managing risk to avoid supply-chain breakdown. Sloan Manag. Rev. **46**, 53–61 (2004)
4. Gallego, G.: When is a base stock policy optimal in recovering disrupted cyclic schedules? Nav. Res. Logist. **41**, 317–333 (1994). References 166
5. Hishamuddin, H., Sarker, R.A., Essam, D.: A disruption recovery model for a single stage production-inventory system. Eur. J. Oper. Res. **222**, 464–473 (2012)

6. Heckmann, I., et al.: A critical review on supply chain risk – definition, measure and modelling (2015). https://doi.org/10.1016/j.omega.2014.10.004.
7. Moinzadeh, K., Aggarwal, P.: Analysis of a production/inventory system subject to random disruptions. Manage. Sci. **43**, 1577–1588 (1997)
8. Park, K.S.: An inventory model with partial backorders. Int. J. Syst. Sci. **13**, 1313–1317 (1982)
9. Parlar, M.: Continuous review inventory problem with random supply interruptions. Eur. J. Oper. Res. **99**, 366–385 (1997)
10. Parlar, M., Berkin, D.: Future supply uncertainty in EOQ models. Nav. Res. Logist. **38**, 107–121 (1991)
11. Parlar, M., Wang, Y., Gerchak, Y.: A periodic review inventory model with Markovian supply availability. Int. J. Prod. Econ. **42**, 131–136 (1995)
12. Qi, X., Bard, J.F., Yu, G.: Supply chain coordination with demand disruptions. Omega **32**, 301–312 (2004)
13. Schmitt, A.J.: Strategies for customer service level protection under multi echelon supply chain disruption risk. Transp. Res. Part B: Methodol. **45**, 1266–1283 (2011)
14. Schmitt, A.J., Snyder, L.V.: Infinite horizon models for inventory control under yield uncertainty and disruptions. Comput. Oper. Res. References 169 (2012)
15. Snyder, L.V.: A tight approximation for a continuous review inventory model with supplier disruptions. Lehigh University, Bethlehem (2008)
16. Tomlin, B.: On the value of mitigation and contingency strategies for managing supply chain disruption risks. Manage. Sci. **52**, 639–657 (2006)
17. Xia, Y., Yang, M.-H., Golany, B., Gilbert, S.M., Yu, G.: Real-time disruption management in a two-stage production and inventory system. IIE Trans. **36**, 111–125 (2004)
18. Yang, J., Qi, X., Yu, G.: Disruption management in production planning. Nav. Res. Logist. (NRL). **52,** 420–442 (2005)

Chapter 6
Opportunities and Challenges for the New Hydrogen Economy: Advances in Renewable Hydrogen

Laís Ferreira Crispino Proença, Alberto Coralli, Fabio Souza Toniolo, Gabriella Machado Darze, Gabriel dos Santos Ribeiro Heluey, Gabriele Freitas Martins, Ruan Carlos Vidal Rodrigues de Oliveira, Paulo Emílio Valadão de Miranda, and Andrea Souza Santos

Abstract In the last years, the pressure to reduce greenhouse gas emissions considerably increased, mainly due to the new policies to achieve an energy transition, contributing to climate change mitigation and minimization of the damage caused by global warming. This ongoing energy transition accelerated the search for new clean forms of energy production, such as those using renewable sources. Regarding the transportation sector, many research works are being conducted toward the use of renewable hydrogen, which is the denomination for the hydrogen produced by renewable and/or clean resources without CO_2 emissions. Traditionally, hydrogen production is made from fossil fuels, mainly through natural gas reforming and coal gasification. However, the mastery and expansion of renewable sources technologies, and hence its cost reduction, have allowed their usage in the production of hydrogen through many different other processes, potentially contributing to a decarbonization of the global economy. Examples of such renewable sources are: renewable biomass and biofuels, solar photovoltaic, wind power energy, and hydroelectricity. This chapter aims to present an overview of the literature regarding the renewable hydrogen production routes, indicating: the different possible renewable sources and their respective participation in the production process, the most common method for producing renewable hydrogen and which route has become more affordable. Also, the current applications and possible markets for the hydrogen and its subproducts in the transportation sector are addressed. Finally, the important hurdles to produce renewable hydrogen and its derivatives, in addition to how they limit initiatives and investments in the technology, are discussed.

Keywords Renewable hydrogen · Hydrogen economy · Climate mitigation

L. F. C. Proença · A. Coralli · F. Souza Toniolo · G. M. Darze · G. dos Santos Ribeiro Heluey · G. F. Martins · R. C. V. R. de Oliveira · P. E. V. de Miranda · A. S. Santos (✉)
Federal University of Rio de Janeiro, Rio de Janeiro, RJ 22010-110, Brazil
e-mail: andrea.santos@pet.coppe.ufrj.br

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_6

6.1 Introduction

In recent years, the concerns regarding climate change and its impacts have increased, and international agreements are fomenting the reduction of greenhouse gasses (GHG) emissions all around the world to decelerate the global warming process. The main gases responsible for the greenhouse effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, which are synthetic. In this context, the main global economies are committing to ambitious GHG reduction targets [1]. To achieve this energy transition goal, countries have been investing heavily in renewable energy generation with solar photovoltaic and wind power as the dominant technologies [2].

The economic sectors that most contribute to GHG emissions are heating, power generation, transport, and industry. However, heating, transport, and industrial processes are still dominated by fossil fuels, and many of these systems are non-electric, and still require the use of fuels [3]. Thus, to adapt them to an environment-and-climate-friendly society, the use of hydrogen as an energy vector through the concept of power-to-X makes renewable energy applicable to these sectors and also can solve one of the energy transition's main hurdles: storage. This concept states that electrical energy can be converted into hydrogen so that it can be stored, converted to thermal or electrical energy, or used as a feedstock to produce chemicals and synthetic fuels [4] and is illustrated in Fig. 6.1. This allows the use of renewable energy for applications in which electrical energy is neither feasible nor supportable, such as heavy-duty and maritime transport, aviation, and industrial activities like: (i) oil refining; (ii) reduction of iron and manufacturing of steel and other metals/alloys; (iii) synthesis of chemicals (mainly, but not limited to, ammonia and methanol; (iv) generation of high-grade heat. In addition, in the power sector, large-scale storage systems for electrical energy are a key technology for power grids with high penetration of solar photovoltaic and wind power generation, in an effort to accommodate their high levels of intermittency [3]. This is due to the need to compensate for the mismatches in supply and demand that can result in periods of significant excess or lack of power generation, creating the need for bulk storage. Thus, the use of hydrogen for renewable energy storage purposes is also an alternative for long periods, such as weeks or months, for which the use of other existing storage systems is not viable [5]. Hydrogen can be stored in liquid or gaseous form, the latter being the preferred option for bulk storage in adequate underground locations, for example, depleted hydrocarbon reservoirs, aquifers, salt caverns, and manmade cavities. During storage and use, it is always necessary to avoid hydrogen accumulation in confined spaces also containing oxygen, where the explosion risk would be considerable, due to the very ample flammability range (4–74% of H_2 in air). To ensure that this precaution is respected, various safety measures are applied, including: (i) installation of storage systems at open air or below slanted roofs, allowing H_2, which is lighter than air, to be diluted in the atmosphere; (ii) hydrogen sensors that can be used to cut off potential ignition sources, like electrical power, in case of leakages; (iii) forced ventilation of closed spaces where H_2 can accumulate in case equipment malfunctioning.

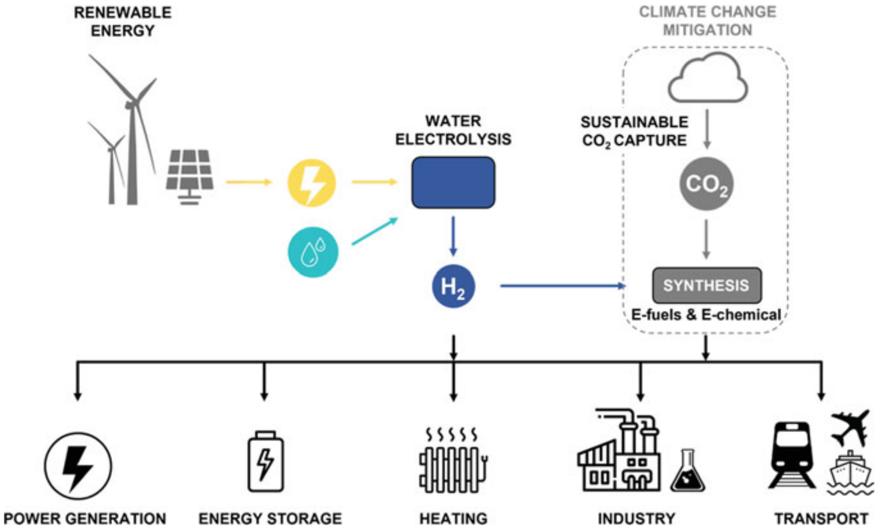


Fig. 6.1 New hydrogen economy. Power-to-X concept: transforming renewable energy into other forms of energy such as gas, liquid, and heat, or using it for energy storage in the form of hydrogen allowing generation of power again. *Source* elaborated by the authors

Recently, a wide range of colors has been used to classify hydrogen production origin in terms of raw material, energy source, and qualitative CO_2 emissions, through which green hydrogen has been frequently associated to the production of "clean" hydrogen, such as from water electrolysis using renewable energy source [6]. However, a consensus has been achieved lately to classify as renewable hydrogen the one that is produced with no CO_2 emissions and as low-carbon hydrogen the one that is produced using carbon-containing raw materials or energy sources, limiting CO_2 emissions by carbon capture, utilization, and/or storage procedures (CCUS) to a minimum level of a magnitude still under discussion [3, 7, 8]. Thus, the renewable hydrogen classification includes hydrogen produced from water electrolysis using renewable energy sources, hydrogen produced from biomass and natural hydrogen [9].

To sum up, the hydrogen market has many opportunities to quickly grow, due to its capacity to couple the renewable energy sector to many others, thus increasing the range of applications that employ renewable resources, including: energy storage, synthesis of fuels and chemicals, energy source for vehicles, and various industrial sectors.

Lastly, the new hydrogen-based economy consists of using hydrogen as energy vector for many applications in a similar way than electricity itself, which will not only permit to decarbonize several activities that currently do not possess carbon–neutral energy alternatives but also to create new value chains to replace the fossil fuels-based ones that currently dominate the world economy. It is convenient to highlight that, in addition to be an energy vector such as electricity, hydrogen is also a fuel, since natural hydrogen occurrences have been identified and explored [10].

This chapter aims to present a review of the current stage of the renewable hydrogen economy, including its main production routes and most promising applications in the transport sector. The methodology used for the literature review is presented, and the main opportunities and challenges related to hydrogen usage in transportation are discussed, together with the future prospects of this new market. The analysis carried out throughout this chapter confirms the solid future of the renewable hydrogen market, especially in non-electric sectors in which GHG emissions are high and hard to abate.

6.2 Methodological Procedure

The methodology of this study consists in a review of the existing literature about the routes and uses of renewable hydrogen with a special focus on renewable hydrogen produced from solar energy or biomass. In order to do so, four steps were considered. **Step 1-Planning:** the objectives of the study are set, and the main keywords and their combinations are chosen. Some combinations of keywords related to specific ways of renewable hydrogen production were used in order to filter out the big number of publications that are related to other modes of production that go beyond the scope of this research. **Step 2-Direct Search:** a direct search using the previous chosen keywords is made in two different database, Scopus and Web of Science. The combinations of keywords and the method used are depicted in Table 6.1. **Step 3-Search Repository Creation:** inclusion and qualification criteria are chosen, and the publications found are selected in accordance with them. After the initial review is made, the search repository is created and analyzed. In searches performed with the keywords related to renewable hydrogen produced using solar energy, the database Web of Science returned 115 studies, while Scopus 65, of which 40 were duplicated. Still in this step, the full screening of the publications was done by means of the application of the inclusion and qualification criteria, and so, the creation of the search repository with 112 publications (25 were not related to the theme). Regarding searches performed with the keywords related to renewable hydrogen produced from biomass, the database Web of Science returned 443 studies, while Scopus 85, of which 57 were duplicated. Still in this step, the full screening of the publications was done by means of the application of the inclusion and qualification criteria, and so, the creation of the search repository with 282 publications (189 were not related to the theme). **Step 4-Discussion and Results:** the applications and use of renewable hydrogen are discussed, and the final conclusions about the theme are presented, as well as a view of the future.

It can be seen in Fig. 6.2 that there is a large increase in the number of publications regarding hydrogen produced from renewable energy over the years. This fact indicates the increasing interest and thus the importance of the area, as well as how this is a promising market.

Table 6.1 Description of search strategies

Criterion	Description
Data base	*Web of Science* and *Scopus*
Topics	***Web of Science***- (1) (*TS* = (*"green hydrogen"*) *OR TS* = (*"renewable hydrogen"*)) *AND TS* = (*"photovoltaic"*); *and* (2) (*TS* = (*"green hydrogen"*) *OR TS* = (*"renewable hydrogen"*)) *AND TS* = (*"biomass"*) ***Scopus***- *(1) (KEY ("green hydrogen") OR KEY ("renewable hydrogen")) AND KEY ("photovoltaic"); and* *(2) (KEY ("green hydrogen") OR KEY ("renewable hydrogen")) AND KEY ("biomass")*
Search Method	Direct Search
Inclusion	(i) Time of coverage: all years in the database (1998–2022); (ii) Is it in line with the objectives? (iii) Source prestige-periodicals with international prestige and technical reports from important institutions on the subject
Qualification	(i) Are the study objectives clear? (ii) Are the arguments stated clearly and without subjective bias? (iii) Does the study present technical innovation? (iv) Does it approach technologies linked to the production of green (renewable) hydrogen based on solar energy/biomass or the use of green hydrogen (renewable) produced from solar energy or biomass?
Search Date	May 27, 2022

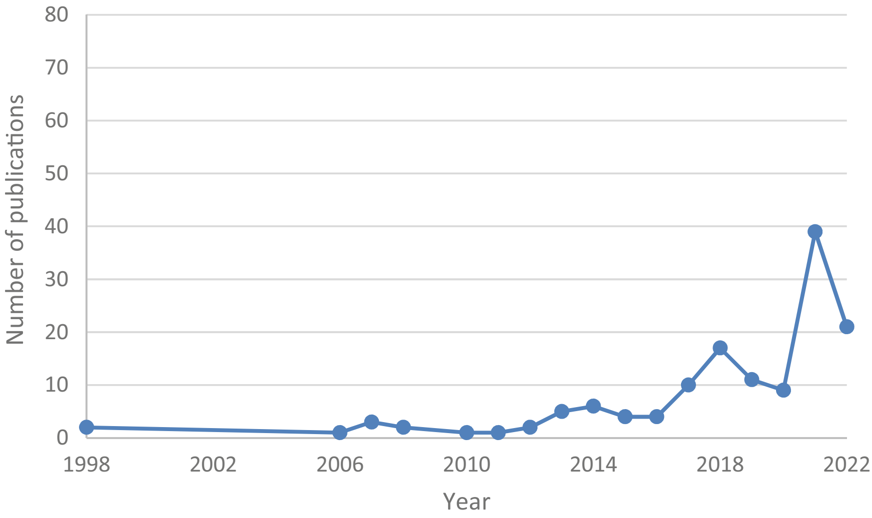


Fig. 6.2 Number of publications per year. Keywords "green hydrogen" or "renewable hydrogen" and "photovoltaic." *Source* elaborated by the authors

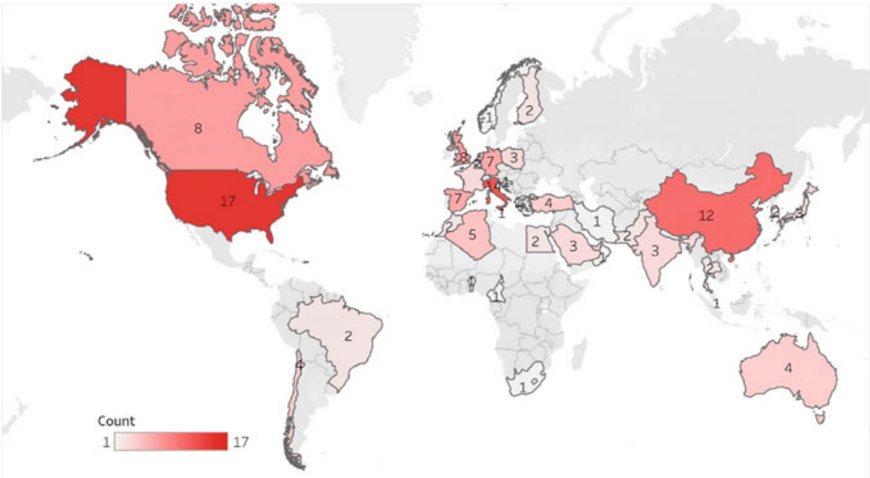


Fig. 6.3 Publications per country. Keywords "green hydrogen" or "renewable hydrogen" and "photovoltaic." *Source*: elaborated by the authors

According to Fig. 6.3, there is a greater number of publications on hydrogen produced from renewable energy in developed countries compared to underdeveloped countries. This result was already expected, as they are the countries that invest the most in research in general.

Regarding searches performed with keywords related to green (renewable) hydrogen from biomass, data from the Web of Science in Fig. 6.4 clearly show an increase in the number of publications in recent years, with a decrease in 2020 that can be explained by the beginning of the COVID-19 pandemic. The data represented by Fig. 6.5 also show that the publications are concentrated in countries that invest heavily on research and development, such as China and the USA.

6.3 Production Routes

In this section, the two main production routes for renewable hydrogen are presented and discussed. The first one consists of renewable hydrogen production through the process of water electrolysis powered by renewable energy. The second route addressed here is hydrogen production from biomass, which is considered in this chapter as another form of producing renewable hydrogen.

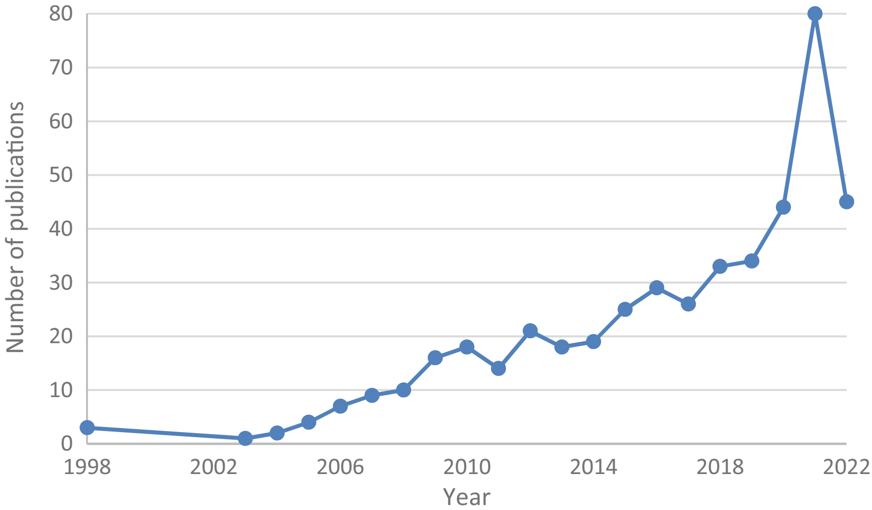


Fig. 6.4 Number of publications per year. Keywords "green hydrogen" or "renewable hydrogen" and "biomass." *Source* elaborated by the authors

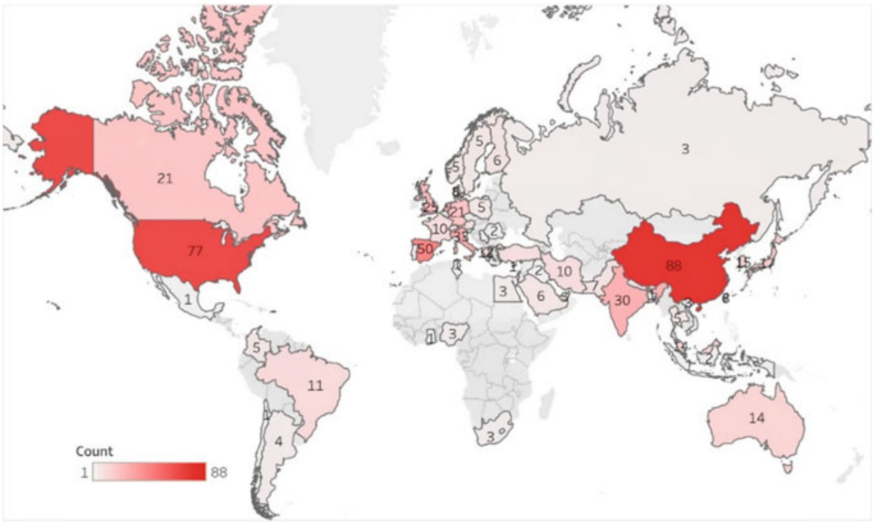


Fig. 6.5 Publications per country. Keywords "green hydrogen" or "renewable hydrogen" and "biomass." *Source* elaborated by the authors

6.3.1 Electrolysis

Currently, the main production route for hydrogen is through steam reforming or gasification of fossil fuels, which emit carbon dioxide in the atmosphere. However, with the expansion of renewable power plants, electrochemical water splitting through electrolysis has been attracting attention from both research and industry sectors [3], since it is a clean method to produce high-purity hydrogen [11].

Electrolysis is the process of using electricity to split water into its components, hydrogen and oxygen, which in turn are released as gas molecules. The former can be used for further applications such as liquid or gaseous fuels synthesis or used to generate power again through a fuel cell. Although it has the capacity of generating a high-purity hydrogen (99.9%), the process is energy intensive; thus, the high costs associated with renewable resources in the past years are the reason why it has not been used more intensively for many decades. However, with the current efforts toward an energy transition to a decarbonized economy and the reduction costs of electrolyzers and renewable energy resources, such as solar PV, wind, or hydropower plants, electrolysis is gaining attention in both industry and academia. Figure 6.6 illustrates the overall hydrogen production process from electrolysis with renewable sources.

Currently, there are two main different methods for water electrolysis being commercialized, which are similar in operating principles, but differ in terms of materials and operating conditions: alkaline electrolysis cells (AEC) and proton exchange membrane electrolysis cells (PEMEC).

AEC is a well-established technology which operates at lower temperatures and uses aqueous solution as electrolyte. Although it has low operating current density and efficiency, its overall costs are smaller than the other technologies. In PEMEC, a

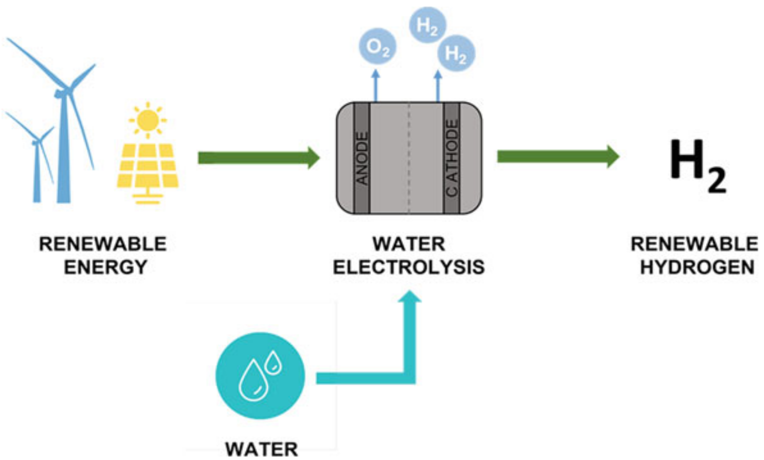


Fig. 6.6 Renewable hydrogen production through water electrolysis using renewable energies. *Source* elaborated by the authors

solid sulfonated polystyrene membrane is used as the electrolyte, which is permeable to protons but not to gasses, acting as a gas separator and resulting in a safer and more efficient process. This technology presents higher efficiency and operating current density, fast response, wider range of operating temperatures, and compact design. Additionally, the fast response of PEMEC technology makes it the best alternative for intermittent renewable sources such as PV and wind, as it quickly reacts to their energy. The costs of the precious metals used as electrocatalysts for PEMEC make it more expensive than AEC [11]. Efforts are to reduce the cost of PEMEC electrocatalysts, while the cumulative production and use of PEM electrolyzers progressively contribute for their cost reduction to become cost competitive to alkaline ones [12].

Innovations and challenges. Besides these two main technologies, there are also new ones either still in development or in early market development: solid oxide electrolysis cells (SOEC) and anion exchange membrane (AEM) electrolyzers. The former operates in high temperatures, resulting in high energy efficiency but also in fast material degradation, compromising in the duration of its operation. In addition, the generated hydrogen mixture with water vapor requires additional treatment to obtain high purity hydrogen. On the other hand, in AEM electrolyzers, the proton exchange membrane is replaced by an anion one, resulting in the union of both AEC and PEMEC advantages. This technology is considered a great promise for future water electrolysis systems [11].

An evaluation of the three presently marketed versions of electrolyzers is useful to compare their characteristics. The main intrinsic and operating features for AEC, PEMEC and SOEC are summarized in Table 6.2. It also simulates a specific comparison between them, in which the AEC and PEMEC are set to be operated at 80 °C and the SOEC at 800 °C. The SOEC presents smaller operating potential and internal resistance and higher hydrogen production rate and hydrogen production per energy consumed, whereas the energy needed for such performance varies from about 1 to 2 kWh/Nm^3H_2 for AEC and PEMEC, but less than 0.5 kWh/ Nm^3H_2 for the SOEC. In addition to that, the SOEC has also prospects to become a cheaper technology than the present incumbent ones [13].

Summing up, PEM electrolysis is considered; nowadays, the technology most suited for hydrogen production due to its fast dynamic response, especially if PV or wind energy is used as main power generation systems, while the SOEC presents the best future prospects, yet considering that it may operate reversibly as an electrolyzer or a fuel cell, hence either producing hydrogen or electricity and heat.

Finally, independently of the technology, the challenge of water electrolysis being energy intensive remains. Regarding this issue, a question is imposed: When is it worth using renewable electrical energy directly by means of sector electrification or doing electrolysis to obtain hydrogen for further use?

The answer for this question is the key to the future of the hydrogen economy and rely on two main points:

- whether it is possible to electrify a sector. If not, hydrogen is a promising energy vector enabling the use of renewable energy in other sectors;
- the efficiency of the conversion process and storage characteristics.

Table 6.2 Summary of different electrolyzer types, their particular features, and a specific comparison among them [10]

Electrolyzers	AEC	PEMEC	SOEC
Electrolyte	Solution of NaOH or KoH	Hydrated polymeric membranes	Ceramic
Charge ion conductor	OH^-	H^+, H_3O^+	O^{2-}
Cathode reaction	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Anode reaction	$2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^-$	$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$
Electrodes	Ni, C	C	Ceramic/cermet
Catalyst	Ni, Fe, Pt	Pt	Ni, perovskites
Interconnector	Metal	Carbon–metal	Stainless steel, ceramic
Operating temperatures (°C)	40–90	20–150	700–900
Specific Comparison			
Operating temperature (°C)	80	80	800
Operating potential (V)	1.9	1.7	1.15
Internal resistance (Ω cm^2)	2.5	0.5	0.15
Hydrogen production rate (mol H_2/m^2h)	50	175	211
Hydrogen production per energy consumed (mol H_2/kWh)	27	40	110

If the sector is electrifiable and electrical energy storage is economically and technically feasible, then hydrogen may not be the best option, as the conversion process has losses associated with it. However, if long-term energy storage is necessary, with a timeframe of weeks, months, or season, then hydrogen is the preferable option. This discussion is readdressed in Sect. 6.5.

6.3.2 Biomass

The use of biomass as a feedstock for the production of hydrogen is considered a promising method for a decarbonized economy, due to neutral carbon emissions, since the CO_2 produced during the process is consumed by plants through the process

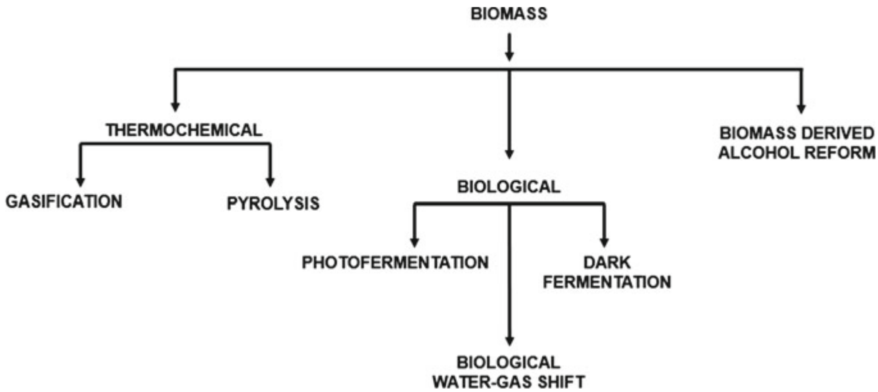


Fig. 6.7 Main routes for converting biomass to hydrogen. *Source* elaborated by the authors

of photosynthesis [14]. The main routes for converting biomass to hydrogen are thermochemical and biological, with the biomass-derived alcohol reforms also possible [15], as shown in Fig. 6.7.

The main thermochemical methods for hydrogen production are gasification and pyrolysis. Gasification is a complex chemical process, with the use of high temperatures, and an oxidizing atmosphere, leading to incomplete combustion of the biomass, generating a synthesis gas formed by H_2, CO, CO_2, with a small amount of a condensable liquid (tar) and char [16, 17]. Among them, tar is an undesirable but inevitable liquid by-product from the low- and medium-temperature gasification operation [18]. The production of hydrogen-rich syngas from biomass gasification is of significant economic interest; however, the formation of tar in this process is a limitation to the production of syngas due to the low condensation temperature, so removal of tar by physical means or lowering the formation of tar by changes in the operating conditions of the gasification process is necessary [19, 20].

The pyrolysis process generates the formation of char, bio-oil and gases, using a non-oxidizing atmosphere and high temperatures, but milder than in gasification [21]. For hydrogen production, the use of fast pyrolysis—where we have a high heating rate and a shorter residence time of the biomass in the reactor—is preferable, since it leads to less char formation. However, to increase hydrogen production and make the process more attractive, the use of catalysts is encouraged to increase the efficiency of the process [15, 22].

The reforming of alcohols produced from biomass is also a possible source of hydrogen. Ethanol, which can be produced from the fermentation of biomass, and glycerol, obtained as a derivative of bio-diesel production, are interesting candidates, as there is a surplus of glycerol in the current market. Ethanol can be used as a feedstock in steam reforming, oxidative steam reforming and partial oxidation processes [15].

The bio-hydrogen production process (the advent of biological routes) has a number of advantages over the use of fossil fuels as feedstocks, highlighting the reduced production of greenhouse gases concomitantly with a lower CO_2 emission into the atmosphere, characterized as a more sustainable and biodegradable energy source. The three main biological routes for producing hydrogen from biomass are photofermentation, dark fermentation, and the biological gas–water displacement reactions [23].

Biological gas–water displacement reactions use photoheterotrophic bacteria in a medium with carbon monoxide and water in the absence of light, reducing H_2O molecules and oxidizing CO, producing hydrogen and CO_2. Photofermentation produces hydrogen through the conversion of biomass using nitrogenases as a catalyst through solar energy in a nitrogen-deficient environment [24], while dark fermentation is an anaerobic process in which hydrogen is produced by the action of anaerobic bacteria in the absence of light, in a temperature range of 25–80 °C. Carbohydrate catabolism is the main approach of this method, which has the main advantage of converting residues that contained cellulosics and lignocellulosics, constituting a method with high residue integration [25, 26]. In addition, the bioreactors used in this process are less expensive and simpler to produce compared to those used in photofermentation, since there is no solar energy.

In addition to the three routes mentioned, two others are worth mentioning—direct and indirect biophotolysis. Regarding direct biophotolysis, water is the substrate for the production of hydrogen, which under anaerobic conditions in the presence of light is converted into hydrogen and oxygen by microalgae. On the other hand, indirect biophotolysis occurs in two steps, in which the reactions of oxygen and hydrogen formation are separated. One of the advantages is the ease of maintaining anaerobic conditions during hydrogen production in the dehydrogenation (second step); however, the high cost of photobioreactors and the low rate of hydrogen production are limiting factors in this process [27].

Innovations and challenges. Currently, biomass gasification is the method of producing hydrogen from renewable feedstocks with the lowest production cost. The main advantages of thermochemical routes such as gasification and pyrolysis are associated with high rates of hydrogen productivity, with extensive applications in several systems. Other thermochemical conversion methods have been studied recently, among them the biomass electrolysis, characterized by a high yield while consuming less electricity than conventional water electrolysis. In addition, several studies have been carried out with the aim of performing the biological conversion of biomass through the action of microorganisms. The advantage of these biological processes would be the use of mild conditions of temperature and atmospheric pressure, which leads to a lower energy expenditure. In addition, the microorganisms used as feedstocks in this route usually have a higher growth rate than other feedstocks from biomass. However, the major limiting challenges for these processes are the low rates of hydrogen conversion and production and the high costs associated with bioreactors [28].

Several government and private incentives have been directed toward the production of hydrogen from renewable sources. The UK, for example, launched in January 2022 a program for the development of innovative technologies called BioEnergy with Carbon Capture and Storage (BECCS) aimed at producing hydrogen from sustainable biomass and waste, with a high capacity to capture and store the carbon released during the process [29].

6.4 Applications in the Transportation Sector

As mentioned in the preceding paragraphs, hydrogen can be used as an energy source or feedstock in a wide variety of economic activities. In this text, a special attention is paid to its applications in the transportation sector, which for several years has constantly been considered the most promising sector for hydrogen usage and responds alone for the 23% of the global GHG emissions [30]. Hydrogen can be used as fuel for vehicles in different ways, depending on the chemical composition of the fuel and on the energy converter employed to transform chemical energy into mechanical energy. From the point of view of fuel composition, hydrogen can be used in its pure form, or as feedstock for the synthesis of a more complex molecule, like ammonia, hydrocarbons, or alcohols. Regarding the energy conversion equipment, the most common devices applied in vehicles are internal combustion engines, gas turbines, and fuel cells. The former two are conventional technologies, although a special design and adaptations are needed to use hydrogen instead of oil-based hydrocarbon fuels. On the other hand, fuel cells are a less diffuse and completely different technology, based on direct electrochemical conversion of a fuel in electrical energy, which can be used in an electric powertrain. Fuel cells systems typically show higher efficiencies (around 50%), lower pollutant emissions and less maintenance needs than incumbent technologies but are still characterized by a higher cost. Normally, vehicles are powered by polymer electrolyte membrane fuel cells (PEMFC) fueled by pure hydrogen, but other solutions are being developed using other kinds of cells or different fuels, like alcohols or hydrocarbons.

6.4.1 Road Transportation

For the general public, road transportation is normally the most obvious application for hydrogen-fueled power systems. However, competitor technologies like biofuels and battery electric vehicles made the prospects for hydrogen use in this field less optimistic, especially in the case of light-duty vehicles [31, 32]. Biofuels are a very interesting option for countries with large available land areas and high biomass yield per hectare, such as Brazil, the USA, or China, due to their high volumetric energy density and drop-in compatibility with the incumbent technologies for fuel production, distribution and use. On the other hand, battery electric vehicles can take advantage of an already established fueling option—the existing electric grid—that favor their diffusion, although permitting only slow low-power battery charging. Moreover, the advances in battery technologies have been very fast in the last decades, permitting the construction of light-duty vehicles with a range of several hundreds of kilometers, enough for most applications. On the contrary, the diffusion of hydrogen-powered vehicles is hindered by the lack of refueling infrastructure, creating a chicken-and-egg situation in which the necessary investment in hydrogen fueling stations is slowed down by the low number of existing vehicles and vice-versa. Therefore, the actual happening of a worldwide diffusion of hydrogen as fuel for light-duty vehicles is not as clear as it was a few decades ago. However, even in this context, various studies suggest that hydrogen-fueled light-duty vehicles based on fuel cells can be an efficient solution both from environmental and economic perspectives in several use cases, mainly the ones that require high driving ranges and short refueling times, being complementary to battery electric vehicles [33]. In fact, the main advantages of hydrogen as fuel for transportation are its high gravimetric energy density, which allows to store and transport high energy quantities without excessively increasing the vehicle weight, and its convenient logistics, similar to other automotive fuels like natural gas.

Actually, the above-mentioned features of hydrogen are the main reason for the fact that this fuel still is a strong candidate for the decarbonization of the heavy-duty transportation sector. In fact, heavy-duty vehicles are responsible for a high consumption of diesel—a fuel with a comparatively high fossil carbon content—and lack an already deployed solution to reduce their CO_2 emissions. Moreover, the high energy consumption related to these vehicles and their need for short refueling times and long distances, together with the limitations of batteries in terms of gravimetric energy density strongly difficult the adoption of purely electric powertrains in most heavy-duty applications, making the prospects for the use of hydrogen-powered vehicles stronger [34, 35]. Also, in the case of heavy-duty road transport, a lower number of hydrogen refueling stations is necessary, due to the fact that most vehicles are fueled either along highways or in garages (in the case of urban buses, for example). Due to these reasons, hydrogen-powered fuel cell buses are being tested and implemented in public transportation systems of several cities worldwide, and hydrogen-powered trucks are close to commercialization [36, 37].

6.4.2 Rail Transportation

Hydrogen as train fuel is already a reality, with a few commercial projects of fuel cell-based locomotives already implemented and several ongoing [38]. In particular, hydrogen powertrains are considered very promising as substitutes for diesel-powered engines, currently still in use in various situations where the railway is not electrified, offering economic and environmental advantages even with respect to railway electrification [39, 40]. Considering what is exposed above, the substitution of diesel locomotives with hydrogen ones can be considered to be mainly limited by the long lifespan of locomotives, which hinders their substitution with new, low-emission models. The relatively small hydrogen refueling stations network needed for the application is an advantage also in this case.

6.4.3 Shipping

Together with air transportation, shipping is one of the most hard-to-decarbonize transportation modalities, due to the high energy consumption of the ships and the very long intervals between their refuelings. Several works in the literature consider hydrogen as a potential solution for net-zero maritime applications, either in pure form or as feedstock for synthetic fuels production [41, 42], although with a longer implementing time than in the case of railways. To complicate the situation, shipping standards are typically international, and the adoption of an innovative technology would probably happen at the same time in most of the world's infrastructure. In this context, electric boats will most probably be limited to short-distance trips, due to the high cost and weight of the batteries needed to supply enough energy to the vehicle. For medium and high ranges, the use of pure hydrogen will probably compete with biofuels and synthetic fuels, like ammonia, either in internal combustion engines or fuel cells [43]. Both biofuels and ammonia present the advantage of a higher volumetric energy density with respect to hydrogen, especially when in gaseous compressed form, which is the hydrogen storage method economically and energetically less expensive. On the other hand, some concerns related to land and resources availability for biofuel production do exist, while ammonia usage is mainly hindered by its high toxicity and water polluting properties. As a consequence, compressed pure hydrogen will probably be applied mostly in short- and medium-range ships to reduce the hydrogen storage cost, while liquid fuels will cover long-range applications.

6.4.4 Aviation

As mentioned above, the emissions related to the aviation sector are very difficult to abate, due to the very stringent constraints in terms of weight and volume of the aircrafts, which makes the use of batteries unviable in most applications. In this case, the use of pure hydrogen is also difficult, mostly due to its low volumetric energy density and related large size of storage equipment. A solution proposed by several studies is instead the use of hydrogen as feedstock for synthetic kerosene synthesis [43, 44], as a competitor of aviation biofuels. However, both technologies are still considered quite far from commercialization, due to the current high fuel production cost. As in the case of shipping, also aviation standards are normally set in an international frame, implying that hydrogen and hydrogen-based fuels adoption for airplanes must proceed approximately at the same speed worldwide.

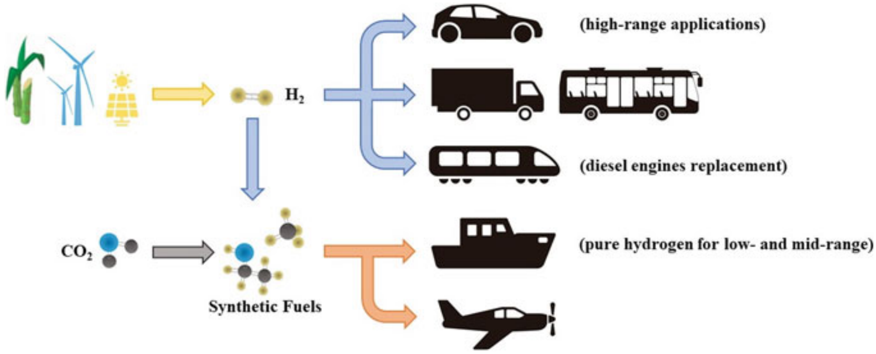


Fig. 6.8 Main applications of hydrogen as transportation energy vector/fuel. *Source* elaborated by the authors

6.4.5 Global Hydrogen-Powered Transportation System

According to what was exposed in the previous paragraphs, renewable and low-emission green hydrogen can potentially have a very important role in the decarbonization process of the transportation sector, either directly or as a component for synthetic fuels, especially in long-range, heavy-duty, and high-power applications. Figure 6.8 contains a schematic of the possible structure of a future hydrogen-based transportation system, showing the most convenient uses of hydrogen in transportation and evidencing its capability to function as energy vector, transferring renewable energy from the sources to the vehicles.

6.5 Final Discussion and Vision of the Future

This study sought to review the current stage of the renewable hydrogen economy, highlighting its opportunities and challenges regarding more specifically both transport and energy sectors and served to demonstrate the future prospects of this new market and the urgency for solving the technology main drawbacks.

The main advantages of utilizing hydrogen energy are the availability of hydrogen, which can be easily obtained and stored for further use by many different processes, allowing the decoupling of power from the electricity sector for use in other sectors. However, the main disadvantages are related to its energy-intensive production process, which reduces its efficiency, and the fact of being a gaseous fuel that poses more hurdles for transportation and storage than liquid ones.

Determining factors for the future of this industry are the scale of production, also both cost and infrastructure to transport and export renewable hydrogen, whether in its pure form, or in the form of ammonia, liquid organic hydrogen carriers and other derivatives. Regarding the scale of production, countries with an abundance of renewable resources have higher potential to be major suppliers. On the other hand, to overcome the hurdles related to transport, export and energetic use of renewable hydrogen, existing infrastructure such as gas pipelines, hydrogen refueling stations, storage facilities, and ships can be used.

Another key factor for the expansion of the renewable hydrogen economy is the cost associated with its production. It has been evaluated that presently the levelized cost of hydrogen production through steam methane reforming without (conventional) and with CCUS is, respectively, 1.26 US$/kg$H_2$ and 1.88 US$/kg$H_2$ [45]. Despite the challenge of making renewable hydrogen competitive compared to conventional hydrogen (produced through steam reforming, without CO_2 capture), recent studies already indicate a cost reduction trend for the next decades mainly due to three factors: drop of capex requirements; decline of levelized cost of energy (LCOE) related to the reduction in renewable energy costs, especially in regions with high solar irradiation and/or high wind availability; higher electrolyzer utilization levels, as larger-scale projects are implemented [44]. The perspective worldwide is that if renewable hydrogen production costs continue to fall more swiftly than previously expected, it could break even with conventional hydrogen from 2030 [3]. On top of that, if carbon costs for emissions are included, this horizon is anticipated to 2028 on [46]. The projected cost reduction of renewable hydrogen will favor its application in the economy, permitting to decarbonize several activities without a considerable cost increase with respect to current, carbon-emitting technologies.

Besides promoting a renewable route for fuels production, the renewable hydrogen market can boost the power sector not only for being an energy vector for storage and energy generation but also for encouraging investments in new renewable energy power generation plants. In this context, many countries are implementing policies to promote the diffusion of hydrogen energy, including: (i) the creation of strategies and roadmaps with public investment commitment and H_2 production and use targets; (ii) the establishment of support schemes to boost hydrogen demand across the economy, help the related technologies to enter the market and mitigate the investment risks; (iii) the promotion of R&D and demonstration projects in the hydrogen energy sector; (iv) the creation and harmonization of regulation, codes and standards, removing regulatory barriers.

However, regarding the power sector, a question that still remains is: when to use hydrogen or the electrical energy itself? The answer to that depends on the application and on the availability of renewable resources. In order to reduce the cost of hydrogen production and compensate for its energy-intensive characteristic, high renewable energy generation is necessary. Besides, the sectors that are most worth investing are those in which electrical energy is not supported, or high capacity and long storage periods is required. An example of the latter is for increasing energy resilience and demand control in the power system, such as when renewable energy generation exceeds the demand, part of this exceeding energy could be stored in the form of hydrogen to be later used during energy shortage periods. This provides more flexibility and reliability to the power grid.

Finally, it is believed that this study has provided: (i) a review on the recent literature on renewable hydrogen; (ii) an overview of its main routes and applications focused on the transport sector, highlighting the main challenges and innovations; and (iii) recommendations and perspective of directions for future studies.

Acknowledgements This publication is a joint realization of UFRJ and the H2Brasil project. This project was agreed within the scope of the Brazil-Germany Cooperation for Sustainable Development, through a partnership between the Ministry of Mines and Energy (MME) of Brazil and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, with support from the German Federal Ministry for Economic Cooperation and Development (BMZ). A. Coralli and P.E.V. de Miranda acknowledge financial support to research projects ICTIM 17/2021, FAPERJ E-26/210.803/2021 and E-26/210.485/2022.

References

1. Kakoulaki, G., et al.: Green hydrogen in Europe-a regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Convers. Manag. 228 (2021)
2. World Energy Transitions Outlook 2022: 1.5°C Pathway. International Renewable Energy Agency (IRENA), Abu Dhabi (2022)
3. Global Hydrogen Review. International Energy Agency (IEA) (2021)
4. Chehade, Z., et al.: Review and analysis of demonstration projects on power-to-X pathways in the world. Int. J. Hydrogen Energy **44**, 27637–27655 (2019)
5. Geopolitics of the Energy Transformation: The Hydrogen Factor. International Renewable Energy Agency (IRENA), Abu Dhabi (2022)
6. Produção e Consumo de Hidrogênio em Refinarias no Brasil 2022. Empresa de Pesquisa Energética, Rio de Janeiro (2022)
7. The role of renewable H2 import & storage to scale up the EU deployment of renewable H2. Energy Transition Expertise Centre (ENTEC) (2022)
8. The EU's hydrogen strategy explores the potential for renewable hydrogen to help decarbonize the EU in a cost-effective way. Energy European Commission (2022)
9. Hidrogênio Renovável (Renewable Hydrogen). Centro de Gestão e Estudos Estratégicos (CGEE), Brasília (2022)
10. Miranda, P.E.V.: Hydrogen energy. In: Miranda, P.E.V. (ed.) Science and Engineering of Hydrogen-Based Energy Technologies, 1st edn, pp. 1–38. Elsevier Academic Press (2019)
11. Chi, J., Yu, H.: Water electrolysis based on renewable energy for hydrogen production. Chin. J. Catal. **39**(3), 390–394 (2018)
12. Path to hydrogen competitiveness-A cost perspective, Hydrogen Council (2020)
13. Godula-Jopek, A. (ed.): Hydrogen Production by Electrolysis, p. 259. Wiley-VCH Verlag GmbH & Co. (2015)
14. Mohanty, P., Pant, K.K., Mittal, R.: Hydrogen generation from biomass materials: challenges and opportunities. Wiley Interdiscip. Rev. Energy Environ. **4**, 139–155 (2015)
15. Pal, D. B., Singh, A., Bhatnagar, A.: A review on biomass-based hydrogen production technologies. Int. J. Hydrogen Energy (2021)
16. Prakash, P., Narayanan, K.S.: Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield–a review. Renew. Energy **66**, 570–579 (2014)
17. Zhibin, L., et al.: Steady state modelling of steam-gasification of biomass for H2-rich syngas production. Energy **238**, 121616 (2022)
18. Zeng, X., et al.: Recent progress in tar removal by char and the applications: A comprehensive analysis. Carbon Resour. Convers. **3**, 1–18 (2020)
19. Shahbaz, M., et al.: A state of the art review on biomass processing and conversion technologies to produce hydrogen and its recovery via membrane separation. Int. J. Hydrogen Energy **45**(30), 15166–15195 (2020)

20. Rios, M.L.V., et al.: Reduction of tar generated during biomass gasification: a review. Biomass Bioenerg. **108**, 345–370 (2018)
21. Demirbas, M.F.: Hydrogen from various biomass species via pyrolysis and steam gasification processes. Energy Sources Part A **28**(3), 245–252 (2006)
22. Kannah, R.Y., et al.: Techno-economic assessment of various hydrogen production methods–a review. Biores. Technol. **319**, 124175 (2021)
23. Levin, D.B., Pitt, L., Love, M.: Biohydrogen production: prospects and limitations to practical application. Int. J. Hydrogen Energy **29**(2), 173–185 (2004)
24. Hallenbeck, P.C., Yuan, L.: Recent advances in hydrogen production by photosynthetic bacteria. Int. J. Hydrogen Energy **41**(7), 4446–4454 (2016)
25. Eker, S., Meltem, S.: Hydrogen gas production from waste paper by dark fermentation: effects of initial substrate and biomass concentrations. Int. J. Hydrogen Energy **42**(4), 2562–2568 (2017)
26. Taipabu, M.I., et al.: A critical review of the hydrogen production biomass-based feedstocks: challenge, solution, and future prospect. Process Saf. Environ. Prot. (2022)
27. Łukajtis, R., et al.: Hydrogen production from biomass using dark fermentation. Renew. Sustain. Energy Rev. **91**, 665–694 (2018)
28. Lepage, T., Kammoun, M., Schmetz, Q., Richel, A.: Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment. Biomass Bioenerg. **144**, 105920 (2021)
29. https://www.gov.uk/government/news/government-launches-new-scheme-for-technologies-producing-hydrogen-from-biomass, UK Government. Accessed 08 July 2022
30. IPCC: Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA (2022)
31. Moriarty, P., Honnery, D.: Prospects for hydrogen as a transport fuel. Int. J. Hydrogen Energy **44**, 16029–16037 (2019)
32. Morrison, G., Stevens, J., Joseck, F.: Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transp. Res. Part C **87**, 183–196 (2018)
33. Roadmap towards zero emissions-The complementary role of BEVs and FCEVs, Hydrogen Council (2021)
34. Ajanovic, A., Glatt, A., Haas, R.: Prospects and impediments for hydrogen fuel cell buses. Energy **235**, 121340 (2021)
35. Keller, V., Lyseng, B., Wade, C., Scholtysik, S., Fowler, M., Donald, J., Palmer-Wilson, K., Robertson, B., Wild, P., Rowe, A.: Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation. Energy **172**, 740–751 (2019)
36. De Miranda, P.E.V., Carreira, E.S., Icardi, U.A., Nunes, G.S.: Brazilian hybrid electric-hydrogen fuel cell bus: improved on-board energy management system. Int. J. Hydrogen Energy **42**, 13949–13959 (2017)
37. Ruf, Y., Baum, M., Zorn, T., Menzel, A., Rehberger, J.: Fuel cells hydrogen trucks-heavy-duty's high performance green solution. In: Fuel Cells and Hydrogen 2 Joint Undertaking & Roland Berger, Brussels (2020)
38. Ruf, Y., Zorn, T., De Neve, P.A., Andrae, P., Erofeeva, S., Garrison, F., Schwilling, A.: Study on the use of fuel cells and hydrogen in the railway environment. In: Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking & Roland Berger, Luxembourg (2019)
39. Piraino, F., Genovese, M., Fragiacomo, P.: Towards a new mobility concept for regional trains and hydrogen infrastructure. Energy Convers. Manage. **228**, 113650 (2021)
40. Study of Hydrogen Fuel Cell Technology for Rail Propulsion and Review of Relevant Industry Standards. U.S. Department of Transportation, Washington (2021)
41. Bacha, H., Bergek, A., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A., Steen, M.: Implementing maritime battery-electric and hydrogen solutions: a technological innovation systems analysis. Transp. Res. Part D **87**, 102492 (2020)

42. Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W., Lenaerts, S.: Challenges in the use of hydrogen for maritime applications. Energy Environ. Sci. **14**, 815 (2021)
43. Energy Technology Perspectives 2020. International Energy Agency (IEA), France (2020)
44. Scheelhaase, J., Maertens, S., Grimme, W.: Synthetic fuels in aviation—current barriers and potential political measures. Transp. Res. Procedia **43**, 21–30 (2019)
45. Moreira dos Santos, R., Szklo, A., Lucena, A.F.P., Miranda, P.E.V.: Blue sky mining: strategy for a feasible transition in emerging countries from natural gas to hydrogen. Int. J. Hydrogen Energy **46**(51), 25843–25859 (2021)
46. Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness. Hydrogen Council (2021)

Chapter 7
Corrosion Protection Practices and Integrity Management Challenges in Oil and Gas Pipeline

Hemalata Jena, Suchismita Satpathy, Sanjukta Sahoo, Sasmita Sahu, and Bijaya Bijeta Nayak

Abstract The present chapter has presented the root causes and contributing causes of the corrosion in the internal and external surfaces of the underground pipelines and their possible mitigation measures. External coating types, application methods, corrosion monitoring principles, and pipeline health assessment practices are discussed. The external surface is in contact with verities of terrain and corroding environment as it passes through long distances and is therefore vulnerable to greater challenges of pipeline surface corrosion. The internal corrosion rate is dependent on the corrosive properties of the crude oil, petroleum products, or gas being transported and the condition of the internal surface. The conditioning and preparation of the pipeline's internal surface also help in reducing the drag. Any reduction in drag intern improves the flow rate of the service fluid in the pipeline.

Keywords Oil and gas pipeline · Corrosion · Coating

7.1 Introduction

In the present development scenario, the production and use of petroleum products, like LPG, petrol (MS), kerosene (SKO), diesel (HSD), aviation turbine fuel (ATF), compressed natural gas (CNG), and several other petroleum products and petrochemicals derived from the petroleum, decide the scale of prosperity and economic activities of countries. Ensuring the availability of these petroleum products at every nook and corner of the country requires reliable and efficient transportation where the role of the pipelines is paramount as the most efficient and safest mode of transportation of these hydrocarbons. These pipelines run over several hundred kilometres, mostly laid underground passing through inhabited localities, villages, cities, etc.

H. Jena (✉) · S. Satpathy · S. Sahu · B. B. Nayak
School of Mechanical Engineering, KIIT Deemed to be University, Bhubaneswar 751024, India
e-mail: hemalata.jenafme@kiit.ac.in

S. Sahoo
Department of Civil Engineering, KIIT Polytechnique, Bhubaneswar 751024, India

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_7

To ensure the healthiness of these pipelines, and public and environmental safety, utmost precautions are taken for their corrosion management and periodic health assessments. Corrosion is a serious issue in the oil and gas pipeline. About 50% of failures are materials corrosion in the petroleum refining and petrochemical industry [1]. This increases the cost of the process if the pipeline will be replaced or repaired, and corrosion also may cause a catastrophic failure resulting in a disaster threatening the very existence of flora and fauna in the vicinity. Due to the significant downtime caused by corrosion-related breakdowns, pipeline corrosion is a serious problem for many oil and gas industries today. Figure 7.1 shows the various causes of pipeline corrosion. Hence, various types of research have been done to improve the corrosion resistance of the pipeline through different coatings. The cathodic protection principle is also another method of external corrosion prevention which uses electricity for underground steel pipelines. Two methods of electrical current injection are used to provide cathodic protection for steel structures: galvanic anode protection (spontaneous) and impressed current protection (non-spontaneous) [1]. The degree of cathodic protection and the calibre of the pipeline coating are the two key elements in decreasing or avoiding the initiation of external corrosion on a pipeline. For corrosion in gas pipelines of carbon steel internal corrosion, coating, as well as corrosion inhibitors, is used to prevent it [2].

Corrosion in petroleum oil and gas pipelines can be controlled by introducing a suitable barrier in between the steel surface and the corrosive environment in contact with it. Pipeline coatings are a natural choice for it. The coating can be of various types and several coating materials have been developed and different formulations have been used over the years for pipeline protection. Wax, coal tar, and vinyl tapes

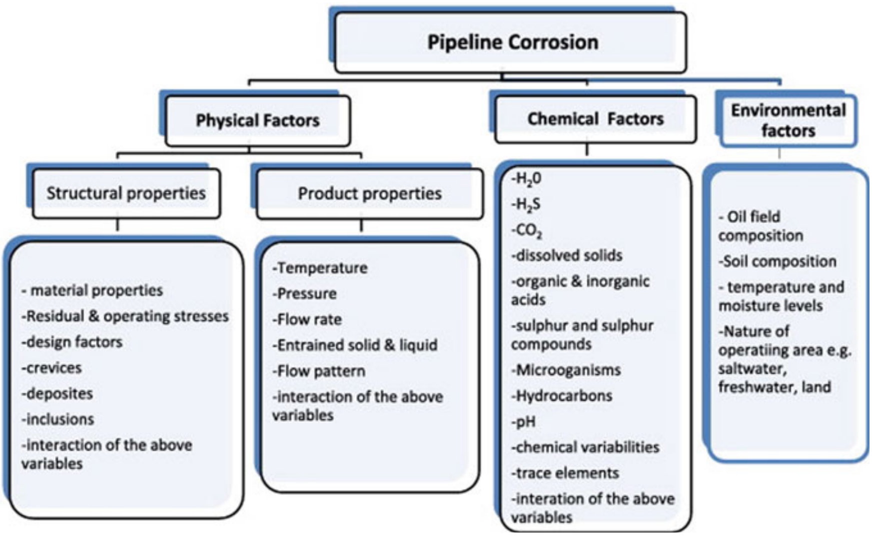


Fig. 7.1 Sources of pipeline corrosion [3]. (Copyright 2015. Reproduced with permission from Elsevier)

were used for pipeline surface coating in the 1940s and 1950s. Asphalt coatings were introduced in the 1960s, and the fusion-bond epoxy (FBE) coatings use started in the 1970s. Polyethylene tape (PE) coatings and extruded polyethylene jackets are in use since the early 1950s [4]. Three-layered polyethylene (3LPE) coatings are also prevalent in the new pipeline being laid. Though there are many types of coatings formulations for underground pipelines, the most common coatings are (i) coal tar enamel, (ii) fusion-bond epoxy (FBE) coating, (iii) three-layer polypropylene (3LPP), (iv) three-layer polyethylene (3LPE) coatings [5]. The present chapter discusses the different types of internal and external corrosion of the pipeline, and their possible mitigation measures through proper corrosion management techniques like coating and cathodic protection which are essential for handling pipeline corrosion. The chapter also discusses the future research plans of the present study which helps the reader to know the future scope of the research.

7.1.1 Material Selection for Pipelines

Pipelines continue to be the safest and most economical means for transportation of large volumes of crude oil, liquid petroleum products like MS, HSD, ATF, kerosene, compressed natural gas (CNG), and several other inflammable petroleum speciality products. Steel has been the preferred material for the construction of these cross-country pipeline networks. Over the last few decades, multiple grades of steel have been developed with varying properties and enhanced strength for use in specific corrosive environments such as pitting, stress corrosion cracking, hydrogen-induced cracking, sulphide corrosion. Carbon steel pipes conforming to API 5L standards are the most common. City gas distribution steel networks normally use low-strength steel pipeline grades such as API 5L Grade-A, B, X42, X46. These steel pipelines are designed with internal design pressure or maximum allowable operating pressure (MAOP) up to 49 bar and typically operate at less than 20 bar [6]. High-pressure pipelines use high-strength grades like API 5L Grade X70, X80, etc. Nesic [7] have reviewed the internal surface corrosion behaviour of carbon steel oil and gas pipelines which are widely used. Carbon steel is used to make pipelines due to its good corrosion resistance [8].

Zhao et al. [9] have established an indicator system for pipe materials selection. According to them, the indicators are divided into three main categories, i.e. prospective materials' service (functional) characteristics, economic value, and environmental attributes which reveals the vital criteria for the selection of material for a pipeline design. Different international and national codes and design standards like the American Society of Mechanical Engineers ASME B 31.2 & ASME B 31.8, American Society of Test and Materials (ASTM), American Petroleum Institute (API) 5L standards and Norwegian Petroleum Standard (NORSOK) are used to identify the material's limitation for particular process conditions.

7.1.2 Corrosion Problem in Pipelines

The service life of pipelines can be extended if the factors causing corrosion and their development are identified in advance and the pipeline network is designed, laid, operated, and maintained with a suitable corrosion management system. Pipelines are prone to both external and internal corrosion. Detailed classification of pipeline corrosion is shown in Fig. 7.2. Pipeline corrosion is classified into two major types, i.e. (a) general/localized metal loss and (b) environmentally assisted cracking [10]. Metal loss mechanism includes CO_2 corrosion, hydrogen sulphide (H_2S) corrosion, top of line corrosion (TOLC), microbiologically influenced corrosion (MIC), under deposit corrosion (UDC), and preferential weld corrosion (PWC). Similarly, environmentally assisted cracking includes hydrogen-induced cracking (HIC), sulphide stress corrosion cracking (SSC), stress-oriented hydrogen-induced cracking (SOHIC).

7.1.2.1 Internal Corrosion

The impurities in the service fluid like moisture, hydrogen sulphide, mercaptans, and carbon dioxide are the main causes of internal corrosion. This type of corrosion is seen inside the pipeline. Different types of internal corrosion are discussed below.

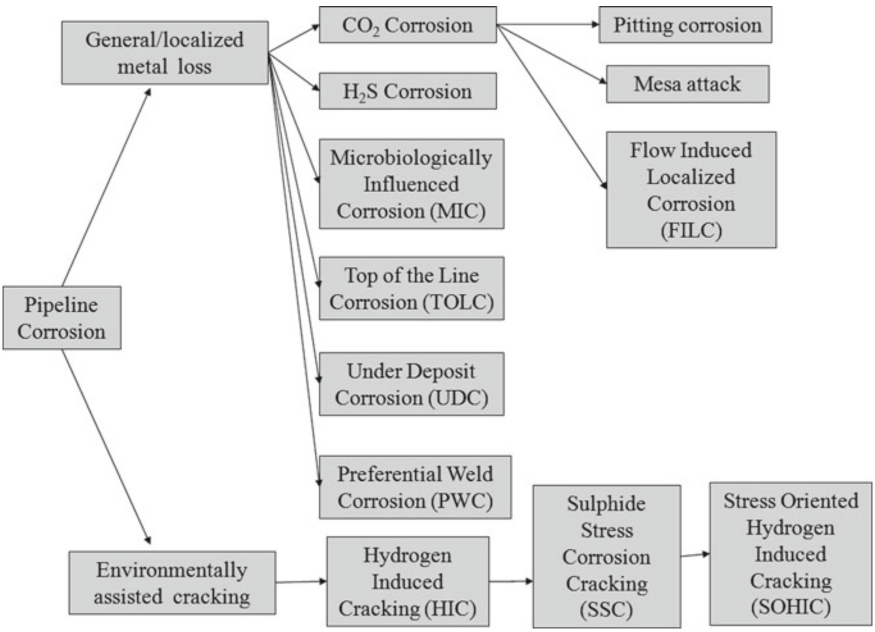


Fig. 7.2 Different types of pipeline corrosion

CO_2 Corrosion: The corrosion influenced by the presence of carbon dioxide is called sweet corrosion which creates a localized mode of failures in hydrocarbon transportation pipelines. In CO_2 corrosion, there is metal loss from the pipeline surface due to the anodic dissolution. The mitigation of this type of pipeline corrosion can be possible by providing sufficient corrosion allowance at the design stage which can compensate for the rate of thinning of the pipeline. CO_2-induced corrosion is divided into three different types of corrosion, i.e. pitting corrosion (due to low flow velocity of fluid), mesa attack (due to low to medium flow velocity of fluid), and flow-induced localized corrosion (due to high flow velocity of fluid) [11]. Figure 7.3a, b shows the pitting corrosion and mesa attack of the pipeline. A mesa attack might occur when the corrosion coatings do not provide full protection to the pipeline. This kind of corrosion is characterized by a local attack that is deep, and frequently flat-bottomed. The progression of this kind of corrosion and the processes underlying the beginning and growth of mesa corrosion attacks have not yet been thoroughly described due to the difficulty in observing the development of mesa attacks [12].

H_2S corrosion: Hydrogen sulphide (H_2S) are present in the hydrocarbon oil and gas known as sour hydrocarbon systems. H_2S easily dissolves in water or moisture present in the oil/gas and breaks into H^+. In this way, the anodic dissolution of iron is increased by capturing more electrons and causes hydrogen evolution due to a cathodic reduction reaction [13]. H_2S corrosion is shown in Fig. 7.4.

Microbiologically Influenced Corrosion (MIC): Microbiologically influenced corrosion (MIC) happens when microorganisms can cause for corrosion process in the metal. MIC in the oil and gas pipeline occurs as localized corrosion as shown in Fig. 7.5. It happens due to the stagnant conditions of fluid inside the pipeline for a long time in the pipe and/or metallic oil and gas pipeline networks are exposed to water or soil [15]. Oil and gas are hydrocarbons which have a large amount of carbon source for a wide variety of microbes like bacteria, archaea, and Eucarya. These are the main reason for MIC. Some chemicals are responsible for the corrosion in the pipeline which is produced by microbial activities like iron-oxidizing bacteria (IOB),

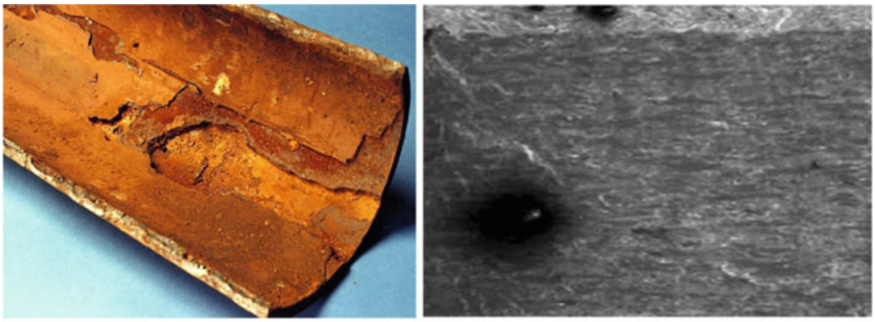

(a) (b)

Fig. 7.3 Pitting corrosion (**a**), mesa attack (**b**) [14] (Open access)

Fig. 7.4 H2S corrosion [13] (Open access)

Fig. 7.5 Microbiologically Influenced Corrosion [14](Open access)

sulphate-reducing bacteria (SRB), acid-producing bacteria (APB), and iron-reducing bacteria (IRB) [16].

Top of the Line Corrosion (TLC): Top of the line corrosion (TLC) is internal corrosion of the natural gas pipeline only where the upper portion of the inside surface of the pipeline is corroded as shown in Fig. 7.6. This corrosion happens when there is wavy-stratified low flow velocity (<3 m/s) of natural gas and existence of liquid and gas phase consist of water vapour and CO_2 [2]. The absence of an inhibitor is also responsible for TLC. The main reason for the TLC in the pipeline is heat exchanged between relatively warmer the pipeline surface and the colder surrounding medium resulting in condensation of water vapour containing corrosive gases like CO_2, H_2S, and acetic acid. Water vapour with high CO_2 is referred to as sweet TLC and water vapour with high H_2S concentrations is known as sour TLC [17]. Usually, this corrosion can be prevented by eliminating water vapour from natural gas and station; providing corrosion allowance; providing thermal insulation on the tube, etc. To remove moisture, the natural gas from oil fields is processed in dehydration units before injecting in cross-country pipelines for long-distance transportation.

Under Deposit Corrosion (UDC): Under deposit corrosion is another problem of the oil and gas pipeline which is responsible for the catastrophic failure of the pipeline. It occurs on the inside wall of the pipeline when the flow velocity is on the lower side.

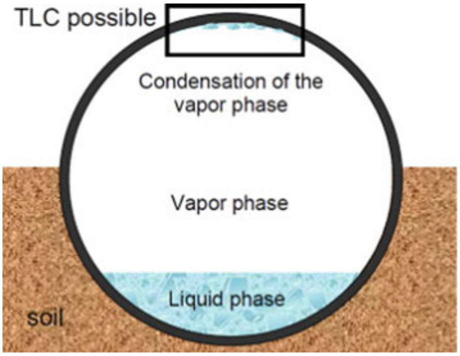


Fig. 7.6 TLC formation on the top of the pipeline [18]. Copyright 2021. Reproduced with permission from Elsevier

Underneath deposits of sludges and scales are formed due to stagnant pipe or during plant shutdown or in dead legs conditions where flow conditions are low [19]. The underneath deposit is the main reason for microbial growth. The difference in pH also aids in rapid microbiological growth corrosion in the pipeline. These deposits are organic deposits (biofilms, bacterial growth, etc.), inorganic deposits (silica sand, clays etc.), and mixed deposits (scales and biomass clays, iron, waxes, asphaltenes, hydrocarbon, etc.). Failure of the pipeline due to UDC and its mechanism is well described by Pandarinathan et al. [20].

Preferential Weld Corrosion (PWC): Preferential weld corrosion (PWC) occurs in the weld metal and heat-affected zone (HAZ) of the pipeline where welding is adopted during the fabrication of the pipe. The weld area is encountered with high flow conditions, high temperature, or corrosive environments; at this time, PWC will happen. Weldment metallurgy plays important role in PWC. Hence, researchers have tried to find the most effective way to control the PWC. Mahajanam et al. [21] have observed that the weld metal resistance against PWC can be effectively increased by a small amount of addition of elements like Mo, Cr, V, Nb, Ti, and Ni into fillers and electrodes.

Environmentally assisted cracking: Wet H_2S conditions are the main reason for stress-oriented hydrogen-induced cracking (SOHIC), hydrogen-induced cracking (HIC), hydrogen blistering, and sulphide stress cracking (SSC) [22]. Hydrogen-induced cracking is described in three steps, i.e. hydrogen generation (due to hydrogen evolution reaction at the steel surface, hydrogen is generated which is adsorbed in this step), hydrogen diffusion (hydrogen atoms desorbs from the steel surface and diffuse into the steel), and hydrogen accumulation (hydrogen atoms inside the steel will diffuse to hydrogen traps which increases the internal pressure leading to crack). Hydrogen embrittlement causes brittle fracture of the pipe when the pipe lost its strength and ductility due to the entry of atomic hydrogen into the metal lattice [23]. Sulphide stress cracking is another variety of hydrogen stress cracking which is seen in the pipeline due to the embrittlement of the pipeline metal by atomic hydrogen formed by the cathodic reaction in sour media. Stress-oriented hydrogen-induced cracking can be seen only in carbon and low alloy steels. Generally, this corrosion is the combined effect of external tensile stress and local strain in the region of the hydrogen-induced cracking. The hydrogen-assisted cracking (HAC) degrades the mechanical and microstructural properties of the steel pipeline more when both stress corrosion cracking and hydrogen embrittlement occur in the pipeline [24].

Normally, the internal coatings are preferred if the sour crude/gas is to be transported (with sulphide content of more than 500 ppm). Internal coating is also preferred in high-pressure gas pipelines with diameters of 18 inches or more. This is intended to avoid internal erosion at a high flow rate. Otherwise, pipeline internal corrosion is usually controlled with the introduction of corrosion inhibitors along with the oil/gas being transported.

7.1.2.2 External Corrosion

External corrosion has various forms described in the literature such as: (1) stress corrosion cracking (SCC); (2) microbiologically induced corrosion (MIC); (3) corrosion fatigue (CF); and (4) weld corrosion (WC) [25]. Underlying oil and gas pipelines are generally encountered with stress corrosion cracking (SCC) which is appeared on the external surface of the pipeline due to the combined effect of tensile loads and various surrounding environments [26]. These may be the high pH value of the surrounding environment. Figure 7.7 shows the factors influencing the SCC in the pipeline.

Most of the cross-country pipelines and the steel pipelines of the city gas distribution system are laid underground. The properties of the soil vary across the length of the pipelines. The soil surrounding the pipeline may be loose or soft soil or hard mud, hard rocks, sand alone, or wet sand containing minerals. These pipelines also pass through rivers, canals, coastal areas having marshy lands, brackish water, or sometimes pass through the sea, and so forth. Due to the inherent corrosive properties of the surrounding soil, protection of the external surface from corrosion is the major challenge. Carbon steel pipelines of various grades are prone to surface thinning, pitting, stress corrosion or microbiological corrosion. Weld corrosion occurs in both the internal and external of the pipeline due to the action of the corroding environment. To minimize weld corrosion, corrosion inhabitation is the best option.

The microbiological corrosion which is caused by the presence of sulphate reducing bacteria (SRB) in the surrounding is one of the serious corrosion problems resulting in faster thickness loss [27]. These SRBs convert sulphate compounds present in the soil to their sulphides, and these sulphides in turn attack the steel surface, resulting in pitting and loss of pipeline strength. Coating the pipeline metal surface with external corrosion-resistant material has been the common corrosion mitigation method. The pipeline coating deteriorates with time due to a corrosive environment and other external factors. Four phases may be used to categorize the performance of a typical barrier coating commencing in the intact state: commencement, active, active/passive, and growth/propagation as shown in Fig. 7.8 [29]. The coating failure may be attributed to improper coating material selection, improper coating application method, possible damages during laying, coating material quality

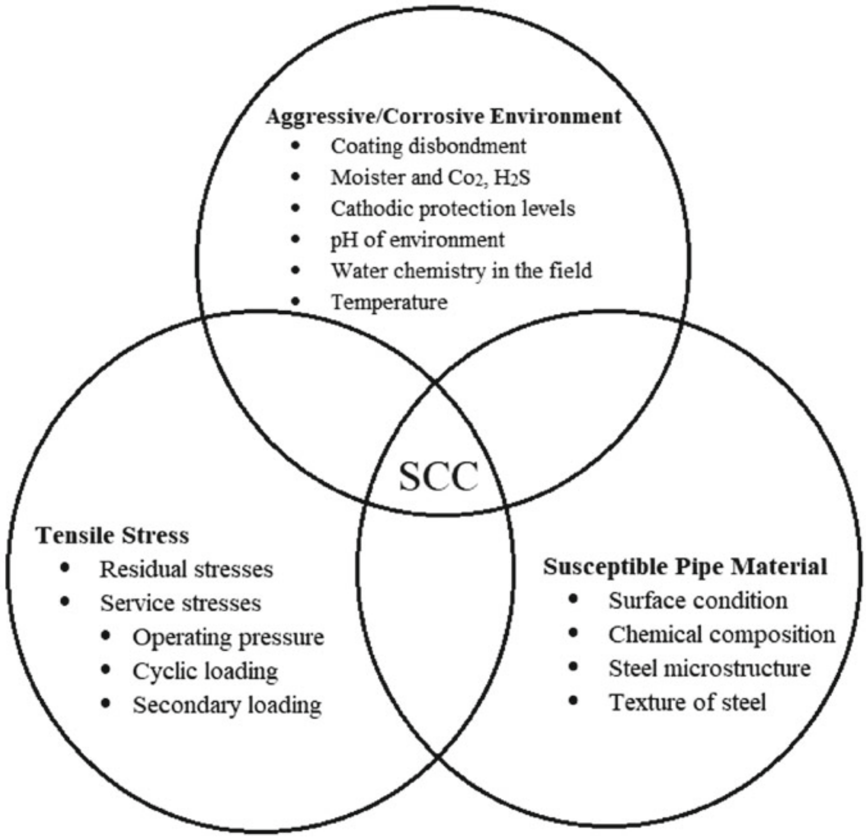


Fig. 7.7 Influencing factor of stress corrosion cracking in the pipeline [28] (Open access)

issues and due to ageing, Hence, in underground pipelines, the external coating alone cannot be sufficient for corrosion protection of pipelines. Additional protection is essential to compensate for this gradual coating degradation for ensuring the long service life of the underground pipelines. Cathodic protection is the most common tool for external corrosion protection. Hence, a complete pipeline protection system comprises a suitable selection of the steel quality, proper coating formulation, surface conditioning for coating, sufficient thickness of coating application, and a cathodic protection system.

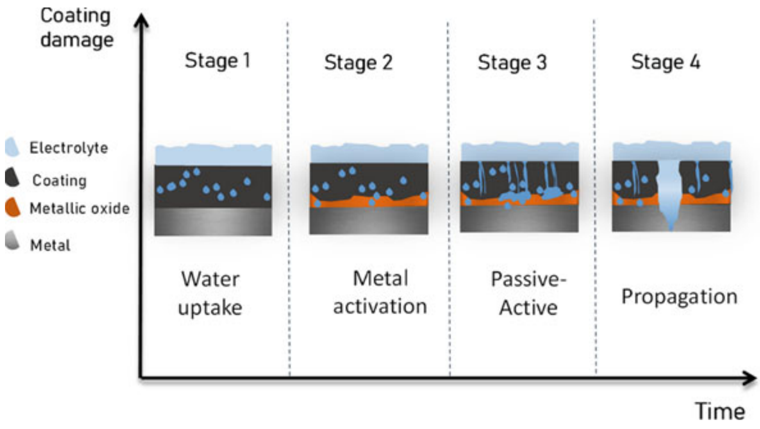


Fig. 7.8 Metal disintegration results from damage progression from intact coating conditions [29] (Open access)

7.2 Methods for Controlling External Corrosion

7.2.1 Painting/Coating of Underground Pipelines

Coating types have been classified into three categories as shown in Fig. 7.9 for ease of understanding and to illustrate any technological advancements that may have occurred in the field of pipeline coatings [30].

(i) First-generation coatings—tapes, coal tar enamel (CTE), heat shrink sleeves (HSSs), asphalt, two-layer PE, single-layer PE
(ii) Second-generation coatings—single-layer fusion-bond epoxy (FBE), multi-component liquid (MCL) coatings
(iii) Third-generation coatings—three-layer polypropylene and three-layer polyethylene—dual-layer FBE.

7.2.1.1 Coal Tar Enamel

Coal tar enamel (CTE) coating is in use for corrosion control of buried pipelines and subsea pipelines for several decades [31]. It is easy to apply on the pipeline surface, low in cost, compatible with available cathodic protection systems and has a useful corrosion prevention record of many decades. This coal tar coating has less affinity to moisture absorption, has excellent resistance to soil chemicals and SRB attacks and has very less affinity for other hydrocarbons. The coal tar coating system consists of an inner primer, coal tar enamel coat and external glass fibre wraps. Over the years, this coal tar enamel coating system has been improved and developed into an advanced system of initial primers application, followed by various plasticized enamel grades and finally wrapped with superior strength resin-bonded glass

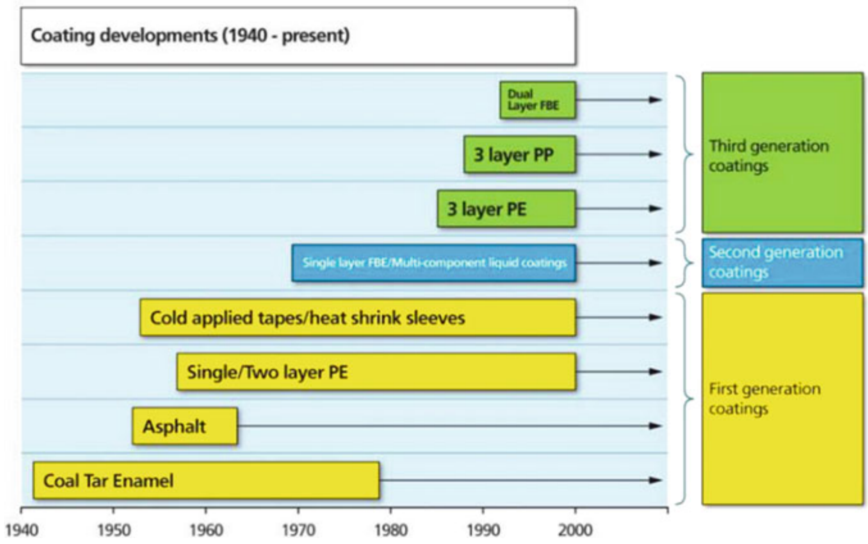


Fig. 7.9 Coating developments of first-, second-, and third-generation coating [30] (Copyright 2015. Reproduced with permission from Taylor & Francis)

fibre. The coal tar pitch obtained from coke oven gas purification units normally comprises polynuclear aromatic heterocyclic stable hydrocarbon compounds. The fillers and coal addition to enamel further improved flexibility and increase coating strength. The strong molecular bonding of coal tar pitch results in exceptional resistance to bacteria and water absorption attacks. Improvements over the past decades have resulted in a sophisticated CTE coating with a wide service temperature range of -28 °C to 80 °C and have improved its bendability and handling characteristics [32]. While selecting the enamel and outer wrap grades, it is essential to consider the service temperature range, available ground conditions and their seasonal variations. Pipelines connecting offshore oil and gas-producing wells are normally concrete weight coated on top of corrosion-resistant coats to prevent their floating due to buoyancy. CTE coat provides a very good surface which is suitable for proper concrete adhesion. However, during the CTE coating application process, there is the emission of carcinogenic vapours which can be a serious hazard to the workers engaged in pipeline coating application. These vapours also have a harmful effect on the environment. Therefore, many countries in the Western world have banned the use of this coal tar as pipeline coating. However, this CTE coating is still in use though sparingly by pipeline operators.

7.2.1.2 Fusion-Bond Epoxy (FBE) Coatings

Out of the commercially available organic coatings materials, epoxies are well known for their strongest resistance to most of the corrosive constituents of soil like moisture, oxygen, and chlorides. Epoxies also have very low thermal conductivity and high dielectric resistance, hence working as very good insulators. These FBE coatings adhere firmly to mild steel pipeline surfaces, possessing excellent bond strength and significantly increasing the service life pipelines by providing consistent performance throughout the life span. Being a thermosetting polymer, epoxy compounds are cross-linked and, once hardened, cannot be melted again. Epoxies are preferred when the surrounding soil is highly corrosive and strong corrosion resistance is the governing factor in selecting the coating [33]. These coatings also possess excellent cathodic disbandment resistance and have good flexibility at −50 °C [2]. The other advantages of FBE coating are convenience in spraying, minimal pollution in the application process and excellent tolerance in high-temperature (−40 to 85 °C) service. These epoxy coatings can be applied on the pipeline surface in a variety of methods like brushing, spraying, applying liquid epoxies, or electrostatically fine epoxy powder spraying on a heated pipe surface thereby melting instantly and setting immediately.

The three major factors determining coating quality are the pipeline surface preparation, uniform heating, and allowing sufficient curing. The surface preparation involves blast cleaning to achieve desired roughness, followed by uniform heating in an induction furnace. The temperature of the pipe surface is generally 180 to 210 °C [2]. Upon achieving the desired temperature, FBE powder is sprayed on the heated pipeline surface by electrostatic spraying technique, melting and fusing on the surface instantly. The coated pipe is quenched instantly. The FBE coating thickness is governed by the pressure of epoxy on the powder, applied electrostatic voltage, and speed conveyor belt. A coating thickness of 350–500 μm coating is desired for a pipeline with nominal diameter ranging from 8 to 36 inches. Fusion-bonded powder coating is used in cross-country transmission pipelines, while the smaller diameter gathering system pipelines are coated with a solution-type epoxy coating [2].

7.2.1.3 Multilayer Coatings

3LPE coating system: The major disadvantage of a thin-coated pipe is its susceptibility to damage during transportation and handling. FBE coatings also do not have good resistance to mechanical strain and humid conditions. To deal with such flaws in FBE coating, additional two coating systems were developed in the 1990s such as the dual-layer FBE system and the 3LPE system. The 3LPE coating system involves the application of 1500 to 3000 μm thickness extruded PE coating over the FBE primer layer of 100–150 μm [2]. The FBE surface does not directly adhere to the PE layer. Hence, an adhesive coat of polyolefin is applied in between, which remains the inner FBE primer layer by its polar functional groups and the outer PE layer by its hydrocarbon groups [4]. The desired temperature for coating the polyolefin adhesive layer is 220 °C and that of PE layers is 238 °C [2]. These two coatings should also be applied within a very short time gap of 13–25 s.

Dual-layer FBE coating system: In dual-layer FBE coating, the outer FBE coat and the inner FBE primer layer are different in composition. The inner FBE layer composition is selected with strong adhesive properties with that of the steel surface. The outer layer composition is selected to have very high toughness and excellent impact resistance. The method of application of dual-layer FBE coating is the same as single FBE coating, and coating is applied in a single coating booth. Both the FBE layer powders are fed to two different guns placed in tandem, to ensure that the outer layer FBE powder is sprayed immediately following the inner layer powder spraying on the surface but before the inner layer is gelled. 250 μm thickness of the inner layer is preferred and the outer layer thickness is varied in proportion to the diameter of the pipe, with 250 μm thickness for pipelines diameter ranging from 8 to 22 inches. For larger diameter pipelines (diameter >22 inches) outer FBE layer of 350 μm thickness is preferred.

In addition to these, several other coatings systems are used for buried pipelines based on specific service requirements. In pipelines operating at higher-temperature, polypropylene (PP) coating is applied instead of polyethylene (PE). Other types of coatings such as polyurea coatings, liquid epoxy coatings, and polyurethane coating in form of tapes or wrappers are occasionally applied to the underground pipeline. These coatings are generally used in pipeline rehabilitation and repairing jobs and on girth welds. Table 7.1 shows the summary of external pipeline coating.

7.3 Internal Coating of Pipelines

The aim of applying an internal coat to the oil and gas pipelines is to reduce pipeline internal corrosion rate and low friction factor thereby improving the flow rate and minimizing sludge or sediments deposit on the internal surface. The internal coat material can be fusion bonded epoxy (FBE), glass flake coatings or polyethylene (PE). FBE anti-corrosion powder coating can be used for moderate service temperatures up to 80 °C. In case of higher service temperature requirements, special FBE grades like TK-216 and TK-236 are used for temperatures up to 95 °C and120 °C, respectively, for internal surface coating [34].

The internal coating process starts with surface preparation and is cleaned by sort blasting to achieve surface roughness of 50 to 100 microns for proper adhesion of the coat. External heat is applied through induction heating for achieving a surface temperature of 180 to 250 °C. The epoxy coat is applied to the heated surface with a spraying gun. The pipeline is rotated around the longitudinal axis, and the spray gun moves along the length of the pipe at a uniform speed spraying the epoxy power on the steel surface. This epoxy melts when contacts the heated surface and gets cross-linked due to heat and hardens forming a uniform coat on the pipeline. Thus, this process is called ‘fusion bonding’ of epoxy or FBE.

Table 7.1 External pipe coating technologies [33] (Copyright 2017. Reproduced with permission from Elsevier)

Coating	Max temperature	Benefit	Disadvantage
FBE	90 °C (194 °F)	• FBE is more flexible than other coatings, meaning pipes can be bent after coating in the filed • Excellent adhesion to steel • Is able to pass catholic protection (CP) current eliminating CP shielding • Cures instantly	• Not as mechanically robust as 3LPE • Pipe must be heated
2LPE	60 °C (140 °F)	• Cheap Effective coating	• Low temperature resistance
3LPE	90 °C (194 °F)	• Damage tolerant, water impermeable coating • Respectable temperature resistance	• Susceptible to catholic shielding
3LPP	140 °C (284 °F)		
Liquid epoxy	~150 °C (302 °F)	• Tends to be a wider range of chemistries available to suit different roles (e.g.; epoxy, polyurethane, etc.) • Usual for field repairs	• Pipe generally bent before coating • Cure is sensitive to temperature and humidity • Very long cure times
Viscoelastic	80 °C (194 °F)	• Excellent corrosion resistance • Excellent cathodic disbondment resistance • Self-healing properties • High tolerance to underprepared surfaces	• Maintenance problematic • Limited temperature

7.3.1 Internal Coating of Operating Pipelines

This internal coating process has evolved over the years to technological developments in the field. Now, a new process has been developed for the internal coating of the pipelines which are already in operation or in-line repairing of internal coatings without stoppage of the pipeline operation. The process is unique in that pipeline pigs are used to remove the deposits on the pipeline's internal surface thereby cleaning it and applying the epoxy coat on the entire length of new and old pipelines in situ, thus helping in rehabilitating up to 20 miles of pipe without segregating the segments. The only access is from the dispatch and the receipt stations of the pipeline. This pig is specially designed with a combination of various tools meant for cleaning, data acquisition, heating, coating, etc. The pipeline remains in the trench during coating. This in situ coating process though very complex can eliminate downtime, increase the flow rate due to reduced friction, and significantly extend the service life of the pipelines.

7.4 Corrosion Prevention by Cathodic Protection

Cathodic protection (CP) is the most common electrochemical corrosion prevention technique used in underground steel pipelines, where the applied external anti-corrosion coating has failed or eroded thereby exposing the bare pipeline metal surface to the surrounding corrosive environment. It has an anode in the electrolyte to build a circuit. The main objective is to protect the surface of the structure when current flows from the anode through the electrolyte to the surface. Corrosion load goes to the anode and prevents corrosion of the system. This method has been in use since the 1930s but over years has evolved into one of the most effective corrosion mitigation measures. Two basic methodologies of the CP system are galvanic type and impressed current type. Figure 7.10a, b shows the galvanic cathodic protection and impressed current cathodic protection.

7.4.1 Galvanic Cathodic Protection

In galvanic cathodic protection, external anodes also called sacrificial anodes are attached to a shielded structure in a circuit. These anodes' inherent potential is more adverse than the potential of the structure. The cathodic protection current flows from the sacrificial anode to the pipeline surface. Magnesium and zinc are normally used as anodes in galvanic CP systems. These anodes should be suitably sized to be commensurate with the pipeline service life. If properly installed, galvanic anodes can protect underground steel pipelines from corrosion. Additionally, such anodes can have a long life, and they are easier to install and do not want an outside power source to work. Galvanic anodes are available in different varieties, like bare metal anodes of zinc, magnesium, and aluminium, backfill packaging for underground use, steel straps for external mounting on metallic structures, ribbon types, etc. However, such galvanic cathodic protection application in cross-country pipelines is limited in use.

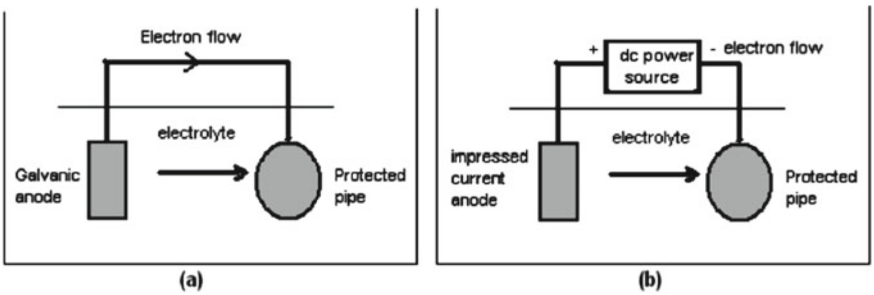


Fig. 7.10 Galvanic cathodic protection (**a**) and impressed current cathodic protection (**b**) [35]. (Open access)

7.4.2 Impressed Current Cathodic Protection

In the impressed current system, an external electrical DC power source is used to create the required potential difference and make the pipeline surface electronegative to minimize metal loss. Impressed current CP stations are installed across the length of the pipeline which houses the DC power supply station, anode ground bed, and associated facilities for the CP system. Maintaining pipeline electrical continuity is essential for an impressed current CP system which enables unimpeded electric current flow along the pipeline. In case of parallel underground pipelines are running in the same pipeline corridor, these pipelines should not be electrically bonded below the ground level and provision should be made for separate connections for CP electric supply for individual pipelines. In the cathodic protection (CP) system, when applied current flows from the anode to the underground pipeline surface being protected, the pipeline's electrical potential will be shifted to more electronegative. These anodes are more prone to corrosion, bearing the load of the corrosion to protect the buried pipe. Applied current flows from the anode bed to the pipeline, thereby protecting it from rapid corrosion. The system is normally separated from above-ground pipeline facilities by insulation joints.

In cathodic protection (CP) system, the CP-induced electrical potential shift is called polarization. The quantum of such polarization is an indication of the CP's current efficacy. Once sufficient polarization is achieved, the pipeline is presumed to be adequately cathodically protected. The actual time required to fully polarize an underground pipeline varies with the material of construction and surrounding soil properties. However, there have been instances of taking weeks to fully polarize a pipeline to the desired level.

7.4.3 Factors Governing Cathodic Protection System Design

The cathodic protection system of an underground pipeline is designed considering the pipeline length, coating thickness, soil properties like the type of soil (clay, sand, etc.), soil corrosive potential, soil resistance to electrical current flow, water table characteristics, and anticipated interference from a high-tension electric line, other pipeline crossings or parallel running pipelines [36]. These influence the quantum of electrical current flow and voltage required for the CP system.

7.4.4 Components of a Cathodic Protection System

The major components comprising the CP system are as under:

- Anode ground beds
- Rectifiers for conversion of AC to DC

- Test leads
- Conductive materials.

7.4.5 Cathodic Protection Monitoring Philosophy

The cathodic protection test leads are provided at various locations across the length of the pipeline. These are the pre-determined monitoring locations for periodic measurement of the voltage levels at regular intervals for monitoring the effectiveness of the CP system. These CP test leads are attached to the pipeline with a gap of about 1.5 kms and are normally installed near the pipeline crossings where the pipeline passes under highways, water bodies, rivers, canals, railway lines, public roads, or crosses other existing pipelines. In urban areas, the test leads should be installed at an interval of one kilometre [37].

Several methods are in use for monitoring the effectiveness of cathodic protection. Those are listed under [38].

(a) Monitoring of power supply module current and voltage
(b) Survey of pipeline to soil potential
(c) Closed interval potential logging (CIPL) review
(d) AC and DC interference survey at electric transmission line crossings and pipelines running close to high tension lines, other pipeline crossings, etc.
(e) Pipeline coating health surveys (current attenuation test, direct current voltage gradient survey and alternating current voltage gradient survey).

There are two major performance criteria per international standards for ensuring the effectiveness of the CP system [38].

(i) Requirement of 100 mV of polarization: This is also widely called the 100 mV shift criteria. The potential of the underground pipeline is calculated without the CP system and again measured after switching on the CP system allowing a sufficient period for polarization. The CP system is thought to be impacted if the potential difference exceeds 100 mV.
(ii) The 850 mV off potential criteria: This criterion needs a higher negative than the −850 mV potential of the system after accounting for all current sources.

During the pipeline laying phase, temporary cathodic protection (TCP) is given till a permanent CP system is operationalized. TCP is simultaneously installed keeping pace with the pipeline laying. Periodic monitoring of this temporary cathodic protection is also essential during the laying period. A permanent CP system should be put into use within one year of pipeline operation. Desired life of the permanent CP system should be adequate to serve throughout the pipeline service life. However, subsequent augmentation of the CP system should be taken up based on its effectiveness.

This impressed current CP system is normally not preferred for highly viscous crude oil pipelines which are electrically traced to maintain the temperature required for maintaining the flow of crude oil and prevent congealing.

7.5 Health Assessment of the Pipelines

The widely used tools for integrity assessment of the cross-country pipelines are In-Line Inspection pigging [39], Hydro or Pressure Testing of In-service Pipelines [40], Direct Assessment tools like External Corrosion Direct Assessment (ECDA) [41], Internal Corrosion Direct Assessment (ICDA) [42], and Stress Corrosion Cracking Direct Assessment (SCCDA) [43]. The pipeline operator should employ at least one integrity assessment tool for the integrity management of the pipeline. The baseline data should be generated during the initial operation of the pipeline and the same shall be compared with the observed values throughout the service period of the pipeline for identification of the potential failure. The fibre optic method is an important method of health assessment of pipelines when the pipeline is under earthquake-induced area [44]. Figure 7.11 shows a complete flow chart for a pipeline integrity management program for in-line inspections. Pipeline pigging is an important method of introduction of the devices known as 'pigs' to the flow path along the follow of service fluid for performing various activities like cleaning, internal inspection, facilitating repair and maintenance, measuring the internal dimension or deformation, and pipeline testing operations. Pigging is used both in new pipelines and existing pipelines. These 'pigs' are constructed of different materials such as polyurethane open cell foam, cast polyurethane, and rubber and are used in different configurations depending on the task to be performed. In near pipelines pigging is done for cleaning to measure internal dimensions and generate baseline data. In operational pipelines, pigging is usually performed along with the product flow thereby saving valuable downtime.

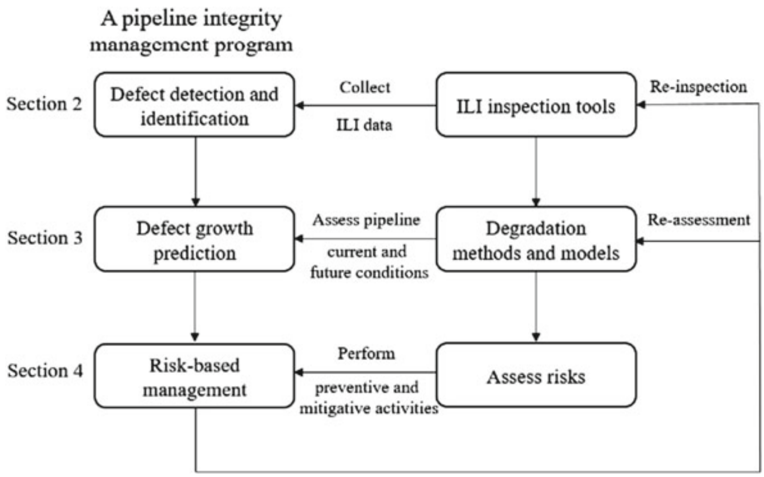


Fig. 7.11 Flowchart for a pipeline integrity management program [45]. (Copyright 2018. Reproduced with permission from Elsevier)

7.6 Conclusions

Pipeline transportation of petroleum/natural gas today involves greater challenges and the potential solutions to these problems are multi-disciplinary in nature. The maintenance and upkeeping of the pipelines require huge recurring expenditures. The pipeline's safety, long service life, design and integrity of pipelines, materials of construction of steel, health monitoring, maintenance, internal flow characteristics of the fluid, and corrosion management of the pipeline are of utmost importance. The present paper has drawn the following conclusion on corrosion protection practices of oil and gas pipeline and their integrity management challenges.

- Corrosion is a serious issue in the oil and gas pipeline. Corrosion in buried steel pipelines is inevitable due to prevailing surrounding conditions and the impurities in service fluid. Corrosion in steel pipelines cannot be stopped completely but its growth can be reduced significantly.
- 3LPE coating is more suitable for underground pipelines. For higher temperature service another suitable coating like 3PP may be preferred. Every coating has functional life; after this period, the coating efficiency is degraded. Suitable repairing and rehabilitation of coating may be required to extend the pipeline service life.
- In gas pipelines, it is very important to avoid impurities like moisture, H_2S, CO_2, etc. for preventing corrosion. Hence, the gas composition is required to be monitored regularly by online analysers and periodic testing.
- The integrity of the cross-country pipelines is assessed using different tools like integrity assessment of the cross-country pipelines are In-Line Inspection pigging, Hydro or Pressure Testing of In-service Pipelines, Direct Assessment tools like External Corrosion Direct Assessment (ECDA), Internal Corrosion Direct Assessment (ICDA), and Stress Corrosion Cracking Direct Assessment (SCCDA).
- Integrity assessment tools and methodologies are developing rapidly. Hence, it is important to develop and regularly update the competency of operating and maintenance personnel to keep them abreast with the latest technologies and deploy suitable monitoring tools for ensuring the long service life of pipelines.

7.7 Future Scope

- The challenges for the operators are to be discussed while selecting the coating for corrosion protection of oil and gas pipelines.
- Discussions are required on electrical interference and cathodic protection shielding of different coatings.
- Discussions are needed on the construction, commissioning, and service of pipelines.

- The corrosion resistance of the pipeline through pigging and inhibitors should be the future work.

References

1. Fernando Mainier, B., Leta Fabiana, R., Feliciano Flávio, F.: Application of anticorrosive techniques compatible with the environment to engineering education. Am. J. Environ. Eng. **4**(6), 176–181 (2014)
2. Groysman, A.: Corrosion problems and solutions in oil, gas, refining and petrochemical industry. Koroze a ochrana materiálu **61**(3), 100–117 (2017)
3. Ossai, C.I., Boswell, B., Davies, I.J.: Pipeline failures in corrosive environments–a conceptual analysis of trends and effects. Eng. Failure Analysis **53**, 36–58 (2015). https://doi.org/10.1016/j.engfailanal.2015.03.004
4. https://www.worldofchemicals.com/media/oil-gas-corrosion-protection-underground-pipeline-protection-strategies/967.html
5. Kumar, N.: 15-Organic coatings for underground pipelines, In: Khanna, A.S. (eds.) Woodhead Publishing Series in Metals and Surface Engineering, High-Performance Organic Coatings, Woodhead Publishing, pp. 307–336 (2008), https://doi.org/10.1533/9781845694739.3.307
6. Jena, H., Das, T., Kumar, A.: Study of transportation prospects and safety regulations of hydrogen in Indian context: a green fuel for greener future. Mater. Today Proc. (2022). https://doi.org/10.1016/j.matpr.2022.05.481
7. Nesˇic, S.: Key issues related to modelling of internal corrosion of oil and gas pipelines–a review. Corros. Sci. **49**, 4308–4338 (2007)
8. Sotoodeh, K.: Analysis and improvement of material selection for process piping system in offshore industry. Am. J. Mech. Eng. **6**(1), 17–26 (2018)
9. Zhao, R., Huang, Y., Yu, Y., Guo, S.: An IVTIFN–TOPSIS based computational approach for pipe materials selection. Appl. Sci. **9**(24), 5457 (2019). https://doi.org/10.3390/app9245457
10. Askari, M., Aliofkhazraei, M., Afroukhteh, S.: A comprehensive review on internal corrosion and cracking of oil and gas pipelines. J. Nat. Gas Sci. Eng. **71** (2019) https://doi.org/10.1016/j.jngse.2019.102971
11. Kermani, M.B., Morshed, A.: Carbon dioxidecorrosion in oil and gas production-A compendium. Corrosion **59**(8), 659–683 (2003)
12. Nyborg, R.: Initiation and growth of mesa corrosion attack during CO_2 corrosion of carbon steel. Paper presented at the CORROSION 98, San Diego, California, March (1998)
13. Chong, T.V.S., Kumar, S.B., Lai, M.O., Loh, W.L.: Effects of wet H2S containing environment on mechanical properties of NACE grade C-Mn steel pipeline girth welds. Eng. Fracture Mech. **131**, 485–503 (2014)
14. Popoola, L.T., Grema, A.S., Latinwo, G.K., Gutti, B., Balogun, A.S.: Corrosion problems during oil and gas production and its mitigation. Int. J. Indus. Chem. **4**(35), 3–15 (2013)
15. Skovhus, T.L., Eckert, R.B.: Practical Aspects of MIC Detection, Monitoring and Management in the Oil and Gas Industry. Corrosion (2014) paper no. 3920 (Houston, TX: NACE, (2014)
16. Papavinasam, S.: Corrosion Control in the Oil and Gas Industry, 1–992 (2013).
17. Al-Moubaraki, A.H., Obot, I.B.: Top of the line corrosion: causes, mechanisms, and mitigation using corrosion inhibitors. Arab. J. Chem. **14**(5), (2021). https://doi.org/10.1016/j.arabjc.2021.103116
18. Singer, M., Camacho, A., Brown, B., Nešić, S.: Sour top-of-the-line corrosion in the presence of acetic acid. Corrosion 67 (2011). https://doi.org/10.5006/1.3615805
19. Obot, I.B.: Under-deposit corrosion on steel pipeline surfaces: mechanism, mitigation and current challenges. J. Bio-and Tribo-Corros. **7**(49) (2021). https://doi.org/10.1007/s40735-021-00485-9

20. Pandarinathan, V., Lepková, K., Bailey, S.I., Gubner, R.: Impact of mineral deposits on co_2 corrosion of carbon steel. In: NACE International (2013)
21. Mahajanam, S.P.V., Joosten, M.W.: Guidelines for filler-material selection to minimize preferential weld corrosion in pipeline steels. SPE Projects Facil. Constr. **6**(1), 5–12(2011)
22. https://era.library.ualberta.ca/items/8f15c351-90f2-4805-9e34-08edb85cc928/view/04b03c58-311e-49e2-a36b-65c500350c3e/Gawor_Steffen_201909_MSc.pdf. Access 12 July 2022
23. Papavinasam, S.: Chapter 5-mechanisms. In: Papavinasam, S. (ed.) Corrosion Control in the Oil and Gas Industry, pp 249–300. Gulf Professional Publishing (2014). https://doi.org/10.1016/B978-0-12-397022-0.00005-4.
24. Khoma, M.S., Vasyliv, K.B., Chuchman, M.R.: Influence of the hydrogen sulfide concentration on the corrosion and hydrogenation of pipe steels (a survey). Mater. Sci. **57**, 308–318 (2021). https://doi.org/10.1007/s11003-021-00546-x
25. Wasim, M., Djukic, M.B.: External corrosion of oil and gas pipelines: a review of failure mechanisms and predictive preventions. J. Nat. Gas Sci. Eng. 100 (2022). https://doi.org/10.1016/j.jngse.2022.104467
26. Cheng, Y.F., Niu, L.: Mechanism for hydrogen evolution reaction on pipeline steel in near-neutral pH solution. Electrochem. Commun. **9**(4), 558–562 (2007). https://doi.org/10.1016/j.elecom.2006.10.035
27. Nagu, M., Rajasekar, A., Ponmariappan, S., Mohanan, S., Maruthamuthu, S., Muralidharan, S., Subramanian, P., Palaniswamy, N., Raghavan, M.: Microbiologically influenced corrosion in petroleum product pipelines-A review. Indian J. Exp. Biol. **41**, 1012–1022 (2003)
28. Mohtadi-Bonab, M.A.: Effects of different parameters on initiation and propagation of stress corrosion cracks in pipeline steels: a review. Metals **9**(5), 590 (2019). https://doi.org/10.3390/met9050590
29. Kim, C., Chen, L., Wang, H., Castaneda, H.: Global and local parameters for characterizing and modelling external corrosion in underground coated steel pipelines: a review of critical factors. J. Pipeline Sci. Eng. **1**(1), 17–35 (2021). https://doi.org/10.1016/j.jpse.2021.01.010
30. Thompson, I., Saithala J.R.: Review of pipeline coating systems from an operator's perspective. Corros. Eng. Sci. Technol. **51**(2), 118–135(2016)
31. Yin, K., Yang, Y., Frank Cheng, Y.: Permeability of coal tar enamel coating to cathodic protection current on pipelines. Constr. Build. Mater. **192**, 20–27 (2018). https://doi.org/10.1016/j.conbuildmat.2018.10.123
32. Thompson, I., Saithala, J.R.: Review of pipeline coating systems from an operator's perspective. Corros. Eng. Sci. Technol. **51**(2), 118–135(2016)
33. Byrnes, T.: 24-Pipeline coatings, In: El-Sherik, A.M. (ed.) Woodhead Publishing Series in Energy, Trends in Oil and Gas Corrosion Research and Technologies, Woodhead Publishing, pp. 563–591 (2017). ISBN 9780081011058, https://doi.org/10.1016/B978-0-08-101105-8.00024-3
34. https://whatispiping.com/. Accessed 10 July 2022
35. Gundogdu, S., Sahin, O.E.M.I.: Effects of cathodic protection on electromagnetic flowmeters. Sensors **7**, 75–83 (2007). https://doi.org/10.3390/s7010075
36. Al-Hazzaa, M.I., Al-Abdullatif, M.O.: Effect of soil conductivity on the design of cathodic protection systems used in the prevention of pipeline corrosion. J. King Saud Univ. Eng. Sci. **22**(2), 111–116 (2010). https://doi.org/10.1016/S1018-3639(18)30498-7
37. https://law.resource.org/pub/in/bis/S10/is.8062.4.1979.pdf. Access 12 July 2022
38. https://pngrb.gov.in/eng-web/knowledge-sharing.html
39. Ma, Q. et al.: Pipeline in-line inspection method, instrumentation and data management. Sensors (Basel, Switzerland) **21**(11) (2021). https://doi.org/10.3390/s21113862
40. Adjogbe, S., Okoronkwo, C., Oguoma, O., Igbokwe, J., Okwu, M.: Investigation of the effect of hydrostatic pressure testing on the microstructure of carbon steel pipeline material. AASCIT J. Mater. **4**(3), 58–65 (2018)
41. van Os, M.T., van Mastrigt, P., Francis, A.: An external corrosion direct assessment module for a pipeline integrity management system. In: Proceedings of the 2006 International Pipeline

Conference, Volume 2: Integrity Management; Poster Session; Student Paper Competition. Calgary, Alberta, Canada, 25–29 Sept 2006, pp. 249–258. ASME. https://doi.org/10.1115/IPC2006-10159
42. Moghissi, O.C., Norris, L., Dusek, P.J., Cookingham, B.: Internal corrosion direct assessment of gas transmission pipelines. Paper presented at the CORROSION 2002, Denver, Colorado, April (2002)
43. Onuoha, C., McDonnell, S., Pozniak, E., Shankar, V., de Guzman, L.: Advancements in stress corrosion cracking direct assessment using an integrated approach. Paper presented at the CORROSION 2018, Phoenix, Arizona, USA, April (2018)
44. Glisic, B., Yao, Y.: Fiber optic method for health assessment of pipelines subjected to earthquake-induced ground movement. Struct. Health Monit. **11**(6), 696–711 (2012). https://doi.org/10.1177/1475921712455683
45. Xie, M., Tian, Z.: A review on pipeline integrity management utilizing in-line inspection data. Eng. Fail. Anal. **92**, 222–239 (2018). https://doi.org/10.1016/j.engfailanal.2018.05.010

Chapter 8
Role of Technology on the Management of Transportation

Richa Verma and Bipin Kumar Singh

Abstract Now a day's the traffic all over world is a major concern toward mitigation of accidents, which is growing day by day. Hence, an effort has been made to examine the degree of technology that is at the heart of traffic management systems and can be acceptable. Therefore, for the proper utilization of advanced systems or technologies, it is indeed to explore all possibilities that can be incorporated into the systems align with public transportation rather than only considering the moving of people from point A to point B. So, the utilization of various forms of communication media provides an additional viable option for enhancing the administration of transportation systems. Hence, in this article an attempt has been made to compile the evolution of transportation system and need of advanced systems alongside the challenges encountered during development of advance transportation system. Furthermore, an effective discussion that provides the grounds for adoption and fulfills the strategic goals of the companies that facilitates the users at high level of contentment with its performance. At last, a comprehensive discussion on the challenges those are associated with public, logistics, goods transportation alongside the solutions that are required for the future possibilities with expansion and acceptance. The discussion is also indeed for high number of people who take advantage of public transit, the regular issues that crop up can be frustrating not only for commuters but also for the businesses that are responsible for providing these services.

Keywords Transportation · Technology · Management · Acceptability · Satisfaction · Requirements

---

R. Verma
Department of Management, IIMT College of Engineering, Greater Noida 201310, India

B. K. Singh (✉)
Department of Mechanical Engineering, Sri Eshwar College of Engineering, Coimbatore, Tamilnadu 641202, India
e-mail: bipinkumarsingh@sece.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_8

8.1 Introduction

The limited resources at a place always pushed the human from one place to another in order to get food, work, social visit, peace, etc. The public movement should be fulfilled at cheaper rate for better societal growth. In this search public transport may provides high efficacy and cost-savings transportation as the fare is shared by every traveler [1]. Apart from public transport systems the management of goods is also point of concern for all developing nation which simultaneously grow. The economy of every nation is directly dependent on the transportation system. So, it is indeed to discussion all the transportation related management for better optimization of resources.

The transportation systems in any country are just like veins present in the body of human, which resembles the strength and power. So, the wealth and modernization of any nation is judged by its transportation system that plays a vital role in economy. The incessant improvement in transportation systems brings us on a stage where high utilization of software or automation is direly required. The researches dedicated on the improvement of transportation systems showed various possibilities toward the enhancement, but still many more to explore for better implementation of software or automation in the transportation system. In the transportation systems automation may be one of the feasible ways that mitigate the accidents and save the human life [2]. Therefore, the transit of human with safer journey is the prime target for any transportation company.

The successful implementation of public transport that gives profit was started in Florida 1888 with rail connectivity of 11 Miles [3]. Then after many rail transits were flourished for public transportation that had ability to lift heavy passenger loads. In modern public transportation transit, speed, proximity, comfort, safety, cost, directness, and timeliness [4] are the seven appeals that have to be considering before implementation. Later, some more modification was incorporated that compiles of safety, comfortable (not congested), nearby (easy to accesses), timely, direct, cheap, and fast [5]. The said factors are accompanied beautifully through modern software, targeted by various private sectors involved in transportation systems but yet there are several challenges toward implementation.

Hence, this study provides an in-depth discussion on the modernization of transport systems and potential of software by which the transportation system can be upgraded. The discussion also elaborately discussed the possible solution and obstacles in the path of modernization of transportation systems with seven appeals (safety, comfortable, nearby, timely, direct, cheap, and fast). This article also deeply elaborates the challenges and solution required for transportation of good through modern technique. Furthermore, the future scenario of advanced techniques may be implemented in the transportation system is discussed. Finally, a conclusive statement for need and importance of software in public as well as goods transportation are made.

8.1.1 Need of Advanced Transportation Management Systems

In logistic movement, transportation management systems are a crucial component of supply chains, due to the fact that they have an impact on every stage of the process (Profit). The stages of planning and procurement, as well as the stages of logistics and lifecycle management, are important toward optimization of supply chain system. So, in today's scenario the plan and carry out transportation operations were more successfully along with high visibility afforded by a computer-based robust system [6], which in turn leads to greater levels of customer satisfaction. As a consequence of this, a greater quantity of sales are accomplished, which is advantageous to the growth of businesses. It is absolutely necessary to have access to a system that can lend assistance in the negotiation of complex trade regulations and compliance procedures in the global trade environment in which we live and conduct business. Hence, a transportation management system, which is more commonly referred to as transportation management software, is a piece of computer software that is utilized to organize and manage the flow of people in addition to the movement of goods. This program can be found on most modern computers. It is possible for a transportation management system to ensure that your freight and commodities are delivered on schedule since the system gives visibility into daily transportation operations as well as trade compliance information and paperwork. With the support of transportation management systems, businesses are able to improve their capacity to manage and optimize their transportation operations. The networking created by various marketing companies also creates huge impact on the economy of nation. These companies used modern technologies to easy access of any freight or items from all over globe.

The first remarkable application of online public transportation through websites and mobile apps is started by ridesharing company in mid-1970 for public transportation [7]. This invention takes place to mitigate the energy as well as oil crisis. Later the idea of carpooling was popular among the college students which provide a booster to the invention. With these systems there are lots of problems like safety practices, congestion, dynamic pricing and price fixing allegations, accessibility failures, Biasness in picking the passengers. Among the said problems safety is prime factor which creates an obstacle for application. But in upcoming days GPS mandate tracking system overcome the problems. Then after there are many transportation companies obey the website and mobile app for transit of public from one place to other and demanding in today's scenario [8–10].

Transportation management systems are also being utilized by businesses in practically every industry like shipping, transporting, and receiving goods ranging from the construction industry to the medical area. Despite the fact that the majority of customers are other enterprises, cloud-based solutions have made it possible for smaller organizations to integrate a transportation management system into a supply chain at a lower cost.

The deployment of a transportation management system and the implementation of contemporary transportation management in general stand to be beneficial to businesses. The following are lists of some of the most important benefits that can be gained:

- Assists to minimize the required time and enhanced the durability.
- Increases profit margin for the company, with satisfaction of the consumer in the long run.
- The automation of company procedures, results in ease of billing and documentation with accuracy and productively.
- Practices in the supply chain that are uniform across all of the locations, modes, and carriers.
- An increase in both visibility and safety, with a special focus on the field of transportation.
- The stricter enforcement of limits placed on imports and exports has resulted in a reduction in the number of fines and shipping delays.
- The ability to track and trace the movement of freight on a single platform, both domestically and globally, regardless of its origin or destination.
- Improved reporting makes it possible for quicker reactions as well as process modifications, which eventually leads to new business insights.
- The ability to meet or exceed the delivery expectations of already established customers, which is a prerequisite for expanding the business.
- An rise in customer satisfaction can be attributed to an increased ability to provide customers with real-time information and faster deliveries.

Therefore, the above mentioned advantages attract many industries to start software-based logistics transportation for better customer satisfaction. Later, said ideas or invention provide birth of new logistics transportation system called as e-marketing or e-commerce. In current scenario the e-marketing or retail e-commerce sales are surpass $5 trillion, which is anticipated to cross $7 trillion by 2025 [11]. Such huge growths in the e-marketing systems are happened due to software-based transportation management [12].

Probably, the first e-commerce systems were started to sell cannabis through ARPANET among the students of Stanford Artificial Intelligence Laboratory and Massachusetts Institute of Technology [13]. After that the ideas of e-commerce was rapidly started by various industries to promote their business and product all over globe. The major revolution comes in 1995 by Jeff Bezos, launched a dedicated company name as Amazon to sales the product and probably the first company that announce annual profit through e-marketing. Now a day's, a numerous of companies were focused to sell their product through online mode, due to easy accessibility and proper management. The government of every nation also promoting the digital transaction that not only provides transparencies but also easy way of transferring the amount of product [14, 15]. Hence, there are many more to discussion on the benefits of e-commerce sales but this analysis only concentrate on the transport management. So, from above discussion it can be concluded that there are huge potential of software-based systems in the e-commerce systems for twenty-first century. These systems not only short comes the problems of accessibility at any place on the globe, but also enhance the transparency in the selling.

8.1.2 Challenges and Potential Remedies in the Realm of Public Transportation

Because of the large number of individuals who take advantage of public transportation, recurring issues can be extremely frustrating. These issues create trouble for both passengers and the businesses that are responsible for operating the various systems. Hence, the goal of public transportation is to fulfill a wider range of social and economic needs rather than just getting people from point A to point B. A review articles on the real-time transit information describing its benefits was published by Brakewood et al. [16]. The saving of time, security of passengers and choice to select the path were possible benefits that were obtained by using real-time transit sharing information. The articles also identifies two gaps, i.e., fluctuation in mind of rider by selecting different path, along with the cost benefits. Later researches also provide an beneficial effect with up gradation of the system and linking with the network [17–20].

The fact that so many people rely on public transportation as their primary method of moving around on a daily basis makes it more difficult to deal with the disruption in the transportation system when they occur. So, there are several issues that are connected to public transportation and propose some answers that are urgently required. These issues have been plaguing the industry for quite some time, that are service (consumers service that is above and above their expectations), easy to accesses, reliability (expectation to fulfill all desire on every ride), sources (Taking precautions to avoid being a victim of fraud), environmental issues.

8.1.3 Service (Consumers Service That Is Above and Above Their Expectations)

Customers in today's market have become accustomed to receiving prompt service and having access to information from all over the world at the touch of a button, all thanks to the proliferation of smartphones. In addition, customers have grown accustomed to having access to information from all over the world at their fingertips. One in every five persons spends up 30–40 h each week on the Internet, while the median person checks their phone once every 12 min. These facts were presented in an article that appeared in the Telegraph. People's lives are becoming increasingly entangled with technology, and as a result, their desires for enhanced ease and comfort, as well as a larger degree of customization, are growing. It is necessary to modernize the public transportation system in order to accomplish these goals.

The proposal asks for combining different modes of public transportation with different kinds of technology in a variety of settings. It is possible that providers of public transportation will be able to improve the customer experience by allowing commuters to use their smartphones as tickets, in a manner comparable to how they can now use their Master Cards to pay for tickets. This would be analogous to the current situation in which commuters can use their Master Cards to pay for tickets. The ubiquitous availability of cellphones is to blame for this phenomenon. So, there are some possible solution by collecting it the public transit system may be improved.

- The utilization of data obtained from customers' smartphones enables transportation companies to have a greater understanding of their customers, which in turn enables them to provide more individualized service.
- Europay, MasterCard, and Visa (EMV) [21] systems have already been installed at automatic ticket collecting gates in a number of countries, allowing travelers to pay for their tickets in a method that is both speedy and simple. This has made it possible for more countries to adopt the technology.
- The usage of interactive transportation apps that allow customers to check in for the next available train, bus, or metro in real time has the potential to improve the overall customer experience. These apps can be downloaded on mobile devices.
- During peak hours, automatic fare collecting gates can be of assistance in controlling and estimating the volume of passengers, which can lead to an improvement in the quality of service. The utilization of these gates has resulted in this immediate consequence.
- Utilizing geolocation, plan the routes that will get them to their destination as quickly as possible, sign up to receive warnings when there are breaks in service, and check to see what facilities are offered at each station.
- Find out what kinds of conveniences are offered at each station by inquiring about them.

8.1.4 Reliability on the Services

The provision of public transportation is a tough endeavor to undertake, given the large number of moving parts that are involved, making it difficult to manage in an efficient manner. A single mistake or delay in one link in the chain, such as driver is unavailable, could kick off a domino effect of complications farther down the line. According to Network Rail, approximately sixty percent of all delays that passengers suffer can be traced back to the firms who operate the rail lines. The remaining delays are the result of a mix of unfavorable weather conditions and illegal trespassing.

The solution of such problems lies in the merging of recently developed technological advancements with pre-existing public transportation networks. In point of fact, the response has not evolved in the least. If companies collect data using mobile devices like smartphones and other forms of technology, it will be much simpler for them to organize their schedules. Businesses will also be able to save time. The availability of data enables transportation firms to better plan for the future by providing vital information such as peak hours and flow rates. This enables the companies to better serve their customers (the amount of persons passing through automatic fare collection gates at any given time). For instance, in order to save money and energy, the number of trains that run during the peak hours of the day should be increased, while the number of trains that run during the off-peak hours should be decreased.

Customers of commuter rail companies will be notified of any potential delays or cancelations via applications that the companies have developed specifically for customers. Virgin Trains offers a wonderful explanation of how something like to this could be implemented and serves as an excellent example. Customers are able to view movies while they are on the road owing to the free software that this company provides. The app not only keeps customers up to date with real-time departure information, but it also works as a booking platform and an entertainment hub. This is just another outstanding illustration of how the quality of the experience that is delivered to customers may be improved.

8.1.5 Challenges to Encounter the Fraud

Businesses that provide transportation may lose a considerable amount of money by customers who don't pay for their rides. Because some customers choose not to pay their fares, the transportation industry experiences annual financial losses as a result.

So, installing fare collection gates that are automated could be possible solution to this problem. The vast majority of airports have automated gates for the purpose of collecting passenger fares; however, these gates will only open if a predetermined requirement has been satisfied. One approach to prove that you have completed this step is to show a valid train ticket when you are checking in at the station. The entrances will stay sealed until a valid ticket can be presented in order to prevent any cases of ticket fraud from occurring.

On the list of things to be concerned about, overcrowding of public along with transport is also a big challenge. When there is a lot of traffic, all of us are inconvenienced. It is harmful for the environment, and on a larger scale, it is bad for the economy since it costs a huge amount of money each year. Both of these things are negative for the economy. In addition to the financial losses, the situation has resulted in a decline in production and an increase in the amount of pollutants in the area around the affected business. Individuals are not the only ones who might be negatively impacted by traffic congestion on the roadways. Inhaling the gases that come from an automobile's exhaust has been linked to the development of respiratory problems in children. At this stage, the fact that there is a backup in traffic which not put salt on the wounds but helping to go forward. People are more concerned with the state of the traffic than they are about their own personal safety, their wealth, or the location of the next place they will live.

This is something that is already happening in a number of different cities all over the world. Because road sensors, phased traffic lights, and smart parking systems have been put into place in Singapore, there has been a dramatic reduction in the amount of congestion in the city's roads. The fact that Singapore has been recognized as the most dynamic city in the world is not something that should come as a surprise to anyone.

The process of transportation planning can benefit from the utilization of a technology known as the integrated transportation management system (ITMS), which is a piece of software. The cornerstone for a city's attractiveness to its residents, as well as for the city's economy and environment, is a public transit management system that can be relied on. Legacy transportation management systems are plagued by buses that are poorly maintained, routes that are not optimized, and buses that come and depart from bus stops in an unpredictable manner, which causes a significant amount of difficulty for the residents of the town. Implementing a solution with intelligent and integrated public transportation that has been capable of meticulously planned and managed in an efficient manner. These improvements make it possible to improve operator operational capability, citizen satisfaction, service reliability, and on-time availability. Citizens also stand to benefit from the solution.

- A system that gives information to passengers is referred to as the passenger information system, or PIS for short.
- The passenger information system is an all-inclusive service that calculates estimated times of departure and arrival using information gathered from tracking devices that have been put in various vehicles.

Commuters now have access to information regarding public transportation through a variety of digital platforms, including websites, mobile applications, and text messaging. The multi-channel commuter interface ensures that citizens have a favorable perception of the local transit system by making it simple to use, which in turn promotes the public's perception of it as a safe and dependable mode of transportation and increases the likelihood that citizens will have a positive perception of it.

The following are some of the components that may be found in the system; as a result of these components, the system is able to give users with data in real time:

- A display screen is often available in bus terminals.
- Televisions installed in all of the motorcoaches.
- Voice announcements are available on buses.

On the website for the public transportation system, you may get information about bus schedules, notifications that can be sent via SMS or a mobile app, and Interactive Voice Response System (IVRS) [22]. The passenger information system display that is located at bus stops makes use of a communication system that was developed within the station in order to deliver real-time route information and anticipated arrival times to passengers.

An automated vehicle detection system is referred to by its acronym AVDS, which stands for "Automated Vehicle Detection Technology". This type of system is able to recognize moving cars on its own. Buses are equipped with tracking systems that utilize the global positioning system (GPS), which record data that can later be used for tracking purposes. The AVLS system makes it possible for the operations team to monitor the movement of vehicles in real time and transmit data to public information devices like bus stops, terminals, and buses, in addition to consumer portals and mobile information delivery systems [23, 24]. Other public information devices include mobile information delivery systems.

The AVLS for city buses is comprised of a number of different components, which are outlined as follows:

- A controller that is based on GPS and has the ability to be mounted on a bus. This controller also has a communication interface that is bidirectional.
- A personal information system (PIS) installed within the automobile (Passenger Information System).
- Passenger information system for Off-Board Passengers Utilizing Data Collected From On-Board Cameras.
- A management and control system for automobiles that is based on a geographic information system.

So, the method opted in the organization of driving shifts and the distribution of vehicles deals with scheduling and dispatching systems for public transit vehicles. It has dynamic scheduling, reports on route condition monitoring and adherence to the schedule, interfaces for reporting on emergencies or incidents, reports on route condition monitoring, in addition to the standard capabilities required to provide computer-assisted scheduling and dispatch services. These features are in addition to the standard capabilities required to provide computer-assisted scheduling and dispatch services. Because the technology that is utilized in public transportation is able to dynamically reschedule vehicle and driver assignments in response to real-time happenings. Hence, the system is able to dynamically organize and optimize the movement of vehicles. This makes public transportation more efficient.

Administrative Section of the Depot one of the capabilities of a transportation management system is the ability to automate tasks. These tasks include the management of the workshop, the management of fuel, the management of traffic, the management of vehicles, and other activities within the depot.

8.1.6 Implications of Current Advance Technologies in the Systems

Despite the fact that taking public transportation is significantly better for the environment than driving a personal vehicle, many of the older and more traditional modes of public transportation continue to rely on antiquated technology, which is a significant contributor to the pollution that affects the entire world. This is because antiquated technology relies on older fuel sources and produces more pollution. The transportation industry in India, which includes public transportation, individual automobiles, and other forms of transportation, is responsible for almost a quarter of the country's total emissions of greenhouse gases. Other industries in India also contribute to the country's overall emissions. These numbers take into account emissions produced by both public and private autos.

We currently have access to the tools that are required to decrease the impact that taking public transportation has on the surrounding environment. The only thing that is left to do is put the reforms into action, which is something that a large number of cities have already started doing. The availability of electric, hybrid, and low-emission buses should be increased so that there is less of an impact on the environment caused by public transportation. These activities are a part of a larger strategy to build a city in the future that is both safe and friendly to the environment in the same package, and that plan will be implemented in the near future.

The concept of a "smart city" refers to a location that has effectively incorporated a variety of different types of technology [25–27]. Objects that are utilized on a day-to-day basis, such as trash cans and traffic signals, have the potential to be connected to the internet by utilizing sensors. These sensors are able to collect data and communicate it with one another, which will ultimately lead to an improvement in the effectiveness of the city as a whole. If a city is managed more effectively, then more people will utilize public transportation because it will be more dependable and, presumably, more fun. This will lead to an increase in the use of public transportation. Because of this, there will be a greater number of individuals using public transportation. Because of this, there will be less cars on the road, which will lead to less pollution, less stress, and a generally happy population as a whole.

8.2 Reasons for Installing a Transportation Management System (TMS)

The above discussion provides an information for different kinds of TMS solutions ranging from more conventional on premise TMS solutions to network TMS solutions. If you have the right transportation management system you will be able to improve how your core business works as well as optimize those processes. There are several factors which effect the TMS for proper application these are discussed below.

8.2.1 Benefits of Software-Based Systems

One of the most effective ways for a company to lower its shipping expenses is to invest in quality transportation management software. The appropriate system will perform an investigation into the monetary components of each logistical path. It will create suggestions geared toward the user for cutting expenses in particular areas such as the amount of fuel consumed.

8.2.2 Coordination of Planning and Working

The newer generations of transport management systems connect seamlessly with the already existing systems that are necessary for the effective management of company transportation requirements.

These are the subsequent:

- Methodologies for the administration of purchases and orders
- Warehouse Management
- Management of Relationships with Customers
- Management of Relationships with Suppliers

Because of this integration, the company will be able to carry out orders using the carrier that offers the lowest possible shipping rates. The company will benefit from improved route planning as well as load optimization as a result of this development. To put it another way the planning and carrying out of orders will be done more effectively and in less time.

8.2.3 The Minimum of Paper Work

By utilizing a TMS for account automation, you will be able to save valuable time as well as money that would have been spent on cumbersome paperwork. The costs associated with administration are cut down significantly. Errors such as inaccurate billing or invoice errors are kept to a minimum which contributes to an increase in overall efficiency.

8.2.4 Management of the Inventory

Businesses are able to acquire real-time status updates on orders and shipments as well as track the lifecycle of those orders and shipments through the use of transportation management system. Users will benefit from having an accurate prediction for the inventory and the accountability of the supply chain network will be improved as a result. Moreover, network-based transportation management system solutions provide various inventory management solutions that operate hand-in-hand with the transportation management system. This makes both the inventory solution and the transportation management system more efficient and smarter than they would be otherwise. Researcher Chandra et al. [28] postulated the concept based on tree structure for the delivery management that encounters the large freight.

8.2.5 Visibility Along the Supply Chain

A bird's eye perspective of the complete supply chain system can be obtained through the use of new generation TMS that integrate across the supply chain. The significant advantages come from having access to actual data from all of the different systems as well as complete operational insight. This gives managers the ability to immediately take advantage of any possibilities or find a solution to any problems that may crop up. It helps you maintain a positive relationship with the clients without sacrificing performance.

8.2.6 Optimization of the Routing Process Through the Use of Pool Distribution

Both the length of time it takes to complete an order and its size have decreased. Because of this proper routing is more important than it has ever been. Users are able to deploy pool distribution which is a way of delivery that is more cost-effective faster and offers greater visibility and control when using the appropriate TMS. The user decides which shipments need to be picked up or delivered and then selects the optimal pool location to employ for this purpose. Orders that are particularly complicated are disassembled and processed one at a time which results in significant time and cost savings.

8.2.7 Monitoring Drivers While They Are on the Road

Driver tracking gives consumers the ability to evaluate the usefulness of various routes taken by drivers which in turn can contribute to the development of a more effective timetable. In addition to that a simple analysis of each individual driver can be carried out. The user is able to monitor their own efficiency and provide input on areas in which there is room for advancement. Additionally, real-time tracking offers significant improvements to safety, particularly in the event of an accident.

8.2.8 Accurate Order Fulfillment

Shipping can reach a higher level of precision with the help of a trustworthy transportation management system. The precision of order fulfillment is significantly improved by having full visibility throughout the supply chain as well as real-time tracking. Shipping problems and discrepancies will no longer occur as a result of using the software. And even if just relatively minor challenges are met along the way the issues can be rectified such that the consumer is not adversely affected in any way.

8.2.9 Enhancing the Experience of the Customer

Customers today expected to make adjustments for their orders at the last minute receive personalized updates regarding delivery timeframes and more. They do not merely demand it rather they consider each order they have placed to come with the aforementioned services already included. It is a significant obstacle for companies to modify their business practices in order to live upto the standards set by customers. Transportation management system or more precisely new generation transport management systems come into play at this point. Transportation management system will bridge the gap between order management and warehouse management systems. Consolidating all of the orders from the customers would make it easier to choose the most reliable carrier at the most affordable pricing. A win–win situation for both the customers and the retailers [29, 30].

8.2.10 Customer Loyalty and Word-of-Mouth Referrals

The appropriate TMS will help you save both time and money. The business will see an increase in both its productivity and its efficiency as a result of this. But perhaps most crucially each of the aforementioned characteristics makes a contribution to your company's ultimate goal which is to acquire new customers who will become repeat customers. You want your clients to keep coming back to practice your facilities also the ideal transport management system will make that happen for you. A better customer experience achieved via the use of TMS will also lead to a rise in the number of referrals.

8.3 The Positive Effects That Technology Has Had on the Transportation Sector

There has never been a time when moving from one location to another was so simple and quick. The most recent technological advancements have completely altered the significance of traveling. Anyone can reach even the most inaccessible parts of the globe with the assistance of recent technologies that are linked to the 5G network and are constructed out of electronic components and industrial gadgets. When traveling, whether for business or pleasure people make use of a huge variety of transportation options.

Since the transportation industry is one of the most important essential industries for a country to function properly it has been one of the industries that have been testing all of the emerging advancements. Roads as well as all other modes of transportation are made significantly safer by drones, as well as any other infrastructure that contains electrical components. The safety of various modes of transportation has never been higher since the introduction of drones and other infrastructures equipped with computerized inventory systems. The organization is able to guarantee exceptional service to its customers regardless of the quantity that is requested by their business partners, this helps to improve the overall productivity of all market participants as the industry evolves.

8.3.1 Improving Our Performance in the Market

Companies are increasingly able to shorten the amount of time it takes for the delivery of their products and to consistently cater to the evolving requirements of their consumers as a result of an effective combination of innovative practices and growing reliance on electronic databases.

Businesses whether they are offline or online may easily track their customers' orders in order to enhance their delivery times all over the world. It is vital and may be readily accomplished to improve communication between the actors. There are a variety of technological and business solutions currently accessible on the market.

For the purpose of boosting their overall efficiency and preventing production bottlenecks, an increasing number of worldwide firms are placing orders for electronic components. In point of fact businesses might encourage all of their partners to purchase electronic components online with the assistance of the most recently updated technology.

The old business practices of electronic providers are being completely upended by the proliferation of online platforms and markets which requires the suppliers to constantly watch the market for best deals and price quotes. Components that are notoriously difficult to track down can be located with relative ease and offered to various business actors at preferential rates.

8.3.2 Improving the Quality of Life for All Concerned

The consumer experience in the realm of public transportation is also being disrupted by technological advancements. The metro and other urban networks are becoming increasingly busy and so the traffic needs to be properly managed in order to ensure that passengers may travel safely.

Companies are able to provide effective services to all customers because their drones are built with a wide variety of high-performance electrical components and their databases are fully populated. The technologies that enable autonomous driving will see increased adoption and will be coupled to centralized and automotive installations.

The combination of artificial intelligence with the most cutting-edge technologies is becoming increasingly developed and is within reach of all relevant stakeholders. Better and more specifically targeted marketing communications are being made possible by the development of databases and new technologies made possible by novel combinations of electronic components. Messages that are polite and encouraging will influence how passengers behave in public transportation and encourage them to observe the various rules. We are living in a time where people are becoming increasingly connected to new technologies. Suppliers of electronic parts always provide their customers with the highest quality electronic parts in order to ease their transition into the new era of artificial intelligence.

8.4 The Significance of Technological Advancements in the Transportation Industry of the Future

The development of intelligent transportation systems which are future technologies that will help to achieve transportation goals will mark each of the four pillars of future transport which are as follows:

1. Decrease emissions, paying special attention to CO_2 emissions
2. Increase the level of security to reduce the number of traffic accidents
3. Bring down expenses while also raising output
4. Constant connectivity on-board Internet connectivity and communication systems in the vehicle

We are accustomed to witnessing fresh and inexorable technology improvements in passenger cars as we go about our daily lives. Since the introduction of new fuels hybrids and electric vehicles advancements in vehicle, along with the entertainment have focused on augmented reality applications.

Since the carrier lives on the road, the industrial vehicle is exactly the same and makes more sense. As a result, the industry is evolving at a rapid pace to accommodate new technological changes that will result in transport steps that are more effective or safe and environmentally friendly while also being always connected.

It is clear that the government is taking this matter very seriously, as evidenced by the fact that it has enlisted the assistance of the Directorate General of Land Transportation or General Management Branch Analysis, Innovation the Directorate General of Highways and the Prospective and Technology Division of Transportation. All of this with the intention of increasing the prevalence of Intelligent Transportation Systems (ITS) and more generally New Technologies (ICT) for the transportation sector.

To achieve these goals, we need to work toward having vehicles that are prepared for each of the following four pillars:

1. **Decreased production of carbon dioxide** (CO_2) as a result of enhanced driving which has been made possible by an expansion of transportation and training systems that aid in the driver's ongoing improvement.
2. To decrease the number of accidents and to improve driving safety.
3. **Create the most cost-effective and lucrative mode of transportation** possible by implementing fleet management technologies and cutting costs.
4. **Maintain a constant connection**.

   There are a great products and services available on the market today that can assist transportation in gradually adjusting to new technologies and maintaining connections. In this day and age there is no excuse for a carrier to not have a GPS tracking system.

8.5 Conclusion

An in-depth discussion on the public as well as goods transportation systems is exemplified, along with the challenges and remedies for implication of advance transportation system. Discussion reveals that the real-time updates regarding their shipments, customers anticipate not only having their orders delivered promptly, but also provide clarity and satisfaction. The discussion reveals about the effect of advance systems on supply chains to adjust the ever-changing restrictions of global trade, which typically entails the acquisition of a transportation management system.

Furthermore, the importance of advanced transportation management system that should be included a TMS in order to maintain its competitive edge and the environment that is always shifting. Even though the rate of savings could be gradual in the beginning, the incremental benefits will increase into improved business operations. It is not a problem of control rather it is a matter of providing location services to other people, reducing the costs of communication and improving the efficiency of routes and procedures. Despite how hard we try to reject the new technologies we need to collaborate with them in order to increase our productivity and make the most of what they can do for us. Because of rising pressure from customers for more immediate reactions and increased needs from businesses for accurate data, transportation management systems need to adapt. Using machine learning, transportation management systems are able to increase their level of expertise over time, which results in more accurate suggestions and estimates. So, the discussion concluded that this change is necessary because global trade is becoming complex. This is being done in order to maintain our position in the competitive market.

References

1. https://moovit.com/blog/history-public-transport/
2. Shaheen, S.A. Finson, R.: Intelligent transportation systems. In: Cleveland, C.J. (ed.) Encyclopedia of Energy, pp. 487–496. Elsevier (2004) ISBN 9780121764807
3. https://en.wikipedia.org/wiki/Public_transport
4. Humphreys, P.: City transport in the 2020s. Transport and Travel. Archived from the original on 2 February 2017. Retrieved 20 January 2017
5. https://transportandtravel.wordpress.com/2016/12/17/city-transport-in-the-2020s/
6. https://blog.intekfreight-logistics.com/best-transportation-management-software-tms
7. https://en.wikipedia.org/wiki/Ridesharing_company
8. Sainato, M.: 'I don't like being treated like crap': gig workers aim to retool a system they say is rigged. The Guardian (2021)
9. Thompson, R.: Uber loses its final appeal in UK Supreme Court in landmark ruling. Mashable (2021)
10. Korosec, K., Lomas, N.: Uber says it will treat UK drivers as workers in wake of Supreme Court ruling. TechCrunch (2021). Archived from the original on April 8, 2021
11. https://www.bigcommerce.com/articles/ecommerce/
12. https://en.wikipedia.org/wiki/E-commerce
13. Power, M.: 'Mike' Online highs are old as the net: the first e-commerce was a drugs deal. The Guardian. Archived from the original on 30 November 2016 (2013). Retrieved 4 May 2021
14. Global e-Commerce sales surged to $29 trillion (Press Release). United Nations Conference on Trade and Development. 29 March 2019. Archived from the original on 2 May 2021. Retrieved 4 May 2021
15. UPI crosses 2 billion transactions milestone in October, up 80% from year-ago; value nears Rs 4 lakh cr. Financialexpress. Retrieved 24 March 2022
16. Candace, B., Kari, W.: A literature review of the passenger benefits of real-time transit information. Transp. Rev. **39**(3), 1–30 (2018)
17. Deng, Y. Chen, M.: Impacts of real-time transit information on bus passengers' travel choices based on travel behaviour survey. Promet [Internet] **33**(4), 539–550 (2021)
18. Pratap, A., Singh, B.K., Sardana, N.: Fracture in self-lubricating inserts: a case study. Mater. Today Proc. (2022). https://doi.org/10.1016/j.matpr.2022.06.005
19. Suresh Kumar, R., Senthil Kumar, S., Murugan, K., Hailegiorgis, S.M.: Green machining characteristics study of Al-6063 in CNC milling using Taguchi method and Grey relational analysis. Adv. Mater. Sci. Eng. (2021). https://doi.org/10.1155/2021/4420250
20. De Vos, J.: Do people travel with their preferred travel mode? Analyzing the extent of travel mode dissonance and its effect on travel satisfaction. Transp. Res. Part A Policy Pract. **117**, 261–274 (2018)
21. https://en.wikipedia.org/wiki/EMV
22. https://en.wikipedia.org/wiki/Interactive_voice_response
23. Arora, N., Kumar, Y., Karkra, R.: Automatic vehicle detection system in different environment conditions using fast R-CNN. Multimed. Tools Appl. **81**, 18715–18735 (2022)
24. Azzedine, B., Jabbar, S.A., Abdelhamid, M.: Automated vehicle detection and classification. ACM Comput. Surv. **50**(5), 1–39 (2017)
25. Tsai, S. Gupta, B.B. Agrawal, D.P. Wu, W., Liu, A.: Recent advances in intelligent transportation systems for cloud-enabled smart cities. J. Adv. Transp. 9792543(2) (2021)

26. Singh, B., Gupta, A.: Recent trends in intelligent transportation systems: a review. J. Transp. Lit. **9**(2), 30–34 (2015)
27. https://www.sciencedaily.com/news/matter_energy/transportation_science/
28. Chandra, A., Pani, A., Sahu, P.K., Majumdar, B.B., Sharma, S.: Identifying large freight traffic generators and investigating the impacts on travel pattern: a decision tree approach for last-mile delivery management. Res. Transp. Bus. Manag. **43**, 100695 (2022)
29. Laroche, F., Lamatkhanova, A.: Effects of open access competition on prices and frequencies on the interurban railway market: evidence from Europe. Res. Transp. Bus. Manag. **43**, 100705 (2022)
30. Marazi, N.F. Majumdar, B.B. Sahu, P.K. Potoglou D.: Congestion pricing acceptability among commuters: an Indian perspective. Res. Transp. Econ. 101180 (2022)

Chapter 9
A Study of Public's Perception of Parking Problems in Vadodara

Anuj Tiwari, Himanshu Raj, and Ram Krishna Upadhyay

Abstract Private vehicle ownership is rapidly increasing in the cities. The increase in the overall population of private vehicles/middle-range vehicles in the city is causing congestion on the roads as well as parking problems. The study is concerned with Vadodara city. Parking facilities in the city are inefficient. "On-street" parking is the norm in almost all the major parts of the city. Commercial plazas are emerging along major routes, but only a few of them have proper parking facilities. It ultimately leads to the illegal occupation of streets for parking, which leads to congestion. Public consensus is required to adopt a suitable parking policy. The work aims to identify and analyze the problems pertaining to parking faced by the public. We aim to understand how the public perceives the problem of urban parking. For this purpose, we have conducted a survey via Google forms of about a hundred residents of the city. The work will focus on identifying current parking planning problems and suggest new or improved parking management strategies.

Keywords Parking · Vadodara · Public perception · Congestion

9.1 Introduction

A vehicle spends most of its life in parking, unutilized by its owner. The normal use of personal vehicles such as cars and bikes are for short market trips, trips to the workplace, and daily commutes [1]. In recent years, Indian cities have seen a massive increase in the number of privately owned vehicles in urban as well as rural areas. With an increasing number of vehicles, the demand for parking is increasing exponentially, and vehicles require parking space at every location we take them with us. There are a number of reasons for the increasing number of vehicles registering in India each passing year. However, public transport facilities also increase at around the same speed [2, 3]. Therefore, making parking is an unignorable topic in every

A. Tiwari · H. Raj · R. K. Upadhyay (✉)
School of Engineering and Applied Sciences, National Rail and Transportation Institute, Vadodara, Gujarat, India
e-mail: ram.upadhyay@gsv.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_9

aspect of planning, infrastructure development, etc., because 96% of a car's time is spent in parking.

There are three main aspects of any transportation system for its efficient running: the vehicles through which the transportation will be done, the right of way for driving, and the terminal for starting and ending the journey. Railway uses locomotives and wagons for transporting passengers and goods on its dedicated right of way, which is solely used by railways and not by any other mode of transport. Railways and terminals are dedicated to railway transportation. For air transportation, there are planes carrying passengers and cargo on their right of way through airports and cargo terminals. In the case of land transportation, cars, trucks, bikes, etc., are the vehicles, and roads, highways, and expressways are the right of way for traveling. Terminals for road transportation are different for different category of vehicles, such as bus stand for buses, auto stand for auto and rickshaws, and personal and public parking spaces for private vehicles (cars and bikes). The number of vehicles by rail and air is limited due to many constraints, but it is not the same in the case of road transportation [4]. With the westernization of India, the number of private vehicles, especially cars, has increased dramatically in the last two decades.

9.1.1 Introduction to Vadodara City

Baroda, situated on the bank of River Vishwamitri, is said to be that name derived from the great Saint Vishwamitra. In 1974 Baroda was changed to Vadodara, but some people still like to call it by its old name. Vadodara is the 3rd largest city in Gujarat. The area under Vadodara Municipal Corporation (VMC) is about 160 sq. km [5]. It has a population of over two people and a population density of 10,415 persons per sq. km, according to the 2011 Census [6]. Vadodara/Baroda city is known as '*Sanskar Nagri*' and '*Sayaji-Nagari.*' The Vadodara city flourished from the year 1875 under the rule of Maharaja Sayajirao III. During his rule, Baroda progressed and achieved a name in all fields, such as establishing compulsory primary education, university, library system, art, and architecture [5].

The city is mainly divided into two parts, one is the old city which has Maharaja Sayajirao University, Laxmi Vilas Palace, Pratap Vilas Palace, and the narrow-gauge line station Pratap Nagar, and the other one is the new city called Alkapuri, which is properly planned and developed with future vision [5]. Since Vadodara was an established city for a long time, it has a substantial population of more than 22 lakhs, and the old city is not planned well to meet future demands. Like many cities in India, Vadodara has narrow streets and crowded markets. With the increasing population, these narrow streets aren't able to handle the demand of traffic, and hence driving in the city becomes a hectic task for local people.

9.1.2 Motorization

There has been a rise in job prospects in our cities due to globalization, privatization, and liberalization. People's income levels have risen as a result. This, combined with the falling cost of automobiles, has resulted in a massive surge in demand for personal vehicles. Because the increase of registered automobiles always outnumbers population growth and new roads are developed, travel risks and traffic exposure grow much higher with rising motorization and expanding road networks [7].

Low-density decentralization wreaks havoc on public transportation. It results in fewer targeted trips in heavily frequented corridors, making transportation more difficult to serve. It has significantly increased vehicle and motorcycle usage in India, resulting in congested roadways, slower bus speeds, higher bus operating expenses, and reduced public transportation utilization. Walking and cycling account for nearly half of all journeys in medium-sized cities and about a third in large cities as cities grow and travel distances increase [7].

However, there is a lot of variety in car usage within the city. According to research, a private automobile is motionless for 96% of its lifetime [8]. Despite this, while traffic congestion, road connection, and road quality are all important factors in urban transportation design, parking remains a minor consideration in urban infrastructure planning. Parking has been identified as a critical component in major cities worldwide, prompting the development of parking policies and plans. However, in India, the issue of parking has not been given the attention it deserves.

Some may claim that parking is one of urban transportation's minor annoyances, yet this viewpoint has resulted in its removal from policy, resulting in numerous traffic jams. As a result, poor quality urban transportation, land abuse, and rising social and environmental costs result. India's cities are all experiencing a transportation issues. While problems like a bad connection, poor road quality, traffic congestion, and air and noise pollution are regularly addressed, parking negligence negatively impacts urban transportation quality [7].

With the rising number of private vehicles on the road, it is critical that parking be viewed as a critical component of creating an effective transportation system in our cities. Parking is a significant issue in the push-and-pull method to better urban transportation, which involves fewer vehicles and more cycling, walking, and public transportation. This study will look at parking as a significant economic element rather than just an externality of private transportation. Instead of seeing parking as a problem to be solved, it should be viewed as a tool that can be used to create jobs and income while also improving the general quality of urban transportation.

India's urban population grew from 2.58 million in 1901 to 121 million in 2011 [7]. This number is rapidly rising as more individuals migrate to cities in search of work and better living conditions. These numbers constitute a severe danger to the current urban transportation infrastructure, especially when the expansion of road space is so small in contrast. This necessitates the establishment of a more comprehensive urban planning strategy. The rising reliance on private autos will only exacerbate traffic congestion. Bridging these gaps will be easier with a better-organized parking system.

9.1.3 Parking Requirements

For a city's prosperity, an efficient motor traffic system is required. Motor traffic can serve many of the city's business and commercial activities. Parking is an integral part of urban mobility. Individuals, communities, and transportation networks are all affected in long- and short-term ways. Parking is an issue contributing to traffic congestion [7]. They need a parking spot where passengers can load and unload their belongings. Individuals who own a car will most likely prefer to travel to their destination by car if parking is conveniently situated at the destination and the cost of parking is fair. In other words, parking is an incentive if it is cheap or free and abundant. Parking is a significant deterrent to driving one's car.

Varied types of buildings have different parking needs. Only a common parking place is required for residential plots of less than 300 sq. m. A minimum of one-fourth of the open land on a residential plot of 500–1000 sq. m should be set aside for parking. At least one parking place may be required for every 70 sq. m of office space. In a restaurant, one parking place is sufficient for ten seats, whereas theaters and cinema halls require only one parking space for 20 seats. As a result, different land use zones have different parking needs.

9.1.4 Key Concerns Related to Parking

1. **Growth in the number of vehicles.**

The city's parking supply is insufficient, given the increase in the car population. In the long run, demand will surpass supply, resulting in tremendous hardship and a terrible standard of living. The necessity of the hour is for a policy to minimize and diminish reliance on private vehicles [7].

2. **Need for Effective Public Transport**

The transition from private vehicles to public transportation must be facilitated by providing efficient transportation options. Multiple modes must be investigated to provide and design an effective public transportation system [7].

3. **Coordinate Operational urban planning**

Change must be brought about through coordinated operational urban planning with the active participation of the planning institutions. The city's present planning tools are woefully insufficient. The provision of parking and the shift to public transportation must be factored into project legislation and operational planning. This necessitates a fresh approach to planning [7].

4. **Enforcement of parking restrictions**

It is necessary to create order on the city's streets. Strict enforcement of parking rules and regulations will bring about a change in people's irresponsible behavior of parking on roads [7].

Although the Building Bye Laws require parking in the basement and an adequate number of car parks in the buildings, there has been widespread violation [7].

Slowly constructing parking infrastructure to fulfill high demand in congested places. Adequate funding for the construction of parking lots and transit-oriented infrastructure is required. The parking policy framework addresses many challenges and concerns [7].

9.2 Study Framework

9.2.1 Need of the Study

1. According to 2006 research by the Central Road Research Institute in New Delhi, the average car is parked 95% of the time and only steers 4% of the time. Every day, each car requires/occupies an average of three separate parking places throughout the city. Every day, each car occupies 69 sq. m of land, most of which is public space.
2. As the number of vehicles and their use in cities grows, so does the need for parking spaces. (Average rise of 1 to 1.2 lakh vehicles in Vadodara).
3. The new trend of using buildings with increased densities of people, such as shopping malls and multiplexes, has resulted in adopting measures for the commercial use of buildings and accompanying parking requirements.
4. An increase in car holdings and private vehicle ownership has aggravated the problems.
5. Increase in traffic every year by 18–20%.
6. Violations of parking bylaws.
7. Insufficient mass transportation facilities increase the number of vehicles on the road.
8. Local Govt. Fail to develop parking lots.

9.2.2 Aim

To assess parking problems in Vadodara city by studying the public's perception of the problems they face on a day-to-day basis. We aim to survey the resident of

Vadodara and want to know their opinion on the present status of the parking problem in the city. This will give us a better understanding of the parking scenario in the city. Based on the citizens' responses, we have tried to analyze the significant problems and suggest measures and recommendations to solve the parking problem.

9.2.3 Objectives

1. To carry out surveys of citizens using online questionnaires to study the existing parking conditions and problems in the city.
2. To find out the major parking problems and their causes in the city.
3. To carry out residents' surveys using online questionnaires to study the existing parking conditions and problems in the city.
4. To study the correlation between various factors of parking behavior and problems faced by the residents.
5. To recommend possible solutions for the problems.

9.2.4 Methodology

Examining the reports and plans that are now available. The study located, gathered, and examined accessible reports, plans, survey data, and statistics relating to parking in Baroda. The parking regulations and practices were investigated. In addition, secondary sources of information were gathered by contacting relevant authorities and government departments.

Analysis of Data and Inferences

- A qualitative study of the responses received
- Graphical representation of the data through bar charts, pie charts, etc.
- Finding a Correlation between the various factors affecting parking behavior, based on the Likert scale

Data from all the parking surveys were analyzed in terms of computing various parking characteristics, such as parking accumulation, parking duration, parking index, parking turnover, the need for off-street parking, and commuters' opinions on the acceptability of various parking management plans. Based on the data analysis, conclusions were formed. Commuter opinion on parking and adoption of various parking management plans. Based on the data analysis, conclusions were formed.

The questionnaire was divided into five segments

- Prevailing parking conditions in Vadodara
- Parking pricing
- Locational choices affecting parking

- Parking preferences
- Problems faced while parking in a complexes

Suggestions and recommendations. The data analysis and inferences generated aided in making ideas and advocating specific strategies to address the parking problem in the neighborhood.

9.2.5 Scope and Limitations

- The scope will be limited to the number of respondents to the online questionnaire.
- The scope of the study is limited to selected areas of Vadodara city.
- It will be based on a small data pool as it is not viable to collect a huge data pool due to resource constraints.
- The study will be limited to responses from one or two citizens from each area of the city which attempts to represent the city trend.
- The impact of the virtual market on parking requirements has not been considered.
- The impact of transit-oriented development has not been studied.

9.3 Data Collection and Data Analysis

9.3.1 Data Collection Matrix

Table 9.1 shows the data collection matrix used in this study.

Table 9.1 Data collection matrix for the survey

List of data	Agency/source	Objectives
Primary data Questionnaire survey of the Users group Public Survey of parking space during peak and non-peak hours/holidays	People from different places in Vadodara	To study the demand and supply of parking spaces To analyze the hardships faced by the public and significant parking problems and their causes
Secondary data		
Demographic data • Population	Census	
Vehicle data	R.T.O	
Parking lots develop by authority and private	Transportation	
Vehicle toeing	Traffic branch of Department of police	
Land price	Land revenue department	
Transportation VITCOS	R.T.O	

9.3.2 Vadodara City Profile

Vadodara, formerly known as Baroda, is the third most populous city in Gujarat, after Ahmedabad and Surat. It is the administrative center of the Vadodara District and is situated on the banks of the Vishwamitri River, 141 km from Gandhinagar, the state capital. The Delhi–Mumbai railway line and the national highway 8 (NH8) pass through Vadodara. Vadodara is one of India's top ten fastest-growing cities, with a population of about 2 million people as of 2011. The city is home to the Lakshmi Vilas Palace, which was originally possessed by the Marathas' royal Gaekwad dynasty [5].

The Maharaja Sayajirao University of Baroda (Vadodara), Gujarat's largest university, is also located here. The city is a significant industrial, cultural, and educational hub in western India, with multiple national and regional institutions and major industries such as petrochemicals, engineering, chemicals, pharmaceuticals, plastics, information technology, and foreign exchange services. By crossing the one-million population milestone in 1991, Vadodara and seven other cities throughout the country became a metropolis. The corporation's boundaries have shifted, and outgrowths have arisen as areas that encompass all of the facilities inside the corporation's boundaries, producing an urban agglomeration [7, 8].

According to Census data, population trends suggest that the population is steadily expanding, despite the fact that the rate of growth in each decade is decreasing. From 1971 to 1981, the highest growth rate was obtained. This could be linked to industrial establishments appearing out of nowhere. When major industrial units are established in a location, several smaller businesses spring up as a result. Recent trends suggest a decreasing growth rate, with a decade-long average of 24.17% from 2001 to 2011 [7, 8]. Table 9.2 shows the metadata of Vadodara city.

Table 9.2 Metadata of Vadodara city

S. No.	Sectors	Till 2019
1	VUDA limits	714.56 sq. km
2	VMC limits	160 sq. km
3	Population 2011	1,725,371
4	Sex-ratio	920 m
5	Literacy rate	81.44%
6	Workforce	33.87%
7	No of household	541,000
8	Average density	811,021/ sq. km
9	Total wards	12
10	Total road length Pucca/Kutcha	84,305 km/172.718 km

9.3.3 Vehicle Data

An expressway, national and state highways, broad-gauge and meter-gauge railways, and an airport connect Vadodara to the rest of the country. The majority of the city's transportation system relies on roadways. The pace of rise in vehicle growth has been boosted by 8.5%. There is a lot of traffic on the roads right now. As a result, considerable air pollution has resulted.

Total vehicles in VMC limit. As per the R.T.O. record, within the VMC limit in 2010, the total number of vehicles was 1,100,037. In 2011, 2012, 2013, 2014, and 2015 total number of vehicles was 1,301,156, 1,409,526, 1,538,259, and 1,673,882, respectively. So, in 2021 total vehicles will be incising 2,493,282 with an average growth rate of 8.5%.

Type of vehicle in VMC limit

Type of vehicle in VMC limit in 2015. Within the Vadodara Municipal Corporation (VMC) limit, out of total vehicles, there are 76% two-wheeler, 16% four-wheelers, 3% three-wheeler, 4% goods, and 1% passenger vehicles are in the year 2015.

Type of vehicle increasing per year in VMC limit. As per the R.T.O. record purchase of vehicles out of total vehicles, 92% of vehicles are purchased in urban centers. The chart shows the growth pattern of various vehicle segments in Vadodara in the last 4 years. In Vadodara, within the VMC limit, the average growth rate of two-wheelers, four-wheelers, and three-wheelers increase by 8.5, 9.33, and 8.25% per year simultaneously. In short, every year, 1.2 lakh vehicles are increasing in Vadodara, which indicates that the demand for parking is increasing drastically.

9.3.4 Data Analysis (Questionnaire Survey)

Current Parking Condition. Most participants are not satisfied with the current parking conditions on the road (Fig. 9.1).

Core Problem for Parking. This question was asked to assess the core problem of parking in the city. 82.7% of the respondents believe that 'Finding a place to park' is the major problem. 9.1% of the respondents feel vehicle safety is a significant parking problem. Other factors, such as parking fares, dedicated parking slots, lack of proper parking areas, etc., are other problems that got minimal responses (Fig. 9.2).

Parking on roads causes congestion. 93.3% of the respondents answered that illegal parking on the roads causes traffic congestion. Illegal parking on the roads is a major contributor to the parking problems in the city (Fig. 9.3).

Main reasons for parking problems on the roads. To assess the main reasons for parking problems, this question was asked. The respondents had mixed opinions. Shopper parking and daily commuter parking are major reasons for the parking

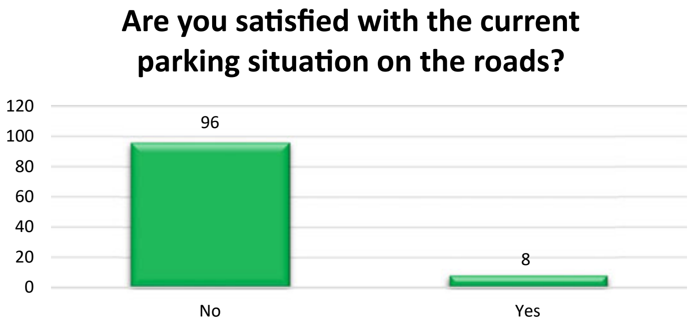


Fig. 9.1 Satisfaction with the current parking situation

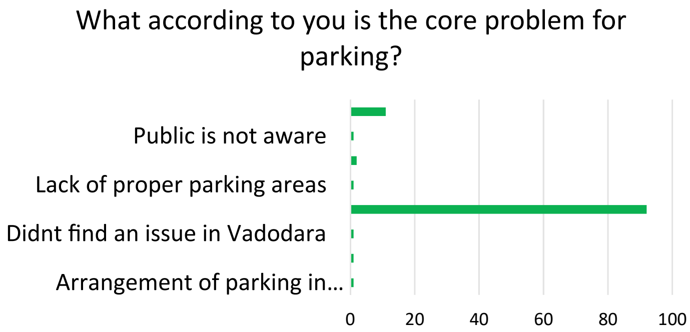


Fig. 9.2 Core problem in parking vehicles

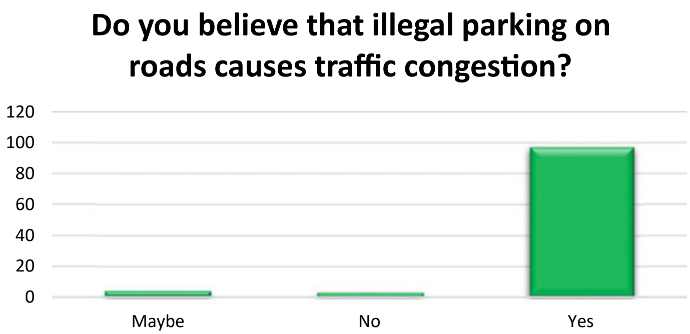


Fig. 9.3 Illegal parking—a cause of congestion of not

problem on the road. Apart from that, Commercial vehicles and residents parking from neighborhood areas account for 55.8 and 41.3% of the responses, respectively. Lack of dedicated parking slots, undisciplined parking, and high vehicle ownership is also a major reason for road parking problems (Fig. 9.4).

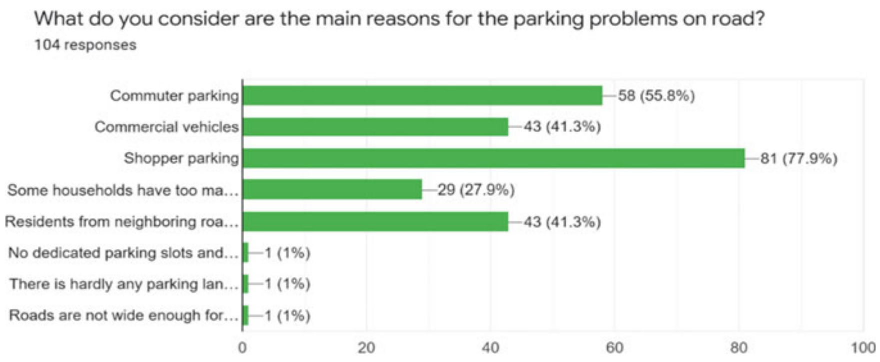


Fig. 9.4 Reasons for parking problems

Timing of the Parking issues

Parking constraints generally happened during the evening time between 3 p.m. to 8 p.m. It accounted for about 63.5% of the parking issues that occurred in the evening time. About 12.5% of the respondents answered that they face parking problems throughout the week, both on the week and the weekdays. The public faces limited parking issues during morning and noon hours (Fig. 9.5).

Parking as a location factor. According to their locational preferences, the respondents asked about parking problems. Respondents faced parking problems mainly in the markets, offices, and railway stations. Markets are the most problematic areas with respect to parking. About 90% of the respondents faced parking issues at the market. Railway stations/Bus stations and Temples followed with 60.6% and 53.8% of the responses (Fig. 9.6).

Parking space availability in residential areas. This question was asked to get an idea of the availability of parking spaces in the respondents' residences. 58.7% of the respondents had enough parking spaces, while 41.3% of the respondents did not have enough parking spaces in their residences (Fig. 9.7).

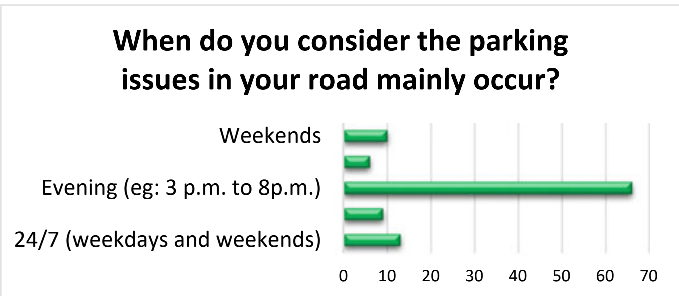


Fig. 9.5 Peak time of parking problem

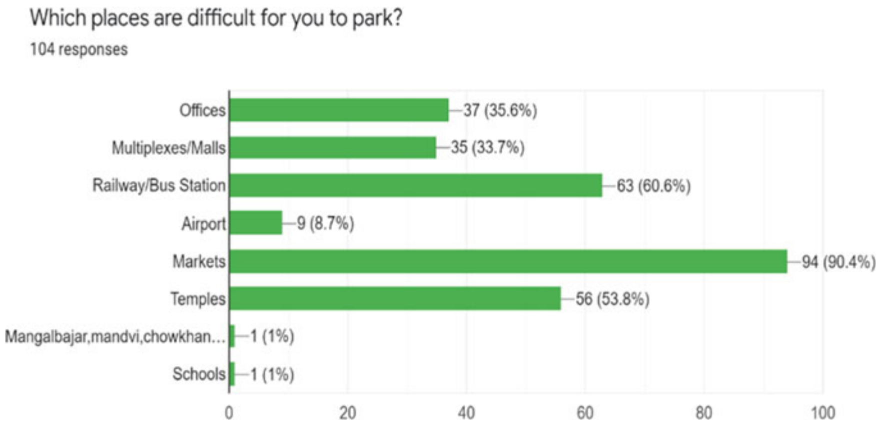


Fig. 9.6 Locations in the city and parking problem

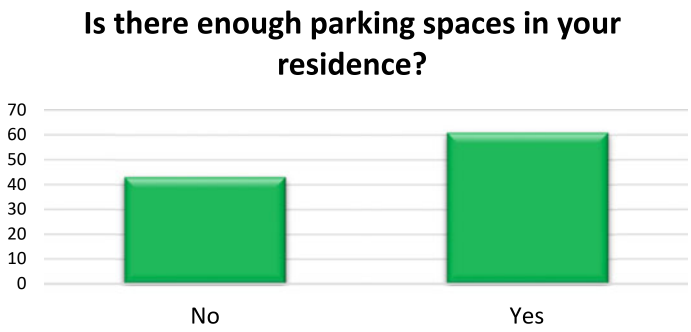


Fig. 9.7 Parking availability at the residence

Parking space availability in working premises. This question was asked to get an idea of the availability of parking spaces in the working premises of the respondents. 69.2% of the respondents had enough parking spaces, while 30.8% of the respondents did not have enough parking spaces in their residences (Fig. 9.8).

Difficulties in finding a space to park in Resident Permit Zones. 43.3% of the respondents could find a space to park without much difficulty in a resident permit zone, while 19.2% of the respondents did not face any difficulties. And about 37.5% of the respondents face the problems occasionally. So, overall, it appears like a mixed response. A significant proportion of the respondents are facing difficulties while others are not (Fig. 9.9).

Difficulties in finding a space to park in Non-Resident Permit Zone. 37.5% of the respondents did not find space to park without much difficulty while parking in a Non-resident permit zone. Approximately 38.5% of the respondents sometimes face these problems, and only 24% of the respondents easily find a parking space.

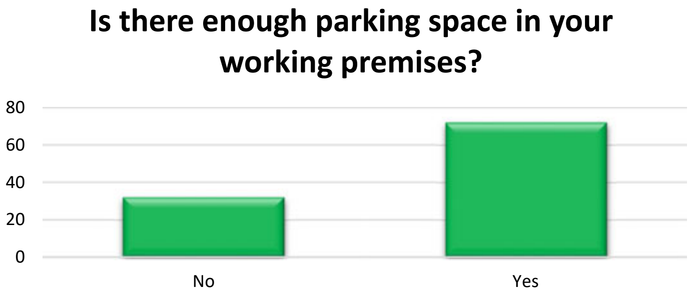


Fig. 9.8 Parking space availability at working premises

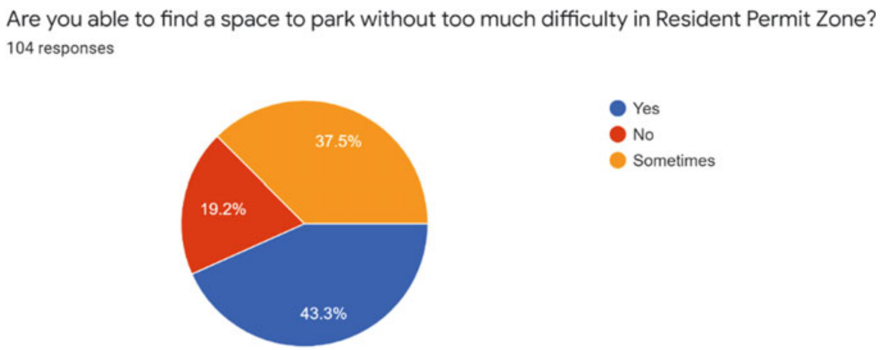


Fig. 9.9 Difficulties in finding parking space in the resident permit zone

This means finding a space to park in a Non-resident zone is a cumbersome job. The majority of the respondents faced parking space constraints sometimes or other (Fig. 9.10).

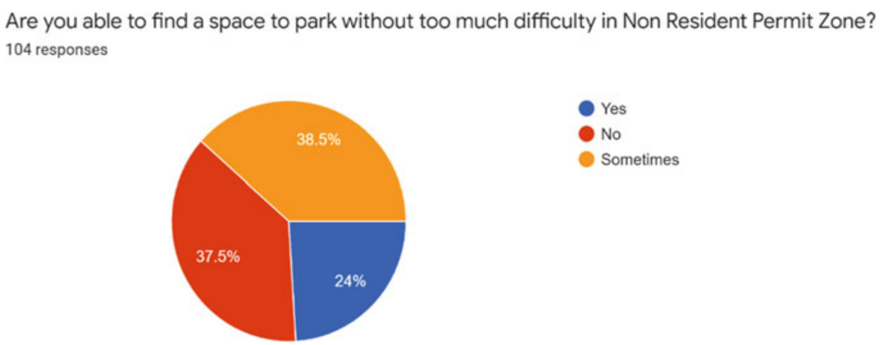


Fig. 9.10 Difficulties in finding parking space in non-residence zone

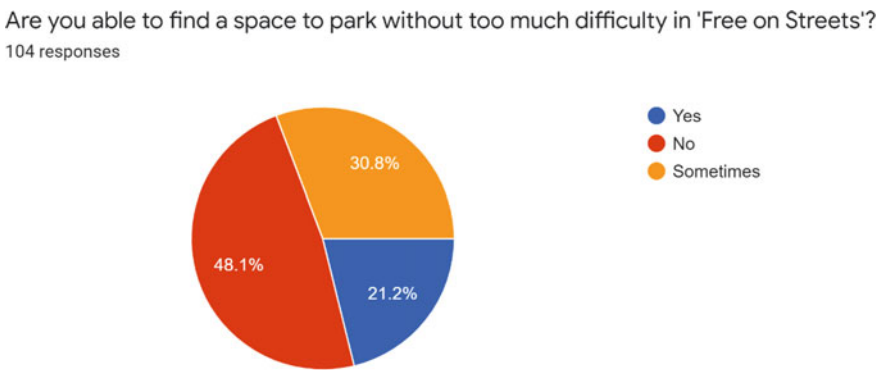


Fig. 9.11 Availability of parking space on the street

Parking for 'Free on Streets.' Free parking on streets is a prevalent practice in the city. Almost half of the respondents did not find space to park without much difficulty while parking on the streets. Approximately 30.8% of the respondents sometimes face these problems, and only 21.2% quickly found a space to park. This means that finding a space to park on the streets is difficult. Free parking on streets is easy for the citizens but finding a space in the first place is a hectic task (Fig. 9.11).

Parking Pricing. In this section, questions were asked to the participants about the price of the parking. It aimed to study the paying behavior and readiness of the respondents while paying parking fees in a parking lot.

Free Parking to the residents. This question was asked to analyze how the residents feel about who should pay the parking fees or whether or not parking should be provided free of charge to the residents by the Government. One-third of the respondents were neutral and had no strong opinion on this statement. About 35.6% of the respondents strongly agreed that parking should be free for the residents. And 15.4% of the respondents strongly opposed the proposition of free parking (Fig. 9.12).

Willingness to pay for Assured Parking. More than 80% of the respondents are firmly convinced that they will pay for parking if guaranteed an assured parking space. At the

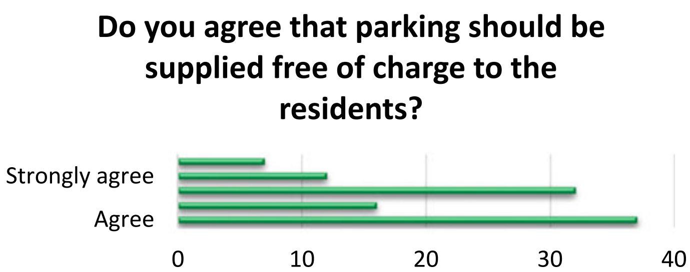


Fig. 9.12 Free parking choice

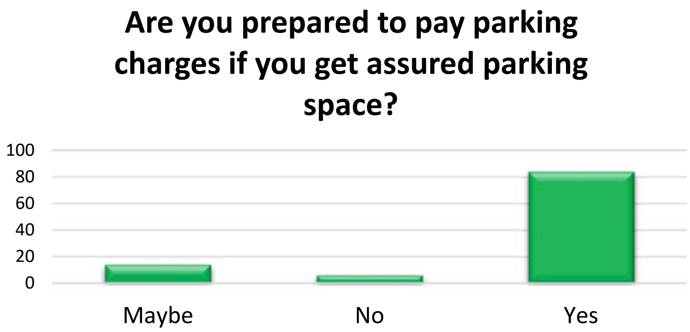


Fig. 9.13 Willingness to pay for assured parking

same time, some of the participants are not willing or unsure about the proposition. There is a strong consensus among the residents that they will pay for the parking if services are provided to them. So, we conclude that, generally, the residents do not want free parking but rather efficient parking services and are ready to pay for it (Fig. 9.13).

Awareness about the parking charges in the city. Only about half of the respondents were aware of the parking charges in the city. The rest of the respondents are either unaware or unsure about the parking charges. So, we conclude there is a lack of information about the parking charges among the residents (see Fig. 9.14).

Usage of Private vehicles if Parking Charges are taken. 44.2% of the respondents will use private vehicles even if parking charges are taken. Parking charges do not have a significant impact on their private vehicle usage. In contrast, a small fraction of the respondents will not use their private vehicles if parking charges are taken from them. So, we can say that charging parking charges will stop some of the residents from using private vehicles. Still, it will not have much impact on curbing the number of vehicles on the road as the majority of the residents will continue to

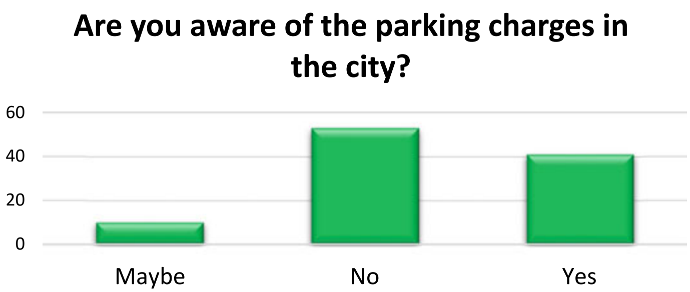


Fig. 9.14 Parking charges in the city

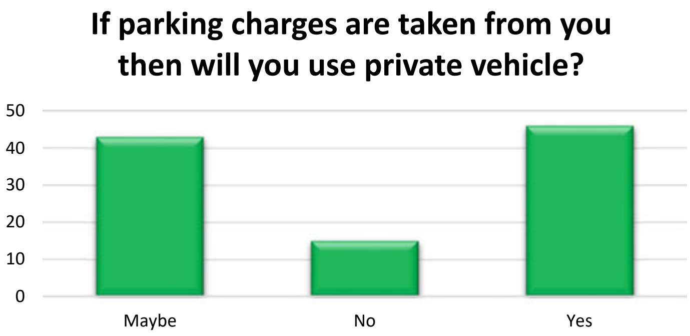


Fig. 9.15 Intention to pay parking charges

Table 9.3 Correlation between various factors of parking pricing

	Willingness to pay parking charges	Aware of the parking charges	Usage of private vehicles if parking charges are taken
Willingness to pay parking charges	1		
Aware of the parking charges	−0.166627111	1	
Usage of private vehicles if parking charges are taken	0.867167934	−0.179428773	1

travel in private vehicles and will pay the charges as demanded (Fig. 9.15). Table 9.3 shows the correlation between various factors of parking pricing.

Correlation between willingness to pay parking charges and awareness of the parking charges

These two factors are slightly negatively correlated, but this value is so close to zero that there isn't strong evidence for a significant association between these two variables.

Correlation between willingness to parking charges and usage of private vehicles

These two factors are strongly positively correlated. A high value of 0.86, which is very near to 1, suggests that those respondents who wish to use private vehicles are ready to pay the parking charges.

Parking charges per hour

It was asked to measure the extent of the amount that the residents are willing to pay for parking for an hour. 54.8%, that is, the majority is ready to pay Rs. 10/h for parking. Some of the residents also agreed to pay Rs. 15 and Rs. 20 per hour. But rare of the residents agreed to pay Rs. 30 per hour for parking. It brings us to the

Fig. 9.16 Parking charges per hour

conclusion that parking charges should be minimal to encourage more people to use the parking facilities (Fig. 9.16).

Public's preferences of Parking. 28.8% of the respondents preferred roadside parking over parking lots. At the same time, about 70% of the respondents agreed to park their vehicle in a parking lot or a multistory parking lot if the parking spaces were available. It reflects the adaptability of most residents to use parking facilities instead of parking on the road, provided efficient parking services are made available to them. However, a particular segment needs to be adequately informed about the ill effects of roadside parking and thus needs to avoid it (Fig. 9.17).

Those respondents, who willingly chose to park on the roadside, were asked to justify their responses. 51.6% of respondents feel that the walking distance from the vehicle to their destination is less when they park on the road. Less time required to park and better choice for a short stay is also an argument given by the respondents. They believe it is easy to park on roads and less time is required to park. So, they willingly chose roadside parking for their own sake of comfort and convenience.

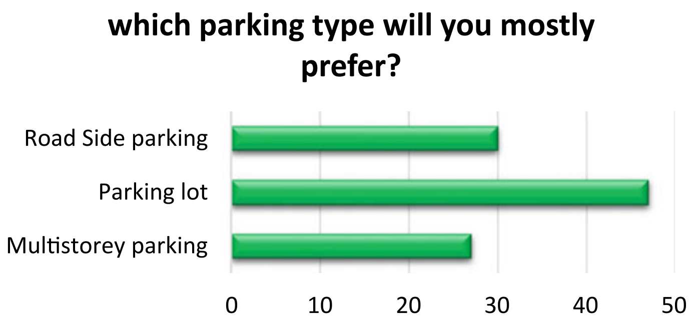


Fig. 9.17 Choice of parking

Here comes the role of towing vans and strict regulations by the Government. The strict regulations and heavy fines will change people's attitudes (Fig. 9.18).

The most important factor of Parking. The respondents were asked to rate the parking experience based on security, convenience, and cost. All these three factors were deemed necessary by the respondents, but the security of the vehicle was the top priority (Figs. 9.19, 9.20 and 9.21).

From the graph, we deduce that vehicle security is the respondents' top priority.

Convenience and cost of parking are also essential factors in parking. But they are overridden by vehicle security. The cost of parking was the least priority of the respondents. What matters the most while parking is the safety and security of the vehicles in addition to the convenience of the commuter (Fig. 9.22). Table 9.4 shows the major correlation between vehicle security, convenience, and the cost of parking.

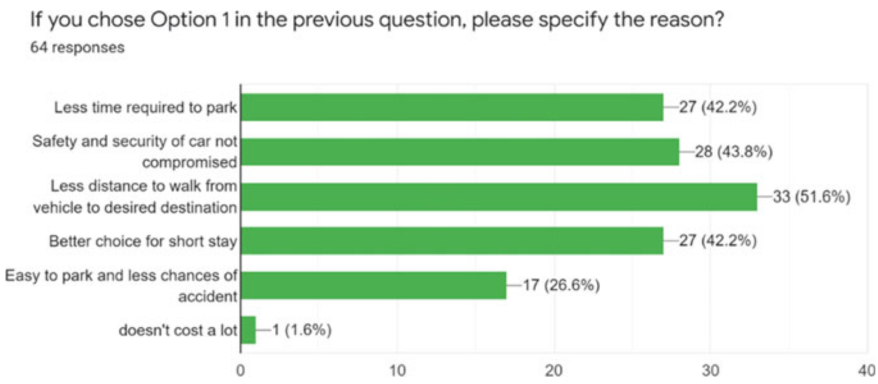


Fig. 9.18 Favorable reason for roadside parking

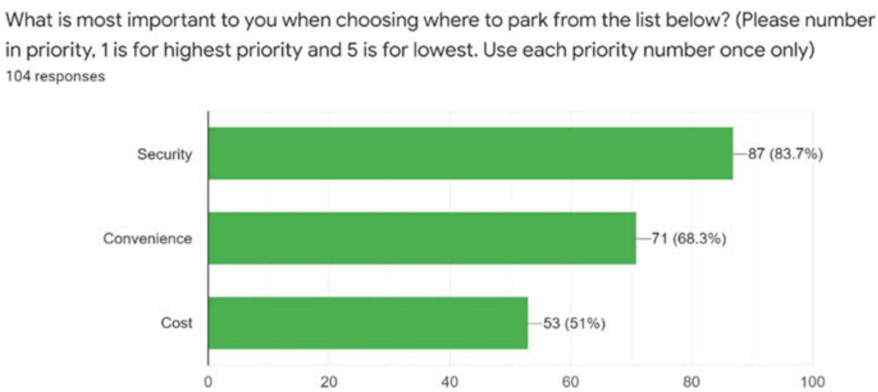


Fig. 9.19 Factors affecting parking

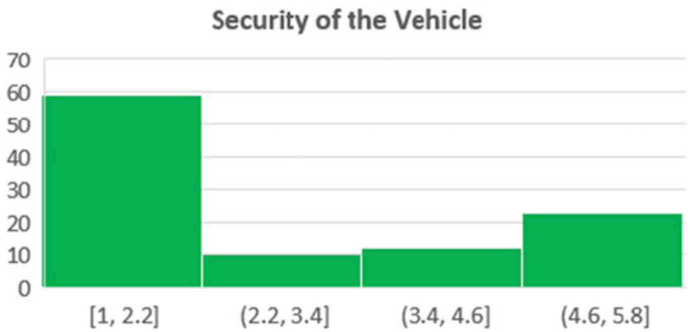


Fig. 9.20 Security as a factor affecting the parking

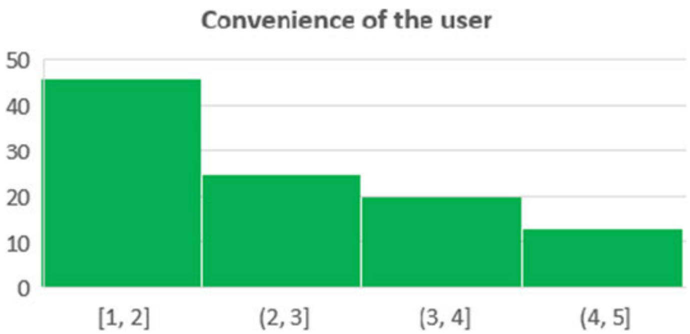


Fig. 9.21 Convenience as a factor affecting parking

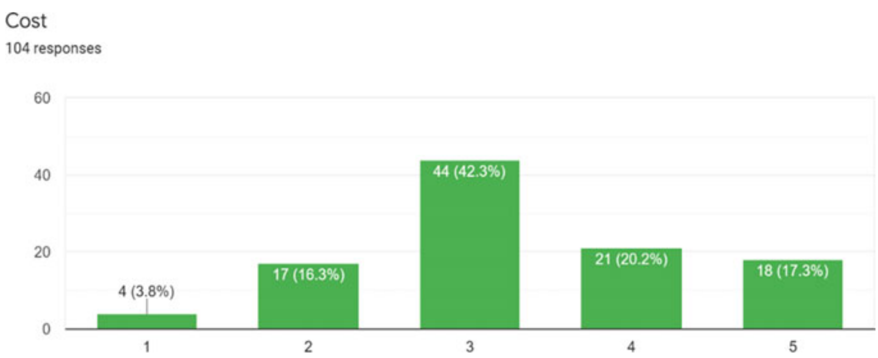


Fig. 9.22 Cost as a factor affecting parking

Table 9.4 Correlation between vehicle security, convenience and cost of parking

	Vehicle security	Convenience	Cost
Vehicle security	1		
Convenience	0.578217736	1	
Cost	0.319408622	0.207579295	1

Correlation between Vehicle security and convenience while parking

Vehicle security and convenience are slightly positively correlated. There is evidence for some association between these two variables.

Correlation between Vehicle security and Cost

Vehicle security and cost are positively correlated, but this value (0.3194) is relatively close to zero. So, there isn't strong evidence for a significant association between these two variables.

Correlation between Convenience and Cost

Vehicle convenience and cost are positively correlated, but this value (0.2075) is relatively close to zero. So, there isn't strong evidence for a significant association between these two variables. That is cost and convenience of parking do have an interrelationship.

Preference of Types of Parking

The respondents were shown in Fig. 9.23 and asked about their parking preferences. About 75% of the respondents chose Angled parking as their 1st preference, followed by perpendicular parking (Fig. 9.24). Parallel parking was the least preferred form of parking. Angled parking is the easiest parking method, and it is relatively easy to park and un-park the vehicle in this arrangement. Although parallel parking requires the least number of spaces, it is inconvenient for commuters.

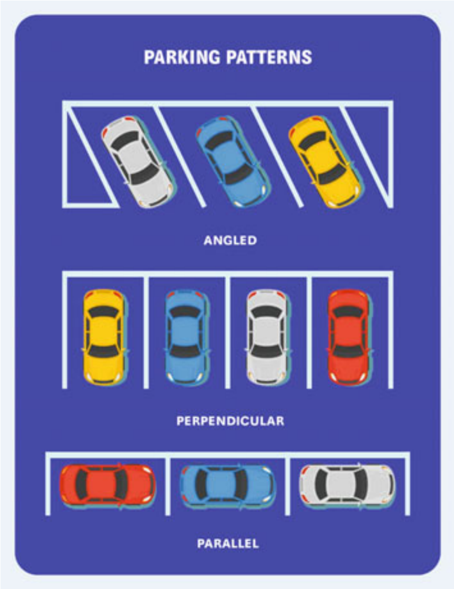


Fig. 9.23 3 Major types of parking patterns

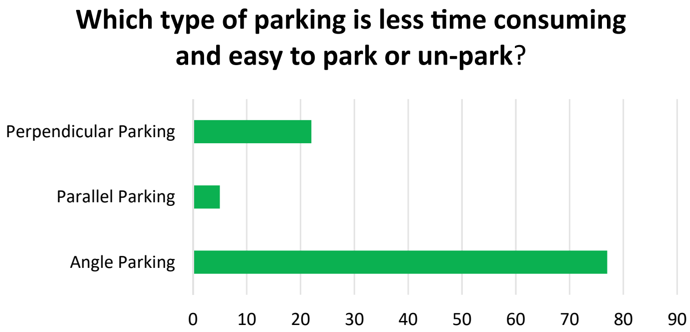


Fig. 9.24 Different types of parking patterns choice

Parking difficulties in a Parking Complex

In this section, questions were framed to assess the parking behavior of the residents while in a parking complex. They were asked to rate the following criterion based on their degree of coherence with the problem:

- Poor visibility (bad lighting, blind corners, etc.)—The majority of the participants were neutral about the visibility issue. They didn't find such an issue in a parking complex or didn't notice it. However, there is also a segment agreeing that such problems exist (Fig. 9.25).

Not enough walkways for Pedestrians—More than 50% of the respondents agreed that there are not enough walkways for pedestrians in the parking complexes. So, there are chances of accidents as there is not enough space for pedestrians and vehicles (Fig. 9.26).

Drivers are not operating vehicles carefully—The respondents strongly agreed with this proposition. They feel that the drivers are not operating the vehicles carefully in the lanes in the parking complexes. While reversing and turning, there is a risk of

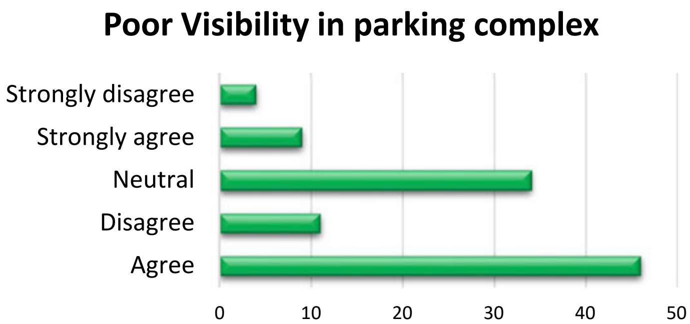


Fig. 9.25 Visibility at parking complexes

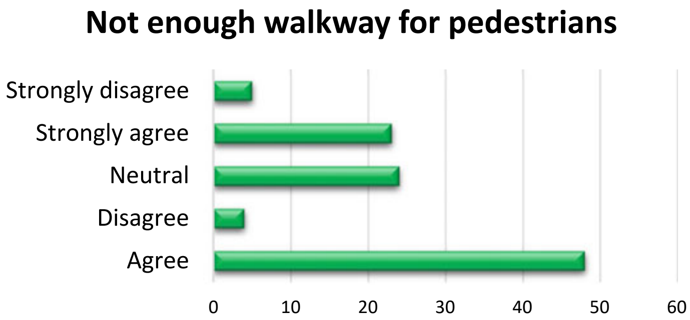


Fig. 9.26 Walkway for pedestrians

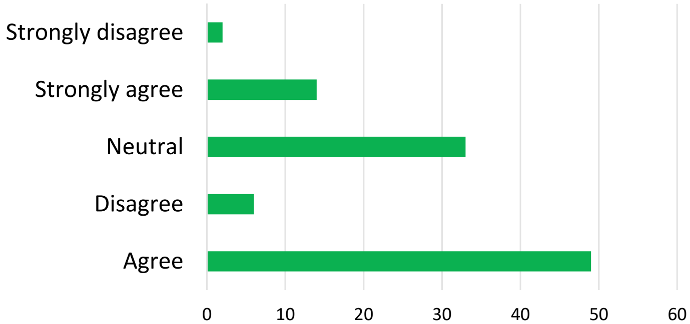


Fig. 9.27 Irresponsible driving of other drivers

collision. It also leads to wear and tear on the parked vehicles in the facility due to the collisions (Fig. 9.27).

Safety and Crowding in a Parking Complex

- Difficulty in finding parking spaces—More than 70% of the respondents agreed that they face difficulty in finding parking spaces in the parking lot (Fig. 9.28).
- Theft of personal property—The neutrality of the respondents reflects that they have reported no major cases of theft of personal belongings. So, theft of belongings is not a significant problem in the parking complexes (Fig. 9.29).
- Vehicle damage from other vehicles—None of the participants strongly disagreed with this proposition. It means that their vehicle has been damaged by other vehicles. Moreover, the trend followed by the majority reflects that almost every respondent faced vehicle damage in the parking lots (Fig. 9.30).
- Crowded (too many vehicles, people, etc.)—We can deduct from the graph that the parking facilities were crowded mostly as the trend of responses is toward ‘agree’ and ‘strongly agree’ (Fig. 9.31).

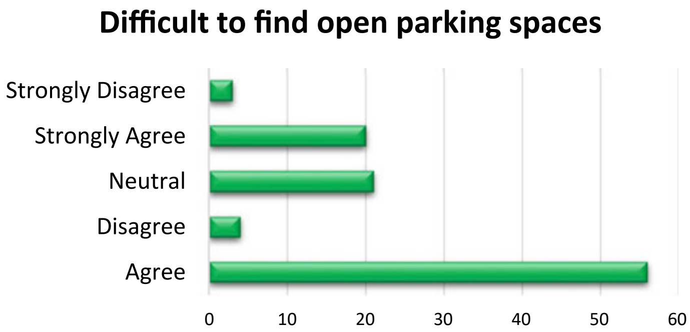


Fig. 9.28 Difficulty in finding parking space in the parking lot

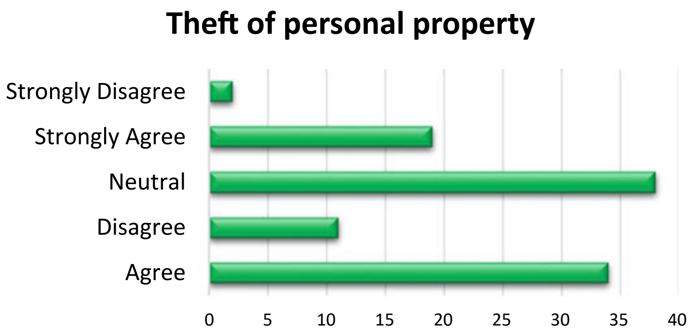


Fig. 9.29 Theft of belongings from the parking lot

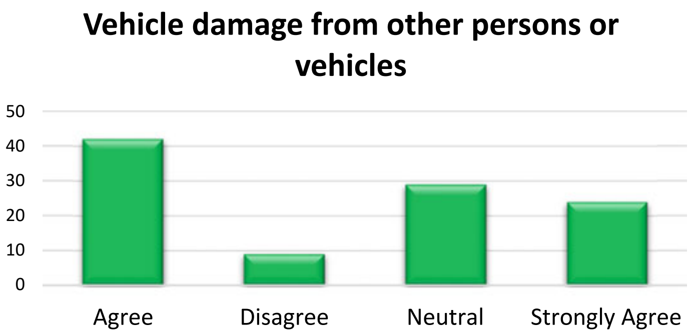


Fig. 9.30 Damage from the collision with other vehicles

Poorly Parked vehicles—There is a solid consensus among the respondents that the vehicles are parked poorly in the complexes. The commuters do not park their vehicles sequentially or properly (Fig. 9.32). Table 9.5 depicts the correlation between the various factors contributing to safety and crowding.

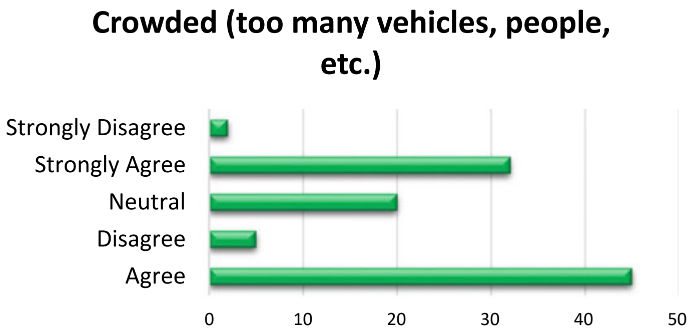


Fig. 9.31 Crowding in the parking lot

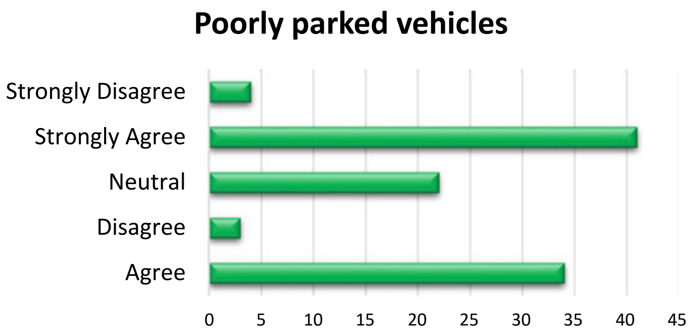


Fig. 9.32 Poorly parked vehicles

Correlation between difficulty in finding parking space and theft of the vehicle

These two factors are positively correlated, but this value is near zero. There isn't strong evidence for a significant association between the two.

Correlation between poorly parked vehicles and Difficulty in finding parking space

The score of 0.6139 suggests that these two factors are strongly positively correlated. That is the difficulty in finding a parking space results from poor and irregular parking behavior at the complexes.

Correlation between Crowd and Difficulty in finding parking space

Crowds and difficulty in finding parking spaces are also strongly positively correlated. It's evident that more crowds will increase parking demand, and thus people will face difficulty finding a parking spot. A score of 0.6139 suggests the same.

Table 9.5 Correlation between the various factors contributing to safety and crowding at the parking complexes

	Difficult to find open parking spaces	Theft of vehicle	Vehicle damage from other persons or vehicles	Crowded (too many vehicles, people, etc.)	Poorly parked vehicles
Difficult to find open parking spaces	1				
Theft of vehicle at parking complex	0.414577821	1			
Vehicle damage from other persons or vehicles	0.546448564	0.55873319	1		
Crowded (too many vehicles, people, etc.)	0.61359647	0.482208688	0.485037378	1	
Poorly parked vehicles	0.613968931	0.426744698	0.396045695	0.75143513	1

Correlation between Crowd and Poorly parked vehicles

The crowd and poorly parked vehicles are strongly positively correlated. That is, poorly parked vehicles lead to crowding. Strong evidence (0.7514) shows the dependency between these two variables.

Correlation between Crowd and vehicle damage at the parking

Surprisingly, there was a slightly positive correlation between crowd and vehicle damage. The value of 0.4145 is relatively close to zero. So, there isn't any substantial evidence to suggest a significant association.

Difficulties at access points of the parking lot

The survey suggests that there is difficulty at the access point. Some have strongly agreed to access difficulty. However, only a few strongly disagreed with access difficulty due to their own facility/fewer available vehicles (Fig. 9.33).

Difficulty turning into a lot from the street—Equal responses are received for neutrality and agreement. So, there is a conflict of opinion in this scenario (Fig. 9.34).

- Difficulty exiting the parking lot to the street—The majority of the respondents agreed that they encounter difficulty exiting the parking lot to a street (Fig. 9.35).

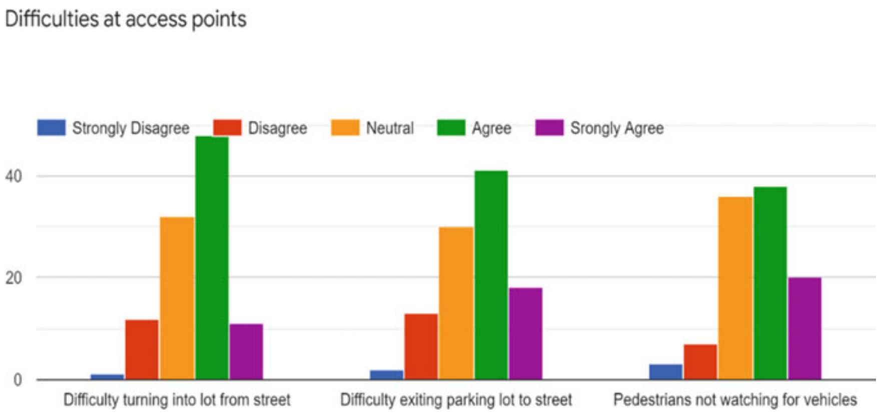


Fig. 9.33 Difficulty at the access point

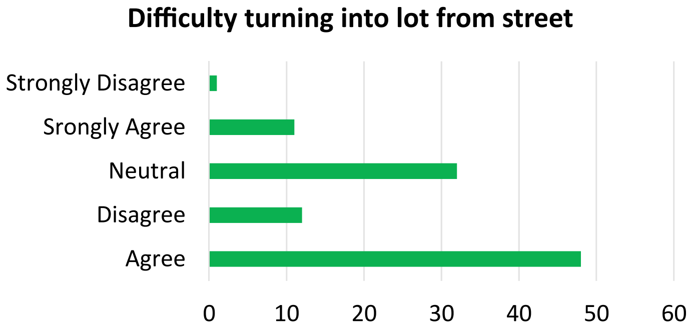


Fig. 9.34 Difficulty turning into the lot from the street

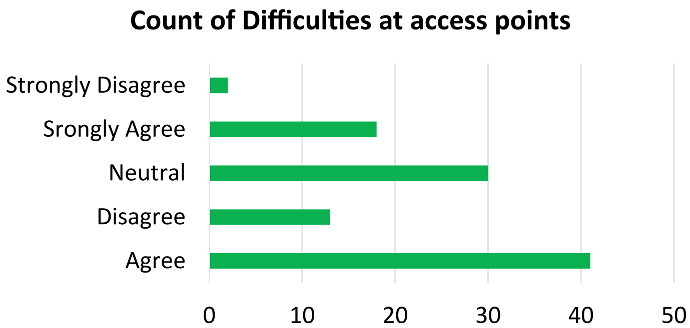


Fig. 9.35 Count of difficulties at the access point

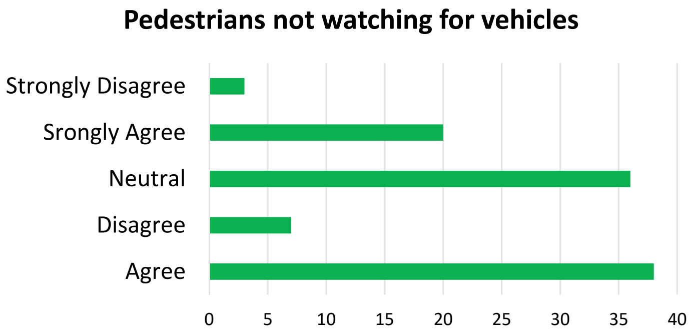


Fig. 9.36 Pedestrians not watching for vehicles

Table 9.6 Correlation between difficulty in entry and exiting the parking lot

	Difficulty turning into the lot from the street	Difficulty exiting the parking lot to the street	Pedestrians not watching for vehicles
Difficulty turning into the lot from the street	1		
Difficulty exiting the parking lot to the street	0.55358230	1	
Pedestrians not watching for vehicles	0.46180562	0.311643493	1

- Pedestrians not watching for vehicles—Pedestrians are roaming carelessly and not watching for the vehicles running in and out of the complexes (Fig. 9.36). Table 9.6 represents a correlation between difficulty in entry and exiting the Parking lot.

The correlation matrix value of 0.5535 suggests a slightly positive correlation. This value is someway between 0 and 1. So, we cannot draw a clear conclusion about the association between the two variables.

9.4 Conclusions and Recommendation

There is high vehicle ownership in the city due to a lack of proper public transport infrastructure. Citizens are forced to use personal transportation due to the lack of public transportation. The parking facilities in the city are inadequate, resulting in illegal occupation of the streets in the city. To assess the public perception of the parking problem. A survey of more than 100 residents of the city was taken, and the following were the results:

1. The current parking condition in the city: 95% of the respondent were not satisfied with the current parking situation on the road. The core parking problem is the unavailability of a suitable parking spot. Other problems include vehicle safety, lack of awareness among citizens, and a smaller number of dedicated parking complexes in the city. Commuters parking in front of shops and residents parking their vehicles on the road are the main reason for parking problems in the city. About 70% of the parking issues happened in the evening between 3 and 8 p.m.
2. Parking as a Location Factor: About 90% of the respondents faced parking constraints in the market. Railway stations and buses stand for more than half of the responses. There were enough parking spaces at the resident's and working places for most of the people. Free parking on the streets is prevalent in the city. Free parking on streets is easy for citizens, but finding space is hectic.
3. Parking Pricing: More than 80% of respondents are certain they will pay for parking if they are promised a spot. So, we conclude that residents do not want free parking; they want efficient parking services and are ready to pay for it. Only about half of the respondents were aware of the parking charges in the city. There is a lack of awareness about parking charges. They are ready to pay up to Rs. 10 per hour for parking.
4. Public preference for parking: People have a solid consensus to park their vehicles in parking lots instead of roadside parking. But there was a significant section which is keen on roadside parking. So, we tried to figure out the reason for the same. Less walking distance from the vehicle to the desired destination motivated them to follow the roadside parking. They willingly choose roadside parking for the sake of their comfort. The respondents were asked to rate their parking experience based on the security of vehicles, convenience, and cost of parking. The security of vehicles is the most critical factor people consider while parking. Angled parking was the most preferred parking mode by the people.
5. Difficulties in parking complexes: Poor visibility, bad lighting, lack of walkways for the pedestrians, and irresponsible attitude of the driver, create the risk of collision while turning and reversing the vehicle. Usually, the parking complexes are too crowded, and the vehicles are poorly parked. Also, people encounter vehicle damage from other vehicles. Entry and exit points of the parking complexes were problematic for commuters.

Based on the study, the following recommendations can be drawn:

- The current practice of free on-street parking needs to be changed. Charging higher on-street parking charges will make change in people's behavior.
- Increasing the existing parking supply in central business district (CBD) areas to meet the increasing demand.
- Increasing the parking fees discourages people from using Private vehicles and shifting to public transport.
- Multilevel parking is required to increase the supply to avoid the new land acquisition for the parking.
- Policymakers should keep proper guidance and information system for parking prices in mind.

Appendix (Survey Questionnaire)

Part 1:

Name
Age*

18–25
25–35
35–45
>45

Gender

Male
Female
I prefer not to say

Current Status

Employed
Student/Unemployed

Income level

Less than 2.5 Lakhs per annum
2.5–5 Lakhs per annum
5–10 Lakhs per annum
10 Lakh Per Annum +

Number of 2-wheelers you own
If you don't own a 2-wheeler, please respond with N.A.
Number of 4-wheelers you own
If you don't own a 4-wheeler, please respond with N.A.

Part 2:

Are you satisfied with the current parking situation on the roads?

Yes
No

What, according to you, is the core problem with parking?

Finding the place to park
Vehicle Safety
Parking fare
Other:

Do you believe that illegal parking on roads causes traffic congestion?

Yes

No
Maybe

What do you consider are the main reasons for the parking problems on the road?

Commuter parking
Commercial vehicles
Shopper parking
Some households have too many vehicles
Residents from neighboring roads parking
Other:

When do you consider the parking issues on your road mainly occurring?

Daytime (e.g., 8 a.m. to 12:00)
Noon (12:00 to 3 p.m.)
Evening (e.g., 3 to 8 p.m.)
Weekends.
24/7 (weekdays and weekends).

Part 3:

Do you agree that parking should be supplied free of charge to the residents? *

Strongly disagree
Disagree
Neutral
Agree
Strongly agree

Do you agree that parking should be supplied free of charge to the commuters? *

Strongly disagree
Disagree
Neutral
Agree
Strongly agree

Are you prepared to pay parking charges if you get assured parking space? *

Yes
No
Maybe

Are you aware of the parking charges in the city? *

Yes
No
Maybe

Should parking prices be calculated based on the exact parking time and not per hour or any other fixed period? *

Yes
No
Maybe

If parking charges are taken from you, will you use a private vehicle? *

Yes
No
Maybe

If yes, then up to what level will you pay the parking charge per hour? *

10
15
20
30

Part 4:

Which places are difficult for you to park in? *

Offices
Multiplexes/Malls
Railway/Bus Station
Airport
Markets
Temples
Other:

Are there enough parking spaces in your residence? *

Yes
No

Are there enough parking spaces in your working premises? *

Yes
No

Are you able to find a space to park without too much difficulty in Resident Permit Zone? *

Yes
No
Sometimes

Are you able to find a space to park without too much difficulty in Non-Resident Permit Zone? *

Yes
No

Are you able to find a space to park without too much difficulty in 'Free on Streets'?*

Yes
No
Sometimes

Part 5:

Suppose you have to visit a marketplace, and parking space is available. Which parking type will you most prefer? *

Road Side Parking
Multistory Parking
Parking lot

If you chose Option 1 in the previous question, please specify the reason.

Less time is required to park
Safety and security of car not compromised
Less distance to walk from the vehicle to the desired destination
The better choice for a short stay
Easy to park and fewer chances of an accident
Other:

What is most important when choosing where to park from the list below? (Please number in priority, one is for the highest priority, and five is for the lowest. Use each priority number once only) *

Security
Convenience
Cost

Vehicle Security*

Highly secured
1
2
3
4
5
Least secured

Convenience*

Highly convenient
1
2
3
4
5

Least convenient

Cost*

High cost
1
2
3
4
5
No cost

Which type of parking is less time-consuming and easy to park or un-park? *

Perpendicular Parking
Parallel Parking
Angle Parking

Part 6:

For a better understanding, below are some factors affecting parking behavior. We would like to know whether or not these problems are faced by you while parking your vehicle*

Strongly disagree
Disagree
Neutral
Agree
Strongly agree

Poor visibility (bad lighting, blind corners, etc.)
Not enough walkways for pedestrians
Drivers not operating vehicles carefully

Layout and design*

Strongly disagree
Disagree
Neutral
Agree
Strongly Agree
The poorly designed parking structure

Safety and crowding*

Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree

Difficult to find open parking spaces
Theft of personal property
Vehicle damage from other persons or vehicles
Crowded (too many vehicles, people, etc.)
Poorly parked vehicles

Difficulties at access points*

Strongly Disagree
Disagree
Neutral
Agree
Strongly Agree

Difficulty turning into the lot from the street
Difficulty exiting the parking lot to the street
Pedestrians not watching for vehicles

References

1. Litman, T.: Parking Management Strategies, Evaluation and Planning [Internet]. 2021 [cited 2022 May 12]. Available from: https://www.vtpi.org/park_man.pdf
2. Evaluation of Parking Characteristics: A case study of Delhi - ScienceDirect [Internet]. [cited 2022 May 12]. Available from: https://www.sciencedirect.com/science/article/pii/S235214652030661X
3. Pressl, R., Rye, T.: Park4SUMP - Parking management as game changer for urban mobility. [cited 2022 May 11]. Available from: https://park4sump.eu/sites/default/files/2020-02/PARK4SUMP_good%20reasons_and_principles_4_parking_management_0.pdf
4. Litman, T: How More Efficient Parking Pricing Can Help Solve Parking and Traffic Problems, Increase Revenue, and Achieve Other Planning Objectives. 2018 Apr 11; 35. Available from: https://cob.org/wp-content/uploads/todd-litman-parking-pricing-implementation-guidelines-2013.pdf
5. History of Vadodara - Baroda [Internet]. History of Vadodara - Baroda. [cited 2022 May 11]. Available from: https://historyofvadodara.in/
6. Vadodara City Population Census 2011–2022 | Gujarat [Internet]. [cited 2022 May 11]. Available from: https://www.census2011.co.in/census/city/338-vadodara.html#futurepop
7. Parking Policy for Vadodara City. 2019 Apr; 87. Available from: https://vmc.gov.in/pdf/VADODARA%20CITY_%20PARKING%20POLICY_(ENGLISH).pdf
8. Parking Management Strategies for Vadodara 2040 | CEPT - Portfolio [Internet]. [cited 2022 May 15]. https://portfolio.cept.ac.in/fp/strategic-plan-for-urban-transport-system-ut4000-spring-2019/parking-management-strategies-for-vadodara-2040-spring-2019-pg180145

Chapter 10
Performance of Highway Subgrade Soil Stabilized with Lime and Slag

Nivedita Panda, Sanjukta Sahoo, and Hemalata Jena

Abstract As soil is the major component of highway transport system, it is essential to check the performance of soil for its strength and plasticity before design and develop any transport related infrastructure. Soft or weak soil faces many difficulties leading to collapse of structures. Soil stabilization is a technique used to maintain or improves the quality and stability of weak soils to achieve the required engineering goals. For enhanced effect of soil stabilization, industrial wastes have been proved promising as admixture. However, the exact content of particular admixture for clayey soil plays an important role in stabilizing and strengthening soil. In this research work, the authors are presenting the experimental results in evaluating the engineering performance of expansive subgrade soil stabilized with lime and Ground Granulated Blast-furnace iron Slag (GGBS). The work methodology includes the stabilization of the expansive soils with various percentages of lime and slag to determine the soil properties and to find their optimum content of stabilization. Extensive laboratory testing has been conducted to determine the soil properties such as consistency, compaction, swelling characteristics, unconfined compressive strength and bearing capacity to depict strength and deformation behavior of the subgrade material. The soil properties were found as increasing continuously up to 11% by the treatment with GGBS and with the addition of lime, the values were observed continuously increasing up to 7% and then decreasing.

Keywords Highway subgrade · Stabilization · Iron slag and lime

N. Panda · S. Sahoo (✉)
Department of Civil Engineering, KIIT Polytechnic, Bhubaneswar 751024, India
e-mail: sanjuktafce@kp.kiit.ac.in

N. Panda
e-mail: Nivedita.pandafce@kp.kiit.ac.in

H. Jena
School of Mechanical Engineering, KIIT Deemed to be University, Bhubaneswar 751024, India
e-mail: hemalata.jenafme@kiit.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_10

10.1 Introduction

First rate urbanization and huge construction of structures need hard and strong soil layers beneath its foundation level [1, 2]. Soil, when used as a subgrade or base material should possess adequate strength and stability under applied load with controlled deformation. However, soft or clayey soils (soil particles < 0.002 mm diameter) face various challenges during design and construction of structures such as foundation, embankments, dams, retaining walls and pavement for their low bearing capacity, low shear and compression strength, large swelling and settlement characteristics and high compressibility [3–5]. Such type of soils require modification of its physical, chemical and biological properties by treating with different types of soil stabilizing agents [6–9]. So, stabilization is needed for soft soil to enhance its shear strength and to limit deformation.

Soil stabilization is the process of modification of the soil properties to improvise its engineering performance in context of structure, texture, strength, plasticity, bearing capacity, swelling and settlement activities etc. [10, 11]. These days the industrial wastes such as fly ash, slag, cement dust, stone dust have been reported as the cost effective and environment friendly soil stabilizers [12–14]. The addition of admixture in soil has shown significant effect on soil properties. However, to achieve enhanced stabilization potential, proper proportion and suitable combination of soil and admixture is a matter of concern. Though huge numbers of investigations are going on for searching suitable materials and its proportion, the optimized result is yet to come. The main objectives of this research are to investigate and compare the engineering performances of iron slag and hydrated lime on a soft or expansive soil. For such investigation, three types of local soil from different parts of Odisha have been collected and their different engineering properties have been compared to find out the weakest soil among them. Further, the weakest soil has been treated with the industrial waste Ground Granulated Blast Furnace iron slag in five different levels of 5, 7, 9, 11 and 15% and with hydrated lime in four different levels of 3, 5, 7, 9% to study and compare the corresponding engineering performances to find out the exact range or content of the particular admixture.

10.2 Experimental Program

In the experimental work, the three different types of soft or clayey soils were collected from different locations such as Nandankanan road, Baranga railway station nearby area of Bhubaneswar and from Jhumpura area of Keonjhar as displayed in Fig. 10.1. The required engineering properties of the above soils have been conducted through various tests in the laboratory to select the most susceptible soil requiring stabilization. The grain size distribution of the soils was conducted as per IS: 2720 (part-4) 1985 using different size of sieves [15] and the grain size distribution curves for the three soils is shown in Fig. 10.2.

Fig. 10.1 Soil sample 1, 2 and 3

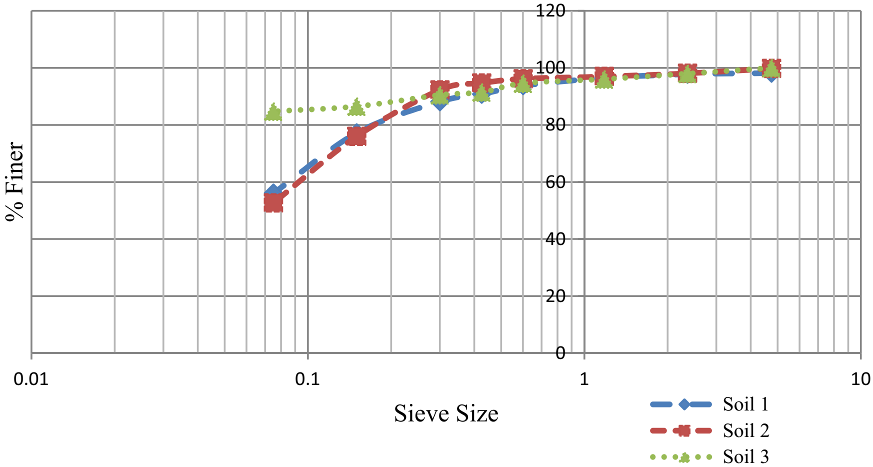


Fig. 10.2 Grain size distribution of soil samples

The consistency of the above three soils have been checked through liquid limit, plastic limit and shrinkage limit tests. The liquid limit and plastic limit of the soils were obtained as per IS: 2720 (part 5)–1985 [16] and the shrinkage limits of soils were obtained as per IS: 2720 (part 6)–1972 [17]. The corresponding results of the above tests were displayed in the Table 10.1.

The specific gravity of the three types of soil were conducted as per IS: 2720 (part 3)–1980 [18]. The compaction characteristics of the three soils were studied by Standard proctor test (AASHTO test) as shown in the Fig. 10.3. The optimum moisture content and maximum dry density were obtained in accordance with IS: 2720 (part 7)–1980 [19]. The results of all the tests conducted on the 3 types of soil are summarized in a tabular form and presented in Table 10.1.

From the study of above three types of soil, it is found that from wet sieve analysis maximum number of fine particles of 84.8% passed through 75 micron sieve in soil 3, which is more than that of soil 1 and 2 indicating the presence of more fines in soil

Table 10.1 Test results pertaining to soil samples

Test conducted	Soil 1	Soil 2	Soil 3
Wet sieve analysis (% Finer through 75 microns)	56.1	52.7	84.8
Swelling index	0	0	57.50%
Specific gravity	2.57	2.54	2.44
Liquid limit (%)	40.1	26.57	60
Plastic limit (%)	23.58	22.05	22.28
Shrinkage limit (%)	13.17	8	12.87
Optimum moisture content (OMC) (%)	14	14	23.52
Maximum dry density (MDD)	1.74	1.82	1.53
AASHTO	A-5	A-4	A-7–6
Group index (GI)	7	0	33

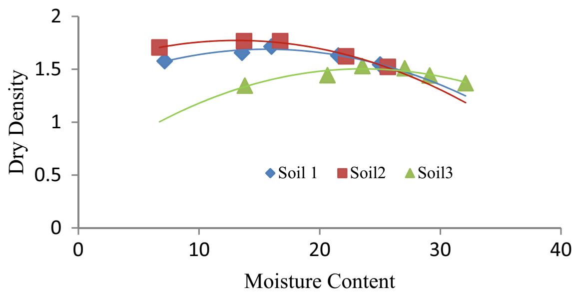


Fig. 10.3 Compaction curves for soil samples

3. In addition to that, the liquid limit of soil 3 is 60% which is much more high than that of soil 1 and 2, and as the liquid limit exceeds 40% so it is clearly indicating as a clayey soil. Further, the soil 3 can also be included in expansive soil as the swelling index value is 57.50%. As per the conditions of American Association of State Highway and Transportation Officials (AASHTO) classification, the soil 3 is included in A-7-6[b], so its constituent materials are clay. Likewise, the group index (GI) value as calculated for the three soils, and the value of soil 3 was found as higher among them, i.e., 33. So, the Soil 3 was considered as a weak soil. After analyzing all the results, it was concluded that Soil 3 that was collected from Keonjhar area was the poor soil so it was chosen for stabilization. To improvise its engineering properties such as strength and stability, the soil was treated with iron slag and lime as admixture with partial replacement.

The iron slag collected from Barbil and the commercially available lime were used as stabilizing agent on the soil 3 as shown in Fig. 10.4. The grain size distribution of the slag and the lime were conducted as per IS: 2720 (part 4) 1985. The specific gravity tests were conducted as per IS: 2720 (part 3) 1980 and found 4.15 for iron slag and 2.31, respectively.

Fig. 10.4 Iron slag and lime used in the experiments

10.2.1 Tests on Iron Slag stabilized and Lime stabilized Soil

The soil samples were prepared with various percentages of slag content (5%, 7%, 9%, 11% and 15%) and lime content (3%, 5%, 7%, 9%) to give rise iron slag stabilized soil and lime stabilized soil. To observe the effects of stabilization on the various engineering properties of soil, the following tests have been conducted on both the types of soil samples as per required IS code.

10.2.1.1 Consistency Tests

To observe the effects of admixtures on the consistency limits of stabilized soil, the liquid limit, plastic limit and shrinkage limit tests were conducted as per IS: 2720 (part 5)–1985 using the Casagrande's apparatus.

10.2.1.2 Compaction Tests

Standard proctor tests (AASHTO) were conducted on all the stabilized soil samples to determine and study the compaction characteristics. The optimum moisture content and maximum dry density were obtained in accordance with IS: 2720 (part 7)–1980.

10.2.1.3 Free Swelling Tests

To observe the effects of iron slag on the expansive behavior of clayey soil, free swelling tests were conducted on samples with different proportions of slag and lime contents.

10.2.1.4 Unconfined Compression Strength (UCS) Tests

The primary purpose of the Unconfined Compression Test is to quickly determine a measure of the unconfined compressive strength of rocks or fine-grained soils that possess sufficient cohesion to permit testing in the unconfined state. This measure is then used to calculate the unconsolidated undrained shear strength of the clay under unconfined conditions. The tests were conducted as per IS 2720 (part 10)–1991. For all the tests, samples with 38 mm diameter and 76 mm height were prepared and tested.

10.2.1.5 California Bearing Ratio (CBR) Tests

The California bearing ratio is a penetration test for evaluation of the mechanical strength of natural ground, subgrade and base courses beneath new carriageway construction. The tests were conducted in accordance with IS: 2720 (part 16)–1987 [20].

10.3 Result and Discussion

10.3.1 Iron Slag Stabilized Soil

The soil test results such as Liquid Limit, Plastic Limit, optimum moisture content (OMC) and maximum dry density (MDD), swelling index, unconfined compressive stress (UCS) and California bearing ratio (CBR) of unstabilized soil and slag stabilized soil are presented in Table 10.2. In addition, the compaction curve, unconfined compressive strength and the CBR curves for unstabilized soil and slag stabilized soils at different level are presented in Fig. 10.5, 10.6 and 10.7.

The test results indicate that Liquid Limit of the original soil is 60% and by adding Iron slag in different proportions, it gradually decreases from 5 to 11%. The Liquid Limit of soil is found minimum at 11% slag content (45.54%) and it increases again with 15% Iron slag content. So up to 11% of slag addition, the soil will produce best engineering performances with lower compressibility and lower shrinkage/swelling potential [21–23]. The Plastic Limit of soil is found maximum at 5% slag content (27.36%) and it decreases continuously with increase in slag content.

From the compaction curve, it was observed that, OMC of the original soil was 25% which decreased with increase in addition of iron slag up to 11% and then remained constant from 11% onwards. Maximum dry density of the original soil was obtained as 1.55 g/cm^3 which gradually increased with increase in iron slag percentage. With 15% iron slag admixture, MDD was observed to be 1.75 g/cm^3 which were the highest. From the compaction test results it was confirmed that up to

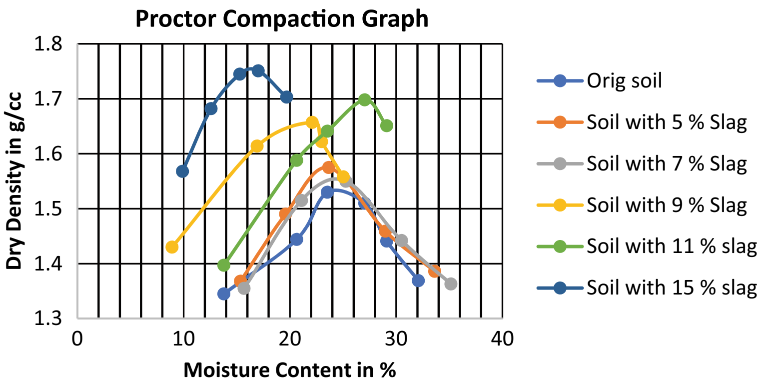


Fig. 10.5 Compaction curves of unstabilized soil and slag stabilized soil

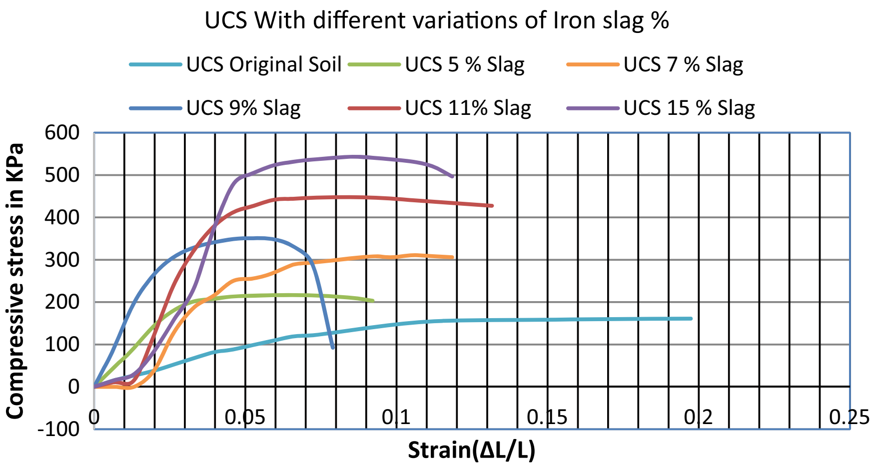


Fig. 10.6 UCS curves for unstabilized soil and slag stabilized soil

11% slag addition, the soil properties will increase with increased strength, decreased permeability and compressibility [24, 25].

It was also observed from the UCS test results that the peak compressive stress increases with increase in slag content. The results indicated that iron slag was effective in increasing shear strength of soil [26]. The CBR tests results indicated that the CBR value of soil increased with percentage of slag content. The highest value of CBR was obtained for 15% slag stabilized soil.

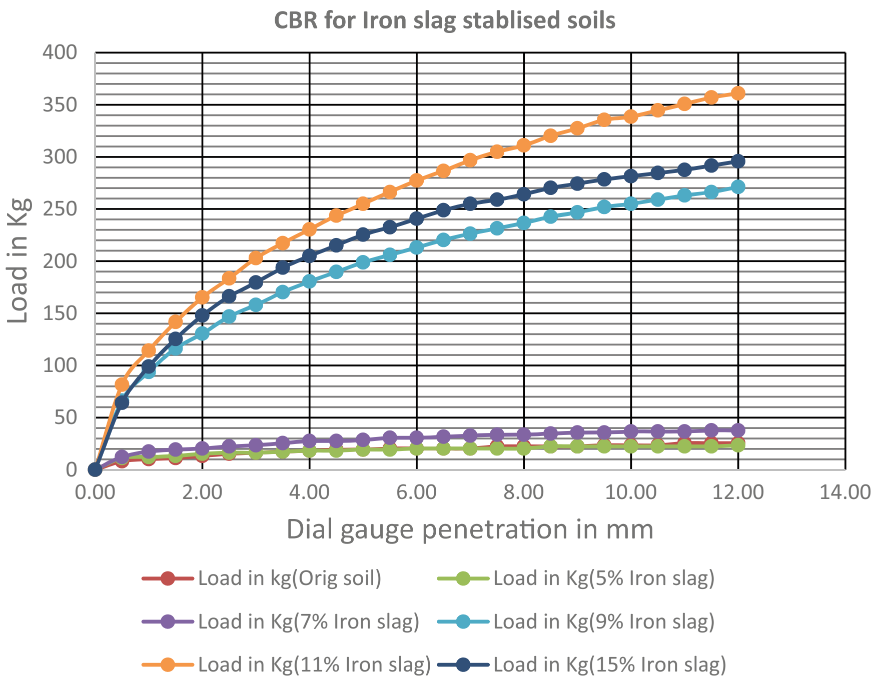


Fig. 10.7 Load versus penetration curve for unstabilized and stabilized samples

Table 10.2 Soil properties of unstabilized and iron slag stabilized soil

Test conducted	Original soil	Soil with 5% slag	Soil with 7% slag	Soil with 9% slag	Soil with 11% slag	Soil with 15% slag
Liquid limit (%)	60	57	53.50	46.20	45.44	47.69
Plastic limit	22.28	27.36	26.13	26.23	26.30	19.43
OMC (%)	25	24.5	20.5	19.5	17	17
MDD	1.55	1.59	1.63	1.66	1.70	1.75
Swelling index	57.5	53	50	40	30	20
UCS (Peak strength in kPa)	161.02	216.32	310.67	350.88	447.73	543.32
CBR (Unsoaked)	1.116	1.190	1.636	10.718	13.398	12.132

10.3.2 Lime Stabilized Soil

The soil test results of unstabilized and lime treated soil for Liquid Limit, Plastic Limit, Plasticity Index, OMC and MDD, swelling index, unconfined compressive stress and California bearing ratio are presented in Table 10.3.

The curves between dry density (g/cc) and moisture content for different lime soil mix were plotted and presented in Fig. 10.8 to obtain MDD and OMC. It was observed that, the Liquid Limit value decreased with increase in lime admixture percentage from 3 to 7%. It reached a minimum of 36.80 at 7% and then increases with 9% lime admixture content. So up to 7% lime content, stabilization will help the soil to enhance the soil performance with low compressibility and low shrinkage/swelling potential [21, 22]. From the index study results, it is concluded that the Plasticity Index of soil decreased significantly with addition of lime and maximum reduction was observed at 7% lime addition. Thus, it can be interpreted as increased interlocking of soil structure formed due to different sizes soil granules which will lead friction in between particles to keep the structure safe [23].

In the compaction tests, as shown in Fig. 10.8, the OMC of the original soil got reduced from 25% to a minimum of 19.85% at 7% lime admixture. OMC then increased from 7 to 9% lime admixture. Thus, the soil properties will be enhanced with increased strength and decreased permeability and compressibility with increasing percentages of lime content only up to 7% [24, 25]. The MDD of the original soil increased from 1.55 g/cm^3 to a maximum of 1.676 g/cm^3 at 3% lime admixture proportion and then reduces with increase in lime admixture content. However, it was observed that the MDD attained for lime treated soils was higher than untreated soil irrespective of proportion of lime. The swelling index of soil was found decreasing with increasing lime content up to 7% and then it increased slightly. Thus, it can be concluded that lime is effective in controlling the expansiveness of the clayey soil [26]. Likewise, the UCS of the original soil was found as160.51 KN/m^2.

Table 10.3 Soil properties of unstabilized and lime stabilized soil

Test conducted	Original soil	Soil with 3% lime	Soil with 5% lime	Soil with 7% lime	Soil with 9% lime
Liquid limit (%)	60	44.25	43.40	36.80	41.80
Plastic limit	22.28	24.3	26.09	28.57	21.95
Plasticity index	37.72	19.95	17.31	8.23	19.85
OMC (%)	25	15.75	19.76	19.85	20.49
MDD	1.55	1.676	1.644	1.619	1.616
Swelling index	57.5	30.76	23.07	11.53	15.38
UCS (after 7 days) in kPa	161.02	200.14	359.29	692.95	416.29
CBR (Unsoaked)	1.116	14.588	16.003	23.148	21.138

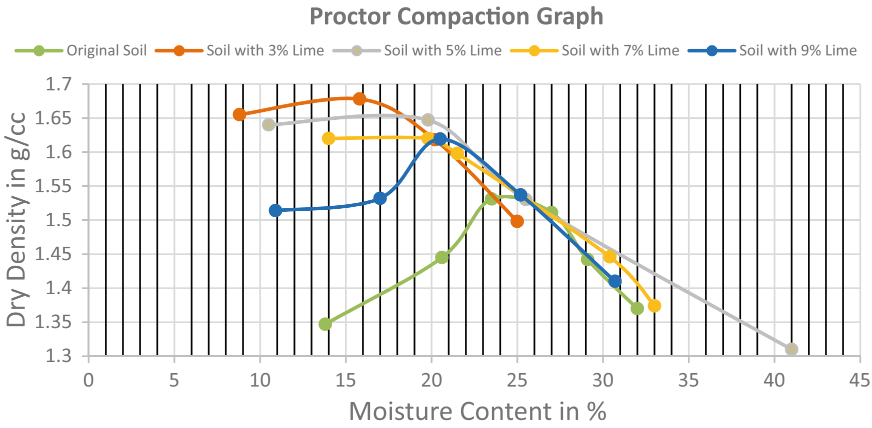


Fig. 10.8 Compaction curves for different lime mixed sample

It increased with lime admixture content and reached a maximum value of 692.95 KN/m^2 at 7% lime content, then it decreased with further increase in lime content and again at 9% it reached a value of 416.29 KN/m^2. From Fig. 10.9, the CBR value for original soil was found 1.09%. The value increased with addition of lime and reached a value of 23% at 7% lime content. With further increase in lime content, the CBR value reduced and reached a value of 20.7% at 9% lime content.

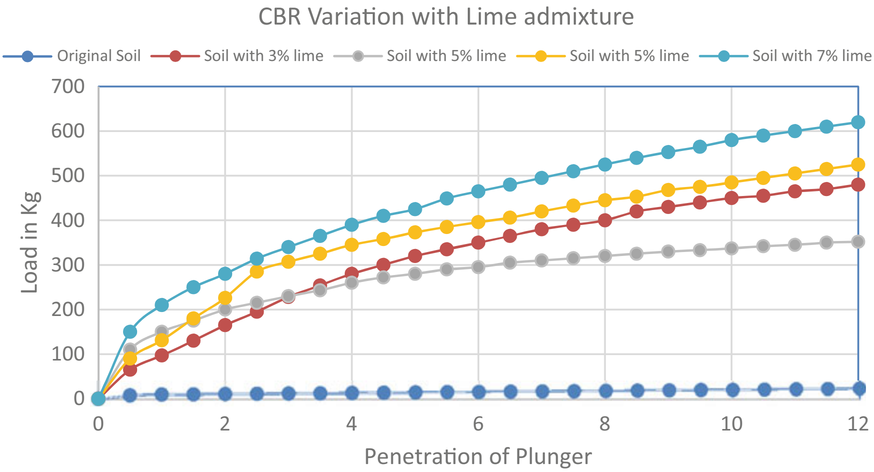


Fig. 10.9 California bearing ratio at different proportions of lime admixture content

10.3.3 Comparative Analysis of Soil Properties Stabilized with Iron Slag and Lime

As shown in the comparative analysis charts (Figs. 10.10, 10.11, 10.12, 10.13, 10.14 and 10.15) of the iron slag stabilized and lime stabilized soil samples, it has been observed that both the admixture have performed well in enhancing the soil properties by decreasing swelling, compressibility potential, however, the lime addition has marked effect compared to slag. Further, the maximum dry density of soil was found to be very high in case of lime addition as compared to slag, whereas the free swelling index with slag mixing was found to be higher than that of lime mixing. Though both the admixtures have helped the soil to improve the CBR value, the lime addition has significant effect than that of slag addition.

From Fig. 10.16, the unconfined compressive strength in case of lime as admixture performed very well up to 7% and after that it has shown poor result. However, in comparison to slag it has shown very high potential.

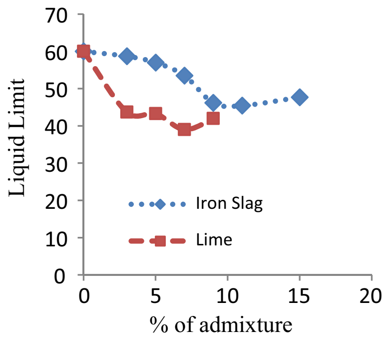


Fig. 10.10 Variation of liquid limit wrt % of admixtures

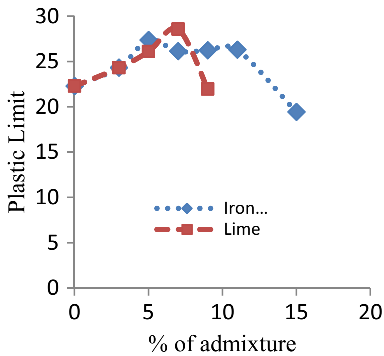


Fig. 10.11 Variation of plastic limit wrt % of admixtures

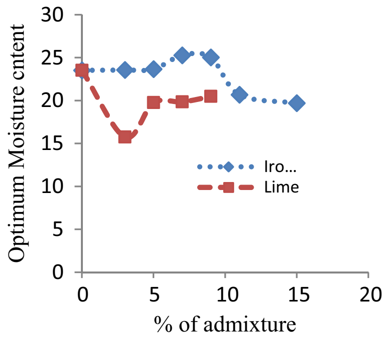


Fig. 10.12 Variation of optimum moisture content wrt % of admixtures

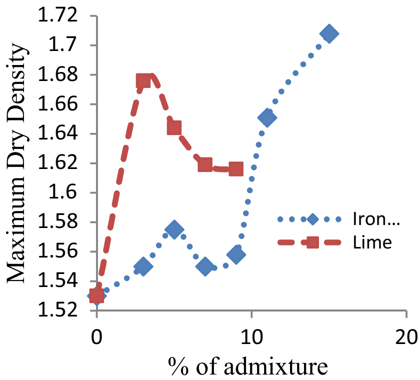


Fig. 10.13 Variation of maximum dry density wrt % of admixtures

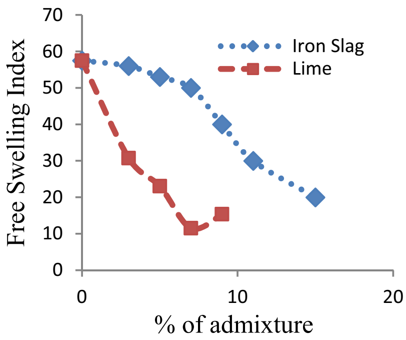


Fig. 10.14 Variation of free swelling index wrt % of admixtures

10.4 Conclusion

The following points we have concluded from the above investigations.

1. Both the stabilizing materials such as iron slag and lime have significant effects on the behavior of stabilized soil. The CBR and UCS values were found as

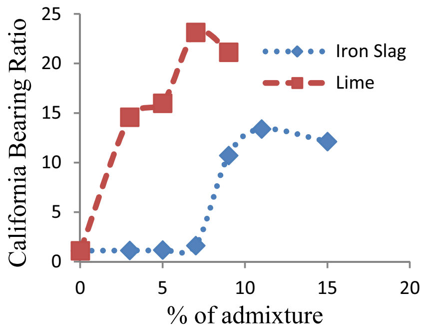


Fig. 10.15 Variation of CBR wrt % of admixtures

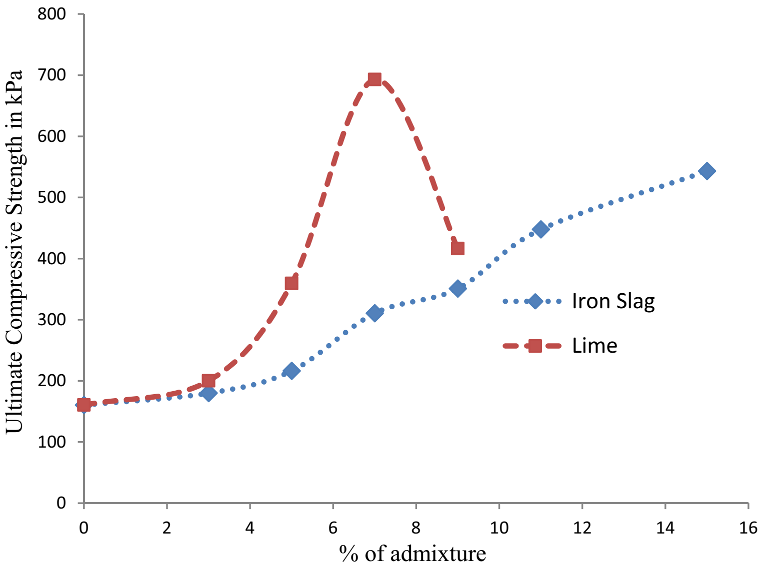


Fig. 10.16 Variation of ultimate compressive strength wrt % of admixtures

increasing continuously up to 11% by the treatment with iron slag and with the addition of lime, the values were observed continuously increasing up to 7% and then decreasing.

2. Liquid limit reduced from 60% to 45.44% by the addition of 11% iron slag whereas plastic limit increased from 22.28 to 26.30%.
3. In case of 7% lime addition, the Liquid Limit reduced from 60 to 39% whereas Plastic Limit increased by 28.23%.
4. OMC reduced by 27.72% when 11% of iron slag was used as an additive but with addition of lime admixture it was reduced initially and then gradually increases with increase in lime percentage.

5. MDD of the soil was continuously increased by 14.37% with the addition of iron slag but with increase in lime admixture percentage it reduced.
6. The Free swelling index was decreased by 65.21 at 15% iron slag additive where as it reduced by 79.94% in case of only 7% lime admixture.
7. The UCS increased by 238.49% showing an value from 161.51 kPa to 543.32 kPa for 15% iron slag admixture, whereas at 7% lime addition, it increased by 331.71% with a value from 160.51 kPa to 692.95 kPa.
8. By adding iron slag, the CBR value showed an increase. The maximum CBR value 13.398% was observed at 11% iron slag content. Thus CBR improved by ~1100% whereas with 7% lime addition it increased by 1974.37%

References

1. Daud, N., Jalil, F., Celik, S., Albayrak, Z.: The important aspects of subgrade stabilization for road construction. In: IOP Conference Series: Materials Science and Engineering, vol. 512, p. 012005 (2019). https://doi.org/10.1088/1757-899X/512/1/012005
2. Khandker, A.A., Anagnostou, J.T., Deo, P.: Geotechnical challenges in highway engineering in twenty first century: lessons from the past experiences and new technologies. In: 7th International Conference on Case Histories in Geotechnical Engineering Chicago, vol 25, 29 April–4 May 2013
3. Kampala, A., Jitsangiam, P., Pimraksa, K., Chindaprasirt, P.: An investigation of sulfate effects on compaction characteristics and strength development of cement-treated sulfate bearing clay subgrade. Road Mater. Pavement Des. **22**(10), 1–14 (2021)
4. Zumrawi, M., Abdelmarouf, A., Gameil, A.: Damages of buildings on expansive soils: diagnosis and avoidance. Int. J. Multidiscip. Sci. Emerg. Res. **6**, 108–116 (2017)
5. Das, A., Roy, S.: Effect of expansive soil on foundation and its remedies. Int. J. Innovative Res. Sci. Eng. Technol. **3**(6), 92–95 (2014)
6. Keller Inc.: Improvement of Weak Soils by the Deep Soil Mixing Method. Keller Bronchure, 32–01E: http://keller-foundations.co.uk/technique/deep-dry-soilmixing. (2011)
7. Khadka, S.D., Jayawickrama, P.W., Senadheera, S., Segvic, B.: Stabilization of highly expansive soils 301 containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum. Transp. Geotech. **302**(23), 100327 (2020). https://doi.org/10.1016/j.trgeo.2020.100327
8. Krishna, K., Gupta, S.: Stabilization of soft soil using industrial waste. Int. J. Adv. Res. Sci. Eng. **7**, 514–18 (2018)
9. Talluri, N., Puppala, A.J., Congress, S.S.C., Banerjee, A.: Experimental studies and modeling of high sulfate soil stabilization. J. Geotechn. Geoenviron. Eng. **146**(5), 1–16, 296 (2016). (in-press). https://doi.org/10.1061/(ASCE)GT.1943-5606.0002240
10. Ikeagwuani, C.C., Nwonu, D.C.: Emerging trends in expansive soil stabilisation: a review. J. Rock Mech. Geotech. Eng. **11**, 423–440 (2019). https://doi.org/10.1016/j.jrmge.2018.08.013
11. Bazyar, M.H., Ebrahimi, M., Lenjani, M.Z., Makarchian, M.: The effect of rice husk ash on mechanical properties of clayey soils stabilized with lime in the presence of sulphate. J. Eng. Geol. **11**, 23–52 (2017)
12. Ehwailat, K.I.A., Ismail, M.A.M., Ezreig, A.M.A.: Novel approach for suppression of ettringite formation in sulfate-bearing soil using blends of nano-magnesium oxide, ground granulated blast-furnace slag and rice husk ash. Appl. Sci. **11**(14), 23–26 (2021). https://doi.org/10.3390/app11146618

13. Biswas, N., Puppala, A.J., Chakraborty, S., Khan, A.: Utilization of Silica-Based Admixture to Improve the Durability of Lime-Treated Expansive Soil. In: IFCEE. ASCE, Dallas, Texas, pp 233– 305 (2021)
14. Beeghly, J.: Recent experiences with lime- fly stabilization of pavement subgrade soils, bas, and recycled asphalt. In: International Ash Utilization Symposium (46). Kentucky, University of Kentucky (2003)
15. IS: 2720 part 4, Determination of Laboratory Grain size distribution, Bureau of Indian Standards, New Delhi (1985)
16. IS: 2720 (Part 5–1985) methods of test for soils for determination of liquid and plastic limit, Indian standards institution, Manak Bhavan, 9 Bahadur Shah Zapar Marg New Delhi 110002
17. IS: 2720 (Part 6–1972) methods of test for soils for determination of shrinkage factors, Indian standards institution, Manak Bhavan, 9 Bahadur Shah Zapar Marg New Delhi 110002
18. IS: 2720 (Part 3–1980) methods of test for soils for determination of specific gravity, Bureau of Indian Standards, Manak Bahavan, 9 Bhavan Shah Zafar Marg New Delhi 110002
19. IS: 2720 (Part 7–1980) methods of test for soils for determination of water content-dry density relation using light compaction, Bueau of Indian Standards, Manak Bhavan, 9 Bahadur Shah Zafar Marg New Delhi 110002
20. IS: 2720 part 16, methods of test for soils for Laboratory Determination of CBR, Bureau of Indian Standards, New Delhi (1987)
21. Rashid, A.S.A., Kalatehjari, R., Noor, N.M., Yaacob, H., Moayedi, H., Sing, L.K.: Relationship between liquidity index and stabilized strength of local subgrade materials in a tropical area. Measurement **55**, 231–237 (2014)
22. Reznik, Y.M.: Relationship between plastic limit values and fine fractions of soils. Geotech. Geol. Eng. **34**, 403–410 (2016)
23. Sharma, B., Bora, P.K.: A study on correlation between liquid limit, plastic limit and consolidation properties of soils. Indian Geotech J **45**, 1–6 (2015)
24. Hillel, D.: Fundamentals of Soil Physics. Academic Press, New York (1980)
25. Sposito, G.: The Chemistry of Soils. Oxford University Press, New York (1989)
26. Harichane, K., Ghrici, M., Kenai, S.: Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study. Environ. Earth Sci. **66**, 2197–2205 (2012)

Chapter 11
Repositioning the Nigerian Rail System for Global Competitiveness: Tackling the Noisome Peculiarities

Olorunfemi Ayodeji Olojede, Folaranmi Olufisayo Akinosun, Oluwatimilehin Gabriel Oluborode, Henry Afolabi, and Peter Bolaji Oladeji

Abstract This chapter x-rays the moribundity of the Nigerian rail system. It posits that despite the huge potential of and acknowledged substantial benefits attributable to rail transport, the Nigerian rail system struggles in operations and patronage dynamics terms. Thus, the country is not reaping the full benefits its rail system could have fetched had it been globally competitive. The chapter contends that most of the culprits behind the fiasco of the Nigerian railway system are largely peculiar. They include the self-serving colonial heritage, lack of coordination in the transport sector, poor financing (partly consequent upon the overconcentration on road infrastructure), low speed (attributable to moribund operations technologies and obsolete facilities), unsustainable ownership structure, inefficiency and systemic corruption, sabotage, encroachment and obstructive human activities, safety and security issues (including terrorism), equity issues, passé energy options, substance abuse among passengers, illegal passage (stowing-away and rooftop riding inclusive), and other irresponsible behaviours. The manifestations of these issues are vividly discussed along with their implications. The chapter contends that the problems have far-reaching consequences for the performance rating of the Nigerian railway system. Consequently, towards holistically fixing the problems and facilitating the repositioning of the Nigerian railway system to make it comply with the best global practices in contemporary railway system dynamics, a quadripartite approach consisting of structural, administrative, financial, and operational overhauling is proffered.

Keywords Nigerian Railway Corporation (NRC) · Rail India Technical and Economic Services (RITES) · China Civil Engineering Construction Corporation (CCECC) · Maglev

O. A. Olojede (✉) · O. G. Oluborode · H. Afolabi · P. B. Oladeji
Department of Urban and Regional Planning, Obafemi Awolowo University, Ile-Ife 220282, Osun State, Nigeria
e-mail: olojedeo@oauife.edu.ng

F. O. Akinosun
Department of Public Administration, Ambrose Alli University, Ekpoma 310006, Edo State, Nigeria

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_11

11.1 Introduction

Any objective narrative of railway transportation in Nigeria must duly acknowledge its characteristically chequered historical development. For many reasons, and in several respects, the evolution of the Nigeria railway system over the decades features many peculiarities. Railway transportation came into being in Nigeria as an initiative of the British colonial masters. With the establishment of the first railway corridor in the country in the year 1898, railway is considered the oldest transport mode in the country [10, 12]. Originally, it was to enhance the penetration of the hinterlands for administrative convenience [24, 52] and to aid the conveyance of agricultural produce from remote locations, especially from the northern part of the country to the coastal cities in the south for onward transmission to Britain for meeting the raw material needs of industries in that country [24, 37, 50]. The system was a single-track network of 3′6″ (1067 mm) narrow gauge consisting of a route length of 3,505 kms with more than 1600 curves of between 4° and 10°, with gradients of 1.5% and two per cent common in some sections with the network consisting of two main lines running in a north-easterly direction starting from the two major ports of Lagos and Port Harcourt [84].

Contrary to what should be expected in an ideal situation, the Nigerian railway network has scarcely developed over the decades compared to what obtains in developed and even developing countries of comparable status with Nigeria. This makes it practically impossible for the country to reap the huge potential and widely acknowledged substantial benefits attributable to rail transport globally. One easily identifiable manifestation of this is the insignificant role the Nigerian railway system plays in urban mass transit services across the country [51, 63]. Apart from Lagos and Ogun States, intra-urban rail mass transit services are not available in Nigerian cities [55].

A major culprit behind the less-than-desirable state and functionality of the Nigerian railway system is the low priority accorded it by successive governments over the decades. For instance, when it introduced the policy of reconciliation, rehabilitation, and reconstruction (3Rs) in the post-civil-war Nigeria, the Nigerian government embarked on a largescale reconstruction of transport infrastructure; however, its reconstruction efforts favoured massive road-building projects to the detriment of other transport modes, rail inclusive. Too much attention was given to road transport, and the lion share of the funds allocated to the transport sector was expended on road infrastructure. Meanwhile, road transport was originally developed to complement the railway system in the country [54]. Subsequent development plans in the country also upheld this lopsided trend.

For instance, over the period of the National Development Plans, there was no time road transport did not receive well over half of the total allocation to the transport sector. Specifically, it received well over two-thirds of the total allocation during the Third National Development Plan and Fourth National Development Plans periods. Conversely, the highest percentage rail transport ever got was 17.2 (1970–1974). It even got as low as a paltry 10.6% during the Third Development Plan period. It is pertinent to note that one United States Dollar ($1) exchanged for between 0.55 Nigerian Naira (N0.55 or 55 kobo) and 0.894 Nigerian Naira (N0.894 or approximately 89 kobo) between 1972 and 1985 [20, 38, 66, 71, 78]. Nigeria only started spending the Naira in January 1973 [21, 22, 29, 35, 64, 72]; arguably therefore, all amounts prior to 1973 must have been converted to the Naira from the British Pound Sterling (£) 0.5 of which exchanged for N1 as of 1 January 1973 when the Naira was introduced, though the Nigerian Pound had been at parity with the British Pound Sterling hitherto [21, 39]. These conversions are important for proper understanding of the huge investment made on the transport sector over the plan period the bulk of which went to road transport development at the expense of rail transport and other transport modes, a lopsidedness that adversely affected the country's railway development in a significant way [49, 52, 84].

In addition to the poor investment outlay, the Nigerian railway subsector has also been bedevilled by several other factors over the years. These include inadequate locomotive capacity, civil-war induced largescale destruction of facilities and infrastructure, obsolescence of railcars and infrastructural facilities, scarcity of skilled labour, poor maintenance culture, excessive failure rates of both steam and diesel locomotives, limited options for procuring mainline locomotives owing to the substandard gauge and light rail sections, negligence and neglect by successive governments, the decline in agricultural produce in the early 1970s (agricultural produced constituted the bulk of the cargo prior to the 1970s), lack of adequate technical and managerial manpower, ineffective financial management, and the lack of functional transport policy [2, 6, 49, 52, 84].

In recent times, other factors have emerged including safety and security concerns, especially with the growing number of train rooftop riders with criminal tendencies [55]. In addition, the stealing of rail track sleepers along several routes has been widely reported by print and electronic news media as well as social media platforms. Such theft locations include Kogi and Enugu States [31, 83], Plateau State [62, 76], Nasarawa State [42, 80], Bauchi State [82], Benue State [68], Kaduna State [47, 81], Ebonyi State [33, 34], and Ogun State [77]. Meanwhile, Yusuf [89] had earlier reported that the crime of keys (*makuli*) and sleepers' (*sikwati*) theft flourished on the rail lines throughout the North and so was not peculiar to any particular state in Northern Nigeria, and that this dates back to as far as 1922 [88].

Terrorism, which features the crimes of kidnapping/abduction, rape, and killing, constitutes another existential threat to the Nigerian railway system. These crimes were mainly associated with road transport in Nigeria [57] until recently when they started featuring in rail transport. The latest of the terrorist attacks on the Nigerian rail subsector was the unprecedented attack on the Abuja-Kaduna train in Katari, Kaduna State. It was launched around 19:45 pm (GMT + 1) on the 28 March 2022. The attackers bombed the train and opened fire on the passengers killing at least eight and injuring over 26 others. Other victims died later, on their way to the hospital, while some died in the hospital. There are also anecdotal reports that some later died in the terrorists' den while over 150 of the passengers were not accounted for. On Saturday, the 11 June 2022, 11 (five male and six female) of the attack survivors were released by the terrorists [27]. According to Mallam Tukur Mamu, the government-bandit negotiator, the health condition of the remaining victims in the terrorists' den was deteriorating as they were subjected to horrible inhumane conditions, and many of them had been bitten by snakes in the forest where they were being held captive [28]. Later, on the 9 July 2022, another batch of seven abductees were released after a ransom of N800 million had been paid. Eventually, the release of the remaining 23 victims was secured by the Nigerian Army at 4:00 pm (GMT + 1) on the 5 October 2022 [16, 75] after they had spent 191 whole days languishing in the kidnappers' den. Meanwhile, the Minister of Transport, Rotimi Amaechi, has since claimed that the attack would have been averted if the surveillance equipment he proposed to the Federal Executive Council had been installed [15]. This is an indication that the Nigerian railway service has been operating without any provision for surveillance hitherto.

Much has been reported on the moribundity of the Nigerian rail system, especially in terms of its operations and patronage dynamics. Objectively viewed, however, it is arguable that many of the culprits behind the fiasco of the Nigerian rail system are largely peculiar. Granted, other countries also have their respective railway systems riddled with challenges; however, what obtains in the Nigerian railway system seems to defy logical explanations as they are atypically endemic. Evidently, the overall macroeconomic and socio-political situation of the country cannot be exonerated when it comes to the pitiable state of the Nigerian railway system. There is hardly any concrete evidence of concerted, sustained, and resolute commitment to the development of the rail system on the part of the successive governments in the country for many decades. Yet, bloated recurrent expenditure amidst ravaging economic crisis has continued unendingly. Thus, the Nigerian railway system has been neglected just as many other sectors and subsectors of the country's economy have been neglected. The thrust of this chapter is the unravelling of the factors behind the current situation of the Nigerian railway system and the evolvement of a workable pathway towards tackling the noisome peculiarities, and the overall overhauling and holistic repositioning of the subsector for global competitiveness.

11.2 Evolution of the Nigerian Railway System

Going by the way events unfolded, the historical development of the Nigerian railway system can be discussed under four periodic headings: the pre-twentieth century period, the 1900–1960 period, the 1961–1999 period, and Year 2000 and beyond. All these periods were characterized by the peculiarities of their respective times. The pre-twentieth century period covered the time between 1879 and 1899. It could be regarded as the years of the beginnings. The 1900–1960 period spanned the beginning of the twentieth century and the year Nigeria attained self-governance or independence. The 1961–1999 period covered series of interventions in the operations and management of the railway system in Nigeria by a set of governments directly run by Nigerians themselves following the exit of the British colonial imperialists. The last

Table 11.1 Railway construction in Nigeria

SN	Section	Year	Distance (km)	Gauge
1	Lagos–Ibadan	1898–1901	193	Narrow gauge
2	Ibadan–Jebba	1901–1909	295	Narrow gauge
3	Kano–Baro	1907–1911	562	Narrow gauge
4	Jebba–Minna	1909–1916	225	Narrow gauge
5	Kaduna Junction–Kafanchan	1916–1924	179	Narrow gauge
6	Kafanchan–Jos	1924–1927	101	Narrow gauge
7	Kuru–Bauchi	1958–1961	166	Narrow gauge
8	Bauchi–Gombe	1961–1963	155	Narrow gauge
9	Gombe–Maiduguri	1963–1964	302	Narrow gauge
10	Itakpe–Ajaokuta	1986–2020	277	Standard gauge
11	Ajaokuta–Warri	1986–2020	275	Standard gauge
12	Port Harcourt–Onne	Underway	19	1067 mm

Source Nigerian Railway Corporation (2010) cited in Ogochukwu et al. [50]

period, year 2000 and beyond, is significant as the country reverted to democracy in 1999 after many uninterrupted years of military interventions featuring several military hegemonies. During the period, several efforts were seen towards the revitalization of the Nigerian railway system. It should be noted, however, that these four periods overlapped in terms of railway construction activities as indicated in Table 11.1.

As presented in Table 11.1, it is evident that the bulk of the construction activities in the Nigerian railway subsector were embarked on during the 1900–1960 and 1961–1999 periods.

11.2.1 The Pre-Twentieth Century Period

The identification of the need for an efficient railway system in Nigeria dated as far back as around 1879. This was some 18 years after the annexation of Lagos as a British colony in 1861. The colonial government of the day accepted applications between 1879 and 1892 from various private interests from the United Kingdom for concession to construct railways across the country. However, owing to the inability of the colonial government to guarantee interest on the huge capital outlay required for the construction, none of the applications was approved. Following a favourable report on the preliminary survey commissioned in 1892 that predicted great potentials for trade, the secretary of state for the colonies in 1895 gave an approval for the construction of the first rail line in Nigeria having had the cost of railway construction estimated. The first rail line spanned 32 kilometres and ran between Iddo and Otta. Thus, the terminals in Iddo and Otta became the first railway terminals in Nigeria when the first line became operative in 1898. Other lines were later constructed to link the northern and southern parts of the country [41, 52]; the first among these major sections was the 193-kilometre Lagos-Ibadan route, the construction of which started in 1898 (Table 11.1).

11.2.2 The 1900–1960 Period

This was the period immediately preceding the independence of the country. According to Table 11.1, at least six major routes were constructed during the 1900–1960 period: the 295-kilometre Ibadan-Jebba route (1901–1909), the 562-kilometre Kano-Baro route (1907–1911), the 225-kilometre Jebba-Minna route (1909–1916), the 179-kilometre Kaduna Junction-Kafanchan route (1916–1924), the 101-kilometre Kafanchan-Jos route (1924–1927), and the 166-kilometre Kuru-Bauchi route (1958–1961). However, Okanlawon also documented the development of the 243-kilometre Port Harcourt-Enugu route (1914–1916), the 220-kilometre Enugu-Makurdi route (1916–1924), and the 238 kilometre Kafanchan-Bauchi route (1958–1961).

As earlier stated, administrative and economic factors were prominent in the determination of the original railway routes in the country. However, it is pertinent to also note that there were anecdotal reports on why the railway routes did not pass through some important cities, especially in the southwestern part of the country. There are at least three versions of these oral accounts that were never written in books, making them largely unverifiable. One has it that some kings and chiefs in the affected domains vehemently kicked against railway routes so that their subjects would not be crushed by moving trains. The fear was quite pervasive then. Another version claims that the kings and chiefs were afraid of losing their wives, children and subjects to slave trade, as they considered the railway a transport mode that could easily aid the preposterous trade. The third version emphasizes the cultural pollution and religious desecration the railway could bring about along its corridor. The railway was seen as a devastating invading force that could wreak unprecedented and irreversible catastrophes in Yorubaland. The Yoruba people in the southwestern part of Nigeria are reputed as a tribe which puts a premium on the sanctity of their cultural values, customs, traditions, and mores. This narrative might also apply to some parts of Igboland in the southeastern part of the country.

A watershed was recorded in the history of the Nigerian railway system on 3 October 1912 with the amalgamation of the Lagos Government Railway and the Baro-Kano Railway. This development led to the establishment of the Government Department of Railways and brought about a nationwide rail service. Some 43 years later, with the passing of the Nigerian Railway Corporation Act of 1955, as amended in the Laws of the Federation of Nigeria 1990, the name Government Department of Railways changed to the Nigerian Railway Corporation (NRC), the current name by which the corporation is known. The Nigerian Railway Corporation Act of 1955 made NRC an autonomous public corporation and gave it the exclusive legal right to construct rail lines and operate rail service in Nigeria [19, 79]. The objectives of NRC could be summarized as: to offer optimal services for the carriage of persons and goods in a manner that would offer customers full value for their money; meet costs of operations; improve market share and quality of service; ensure safety of operations and maximum efficiency; and meet social responsibility in a manner that would meet the requirements of rail users, trade, commerce, and the general public [19, 52].

According to Abubakar (2002) cited in Okanlawon [52], a broader perspective of NRC's objective was to lay a sound technical and economic foundation for a steady and successful operation in subsequent years. NRC was therefore to operate in a manner that would ensure its sustained growth by marketing an efficient, technically competent transportation service in pursuit of Nigeria's socioeconomic development; developing and marketing new business capabilities in areas complimentary to existing railway activities; ensuring that the corporation's efficiency and operational capabilities are maintained; improving the corporation's image by its service generally; continuing with and accelerating the rehabilitation of existing railway capabilities in terms of rolling stock, locomotives, buildings, telecommunications and signalling, tracks, culverts and bridges, retooling of workshops and sheds, reorganization, development and control of manpower; restructuring of traffic operating techniques of NRC to ensure maximum utilization of available capabilities; adopting measures to reduce accidents by intensifying campaigns for improved knowledge among its operating staff; stepping up commercial drive with a view to ensuring the acquisition and retention of a large chunk of the market; providing a sturdy structure for enhanced traffic budgeting and improved performance accountability; improving the financial management policy and practices in the corporation, thereby ensuring regular availability and proper utilization of funds; and broadening the business scope of railway activities so as to boost NRC's financial viability through, for example, real estate development, complementary road transport services, hospitality services, and other corresponding enterprises.

11.2.3 The 1961–1999 Period

The Nigerian railway network reached its maximum extent in 1964. This was shortly after the country's independence. Shortly after that, however, a long period of decline set in as NRC exhibited inept managerial propensities and failed to conscientiously sustain a maintenance culture on its rail and locomotive assets. In 1988, the corporation declared bankruptcy consequent upon which all its rail traffic and other activities were halted for six months. Later, its activities resumed but only where the tracks were still usable. Passenger services were to be suspended later again, however [5]. Several factors were responsible for the debacle that characterized the NRC of 1980s. Prior to 1970, agricultural produce, especially from the northern part of the country, constituted the bulk of the Nigerian railway's major freight. For instance, over the 1967/1968 period, it made up 41% of the entire railway freight traffic with internal traffic representing an additional 13%. However, by 1970/1971, agricultural produce freight had significantly dropped from the 863,821 tonnes it was 10 years earlier to 355,691 tonnes—well over 58% cutback. This adversely affected the viability and sustainability of NRC as the corporation could not break even. It was evidently an existential threat as NRC battled perennial operational and organizational challenges for many years [84].

With a view to reviving the rail transport subsector, the military administration of Olusegun Obasanjo in 1978 contractually engaged the Rail India Technical and Economic Services (RITES) Limited of New Delhi to resuscitate it. RITES was charged with the responsibility of rehabilitating and managing the Nigerian railway tracks and building a standard gauge railway line within the five-year contract period (1978 through 1982). Consequently, a provision was made for this in the Third National Development Plan (1975–1980). All the mission objectives of the RITES contract were achieved, and NRC was given a new lease of life. Staff welfare and motivation were accorded top priority; rail services were also improved on in terms of regularity, suitability, and safety. However, these gains were short-lived as an abrupt termination was brought upon the joint venture [10, 49, 50, 52].

Hardly had the Indian experts left when the Nigerian railway services nosedived. Crass operational inefficiency crept back in, resulting in rapid decay of the railway infrastructure and the plummeting of finances. All the gains of the immediate past five years were completely lost. In a bid to restore normalcy, the Ibrahim Babangida military administration in 1989 appointed Dr. Samuel Ogbemudia Sole Administrator of NRC. This period came to be popularly known as the Ogbemudia Revolution. Being visionary and highly influential, Ogbemudia singlehandedly accomplished a complete turnaround of NRC. Specifically, among other things, he divided NRC into nine director-headed departments; checkmated unionism by regularly briefing staff on all management decisions; prioritized staff motivation by paying salaries and other entitlements promptly; reactivated workshops as bee-hives of activity; upgraded the research unit to directorate level such that it could develop local DMUs, EMUs, carriages, wagons, concrete sleepers, rails, and the like; introduced mass transit trains; persuaded the then military president to publicly support train services by taking a presidential train ride; organized Conference on Wheels, a unique seminar on the morning train between Lagos and Ilorin to publicize railway activities; and boosted NRC financial resources [49, 50]. Another important feature of NRC that coexisted with the Ogbemudia Revolution was the award of the 10-year Romania project contract for the supply of rolling stock starting from 1986 [50]. Evidently, the Ogbemudia Revolution marked another epoch in the Nigerian railway development history. For instance, NRC generated a total revenue of 73 million naira in 1989. This was far more than the 52.81 million naira generated in the previous year [49].

Unfortunately, the Ogbemudia Revolution was also short-lived as it was summarily kicked out by witless political monkeyshines and shenanigans. As soon as Ogbemudia was booted out of NRC, all his scheduled action programmes, including revitalization, modernization and development of railway facilities and infrastructure, improved services, self-supporting railway with new marketing strategy, and other proposed pragmatic innovations were done away with by successive administrations. Thus, again, NRC took several giant strides backward. Some nine years after the exit of Ogbemudia, the federal military government of Sani Abacha in 1995 awarded a new 15-year six-million-dollar contract to the China Civil Engineering Construction Corporation (CCECC) towards the transformation of the country's railway system through the rehabilitation of railway tracks and supply of rolling stock including 50 locomotive, 150 coaches, 400 wagons, and 20 railbuses. The corporation was also to provide technical training for the NRC staff towards capacity building. The required communication equipment (microwave) was to be supplied by an Israeli company [10, 49, 50].

11.2.4 Year 2000 and Beyond

A comprehensive and detailed account of railway construction in Nigeria between 1999 and 2019 was compiled by AutoJosh [14]. According to the account, acknowledging the indispensability of a coherent, integrated, efficient, and reliable transportation system, President Olusegun Obasanjo, who had come in again in 1999 as a civilian president, conceived a modern railway project for Nigeria in 2006. Consequently, he inaugurated the project to revitalize the country's 3500-kilometre railway network. The project, awarded to CCECC for 8.3 billion US dollars, was dubbed the Lagos-Kano Standard Gauge Modernization Project. The funding need of the 25-year project was to be met through a soft loan from China. However, owing to funding issues, the project was later redesigned to be executed in standalone segments with the Abuja-Kaduna segment coming first in the 1,124-kilometre Lagos-Kano Line. Another 100-kilometre Minna-Abuja was added, continuing for 205 kilometres beyond Abuja to Kaduna. The reconstruction of the Port Harcourt-Jos route was also scheduled to be part of the second phase of the project.

The project suffered a major hitch in November 2007, however, as the Musa Yar'Adua's administration could not continue with it owing to what it described as 'paucity of funds'. Later in October 2009, as part of its seven-point agenda, the federal government made a move to revitalize the country's railways. Thus, it signed the 875-million-dollar Abuja-Kaduna rail construction contract which was designated as the Phase/Segment I of the rescoped railway modernization project. It was to cover the Abuja (Idu)-Kaduna axis in the new agreement with CCECC. The project cost was downwardly reviewed from the initial 8.3 billion dollars signed by the Obasanjo administration. In 2009, the abandoned 276-kilometre Warri-Ajaokuta route project was resuscitated having been originally conceived in 1987 to carry raw materials and steel products from Delta Steel Company, Aladja, Warri. However, it was later abandoned owing to funding constraints after some 254 kilometres had been done [14, 50].

By mid-2011, President Goodluck Jonathan initiated the high-speed Lagos-Kano rail project being the first phase of the Lagos-Kano rail line that was to connect Lagos, Kano, Kaduna, Warri, Bauchi, Abuja, and Port Harcourt. It was designed to be executed over a 25-year period in six phases at the projected cost of 13 billion dollars, the bulk of which will be financed with a loan from a Chinese bank. Between February and October 2010, a total of 25 new locomotives were purchased by the Federal Government from South America and deployed to boost train services across the country's railway routes. The Abuja-Kaduna segment was the first segment to be implemented as part of the Lagos-Kano standard gauge project under the first Standard Gauge Railway Modernization Projects (SGRMP) in the country. The government also signed a Memorandum of Understanding for the construction of the 1.5 billion dollars Lagos–Ibadan rail project with CCECC in August 2012. It was a double-track railway line modernization project the standard gauge line of which was to link Lagos, Ibadan, Ilorin, Minna, Kano. A phase that would take off from Minna to Abuja was also made part of the project. In 2012, work commenced on the Warri-Itakpe-Ajaokuta route which, when completed, would facilitate the movement of trains from Warri (through Itakpe, Ajaokuta, Agbor, and Warri) to Ore with six stations in between. In June 2014, two sets of Diesel Multiple Units (DMUs) and 68-seater air-conditioned passenger coaches acquired NRC were commissioned. In October 2014, the federal government approved 6.6 million dollars for the procurement of two locomotives for the Abuja-Kaduna rail. Generally, the efforts made by the Jonathan administration were adjudged fruitful. The construction of the Abuja-Kaduna rail line which started in February 2011 was completed in December 2014. Moreover, in 2014, KPMG, a leading multinational consulting firm rated the Abuja-Kaduna rail line project to be among the global top 100 world-class infrastructure projects [14, 17].

A year into the Muhammadu Buhari's administration in July 2016, the president commissioned the 187-kilometre Kaduna-Abuja standard gauge line with the tracks running from Idu, near Abuja, to Kaduna in the north-western region of the country. The Abuja light rail is a different project from the Abuja-Kaduna rail line, but still part of the grand plan of the Obasanjo administration. In April 2017, NRC began the construction of the 36-kilometre Lagos-Ibadan standard gauge railway line. The project was rewritten and renegotiated from the initial 1.5 billion naira [14]. Also, in 2019, the Buhari administration sent over 150 Nigerian youths to understudy Chinese engineers. They were put in two Chinese universities to study railway engineering with a view to ensuring capacity building towards the maintenance and sustainability of trains in Nigeria. Another leg of the plan was the establishment of a specialized transportation university in Daura, Katsina State. The goal was to ensure that the country develop the requisite technical knowhow and competence to take over from the Chinese and localize railway technology [36].

One of the latest developments in the Nigerian railway system is the passing of various new bills that are targeted at providing a legal framework that would facilitate the active involvement of actors from the organized private sector and sustaining the railway networks in the country. Principal among the bills is the Nigeria Railway Authority Bill which seeks to promote and regulate the efficient and sustainable development as well as operation of the Nigerian railway subsector; aid its market competitiveness in the provision of railway services; advance the safety, reliability and efficiency of railway services; expand the scope of the railway services and enhance accessibility to its infrastructure throughout the country; stimulate the participation of the organized private sector, state and local governments in railway infrastructure financing and management; and guarantee an environment conducive to the protection of the rights and interests of all stakeholders in the railway sector. Furthermore, the bill is set to replace the Nigerian Railway Corporation Act by providing for the creation of the Nigeria Railway Authority which will pave the way for the active involvement of the organized private sector in the provision of rail services, and regulate the railway subsector in the country [25, 67].

11.3 Features and Operational Dynamics of the Nigerian Railway System

Statutorily, NRC provides four types of services: passenger services including express trains for long-distance travel, intercity trains for medium journeys, mass transit trains for linking rural and urban areas, as well as commuters for intracity movement; freight services including covered wagons suitable for loading dry goods, open wagons suitable for loading dry goods, special wagons, tank wagons (for liquid goods), baggage vans (for parcels, household items, and other courier services), and SBX/CBX (for animals/general goods and farm products), workshop services including maintenance of locomotives and rolling stock, foundry services (such as bricks making and carpentry), and other commercial services; and ancillary services including medical services, advertising facilities, printing press, catering, and real estate [19]. Indeed, in terms of landed property, NRC remains the government-owned entity with the largest asset base in Nigeria [10].

A breakdown of the scope of demand for rail services between 1999 and 2003 done by BPE [19] using data obtained from NRC shows that the major users of rail services in the country are the manufacturing companies that produce goods, the oil companies that move petroleum products across the country, marketing companies, construction companies, as well as importers and exporters. However, this arrangement only became the order as Nigeria gradually slid down the slope as an exporter of agricultural produce in the 1970s and shifted its focus to oil. According to Robinson et al. [73], in the 1960s, especially at the early stage of Nigeria's independence, the overland freight traffic in the country was dominated by the railway. Then, the railway controlled well over 30% of the freight market share. Thus, the Nigerian railway was recognized as a significant producer-price incentive for sufficient farmers' engagement in the production of cash crops that were in high demand by manufacturing industries in Britain [30]. This narrative changed when focus shifted from agriculture, and the period which followed marked the first major stage of struggle for rail transport in Nigeria as road transport started gradually mopping up the railway's share of the freight traffic. This road's takeover and dominance of terrestrial transport in the country became so formidable that by the end of the 1990s, the use of rail transport was reported to have fallen to utter insignificance [10, 24, 30, 48].

Moreover, the foundational colonial-centric orientation of the Nigerian railway system still goes a long way in determining its current situation. When the railway network of the country was mapped out, no apparent consideration was given to how it could facilitate the country's industrial development. Also, there was no attempt towards any form of coordination between the rail system and other transport modes, especially the road transport subsector. This is in sharp contrast to what obtains in many other countries. In a country like South Africa, for example, the rail and road transport modes are coordinated. Level crossings are hardly present but Road Over Bridge (ROB) and Road Under Bridge (RUB), where the road traffic passes over and under the railway track respectively. Conversely, in Nigeria, railway and roads are not designed to functionally complement each other. For instance, at most of the level crossings, manually operated barricades are installed that momentarily stop the flow of road traffic for the train to pass. These barricades are even not in place at many intersections. So, road users must look out to avoid being crushed by moving trains. Apparently, this is a risky arrangement that is bound to result in casualties. Many of such accidents have been witnessed in Nigeria over the years.

In addition to the lack of coordination in the country's transportation system, the poor financing of the railway subsector is another evil that has hampered railway development in Nigeria. As earlier pointed out, this manifests in the overconcentration on road infrastructure to the detriment of the railway subsector. For many years, this made the Nigerian railway system have to cope with antiquated infrastructure, low-speed rolling stock, moribund operations technologies, and obsolete facilities. Unsustainable ownership structure has not helped the Nigerian railway either. The various administrations have over the years tried out two major management options. The public management option was experimented with under NRC, while the concession option was employed with the involvement of the organized private sector in line with global best practices in railway infrastructure provision and service delivery [13, 23, 50]. However, the Nigerian government has not been consistent as it keeps terminating contracts entered with foreign companies.

Other challenges that the Nigerian railway has encountered over the years include inefficiency, encroachment and obstructive human activities, passé energy options, systemic corruption, sabotage, as well as such social vices as substance abuse and other irresponsible behaviours among some passengers. Inefficiency was first brought about with overstaffing, especially after the Nigeria civil war (1967–1970). At a time after the war, NRC became the largest Nigerian state enterprise with almost 40,000 employees. This overmanning contributed immensely to the inefficiency and poor competitiveness of the Nigerian railway [84]. Encroachment and obstructive human activities along the Nigerian railway corridor include unauthorized building of permanent structures [4, 11, 43], trespass and invasion by men and animals [1], hawking and other business activities, as well as the abuse of railway tracks as parking lots and walkways with some pedestrians even wearing headphones while jaywalking on the railway tracks [9].

The passé energy option in the Nigerian railway system consists in the use of diesel locomotives even in the twenty-first century when locomotives powered by electricity from overhead lines, a third rail or onboard energy storage such as a battery or a supercapacitor abound in many countries of the world. This is to say nothing of the maglev train. Worse still, the sufficient fuelling of the diesel-powered locomotives is not even guaranteed. A case in point was the stranding of hundreds of the Ibadan-Lagos train passengers in the middle of nowhere on the 10 March 2022 owing to an abrupt fuel gauge failure on the passenger train service. Investigations revealed that a shortage of diesel on which the locomotive was running was responsible for the failure. It took about two hours to restart the locomotive after diesel was brought in in jerrycans to refuel the engine [7, 45, 70].

Among the social vices dogging the Nigerian railway subsector are substance abuse and other irresponsible behaviours among some passengers, especially the rooftop riders. According to Olojede [55], rooftop riding is so rampant and constitutes one of the major challenges hampering the smooth operation of the Lagos Shuttle Services. Some of the notorious rooftop riders could be so violent that it would be a serious risk for anyone to make any attempt to get in their way. This is because they sometimes carry dangerous weapons with them and even pelt people who dare take their pictures. Other vices include smoking and ticket racketeering; cases of overloading have also been reported [8].

The implications of the various types and dimensions of the problems associated with the Nigerian railway system are many. The most apparent is the low level of patronage. As of today, railway accounts for a negligible part of the country's transport subsector and contributes an insignificant proportion of value added in the overall transportation system. For instance, intra-urban rail mass transit services are only available along the Lagos-Ogun route while only two long-distance segments are operational: Lagos-Kano and Abuja-Kaduna. This implies that such geopolitical zones as the South-East, South-South and North-East enjoy very limited service. However, in a way, this is still traceable to the aftermaths of the Nigerian civil war which caused the extensive destruction to the Nigerian railway rolling stock (locomotives, wagons, and coaches) resulting in rendering operations of the Eastern Line which connects Port Harcourt with the interior practically impossible such that even the post-war rehabilitation was unable to restore the pre-war operating levels. This trend of underperformance has been sustained for decades and has worsened with the present situation of things. A major fallout of this development is that rail transport has been relegated to the background with road transport taking over virtually all the freight services previously rendered by railway. This has greatly affected the revenues and sustainability of the Nigerian railway. Despite the several attempts made by successive governments to revive the country's railway subsector, not much success has been recorded hitherto [50]. Thus, it is safe to conclude that, overall, when objectively viewed within the context of the global best practices in rail transport, Nigeria does not stand any chance in terms of competitiveness.

11.4 Revamping the Nigerian Railway System: The Way Forward

Despite the federal government's effort over the decades to revamp the railway transportation system in Nigeria, the country's railway subsector has remained largely inefficient and moribund. Arguably, this is because approaches that have always proved inefficacious are more often than not mindlessly regurgitated. If the narrative of the Nigerian railway system will change, and if it will ever exude the established global best practices in contemporary railway system dynamics and compete favourably with other countries, the trajectory of its dynamics must change. There must be a holistic overhauling, a total paradigm shift. Revamping does not come cheaply by wishful thinking or by propaganda; conscientious efforts must be made. Generally, all the identified problems facing the Nigerian railway subsector discussed in this chapter can be broadly categorized into four: structural, administrative, financial, and operational. Towards overcoming the problems, therefore, a quadripartite approach is hereby recommended: structural overhaul, administrative overhaul, financial overhaul, and operational overhaul.

11.4.1 Structural Overhaul

This is perhaps the most important overhauling that must be made to make the Nigerian railway truly functional. It starts with intentionally introducing the much-needed coordination between railway and other terrestrial transport modes, especially roads. A future road map for the Nigerian railway subsector should not be embarked on without accounting for and incorporating the road subsector in the blueprint. The country's transport sector should be replanned such that the specific and complimentary roles of both the railway and road subsectors will be clearly spelt out. The Nigerian railway network must be mapped out and every point of intersection with roads identified for effective coordination. One mode should not be allowed to interfere with the smooth operation of the other. To this end, flyovers or overpasses should be built, in form of ROB and RUB, where appropriate to aid seamless and harmonious co-existence of the two modes. In addition, every necessary retrofitting should be done to enhance access equity, especially in the interest of physically challenged travellers. Efforts should also be made to put facilities in place for the convenience of pedestrians and car owners who embrace active transport (choice riders) and thus require parking facility while taking mass transit. This is consistent with what obtains in global best practices for the railway system. It is an important issue as Nigerian cities are notorious for their poor active transport infrastructure [58–61].

Another important step is to address the relics of the agelong colonial heritage in the development of the country's railway system. The Nigerian railway system should be made to be inclusive and truly nationwide by incorporating all the 36 states, ensuring that no region is left behind or marginalized. The objectives should clearly be modified and translated beyond merely providing for the passage of agricultural produce to the coastal cities and the integration of the hinterlands for colonial administrative purposes. The new or modified goal should be towards national economic and industrial prosperity. Thus, every region and state should be connected by the railway network as this is important for inclusive national development. The Nigerian railway should serve all parts of the country as practicably as possible, leaving no terrain behind: from the southern lowlands and the central wooded countryside through the plateaus and eastern mountains, all the way to the northern plains. A major glaring positive effect of this will be great relief for the roads which are visibly sagging under the heavy burden of goods' trucks that convey freight that is best transported by trains. Besides, it will cut down on the effects of road congestion and rising fuel prices. It will also serve as a Nigerian local means of stemming carbon emissions (or decarbonization) in the context of concerns about global warming. It is on record that transport accounts for about a quarter of total global energy-related carbon emissions [26, 56].

Furthermore, every form of encroachment and obstructive human activities along the railway corridor and reserve must be checked using stringent measures. All unauthorized structures should be pulled down, and every form of trespass should be proscribed. Where practicable, fences should be built to fend off intruders. This also has positive implications for safety and security. Moreover, all forms of irresponsible behaviour should be discouraged among unruly passengers. Such misbehaviours as stealing, substance abuse, illegal passage (stowing-away and rooftop riding) should be checked. In addition, pandemic responsiveness should be prioritized towards responsible and safe rail transport in the wake of the COVID-19 pandemic. This measure may also call for some retrofitting.

11.4.2 Administrative Overhaul

It has been widely reported and sufficiently proved that management problem is one of the biggest issues that dog the Nigerian railway system. Thus, this aspect of the Nigerian railway system should be addressed. First, there should be a sustainable and workable ownership structure. The Nigerian government should make a decisive decision on the most preferable ownership option for the Nigerian railway system if there is to be reform. As much as possible, the organized private sector should be encouraged to invest in the country's railway system. The overriding objective of any reform to be embarked on for the betterment of the country's railway system must prioritize attracting the organized private sector's sustained involvement and investments. In addition, such contemporary efficient management systems as unbundling should be explored. By unbundling, it is implied that the railway corporation will be compartmentalized into easily manageable units for effectiveness. This will also enhance accountability and cut down on corruption and other undesirable propensities.

Another benefit of administrative overhauling is that it would bring a permanent end to overstaffing in NRC. Overstaffing is a notorious problem in many public corporations in Nigeria, and it keeps adversely affecting the system. With administrative overhauling, all expedient downsizing and rightsizing would be done. Necessary deployments would also be an option. A situation whereby six individuals are taken on by the corporation to mind the workload of an individual would not augur well for any organization. Administrative overhauling also serves as a veritable plughole for wasteful spending and other inappropriate behaviour.

11.4.3 Financial Overhaul

Not unlike what obtains for other infrastructure projects worldwide, railway projects in Nigeria can be financed under three different mechanisms: sovereign financing, corporate financing, and project financing. Being the most popular funding solution for railway systems worldwide, the sovereign financing approach can be employed in Nigeria. Serving as a public sponsor, the Ministry of Transportation can borrow or guarantee the required loans for the railway project. Since the project promoter is a public body, the return on investment is accounted based not only on the internal rate of return of the railway infrastructure but also on the social welfare generated for the country. This is the most common financing scheme in Africa [3]. It should be preferred to Chinese loans that might land the country in a serious situation such as a compulsory infrastructure takeover.

There have been allegations that China has been covertly taking over critical and valuable national assets of debtor nations who default in the repayment of loans obtained from the country for infrastructural development. Cases usually cited include Sri Lanka, Malaysia, and Zambia; however, the allegations have been denied and debunked concerning Sri Lanka and Malaysia while Zambia has been reported to be embattled with painful economic reforms such as the removal of unsustainable high energy and agricultural subsidies [46, 69, 86]. The possible takeover of Uganda's only international airport in Entebbe and other strategic assets owing to the country's inability to repay a $207 m loan obtained from the Export–Import Bank of China in 2015 is another popular illustration of 'China's debt-trap' [53, 65]. While it is true that there is emerging consensus among scholars and analysts that the 'China's debt-trap' is a mere myth for lack of evidence, there are still pervasive anxieties and wide claims that China has been taking over key national assets in several developing countries [40, 46]. Just these speculations and anxieties are enough to make a responsible government reconsider its stance of such loans as these. There would be grave political (sovereignty-related), social, and economic consequences if any key asset of the country is taken over by another country. The government should not be irresponsible and reckless with loans obtained for infrastructure development from such a body as AfDB for infrastructure development either.

Corporate financing is another option that can be considered for the Nigerian railway financial overhauling. It directly involves the organized private sector. With the organized private sector's sustained involvement and investments in the Nigerian railway subsector, financing issues would drastically reduce as workable financing options would be guaranteed. Adequate financing would come through commercialization and privatization. Also, investment funds could be raised through loans as well as debentures, shares, and other financial instruments [3]. The involvement of the organized private sector would also put an end to every form of financial misappropriation that has been perpetrated with impunity in NRC for decades.

11.4.4 Operational Overhaul

It is on record that NRC boasts 3,557 kilometres of rail. This is in comparison with 2,084 kilometres for South Africa. However, only 52 kilometres of the Nigeria's extensive rail network is up to standard gauge. Besides, it is not electrified and mostly currently dysfunctional [5]. Consequently, the upgrading of the existing infrastructure (especially, the rolling stock), operations technologies, and facilities is imperative. Towards this end, sustainable and environment-friendly energy options should be considered.

Although not yet feasible in a country like Nigeria, a futuristic long-range plan should be in place for such a modern train technology as the magnetic levitation (maglev). The maglev technology has been developed and touted as the future of train transportation [87], with six commercial maglev systems already in operation around the world, specifically in Asia: one in Japan, two in South Korea, and three in China [18]. The unmistakable dominance of Germany, Europe, in maglev has also been reported [32]. Maglev stands tall as the future of train transportation considering its amazing speed (up to 620 kilometres per hour, a new record for land transportation speed) and an incredible safety rating [32, 44, 74, 85]. In addition, it does not require unsustainable and environment-unfriendly energy sources like petroleum or coal. It only uses liquid nitrogen and will not emit any harmful gas [32]. The maglev technology may not yet be feasible in Nigeria considering its prohibitive initial capital outlay. Besides, it is a typical greenfield railway project that requires the design and construction of completely new infrastructure including bridges, tunnels, embankments, and cuttings required to build the whole track, stations, and signalling systems. Nevertheless, it is an option worth being kept in view.

11.4.5 Exogeneous Considerations

In addition to the foregoing recommendations, there are other distinct issues that should be considered which are not exclusive to the Nigerian railway subsector but which pertain to the general situation of things in Nigeria. Decisively, the purported lack of political will and perceived indulgent body language of the government of the day towards the plunging macroeconomic indices, intractable corruption, and worsening insecurity in the country should be addressed. This is imperative as no astute investor or shrewd venture capitalist would put in scarce financial resources in a country characterized by economic doldrums and an unstable or unpredictable business environment.

11.5 Conclusion

This chapter has examined the moribund state of the Nigerian railway system and the factors behind its current situation. It argues that Nigeria is not reaping the full benefits of a globally competitive rail system as it lags far behind other countries in terms of the contemporary railway dynamics. Positing that many of the problems associated with the Nigerian railway system are largely peculiar, it discusses them and highlights their implications. The chapter advances a workable pathway towards tackling the noisome peculiarities of the Nigerian railway system and repositioning it for global competitiveness by recommending a total paradigm shift that consists in inclusive and holistic overhauling. The contention is that, with concerted and conscientious efforts, the Nigerian railway system can be resuscitated and brought up to globally acceptable standards. A major step in this direction is the prioritization of periodic research into its operations with a view to continually keeping it abreast of global best practices and international standards.

References

1. Aborisade, S.: Encroachment: NRC begins nationwide fencing of rail lines. Punch (2018). https://punchng.com/encroachment-nrc-begins-nationwide-fencing-of-rail-lines/
2. Abubakar, A.A.: Nigerian railways: past, present and future perspectives. Rail News **4**(6), 4 (2006)
3. AfDB: Rail infrastructure in Africa financing policy options. Transport, Urban Development & ICT Department, African Development Bank, Abidjan 01, Côte d'Ivoire (2015)
4. Adegoke, S.: Group cautions against encroachment of railway setback in Osun. Voice of Nigeria (2022). https://von.gov.ng/group-cautions-against-encroachment-of-railway-setback-in-osun/
5. Adejumo, A.: The urgent need for rail transport in Nigeria. Nigeriaworld (2006). https://nigeriaworld.com/articles/2006/oct/316.html
6. Ademiluyi, I.A., Dina, O.A.: The millennium development goals and the sustainable future for Nigeria's urban environment: a railway strategy. J. Hum. Ecol. **33**(3), 203–209 (2011)
7. Adenubi, T.: Hundreds of passengers stranded as Ibadan-Lagos train runs out of fuel. Nigerian Tribune (2022). https://tribuneonlineng.com/hundreds-of-passengers-stranded-as-ibadan-lagos-train-runs-out-of-fuel/
8. Akintifonbo, O.: A study of the operation and patronage of the Lagos Shuttle Train. M.Sc Thesis. Department of Urban and Regional Planning, Obafemi Awolowo University, Ile-Ife, Nigeria (2017)
9. Akomo, B.: Nigerian Railway warns against encroachment on rail tracks. WorldStage Media (2018). https://worldstagenews.com/nigerian-railway-warns-against-encroachment-on-rail-tracks/

10. Akwara, A.F., Udaw, J.E., Ezirim, G.E.: Adapting colonial legacy to modernism: a focus on rail transport development in Nigeria. Mediterr. J. Soc. Sci. **5**(6), 465–475 (2014)
11. Alabi, C.T.: NRC boss decries encroachment into railway lands. Daily Trust (2016). https://www.pressreader.com/nigeria/daily-trust/20161031/281861528056427
12. Amba, D.A., Danladi, J.D.: An appraisal of the Nigerian transport sector: evidence from the railway and aviation sub-sectors. J. Econ. Sustain. Dev. **4**(10), 163–170 (2013)
13. Amos, P.: Reform, commercialization and private sector participation in railway in Eastern Europe and Central Asia. Transport Papers TP-4. The International Bank for Reconstruction and Development/The World Bank, Washington (2005)
14. AutoJosh: 30 things to know about recent railway construction in Nigeria (1999–2019). AutoJosh (2019). https://autojosh.com/30-things-to-know-about-recent-railway-construction-in-nigeria-1999-2019/
15. Ayitogo, N.: Kaduna train attack: timeline of events three weeks after incident without decisive action by govt. Premium Times (2022). https://www.premiumtimesng.com/news/top-news/524593-kaduna-train-attack-timeline-of-events-three-weeks-after-incident-without-decisive-action-by-govt.html
16. Balogun, Y.: Military secures release of 23 remaining passengers of Abuja-Kaduna train attack. Daily Post (2022). https://dailypost.ng/2022/10/05/military-secures-release-of-23-remaining-passengers-of-abuja-kaduna-train-attack/
17. Bisiriyu, R.: Nigerian railway: a tale of failed contracts, dashed hope. Punch (2016). https://punchng.com/nigerian-railway-a-tale-of-failed-contracts-dashed-hope/
18. Boslaugh, S.E.: 'maglev'. Encyclopedia Britannica (2020). https://www.britannica.com/technology/maglev-train
19. BPE: Nigerian Railway Corporation. Bureau of Public Enterprises, Presidency, Abuja, Nigeria (2018). https://www.bpe.gov.ng/nigerian-railway-corporation/#:~:text=It%20however%20became%20an%20autonomous,safety%20of%20operations%20and%20maximum
20. CBN: Exchange Rate Archives: Nigerian Naira Exchange Rate. CBN (2022a). https://www.cbn.gov.ng/rates/ExchangeArchives.asp
21. CBN: History of Nigerian Currency. CBN (2022b). https://www.cbn.gov.ng/Currency/historycur.asp
22. CBN: Currency Gallery. CBN (2022c). https://www.cbn.gov.ng/Currency/gallery.asp
23. Chigbue, I.: Nigeria railway reforms: status update. A paper presented at the National Workshop on the Reform, Restructuring and Concessioning of the Nigerian Railway Corporation, held at Crystal Garden Hotel, Kaduna, Nigeria (2005)
24. Elechi, S.I.O.: Rail transport in Nigeria: problems and prospects. In: Eniola, J.O. (ed.) Transport, A Developmental Catalyst, pp. 241–255. Trance Nigeria Ltd., Lagos (1998)
25. Emejo, J., Alaran, F.: Experts Seek Passage of Railway Reform Bills to Boost Devt. ThisDay (2001). https://www.thisdaylive.com/index.php/2021/02/08/experts-seek-passage-of-railway-reform-bills-to-boost-devt/
26. Farrag-Thibault, A.: Climate change: implications for transport. The Fifth Assessment Report from the Intergovernmental Panel on Climate Change. University of Cambridge, Cambridge (2014)
27. Gabriel, J.: Terrorists Release Names of 11 Freed Kaduna-Abuja Train Attack Victims. Daily Post (2022). https://dailypost.ng/2022/06/11/terrorists-release-names-of-11-freed-kaduna-abuja-train-attack-victims/
28. Gabriel, J.: Abuja-Kaduna Train Attack Victims May Soon Die—Negotiator. Daily Post (2022). https://dailypost.ng/2022/06/21/abuja-kaduna-train-attack-victims-may-soon-die-negotiator/
29. Guardian: The Evolution of Our Currency (2016). https://guardian.ng/life/culture-lifestyle/the-evolution-of-our-currency/
30. Hogendorn, J.S.: Nigerian Groundnut Exports: Origins and Early Development. Ahmadu Bello University Press, Zaria (1978)
31. Hope for Nigeria: W-I-C-K-E-D-N-E-S-S!!! Vandals are crippling railway reforms—NRC. Hope for Nigeria (2014). https://mobile.facebook.com/hopefornigeria/photos/a.152919604766170.37823.100484630009668/689176367807155?_rdc=1&_rdr

32. Hot Topics Time: China is Developing the Fastest High Speed Rail, the High Temperature Superconducting Maglev Train! (2022). https://www.youtube.com/watch?v=rvE4jzCD8Wo
33. Igbonwelun, P.: Police Arrest Railway Vandals, Recover Stolen Tracks. The Nation (2022). https://thenationonlineng.net/police-arrest-railway-vandals-recover-stolen-tracks/
34. Ikeji, L.: Police Arrest Railway Vandals and Recover Stolen Tracks. LindaIkeji Blog (2022). https://www.lindaikejisblog.com/2022/4/police-arrest-railway-vandals-and-recover-stolen-tracks.html
35. InfomediaNG: History of Naira (Nigerian Currency). Actionable Info (2022). https://infomediang.com/naira-nigerian-currency/
36. Iroanusi, Q.: FG sends 150 Nigerians to China to study railway engineering—Minister. Premium Times (2019). https://www.premiumtimesng.com/news/more-news/358897-fg-sends-150-nigerians-to-china-to-study-railway-engineering-minister.html
37. Jakpa, P.E.: Nigerian Railway in the 1980s. In: Onakomaiya, S.O., Ekanem, N.F. (eds.) Transport in Nigerian National Development, pp. 67–89. NISER, Ibadan (1981)
38. Joseph, G.: Naira to dollar exchange rate from 1972. DailySchoolnews (2022). https://www.dailyschoolnews.com.ng/naira-to-dollar-exchange-rate/
39. Krause, C.L., Mishler, C.: Standard Catalog of World Coins: 1801–1991, 18th edn. Krause Publications, Iola, Wisconsin (1991)
40. Kumar, N., Pike, L.: 'Debt bomb' Risks: More than 40 Nations are at Risk of Default—and That's a Problem for us All. Grid News (2022). https://www.grid.news/story/global/2022/08/02/debt-bomb-risks-more-than-40-nations-are-at-risk-of-default-and-thats-a-problem-for-us-all/
41. Labisi, A.: Rail transport. In: Balogun, Y. et al. (eds.) Lagos State in Maps, pp. 66–67. Rex Charles Publication in Association with Connel Publications, Ibadan
42. Lafia, H.G., Elusoji, S.: 'Night Operation, Chinese Connection': How a Rail Vandalism Operation Thrived in Nasarawa. Channels TV (2021). https://www.channelstv.com/2021/06/21/night-operation-chinese-connection-how-a-rail-vandalism-operation-thrived-in-nasarawa/
43. Lagos Business News: States' Properties Risk Demolition Over Railway Land Encroachment. Lagos Business News (2021). https://lagosbusinessnews.ng/states-properties-risk-demolition-over-railway-land-encroachment/
44. Luu, T., Nguyen, D.: MagLev: The train of the future. In: Fifth Annual Freshman Conference, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania (2005). http://www.teslasociety.com/ttrain.doc
45. Mboho, J.: Nigerians React as Lagos-Bound Train Runs Out of Fuel in the Middle of Nowhere. Nairametrics (2022). https://nairametrics.com/2022/03/11/nigerians-react-as-lagos-bound-train-runs-out-of-fuel-in-the-middle-of-nowhere/
46. Mboya, C.: China Won't Seize Assets from African Countries, But Won't Forget the Debts. The Africa Report (2021). https://www.theafricareport.com/156470/china-wont-seize-assets-from-african-countries-but-wont-forget-the-debts/
47. NAN: Rail Track Vandalism: Police Arrest 5 Suspects in Kaduna. The Guardian (2021). https://guardian.ng/news/rail-track-vandalism-police-arrest-5-suspects-in-kaduna/
48. NSA: Transport Statistics and National Development: Programme and Summary of Conference Paper. 2000 annual conference, November 7–9, Ikeja. NSA (2000)
49. Odeleye, J.A.: Public–private participation to rescue railway development in Nigeria. Japan Railway Transp. Rev. **23**, 42–49 (2000)
50. Ogochukwu, C.G., Ogochukwu, O.F., Ogorchukwu, I.M., Ebuka, I.A.: Assessment of the performance of railway transportation in Nigeria from 1970 to 2010. Sci. Afri. **15**(2022), e0112 (2022). https://doi.org/10.1016/j.sciaf.2022.e01120
51. Okanlawon, K.R.: Towards enhancement of light rail system in efficient transportation of commuters in Lagos State. J. Soc. Policy Soc. **1**(1), 22–27 (2006)
52. Okanlawon, K.R.: A study of rail mass transit in Lagos and its environs. Ph.D Thesis. University of Lagos, Lagos, Nigeria (2011)
53. Olisah, C.: DMO reacts to reports of possible takeover of national assets by China due to loan default. Nairametrics (2021). https://nairametrics.com/2021/12/18/dmo-reacts-to-reports-of-possible-takeover-of-national-assets-by-china-due-to-loan-default/

54. Olojede, O.A.: Urban transport security: analysis of transit crime in Osogbo, Nigeria. Analele Universităţii din Oradea, Seria Geografie **29**(1), 9–18 (2019)
55. Olojede, O.A.: The hell-bound bandwagon: train rooftop riding in Lagos Metropolis, Nigeria. Urban Rail. Transit. **5**(1), 29–38 (2019). https://doi.org/10.1007/s40864-018-0097-1
56. Olojede, O.A.: Transport decarbonisation in South Africa: A case for active transport. Sci. J. Silesian Univ. Technol. Ser. Transp. **110**, 125–142 (2021). https://doi.org/10.20858/sjsutst.2021.110.11
57. Olojede, O., Daramola, O., Olufemi, B.: Metropolitan transport safety and security: an African experience. J. Transp. Saf. Secur. **9**(4), 383–402 (2017). https://doi.org/10.1080/19439962.2016.1230164
58. Olojede, O., Yoade, A., Olufemi, B.: Determinants of walking as an active travel mode in a Nigerian city. J. Transp. Health **6**, 327–334 (2017). https://doi.org/10.1016/j.jth.2017.06.008
59. Olojede, O.A., Agbola, S.B., Samuel, K.J.: Residents' assessment of local government road infrastructure delivery in Ile-Ife, Nigeria. Local Econ. **34**(4), 346–363 (2019)
60. Olojede, O.A., Oluborode, O.G.: Transportation: The agathokakological vehicle of pandemic transmission and management. Sci. J. Silesian Univ. Technol. Ser. Transp. **115**, 107–120 (2022)
61. Olojede, O.A., Owolabi, O.D.: High school students' psychometric assessment of pedestrian safety and risk factors in Ile-Ife, Nigeria. Int. J. Arch. Plann. **2**(2), 37–45 (2022). https://doi.org/10.51483/IJARP.2.2.2022.37-45
62. Oluokun, A.: Nigerian court jails Chinese Arvin Wu over stolen rail track sleepers. PM News (2021). https://pmnewsnigeria.com/2021/03/24/nigerian-court-jails-chinese-arvin-wu-over-stolen-rail-track-sleepers/
63. Oni, S.R., Okanlawon, K.R.: An assessment of the usage of Lagos mass transit trains. Int. J. Railway **5**(1), 29–37 (2012)
64. Onyeakagbu, A.: A trip down memory lane: the timeline of currency in Nigeria. pulse.ng (2022). https://www.pulse.ng/lifestyle/food-travel/a-trip-down-memory-lane-the-timeline-of-currency-in-nigeria/257f84d
65. Orjiude, A., Olatunji, S.: Nigeria risks losing assets to China over $3.48bn loan, experts warn FG. Punch (2021). https://punchng.com/nigeria-risks-losing-assets-to-china-over-3-48bn-loan-experts-warn-fg/
66. Osewa, O.: Naira to dollar exchange rate history (1972–2022)—Politics—Nairaland. Nairaland Forum (2022). https://www.nairaland.com/7161648/naira-dollar-exchange-rate-history
67. Placbillstrack: HB 22: Nigerian Railway Authority Bill, 2015 (2017). https://placbillstrack.org/view.php?getid=2012
68. Plus TV Africa: Volunteer Guards Impound Stolen Railway Property. Plus TV Africa (2021). https://www.youtube.com/watch?v=1wpeqLCBc-I
69. Premium Times: ANALYSIS: What to know about China loans and their implications for Nigeria. Premium Times (2020). https://www.premiumtimesng.com/news/headlines/406753-analysis-what-to-know-about-china-loans-and-their-implications-for-nigeria.html
70. Premium Times: Why Ibadan-Lagos Train Got Stuck—Official. Premium Times (2022). https://www.premiumtimesng.com/news/top-news/516622-why-ibadan-lagos-train-got-stuck-official.html
71. Quadri, O.: Timeline of CBN Exchange Rate From 1972 Till Date. Actionable Info (2022). https://infomediang.com/cbn-exchange-rate/
72. Remitly: Everything You Need to Know About Nigerian Currency. Remitly (2022). https://blog.remitly.com/finance/facts-you-probably-didnt-know-nigerian-naira/
73. Robinson, H., Smith, S.R., Clare, K.G.: The Economic Coordination of Transport Development in Nigeria. Stanford Research Institute, Carlifornia (1961)
74. Rogers, W.: Magnetic levitation raises the bar for safety standards in rail. Glob. Railway Rev. (2022). https://www.globalrailwayreview.com/article/132872/magnetic-levitation-raises-the-bar-for-safety-standards-in-rail/
75. Sanusi, A.: Terrorists Free 23 Remaining Train Attack Victims. Punch (2022). https://punchng.com/breaking-terrorists-free-23-remaining-train-attack-victims/

76. Ships & Ports: Court Jails Chinese Over Stolen Rail Track Sleepers. Ships & Ports (2021). https://shipsandports.com.ng/court-jails-chinese-over-stolen-rail-track-sleepers-2/
77. Solanke, A.T.: Ogun Police Command recovers vandalised railway sleepers, railway joint bars, rail spikes and rail clips ballast. Amebo Online Newspaper (2022). https://www.amebo9jafeed.com.ng/2022/03/here-arrested-general-overseer-for.html
78. Sparkgist: Naira to Dollar Exchange Rate Record Over 48 Years (1972–2022). Spark Gist (2020). https://www.sparkgist.com/naira-dollar-exchange-rate-record/
79. Stocker, J.: Nigerian Railway Jubilee, 1901–1951: An Illustrated and Descriptive History of the Nigerian Railway (Lagos Railway, Wushishi Tramway, Baro Kano Railway). Railway Printer, Michigan (1951)
80. Sunday, C.: NRC laments as Nasarawa vandals steal 970 sleepers, suspects flee. Punch (2021). https://punchng.com/nrc-laments-as-nasarawa-vandals-steal-970-sleepers-suspects-flee/
81. Sunday, O.: Army officer, 13 others nabbed for vandalisation, stealing railway property. The Guardian (2022). https://guardian.ng/news/army-officer-13-others-nabbed-for-vandalisation-stealing-railway-property/
82. TheCable: DHQ: 42 bandits, terrorists killed in northern Nigeria in two weeks. TheCable (2021). https://www.thecable.ng/dhq-42-bandits-terrorists-killed-in-northern-nigeria-in-two-weeks
83. ThisDay: Nipping Rail Vandalisation in the Bud. ThisDay (2021). https://www.thisdaylive.com/index.php/2021/06/27/nipping-rail-vandalisation-in-the-bud/
84. Tolofari, S.R., Gubbins, E.J.: Nigerian railways: problems and prospects. Transp. Plan. Technol. **8**, 225–235 (1984)
85. US Department of Energy: How Maglev Works. US Department of Energy (2016). https://www.energy.gov/articles/how-maglev-works
86. Wang, K.: China: Is it burdening poor countries with unsustainable debt? BBC (2022). https://www.bbc.com/news/59585507
87. Wang, S., Cripps, K.: China unveils 600 km/h maglev train prototype. CNN (2019). https://edition.cnn.com/travel/article/china-highspeed-maglev-prototype/index.html
88. Yusuf, S.T.: The incidences of theft of railway metals in colonial Northern Nigeria. Afro Asian J. Soc. Sci. **2**(2), 1–23 (2011)
89. Yusuf, S.T.: The socio-economic impact of the railway in Northern Nigeria: a study in transformation of the rural communities along the rail line between Kano and Zaria, 1908–1970s. Ph.D Thesis. Universiteit Leiden, Leiden, The Netherlands (2015). https://hdl.handle.net/1887/32000

Chapter 12
Mobile Aerial Ropeways Based on Autonomous Self-propelled Chassis: Layout of Technological Equipment

Alexander V. Lagerev and Igor A. Lagerev

Abstract Single-span ropeways based on autonomous self-propelled wheeled chassis of high load capacity and cross-country capability are a promising type of mobile transport and overloading equipment for the rapid creation of logistics infrastructure for the sustainable development of hard-to-reach areas with complex natural terrain. They can also be effectively used for rapid deployment during transport operations in the foci of natural or man-made disasters. The chapter presents mathematical models and calculation methods that make it possible to perform the optimal layout of the main technological equipment on the bearing frame of wheeled chassis and ensure the selection of such optimal characteristics of the location of the end tower in the transport position, in which for self-propelled units, when they are moved to the place of operation, regulatory restrictions on the overall dimensions of vehicles for highways are observed. The methods of designing and calculating the placement of key elements of promising design options for the mechanism of installation and fixation of the end tower in its extreme positions on the wheeled chassis are also presented. The chapter will be of interest to researchers and production specialists in the field of design and operation of transport rope systems.

Keywords Mobile ropeway · Wheeled chassis · Terminal unit · End tower · Layout · Optimization

12.1 Introduction

Currently, rope systems using the principle of motion transmission based on flexible metal ropes are used as a key structural element in the creation of transport and overloading equipment for solving various logistical tasks [1–3]. Although the experience of using transport rope technologies has a long history [4], in recent decades, there has been an increase in interest in this type of transport [5]. This is directly related to the development in the modern world of such global processes as increasing the

A. V. Lagerev (✉) · I. A. Lagerev
Academician I G Petrovskii Bryansk State University, Bryansk 241036, Russia
e-mail: avl-bstu@yandex.ru

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_12

importance of environmental requirements in assessing the quality of functioning of industrial and social facilities or protected natural ecosystems, the implementation of the "Smart City" concept, the transition to Industry 4.0 technologies in relation to transport [6, 7].

In particular, the undoubted advantages of transport equipment based on rope technologies in the field of ecology are the absence of the need to use internal combustion engines to ensure the operation of drive mechanisms (since more environmentally friendly electric or hydraulic engines are used), minimum requirements for land disposal to accommodate transport infrastructure and causing minimal damage to the terrestrial ecosystem (since no laying of surface roads is required due to the overhead nature of the rolling stock movement), etc. [8]. When implementing the "Smart City" concept, rope transport equipment is promising for the functioning of such a key component of this concept as "Smart Mobility". This equipment allows a more flexible approach to the creation of passenger and cargo transport infrastructure in highly urbanized areas of large cities and megacities [7, 9].

Thus, the development of rope transport technologies and the improvement of the transport technological equipment implementing them can be considered as one of the effective directions for the implementation of the principles of sustainable development [1, 10].

Currently, rope transport technologies are implemented in the form of two technical concepts—stationary ropeways and mobile ropeways. Today, stationary ropeways have become the most widespread, which are widely used in many industries (mining, metallurgical, construction, forestry, agricultural, etc.) [11, 12], as urban public transport systems [13, 14], as a transport element of sports, tourist or recreational infrastructure [15, 16]. Their principal feature is to work at one installation site during the entire service life, changing the installation location is usually carried out in exceptional cases. However, quite often there are such tasks that require high mobility from the transport technological equipment used to solve them. Such tasks include carrying out transport and overloading operations in hard-to-reach or ecologically vulnerable territories, in the absence of the necessary transport infrastructure, territories with unfavorable natural relief, in areas of destruction of natural or man-made accidents, etc. To solve these problems, mobile ropeways are a natural structural and functional analogue of stationary ropeways [8, 17].

The designs and design methods of stationary aerial ropeways have been sufficiently developed [11, 18, 19]. However, the existing design and operation experience accumulated to date in relation to stationary ropeways cannot be fully used in the design and operation of mobile ropeways. The main reason is that existing approaches, calculation methods and recommendations cannot form a scientific basis for creating promising mobile ropeways based on autonomous self-propelled units due to significant fundamental differences in the design of the main technological equipment, operating conditions and modes, principles of intelligent control, taking into account the influence of wheeled or tracked chassis, processes of its interaction with deformable supporting base, etc.

Despite the existence of practical needs for the use of mobile rope equipment, there is currently a shortage of such transport and overloading rope systems for the aboveground movement of passengers or cargo. One of the reasons for this situation is the lack of sound design methods for this type of transport, with the help of which it is possible to create competitive rope equipment.

This chapter discusses the methods of optimal placement of the main technological equipment on self-propelled wheeled chassis of high cross-country and carrying capacity, currently produced by manufacturers from different countries, when creating autonomous terminal units for the formation of single-span mobile ropeways.

12.2 Structural Types and Kinematic Schemes of Rope Technological Equipment for Autonomous Self-propelled Units

The greatest degree of mobility is possessed by single-span aerial ropeways, which are formed with the help of two autonomous terminal units connected by a single rope transport system on the basis of self-propelled wheeled or tracked chassis of high cross-country ability and carrying capacity.

A typical design of such a mobile ropeway is shown in Fig. 12.1. It is formed with the help of two similar terminal units based on self-propelled chassis 1, which are interconnected by a common transport rope system. The terminal units are located on the ground at the terminal points of the ropeway car route (sections 1-2 and 5-6). The main technological equipment, which is installed on the load-bearing frame of each self-propelled chassis, ensures the pendulum movement of goods along the ropeway route (sections 3-4) between the loading and unloading points (sections 2-3 and 4-5). Near the locations of the terminal units, there are sections for storing transported goods (sections 0-1 and 6-7). Technological operations for suspending and removing cargoes from the load handling fixtures 5 located on the carrying-traction rope 4 are carried out using loading and unloading machines, mechanisms or devices of various types (for example, crane-manipulator cranes 3, loaders, conveyors, etc.). During the operation of a mobile ropeway, one of the terminal unit is a drive unit for the carrying-traction rope, and the second terminal unit is a tension unit. It provides optimal tension of the carrying-traction rope depending on the length of the route, the height difference between the terminal points of the route and the weight of the cargo [20].

Figure 12.2 shows the main design types of self-propelled terminal units, which are advisable to use in the formation of mobile single-span ropeways of the pendulum type [21–24]. They differ in several features [25], which determine the design of the main technological equipment installed on the load-bearing frame of the chassis:

- at the location of the end tower in the working position (with a central, terminal or remote location),

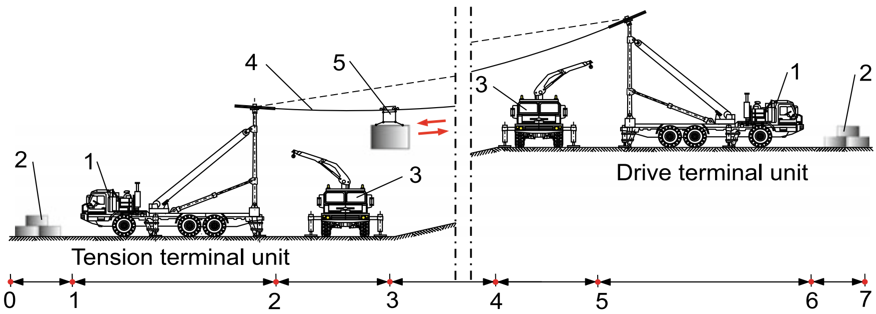


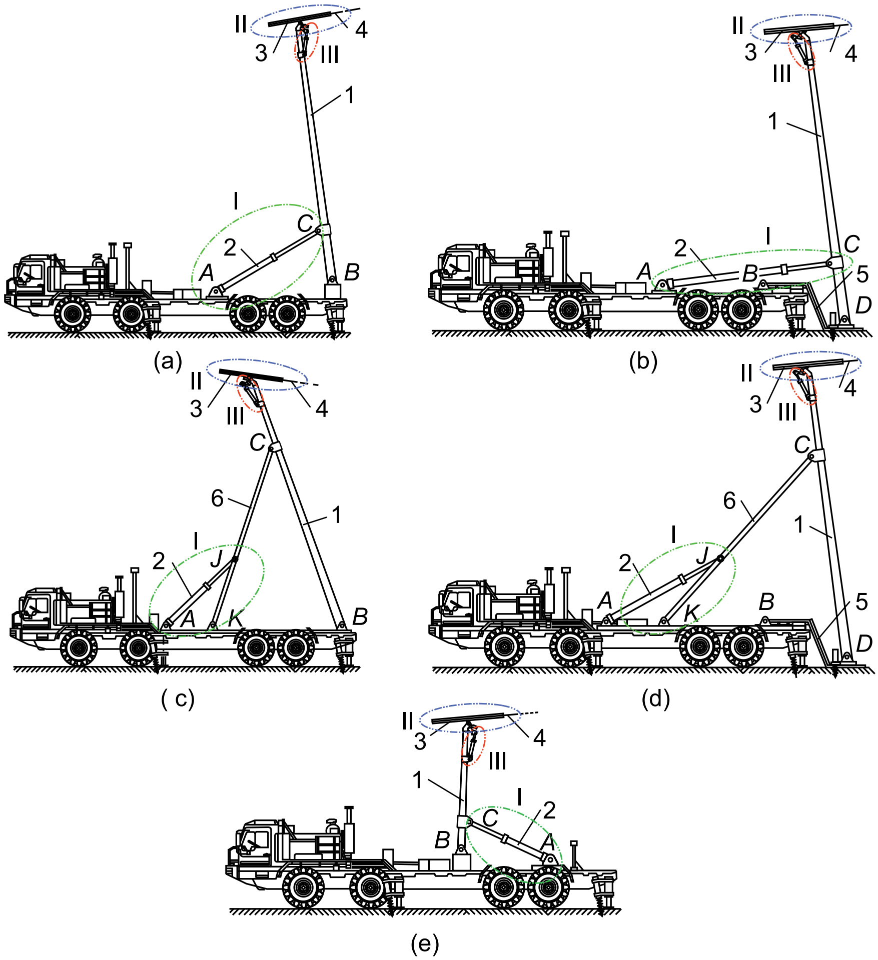
Fig. 12.1 Typical design of a mobile ropeway based on self-propelled terminal units

- according to the method of lifting the end tower from the transport position to the working position (using a lifting hydraulic cylinder, folding rod or auxiliary hydraulic cylinder),
- according to the method of fixing the end tower in the working position (hydraulic, rope, rope-hydraulic or rod fixation).

The main technological equipment includes such key elements as an end tower 1 to ensure the required high-altitude position of the rope pulley 3 with a carrying-traction rope 4, a turning platform 5, mechanism of installing and fixing of the end tower I with lifting hydraulic cylinder 2 and folding rod 6, carrying-traction rope movement mechanism II, rope pulley spatial orientation mechanism III, additional devices, mechanisms and systems and pumping system [8].

The design types of terminal units shown in Fig. 12.2 have similar design and operational features. Common to all types of terminal units, the main supporting metal structure for the rope pulley 3 and the rope system 4 of the mobile ropeway is the end tower 1. It also serves to fasten the structural elements of the carrying-traction rope movement mechanism II and the rope pulley spatial orientation mechanism III. The end tower can occupy two extreme positions: transport and working. In the transport position, the slope of its longitudinal axis is close to the horizontal plane, which allows the self-propelled terminal unit to move along general-purpose highways. In the working position, the slope of its longitudinal axis is close to the vertical plane. To transfer the end tower from the transport position to the working position and back, the mechanism of installing and fixing of the end tower I is used. The main element of this mechanism is a lifting hydraulic cylinder 2 (or two parallel-mounted and synchronously operating hydraulic cylinders), which is directly or by means of a folding rod 6 pivotally connected to the end tower.

For terminal units with a terminal (Fig. 12.2a, b) or central (Fig. 12.2e) location of the end tower, turning relative to the cylindrical hinge *B* connecting the load-bearing frame to the base of the end tower leads to its lifting into the working position. For terminal units with a remote location of the end tower (Fig. 12.2b, d), turning relative



1 - end tower, 2 - lifting hydraulic cylinder for installing and fixing the end tower, 3 - rope pulley, 4 - carrying-traction rope, 5 - turning platform, 6 - folding rod, A, B, C, D, K, J - cylindrical hinges, I - mechanism of installing and fixing of the end tower, II - carrying-traction rope movement mechanism, III - rope pulley spatial orientation mechanism

Fig. 12.2 Structural types of terminal units with various variants of the main technological equipment: with the terminal location of the end tower and lifting hydraulic cylinder (**a**), with the remote location of the end tower and lifting hydraulic cylinder (**b**), with the terminal location of the end tower and folding rod (**c**), with the remote location of the end tower and folding rod (**d**), with the central location of the end tower and lifting hydraulic cylinder (**e**) to the cylindrical hinge B connecting the load-bearing frame to the turning platform leads to lowering of the turning platform to the ground, and then further turning relative to the cylindrical hinge D connecting the end tower to the turning platform moves the tower to the working position.

The key problem in the design of terminal units is the layout of the lifting hydraulic cylinder, the end tower and the folding rod on the load-bearing frame of the self-propelled chassis, taking into account the longitudinal length allowed for the placement of the platform attachment equipment. The purpose of such a layout is to comply with the requirements of regulatory documents for the vertical dimension of wheeled vehicles in relation to terminal units with an end tower in the transport position and the requirements of the design specification for the maximum angle of turning when installing the end tower in the working position. The use of the optimization procedure in the layout allows minimizing the weight and size characteristics of the mechanism of installing and fixing of the end tower and ensuring the maximum possible length of the end tower.

The design procedures performed during the layout of the main technological equipment are aimed at determining the characteristic overall and installation sizes of a given kinematic scheme of the mechanism of installing and fixing of the end tower, taking into account the necessary design limitations. The indicated kinematic schemes, which correspond to the considered structural types of the terminal units (Fig. 12.2), are shown in Fig. 12.3 for two extreme cases of possible position of the end tower—transport and working positions.

The orientation of the longitudinal axis of the end tower in the vertical plane is characterized by the following design parameters, initially set before the layout of the main technological equipment on a wheeled chassis:

- the inclination angle of the longitudinal axis of the end tower to the plane of the load-bearing frame in the transport position γ_{ts};
- the deviation angle of the longitudinal axis of the end tower from the perpendicular to the plane of the bearing surface of the turning platform γ_{ts1};
- the inclination angle of the longitudinal axis of the end tower to the perpendicular to the ground surface in the working position γ_{ws};
- the distances between the characteristic points i and j of the kinematic scheme l_{ij};
- the angle of the relative position of the hinges B and D and the distance between them

$$\gamma_{BD} = \arcsin[(l_{Dd} - l_{nm} \sin \phi_t)/l_{BD}], \tag{12.1}$$

$$l_{BD} = [(l_{Bn} + l_{dm} - l_{mn} \cos \phi_t)^2 + (l_{Dd} - l_{mn} \sin \phi_t)^2]^{0,5}, \tag{12.2}$$

- the angle of the relative position of the gravity center of the turning platform and the hinge B $c.g._{pl}$ and the distance between them

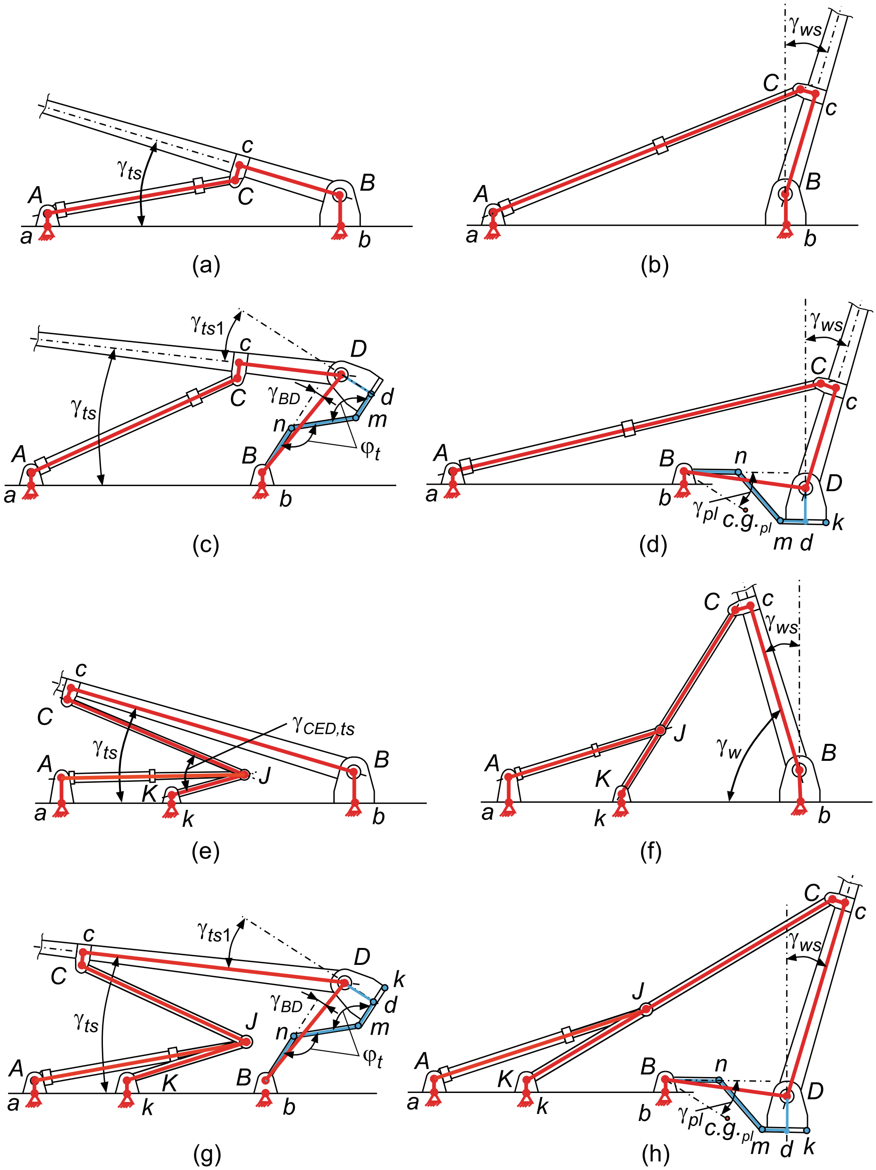


Fig. 12.3 Kinematic schemes of the mechanism of installing and fixing of the end tower with various variants of the main technological equipment: with the terminal (or central) location of the end tower and lifting hydraulic cylinder (**a**, **b**), with the remote location of the end tower and lifting hydraulic cylinder (**c**, **d**), with the terminal location of the end tower and folding rod (**e**, **f**), with the remote location of the end tower and folding rod (**g**, **h**), with the central location of the end tower and lifting hydraulic cylinder (**e**) in the transport (**a**, **c**, **e**, **g**) and working (**b**, **d**, **f**, **h**) position

$$\gamma_{pl} = -arctg\{(0,5G_{mn} + G_{km} + G_{an})(h_{lb} + h_{of} + l_{Bb}) \times \\ \times [0,5l_{Bn}G_{Bn} + (l_{Bn} - 0,5l_{mn}\cos\phi_t)G_{mn} + (l_{Bn} - l_{mn}\cos\phi_t + l_{dm})G_{km} + \\ + (l_{Bn} - l_{mn}\cos\phi_t + l_{mo})G_{an}]^{-1}\}, \quad (12.3)$$

$$l_{pl} = (G_{Bn} + G_{mn} + G_{km} + G_{an})^{-1}\{(0,5G_{mn} + G_{km} + G_{an})^2(h_{lb} + h_{of} + l_{Bb})^2 + \\ + [0,5l_{Bn}G_{Bn} + (l_{Bn} - 0,5l_{mn}\cos\phi_t)G_{mn} + (l_{Bn} - l_{mn}\cos\phi_t + l_{dm})G_{km} + \\ + (l_{Bn} - l_{mn}\cos\phi_t + l_{mo})G_{an}]^2\}^{0,5}, \quad (12.4)$$

where $l_{mn} = (h_{lb} + h_{of} + l_{Bb})/\sin\phi_t$; ϕ_t is the bending angle of the turning platform; h_{of} is the height of the overframe structure; G_{Bn}, G_{mn} are the weight of sections Bn and mn of the turning platform; G_{km} is the total weight of the platform section km and the end tower attachment unit; G_{an} is the weight of anchor devices located on the platform; l_{mo} is the distance from point m to the location of anchor devices on the platform section km.

When setting the size l_{cD}, it is necessary to exclude the possibility of contacting the lifting cylinder body with the overframe structure. This requirement is provided when the following condition is met

$$l_{cD} \geq l_{cD}^{\min} = \max\begin{cases} (h_{lb} + h_{of} + l_{Aa} - l_{Dd})/\cos\gamma_{ws} \\ (h_{lb} + h_{of} + l_{Aa} - l_{Dd})/\cos\gamma_{ts1} \end{cases}. \quad (12.5)$$

When setting the lengths of the mating parts of the folding rod l_{CJ} and l_{JK}, it is necessary to exclude the possibility of their contact with the metal structures of the end tower and the overframe structure. To do this, the condition must be met in the transport position

$$\gamma_{CED,ts} > [\gamma_{CED}]_{\min}, \quad (12.6)$$

where $[\gamma_{CED}]_{\min}$ is the angle that is minimally permissible under the condition of the location of the mating parts of the folding rod in the space under the end tower.

12.3 Preliminary Layout of the Main Technological Equipment in the Transport Position

The purpose of the preliminary layout of the main technological equipment on the load-bearing frame of a self-propelled wheeled chassis in the transport position is to comply with the standard size of the approach in height in order to safely travel under bridge structures and overpasses when moving end tower on public highways. The standard size is provided if the following condition is met

$$H_{mc} \leq [H], \tag{12.7}$$

where H_{mc} is the vertical coordinate of the highest point of the main technological equipment of the terminal unit in the transport position (vertical overall dimension).

12.3.1 Terminal Units with Terminal or Central Location of the End Tower and the Lifting Hydraulic Cylinder

The design schemes used in the layout of the main technological equipment in the transport position for these design types of terminal units are shown in Fig. 12.4. These schemes show the limit (maximum low and maximum high) positions of the end tower.

The vertical overall dimension of the terminal unit H_{mc} is determined by the elevation of the end tower top and is calculated by the equation

$$H_{mc} = h_{lb} + h_{of} + l_{Bb} + H_t \sin\gamma_{ts} + 0,5D_p \sin(\gamma_{pt} - \gamma_{ts}), \tag{12.8}$$

where D_p is the diameter of the rope pulley; γ_{pt} is the inclination angle of the rope pulley to the longitudinal axis of the end tower in the transport position.

The maximum possible inclination angle of the end tower in the transport position $\gamma_{ts}^{\max}$ satisfying condition (12.7) is determined by the solution of a nonlinear equation

$$H_t \sin\gamma_{ts}^{\max} + 0,5D_p \sin(\gamma_{pt} - \gamma_{ts}^{\max}) + h_{lb} + h_{of} + l_{Bb} - [H] = 0. \tag{12.9}$$

With small values of the angle γ_{ts} for terminal units with the terminal location of the end tower, there is a danger that the end tower cannot be placed due to the height size of the driver's cab. Therefore, the minimum possible inclination angle of the end tower in the transport position $\gamma_{ts}^{\min}$ is determined by the solution of the nonlinear equation

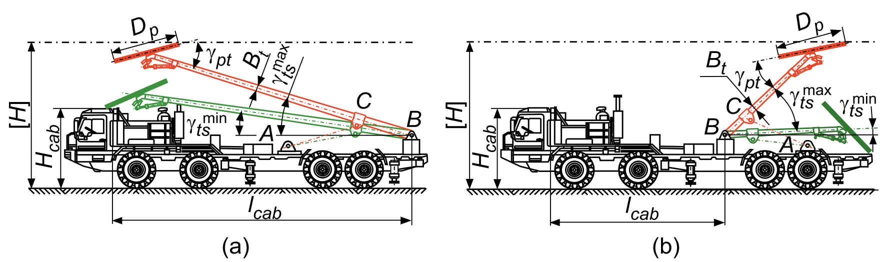


Fig. 12.4 Design schemes of preliminary layout for terminal units with a terminal location of the end tower (**a**) and with a central location of the end tower (**b**)

$$l_{cab}\sin\gamma_{ts}^{\min} - \frac{B_t}{2\cos\gamma_{ts}^{\min}} + h_{lb} + h_{of} + l_{Bb} - H_{cab} = 0, \tag{12.10}$$

where l_{cab} is the distance between the rear wall of the driver's cab and the hinge B in the end tower mounting; B_t is the height of the cross section of the end tower; H_{cab} is the height of the driver's cab.

For terminal units with a central location of the end tower at low angle values γ_{ts}, there is a danger that the rope pulley will be excessively lowered relative to the load-bearing frame of the chassis. Therefore, the minimum possible inclination angle of the end tower in the transport position $\gamma_{ts}^{\min}$ is determined by the solution of the nonlinear equation

$$H_t\sin\gamma_{ts}^{\min} - 0,5D_p\sin(\gamma_{ts}^{\min} + \gamma_{pt}) + l_{Bb} = 0. \tag{12.11}$$

The inclination angle of the end tower γ_{ts}, permissible under the conditions of the layout of the main technological equipment in the transport position, should be selected from the interval $\gamma_{ts}^{\min} \le \gamma_{ts} \le \gamma_{ts}^{\max}$. Its boundary values are determined according to Eqs. (12.9)–(12.11). It should be taken into account that the minimum possible inclination angle of the end tower $\gamma_{ts}^{\min}$ will correspond to the minimum possible vertical overall dimension of the terminal unit in the transport position, determined by the equation

$$H_{mc}^{\min} = h_{lb} + h_{of} + l_{Bb} + H_t\sin\gamma_{ts}^{\min} + 0,5D_p\sin(\gamma_{pt} - \gamma_{ts}^{\min}). \tag{12.12}$$

Calculations show that for terminal units with a terminal location of the end tower, the range of permissible inclination angles of the end tower in the transport position $\Delta\gamma_{ts} = \gamma_{ts}^{\max} - \gamma_{ts}^{\min}$ is very narrow, ranging from 1 to 5°. This significantly complicates the layout of the main technological equipment on the load-bearing frame of the chassis. On the contrary, for terminal units with a central location of the end tower, the range of permissible angles $\Delta\gamma_{ts}$ is very wide and is in the range from 18 to 25 degrees. This simplifies the layout and allows you to achieve a significantly small vertical overall dimension $H_{mc}^{\min}$, up to the situation when $H_{mc}^{\min} < H_{cab}$.

12.3.2 Terminal Units with Remote Location of the End Tower and the Lifting Hydraulic Cylinder

The design schemes used in the layout of the main technological equipment in the transport position for these design types of terminal units are shown in Fig. 12.5.

The vertical overall dimension of the terminal unit of this constructive type H_{mc} is located as the maximum value of the vertical coordinates of two characteristic points—the end tower top and the rear face of the turning platform (point k in Fig. 12.3):

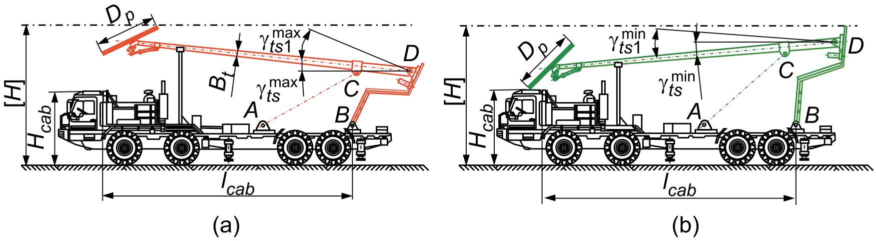


Fig. 12.5 Design schemes of preliminary layout for terminal units with a remote location of the end tower for the maximum protrusion of the end tower top (**a**) and the turning platform (**b**)

$$H_{mc} = \max\begin{cases} h_{lb} + h_{of} + l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + H_t \sin\gamma_{ts} + 0,5D_p \sin(\gamma_{pt} - \gamma_{ts}) \\ h_{lb} + h_{of} + l_{Bb} + (l_{BD} + l_{km} - l_{dm})\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{Dd}\sin(\gamma_{ts} + \gamma_{ts1}) \end{cases}. \quad (12.13)$$

For terminal units with a remote location of the end tower (as opposed to terminal units with a terminal or central location of the end tower), the boundary values $\gamma_{ts}^{\min}$ and $\gamma_{ts}^{\max}$ of the inclination angle of the end tower in the transport position γ_{ts} depend on the accepted angle γ_{ts1}. The maximum value of the angle $\gamma_{ts1,\max}$ depends on the position of the hinge D on the turning platform and is calculated by solving a nonlinear equation

$$(l_{dm} - h_{lb}\cos\phi_t)\cos\gamma_{ts1,\max} - 0,5B_t/\sin\gamma_{ts1,\max} + 0,5h_{lb}\sin 2\phi_t + l_{Dd} = 0. \quad (12.14)$$

For terminal units with a remote location of the end tower, condition (12.7) can be written in the form

$$H_{mc}(\gamma_{ts}; \gamma_{ts1}) \le [H]. \quad (12.15)$$

Thus, the layout of the main technological equipment on a self-propelled chassis in the transport position requires setting an agreed combination of angles γ_{ts} and γ_{ts1}. As can be seen from Fig. 12.5, increasing the angle γ_{ts1} makes it necessary to increase the angle γ_{ts}. As a consequence, the vertical overall dimension of the terminal unit in the transport position H_{mc} is determined by the height position of the end tower top. With a decrease in the angle γ_{ts1}, a decrease in the angle γ_{ts} is observed (up to negative values) and the vertical overall dimension H_{mc} is determined by the height position of the rear face of the turning platform.

With negative and small positive values of the angle γ_{ts}, it is possible that the end tower cannot be placed on the chassis load-bearing frame due to the height size of the driver's cab. To exclude such a situation, it is necessary that the following restriction is met

$$H_{\min} \ge H_{cab}, \quad (12.16)$$

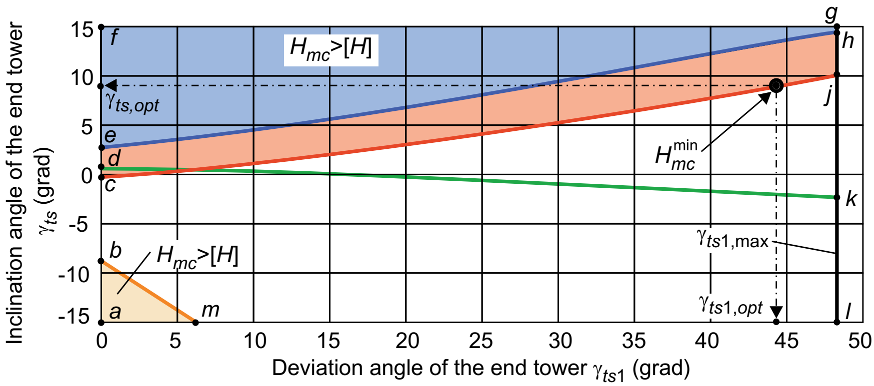


Fig. 12.6 Location of characteristic zones of angles combination γ_{ts} и γ_{ts1}

where $H_{\min} = h_{lb} + h_{of} + l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + H_t \sin\gamma_{ts} - 0,5D_p \sin(\gamma_{pt} - \gamma_{ts})$ is the lower height position of the end tower top.

An idea of the mutual influence of the inclination angle γ_{ts} and the deviation angle γ_{ts1} on the vertical overall dimension of the terminal unit is given by Fig. 12.6. There are several characteristic zones within the zone of a possible combination of angles $(\gamma_{ts}; \gamma_{ts1})$. They are bounded by lines:

- the lines *bm* and *eh* are the geometric places of the points of combinations $(\gamma_{ts}; \gamma_{ts1})$ satisfying condition (12.15) of the form $H_{mc}(\gamma_{ts}; \gamma_{ts1}) = [H]$;
- the line *cj* is the geometric places of the points of combinations $(\gamma_{ts}; \gamma_{ts1})$ satisfying condition (12.16) of the form $H_{\min} = H_{cab}$;
- the line *dk* is the geometric places of the points of combinations $(\gamma_{ts}; \gamma_{ts1})$ separating the zone of such combinations $(\gamma_{ts}; \gamma_{ts1})$, in which the vertical overall dimension H_{mc} is determined by the height position of the end tower top (zone *dfgk* in Fig. 12.6), from the zone of such combinations $(\gamma_{ts}; \gamma_{ts1})$, in which the vertical overall dimension

H_{mc} is determined by the height position of the rear face of the turning platform (zone *adkl* in Fig. 12.6).

These lines divide the zones of the combination of angles $(\gamma_{ts}; \gamma_{ts1})$ into several characteristic zones:

- in the *abm* and *efgh* zones, it is impossible to obtain an end tower layout that satisfies condition (12.15) of ensuring the normative value of the vertical dimension $[H]$;
- in the *behlm* zone, it is possible to obtain an end tower layout that meets only the condition (12.15) of ensuring the normative value of the vertical dimension $[H]$;
- in the *bcjlm* zone, it is possible to obtain an end tower layout that satisfies condition (12.15), but does not satisfy condition (12.16) of taking into account the height size of the driver's cab H_{cab};

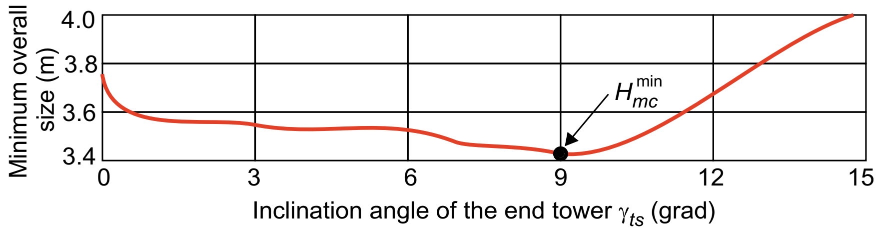


Fig. 12.7 Change in the vertical overall dimension along the condition (12.16)

- in the *cehj* zone, it is possible to obtain an end tower layout that satisfies both the conditions (12.15) and (12.16).

Thus, only the selection of a point within the *cehj* zone allows you to get a workable layout of technological equipment. In this zone, each point of combination (γ_{ts}; γ_{ts1}) corresponds to its own value of the vertical overall dimension H_{mc}. For example, Fig. 12.7 gives an idea of the change in the value $H_{mc}(\gamma_{ts};\gamma_{ts1})$ at points lying on the line *cj*.

In the *cehj* zone, there is such a combination (γ_{ts}; γ_{ts1}), which allows you to get the layout of technological equipment with the minimum possible value of the vertical overall dimension $H_{mc}^{\min}$.

The determination of the value $H_{mc}^{\min}$ and the corresponding combination (γ_{ts}; γ_{ts1}) is determined in the process of solving the problem of conditional nonlinear optimization. The controlled parameters that need to be determined in the process of finding the optimal solution $H_{mc}^{\min}$ are the angles of inclination γ_{ts} and deviation γ_{ts1} of the end tower. They form a vector of controlled parameters

$$\{x\} = \left\{ \begin{matrix} x_1 \\ x_2 \end{matrix} \right\} = \left\{ \begin{matrix} \gamma_{ts} \\ \gamma_{ts1} \end{matrix} \right\}. \qquad (12.17)$$

The rest of the originally specified design parameters included in the Eqs. (12.7), (12.13)–(12.16), accepted as unmanaged (fixed) parameters. They form a vector of unmanaged parameters

$$\{z\} = \{z_1\ z_2\ z_3\ z_4\ z_5\ z_6\ z_7\ z_8\ z_9\ z_{10}\ z_{11}\ z_{12}\ z_{13}\ z_{14}\} = \\ \{h_{lb}\ h_{of}\ l_{Bb}\ l_{Dd}\ l_{dm}\ l_{km}\ l_{BD}\ D_p\ H_t\ \phi_t\ \gamma_{BD}\ \gamma_{pt}\ \gamma_{ts1,\max}\ H_{cab}\}. \qquad (12.18)$$

The task of finding the optimal (minimum possible) value of the vertical dimension $H_{mc}^{\min}$ is reduced to finding the minimum of the objective function

$$O(\{x\},\{z\}) = \max\left\{ \begin{matrix} z_1 + z_2 + z_3 + z_7\cos(x_1 + x_2 - z_{11}) + z_9 \sin x_1 + 0,5 z_8 \sin(z_{12} - x_1) \\ z_1 + z_2 + z_3 + (z_7 + z_6 - z_5)\cos(x_1 + x_2 - z_{11}) - z_4 \sin(x_1 + x_2) \end{matrix} \right. \rightarrow \min, \qquad (12.19)$$

under constraints by inequalities:

- structural constraints

$$x_1 - x_{1,\min} \geq 0, x_{1,\max} - x_1 \geq 0, x_2 \geq 0, z_{13} - x_2 \geq 0, \tag{12.20}$$

- the condition for exceeding the lower height position of the end tower top of the height size of the driver's cab

$$z_1 + z_2 + z_3 + z_7 \cos(x_1 + x_2 - z_{11}) + z_9 \sin x_1 - 0,5 z_8 \sin(z_{12} - x_1) - z_{14} \geq 0, \tag{12.21}$$

- the conditions for not exceeding the vertical overall dimensions of the end tower top and the rear face of the turning platform for fixing the end tower of the standard dimension of the approximation in height

$$[H] - z_1 - z_2 - z_3 - z_7 \cos(x_1 + x_2 - z_{11}) - z_9 \sin x_1 - 0,5 z_8 \sin(z_{12} - x_1) \geq 0, \tag{12.22}$$

$$[H] - z_1 - z_2 - z_3 - (z_7 + z_6 - z_5) \cos(x_1 + x_2 - z_{11}) + z_4 \sin(x_1 + x_2) \geq 0, \tag{12.23}$$

where $x_{1,\min}$, $x_{1,\max}$ are the specified minimum and maximum values in which the inclination angle of the end tower γ_{ts} can change when solving the optimization task.

To calculate the optimal combination of controlled parameters,

$$\{x\}^{opt} = \begin{Bmatrix} x_{1,opt} \\ x_{2,opt} \end{Bmatrix} = \begin{Bmatrix} \gamma_{ts,opt} \\ \gamma_{ts1,opt} \end{Bmatrix}, \tag{12.24}$$

one of the known direct or quasi-gradient optimization methods can be used [26].

Figure 12.6 and 12.7 show the found point of the optimal combination of angles ($\gamma_{ts,opt}$; $\gamma_{ts1,opt}$), which provides the minimum vertical overall dimension $H_{mc}^{\min}$ of the terminal units on a four-axle wheeled chassis with a length of the end tower of 10 m.

12.3.3 Terminal Units with the Folding Rod

The design schemes used in the layout of the main technological equipment in the transport position for these design types of terminal units are shown in Fig. 12.8.

The vertical overall dimension of the terminal unit in the transport position H_{mc} is determined by the elevation of the cylindrical hinge J, which creates a movable connection of the lower and upper mating parts of the folding rod (Fig. 12.8). This is possible if the length of the lower part of the rod l_{JK} exceeds the maximum allowable

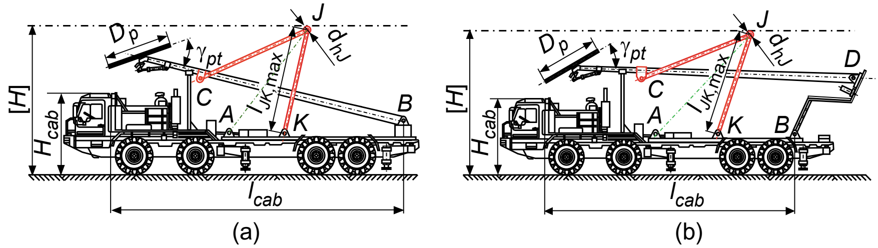


Fig. 12.8 Design schemes of preliminary layout for terminal units with a terminal location of the end tower (**a**) and with a remote location of the end tower (**b**)

value $l_{JK,\max}$. The value $l_{JK,\max}$ together with the value of the center coordinate x_J of the hinge J is the solution of a system of two nonlinear equations

$$\begin{cases} (x_J - l_{ak})^2 + ([H] - h_{lb} - h_{of} - d_{hJ}/2 - l_{Kk})^2 - l^2_{JK,\max} = 0 \\ (x_J - x_{C,ts})^2 + ([H] - h_{lb} - h_{of} - d_{hJ}/2 - y_{C,ts})^2 - (L_{sh} - l_{JK,\max})^2 = 0 \end{cases}, \quad (12.25)$$

where d_{hJ} is the overall size of the hinge joint of the mating parts of the rod; x_C, y_C are the coordinates of the center of the hinge C in the transport position (Fig. 12.3e, g); L_{sh} is the length of the folding rod in the unfolded state.

The sizes $x_{C,ts}$, $y_{C,ts}$ and L_{sh} required for determination $l_{JK,\max}$ are calculated using the following equations:

- at the terminal or central location of the end tower

$$x_{C,ts} = l_{ab} - l_{Bc}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}, \quad (12.26)$$

$$y_{C,ts} = l_{Bb} + l_{Bc}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts}, \quad (12.27)$$

$$L_{sh} = l_{JK} + l_{CJ} = \sqrt{(l_{ab} - l_{ak} + l_{Bc}\sin\gamma_{ws} - l_{Cc}\cos\gamma_{ws})^2 + (l_{Bb} - l_{Kk} + l_{Bc}\cos\gamma_{ws} + l_{Cc}\sin\gamma_{ws})^2}, \quad (12.28)$$

- at the remote location of the end tower

$$x_{C,ts} = l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}, \quad (12.29)$$

$$y_{C,ts} = l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{cD}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts}, \quad (12.30)$$

$$L_{sh} = l_{JK} + l_{CJ} = [(l_{ab} - l_{ak} + l_{BD}\cos\gamma_{BD} + l_{cD}\sin\gamma_{ws} - l_{Cc}\cos\gamma_{ws})^2 + \\ + (l_{Bb} - l_{Kk} + l_{BD}\sin\gamma_{BD} + l_{cD}\cos\gamma_{ws} + l_{Cc}\sin\gamma_{ws})^2]^{0,5}. \quad (12.31)$$

Figure 12.9 shows the change in the maximum permissible length of the lower part of the folding rod $l_{JK,\max}$ and the relative length $l_{JK,\max}/L_{sh}$, depending on the distance between the hinges B (or D) and C l_{Bc} (or l_{cD}) and the inclination angle of the end tower with a length of 10 m in the working position γ_{ws}. With an increase in the angle γ_{ws}, a proportional increase in the value $l_{JK,\max}$. This is due to the need to increase the length of the folding rod in the unfolded state at the working position of the end tower. However, the relative length $l_{JK,\max}/L_{sh}$ varies slightly. The range of its values is $\Delta(l_{JK,\max}/L_{sh}) < 0.03$.

In Fig. 12.10, the scale shows the relative position in the transport position of the end tower, the folding rod and the lifting hydraulic cylinder for $H_{mc} = [H] = 4$ m and the maximum permissible length of the lower part of the folding rod $l_{JK,\max}$. Calculations show that when the sizes l_{Bc} and γ_{ws} change, the horizontal coordinate of the hinge J changes relatively little. For example, for a terminal unit on a four-axle wheeled chassis with a 10 m end tower width, it lies in the range $\Delta x_J < 0.9$ m.

The length of the lower part of the folding rod l_{JK} is also limited by the minimum allowable value $l_{JK,\min}$

$$l_{JK} > l_{JK,\min}, \tag{12.32}$$

which is determined by the equation:

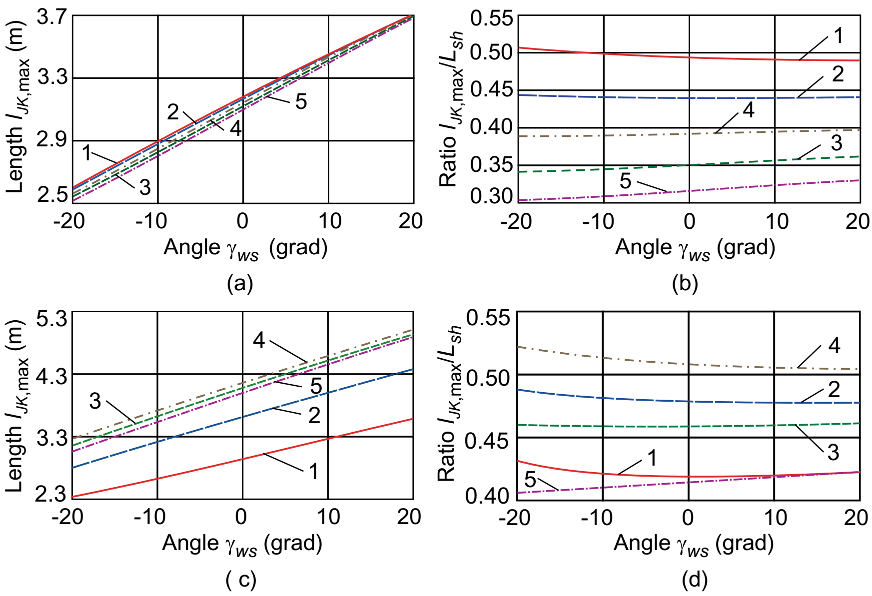


Fig. 12.9 Impact of the distance between the hinges and the inclination angle of the end tower on the maximum permissible length of the lower part of the folding rod at the terminal or central location of the tower (**a**, **b**) and at the remote location of the tower (**c**, **d**): 1—$l_{Bc}(l_{cD}) = 5$ m, 2—$l_{Bc}(l_{cD}) = 6$ m, 3—$l_{Bc}(l_{cD}) = 7$ m, 4—$l_{Bc}(l_{cD}) = 8$ m, 5—$l_{Bc}(l_{cD}) = 9$ m

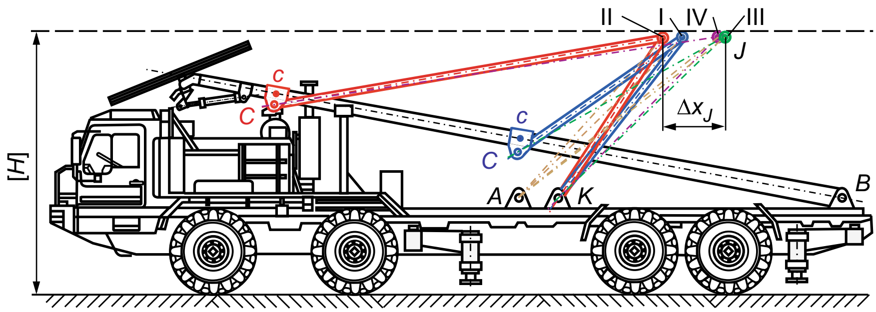


Fig. 12.10 Example of the layout of the main technological equipment in the transport position when the vertical dimension is limited by the location of the hinge J: I—$l_{Bc} = 5$ m, $\gamma_{ws} = -10°$; II—$l_{Bc} = 9$ m, $\gamma_{ws} = -10°$; III—$l_{Bc} = 5$ m, $\gamma_{ws} = 10°$; IV—$l_{Bc} = 9$ m, $\gamma_{ws} = 10^{\text{o}}$

- at the terminal or central location of the end tower

$$l_{JK,\min} = \frac{1}{2}\Big\{L_{sh} - \big[(l_{ab} - l_{ak} - l_{Bc}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts})^2 + \\ +(l_{Bb} - l_{Kk} + l_{Bc}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts})\big]^2\Big\}, \tag{12.33}$$

- at the remote location of the end tower

$$l_{JK,\min} = \frac{1}{2}\Big\{L_{sh} - \Big[(l_{ab} - l_{ak} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts})^2 + \\ + \ (l_{Bb} - l_{Kk} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{cD}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts})\Big]^2\Big\}. \tag{12.34}$$

12.4 Final Layout of the Main Technological Equipment on a Self-propelled Wheeled Chassis

During the final layout of the main technological equipment, the overall sizes of the structural elements of the mechanism for installing and fixing the end tower in the extreme (transport and limit working) and intermediate positions of the end tower as well as the length and stroke of the lifting cylinder rod or the sizes of the folding rod are determined, taking into account the possibility of their location on the load-bearing frame of the wheeled chassis relative to the end tower.

12.4.1 Terminal Units with Terminal or Central Location of the End Tower and the Lifting Hydraulic Cylinder

The minimum $(l_{AC})_{\min}$ and maximum $(l_{AC})_{\max}$ distances between the centers of the cylindrical hinges A and C for the lifting hydraulic cylinder connection correspond to the transport and limit working positions of the end tower. They are calculated using the equations

$$(l_{AC})_{\min} = \left[(l_{ab} - l_{Bc}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts})^2 + (l_{Bb} - l_{Aa} + l_{Bc}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts})^2\right]^{0,5}, \tag{12.35}$$

$$(l_{AC})_{\max} = \left[(l_{ab} + l_{Bc}\sin\gamma_{ws} - l_{Cc}\cos\gamma_{ws})^2 + (l_{Bb} - l_{Aa} + l_{Bc}\cos\gamma_{ws} + l_{Cc}\sin\gamma_{ws})^2\right]^{0,5}. \tag{12.36}$$

Size $(l_{AC})_{\min}$ determines the length of the lifting hydraulic cylinder L_{hc} (taking into account the thickness of the end caps and the size of the connecting devices), which can be placed in the space under the end tower in the transport position and which can ensure its turning to the maximum working position, i.e., $L_{hc} \approx (l_{AC})_{\min}$. Size $(l_{AC})_{\max}$ determines the full stroke of the hydraulic cylinder rod Δ_{hc}, which is necessary for turning the end tower from the transport position to the maximum working position:

$$\Delta_{hc} = (l_{AC})_{\max} - (l_{AC})_{\min}. \tag{12.37}$$

The full stroke of the rod Δ_{hc} must be less than the length of the hydraulic cylinder L_{hc}. The ratio between these values is conveniently expressed in terms of the coefficient of the hydraulic cylinder rod motion:

$$\xi_{hc} = \Delta_{hc}/L_{hc} \approx \Delta_{hc}/(l_{AB})_{\min}, \tag{12.38}$$

which changes in the interval $0 < \xi_{hc} \le \xi_{hc,\max}$. The maximum value of the coefficient $\xi_{hc,\max}$ corresponds to the maximum possible stroke of the rod $\Delta_{hc,\max}$. It is determined by the design of the lifting hydraulic cylinder used. As a rule, for industrial hydraulic cylinders, the value is in the range from 0.6 to 0.9.

The layout of the hydraulic cylinder in the space under the end tower located in the transport position is possible only when the condition is met

$$\xi_{hc} = (l_{AC})_{\max}/(l_{AC})_{\min} - 1 \le [\xi_{hc}], \tag{12.39}$$

where $[\xi_{hc}]$ is the coefficient of the hydraulic cylinder rod motion, specified during the design of the terminal unit ($[\xi_{hc}] \le \xi_{hc,\max}$).

The layout condition (12.39) is provided by a rational choice of a combination of two design sizes of the kinematic scheme l_{ab} and l_{Bc} (Fig. 12.3). With the initial connection size l_{ab}, the required size l_{Bc} of the connection point of the hydraulic cylinder to the end tower is the solution of a nonlinear equation

$$\sqrt{\frac{(l_{ab}+l_{Bc}\sin\gamma_{ws}-l_{Cc}\cos\gamma_{ws})^2+(l_{Bb}-l_{Aa}+l_{Bc}\cos\gamma_{ws}+l_{Cc}\sin\gamma_{ws})^2}{(l_{ab}-l_{Bc}\cos\gamma_{ts}-l_{Cc}\sin\gamma_{ts})^2+(l_{Bb}-l_{Aa}+l_{Bc}\sin\gamma_{ts}-l_{Cc}\cos\gamma_{ts})^2}}-1-[\xi_{hc}]=0. \tag{12.40}$$

When performing calculations according to Eq. (12.40), setting the rod motion coefficient $\xi_{hc,\max}$ allows you to determine the smallest required length of the hydraulic cylinder L_{hc}, since in this case

$$\Delta_{hc}=\Delta_{hc,\max}. \tag{12.41}$$

Figure 12.11 shows the zones of combinations of sizes l_{ab} and l_{Bc} for $[\xi_{hc}] = \xi_{hc,\max} = 0.9$, determined by condition (12.39) and Eq. (12.40). Figure 12.11 also shows the maximum values of sizes $l_{ab,\max}$ for wheeled chassis with a different number of axles. Lines $O_1O_2O_3O_4$ delimit zones with $\xi_{hc} > [\xi_{hc}]$ and $\xi_{hc} < [\xi_{hc}]$. With a combination of dimensions l_{ab} and l_{Bc} lying inside the zone $\xi_{hc} > [\xi_{hc}]$ (for example, point $I\,(l_{Bc,I}; l_{ab,I})$), to turn the end tower from the transport position to the maximum working position, such a stroke of the rod Δ_{hc} is required that a lifting hydraulic cylinder of a given design cannot provide. Thus, this zone is unacceptable by the layout condition (12.39). With a combination of dimensions l_{ab} and l_{Bc} lying inside the zone $\xi_{hc} < [\xi_{hc}]$ (for example, point $II\,(l_{Bc,II}; l_{ab,II})$), a rod stroke is required to transfer the end tower, which a lifting hydraulic cylinder of a given design can provide. This zone of the combination of sizes l_{ab} and l_{Bc} allows the layout of the mechanism for installing and fixing the end tower in accordance with condition (12.39), although $\Delta_{hc} < \Delta_{hc,\max}$. The best combinations of sizes l_{ab} and l_{Bc} should be considered those that lie on the boundary line $O_1O_2O_3O_4$ (e.g., point $III\,(l_{Bc,II}; l_{ab,II})$). In this case, the layout condition (12.39) and the requirement (12.41) are simultaneously met. The boundary lines O_1O_2 and O_3O_4 can be expressed by linear equations:

- the line O_1O_2

$$l_{Bc,1-2}=a_{Bc,1-2}+b_{Bc,1-2}l_{ab}, \tag{12.42}$$

- the line O_3O_4

$$l_{Bc,3-4}=a_{Bc,3-4}+b_{Bc,3-4}l_{ab}, \tag{12.43}$$

where $a_{Bc,1-2}$, $b_{Bc,1-2}$, $a_{Bc,3-4}$, $b_{Bc,3-4}$ are the approximation coefficients.

Figure 12.11 shows that one value of size l_{ab} corresponds to two values of size l_{Bc}, that is, there are two alternative variants for the layout of the lifting hydraulic cylinder. Both variants ensure the transfer of the end tower from the transport position to the maximum working position at the maximum stroke of the hydraulic cylinder

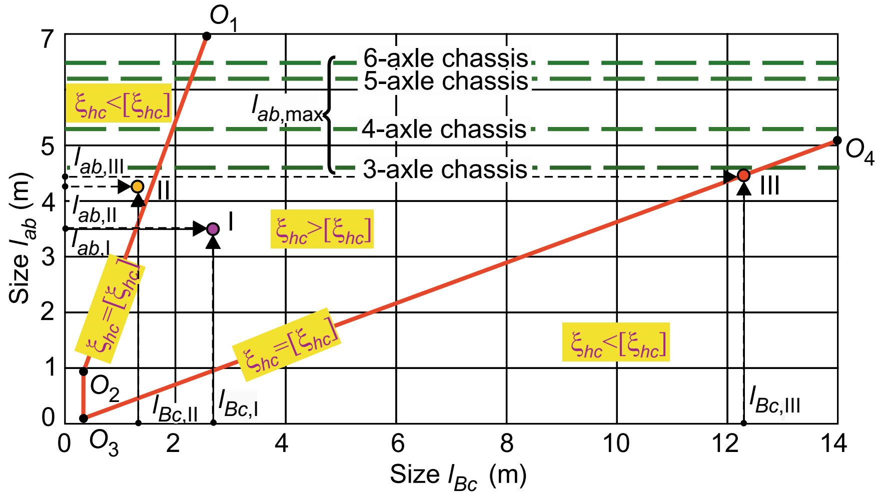


Fig. 12.11 Zones of possible layout of the lifting hydraulic cylinder at the terminal or central location of the end tower

rod $\Delta_{hc} = \Delta_{hc,\max}$. Figure 12.12 shows alternative variants for a four-axle wheeled chassis with an end tower length of 10 m. The variants differ in the length of the lifting hydraulic cylinder L_{hc} (Fig. 12.13). If the combination of sizes l_{ab} and l_{Bc_I} lies on the line $O_1O_2O_3$ (variant I), then such an alternative variant requires the use of a hydraulic cylinder of a shorter length than variant II with a combination of sizes l_{ab} and $l_{Bc_{II}}$ lying on the line O_3O_4.

The location of the zones $\xi_{hc} < [\xi_{hc}]$ and $\xi_{hc} > [\xi_{hc}]$ on the coordinate plane $(l_{ab} - l_{Bc})$ depends on the size of the mechanism for installing and fixing the end tower, in particular, on the size $\Delta l = l_{Aa} - l_{Bb}$ and angle γ_{ws} (Fig. 12.14). An increase in the height difference Δl of the bracing of the lifting hydraulic cylinder and the end tower to the load-bearing frame of the chassis and a decrease in the inclination angle of the end tower in the maximum working position γ_{ws} have a positive effect on the possibility of assembling the mechanism due to a decrease in the zone $\xi_{hc} > [\xi_{hc}]$.

12.4.2 *Terminal Units with Remote Location of the End Tower and the Lifting Hydraulic Cylinder*

The minimum $(l_{AC})_{\min}$ and maximum $(l_{AC})_{\max}$ distances between the cylindrical hinges centers of the lifting hydraulic cylinder bracing correspond to the transport and maximum working positions of the end tower. They are calculated using the equations

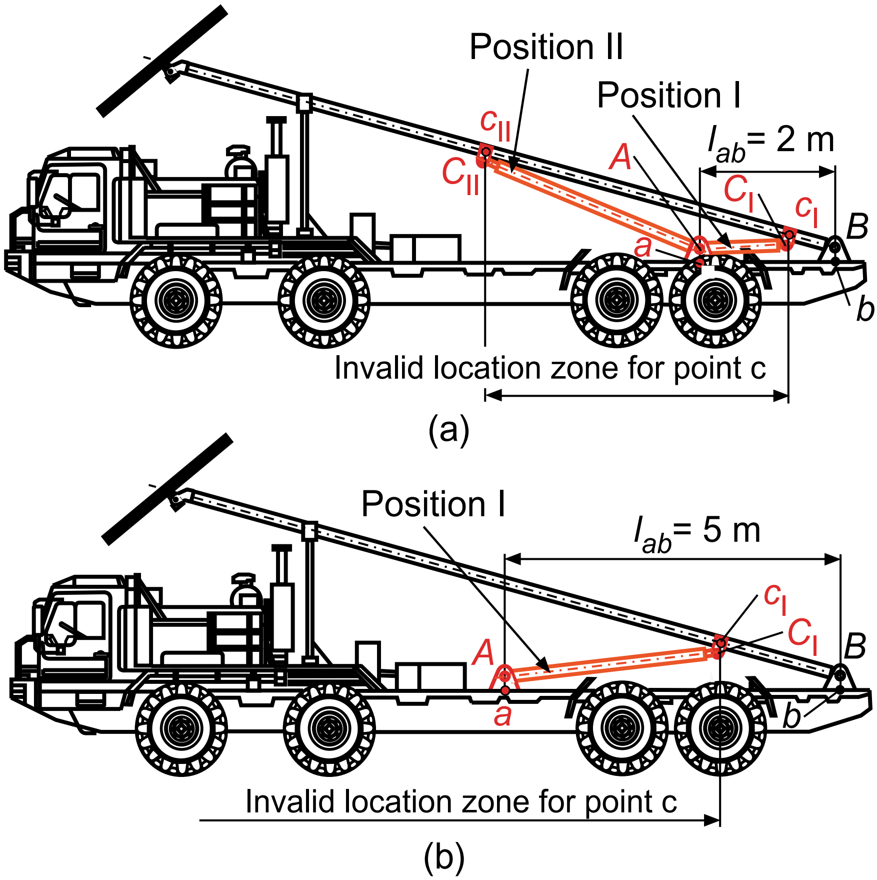


Fig. 12.12 Example of alternative layout options for a lifting hydraulic cylinder on a 4-axle wheeled chassis with a length of the end tower of 10 m depending on the distance between the hinges A and B 2 m (**a**) and 5 m (**b**)

$$(l_{AC})_{\min} = \Big\{ \big[l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}\big]^2 + \\ + \big[l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{cD}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts} - l_{Aa}\big]^2\Big\}^{0,5}, \tag{12.44}$$

$$(l_{AC})_{\max} = \Big\{ \big[l_{ab} + l_{BD}\cos\gamma_{BD} + l_{cD}\sin\gamma_{ws} - l_{Cc}\cos\gamma_{ws}\big]^2 + \\ + \big[l_{Bb} + l_{BD}\sin\gamma_{BD} + l_{cD}\cos\gamma_{ws} + l_{Cc}\sin\gamma_{ws} - l_{Aa}\big]^2\Big\}^{0,5}. \tag{12.45}$$

The layout condition (12.39) is provided by a rational choice of a combination of two sizes l_{ab} and l_{cD} (Fig. 12.3). With the initially accepted connection size l_{ab}, the required size l_{cD} of the bracing point of the hydraulic cylinder to the end tower is the

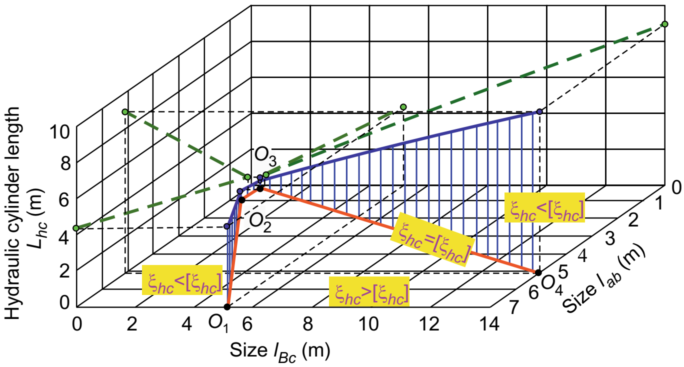


Fig. 12.13 Length of the lifting hydraulic cylinder for various combinations of sizes l_{ab} and l_{Bc} for $\xi_{hc} = [\xi_{hc}] = 0.9$ (4-axle wheeled chassis with a length of the end tower of 10 m)

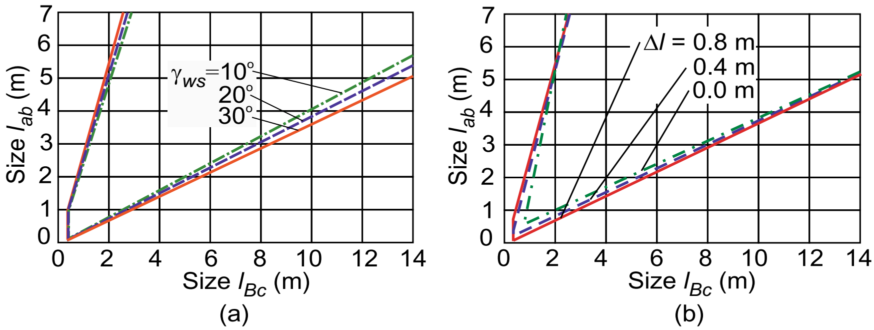


Fig. 12.14 Dependence of the sizes of the mechanism for installing and fixing the end tower on the inclination angle of the tower in the working position (**a**) and the height difference of the hinges (**b**) for a 4-axle wheeled chassis with a length of the end tower of 10 m

solution of a nonlinear equation

$$\frac{(l_{AC})_{\max}}{(l_{AC})_{\min}} - 1 - [\xi_{hc}] = 0. \tag{12.46}$$

Figure 12.15 shows the zones of combinations of sizes l_{ab} and l_{cD} at $[\xi_{hc}] = \xi_{hc,\max} = 0.9$, determined by condition (12.39) and Eq. (12.46). Analysis of Fig. 12.15 is similar to the analysis of Fig. 12.11 made in Sect. 12.4.1. The shaded zone determines those values of size l_{cD} that do not meet the condition (12.5). The boundary lines O_1O_2 and O_3O_4 can be expressed by linear equations:

- the line O_1O_2

$$l_{cD,1-2} = a_{cD,1-2} + b_{cD,1-2} l_{ab}, \tag{12.47}$$

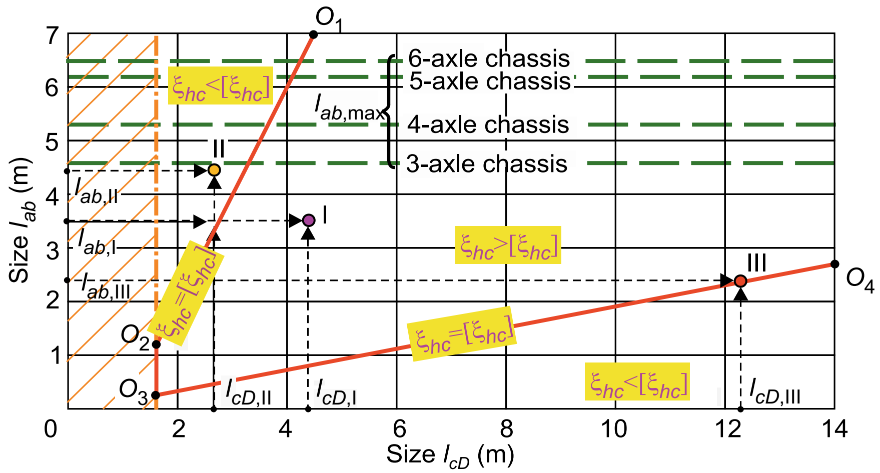


Fig. 12.15 Zones of possible layout of the lifting hydraulic cylinder at the remote location of the end tower

- the line O_3O_4

$$l_{cD,3-4} = a_{cD,3-4} + b_{cD,3-4} l_{ab}, \tag{12.48}$$

where $a_{cD,1-2}$, $b_{cD,1-2}$, $a_{cD,3-4}$, $b_{cD,3-4}$ are the approximation coefficients.

For the remote location of the end tower, the boundary line O_3O_4 is located more hollow than with the terminal or central location of the end tower. This suggests that when layout the mechanism for installing and fixing the end tower, a lifting hydraulic cylinder is required, the length of which is significantly longer than shown in Fig. 12.13. Thus, when designing and layout the main technological equipment, it is advisable to focus only on the line O_1O_2 and the adjacent zone $\xi_{hc} < [\xi_{hc}]$.

According to Fig. 12.15, one value of size l_{ab} corresponds to two values of size l_{cD}, that is, there are two alternative variants for the layout of the lifting hydraulic cylinder. As in the case of the terminal or central position of the end tower, the existence of two alternative variants is due to the presence of a zone in the middle part of the end tower, within which the hinge C cannot be placed. Both variants ensure the transfer of the end tower from the transport position to the maximum working position at the maximum stroke of the hydraulic cylinder rod $\Delta_{hc} = \Delta_{hc,\max}$ and differ in the length of the lifting hydraulic cylinder L_{hc} (Fig. 12.16).

The location of zones $\xi_{hc} < [\xi_{hc}]$ and $\xi_{hc} > [\xi_{hc}]$ on the coordinate plane $(l_{ab} - l_{cD})$ depends on the sizes of the mechanism kinematic scheme as well as the angles γ_{ts}, γ_{ts1} and γ_{ws}. Figure 12.17 shows the effect of these angles on the position of the boundary line O_1O_2 for a four-axle wheeled chassis with an end tower of 10 m in length with an optimal combination of $\gamma_{ts} = 9°$ and $\gamma_{ts1} = 44°$ (Sect. 12.3.2). A decrease in the inclination angle γ_{ws} and the height difference Δl has a positive effect on the possibility of layout the mechanism installing and fixing the end tower

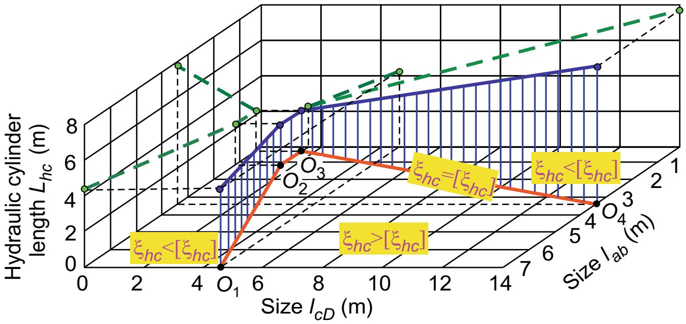


Fig. 12.16 Length of the lifting hydraulic cylinder for various combinations of sizes l_{ab} and l_{cD} for $\xi_{hc} = [\xi_{hc}] = 0.9$ (4-axle wheeled chassis with a length of the end tower of 10 m)

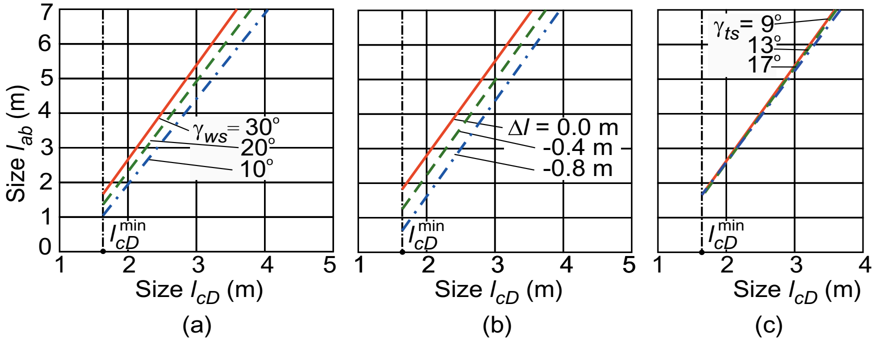


Fig. 12.17 Dependence of the sizes of the mechanism for installing and fixing the end tower on the inclination angle of the tower in the working position (**a**), the height difference of the hinges (**b**) and inclination angle of the tower in the transport position (**c**) for a 4-axle wheeled chassis with a length of the end tower of 10 m

due to a decrease in the zone $\xi_{hc} > [\xi_{hc}]$. The angles γ_{ts} and γ_{ts1} have no practically significant effect on the reduction of the zone $\xi_{hc} > [\xi_{hc}]$.

12.4.3 Terminal Units with the Folding Rod

As researches show, the results of which are given in [8], when using a folding rod in the design of the mechanism for installing and fixing the end tower, a terminal unit with a remote location of the end tower is more suitable.

The primary design solution is to set the length of the lower part of the folding rod l_{JK}. It must meet the condition of ensuring the permissible vertical overall dimension of the terminal station:

$$l_{JK} \leq l_{JK,\max}. \tag{12.49}$$

Then, the horizontal $x_{J,ts}$ and vertical $y_{J,ts}$ coordinates of the center of the hinge J at the transport position of the end tower can be determined by solving a system of two nonlinear equations

$$\begin{cases} (x_{J,ts} - l_{ak})^2 + (y_{J,ts} - l_{Kk})^2 - l_{JK}^2 = 0 \\ (x_{J,ts} - l_{ab} - l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{cD}\cos\gamma_{ts} + l_{Cc}\sin\gamma_{ts})^2 + \\ +(y_{J,ts} - l_{Bb} - l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\sin\gamma_{ts} + l_{Cc}\cos\gamma_{ts})^2 - (L_{sh} - l_{JK})^2 = 0 \end{cases}. \tag{12.50}$$

On workable configurations of kinematic schemes of terminal units (Fig. 12.3) with a folding rod, restrictions are imposed on the possible spatial location of the center of the hinge J in the transport position. Its permissible horizontal $x_{J,ts}$ and vertical $y_{J,ts}$ coordinates should lie in the following intervals

$$-[x_J] \leq x_{J,ts} \leq l_{ab};\ [y_J] \leq y_{J,ts} \leq [H] - h_{lb} - h_{of}, \tag{12.51}$$

where $[x_J]$ is the maximum possible displacement of the center of the hinge J from the center of the hinge A toward the chassis cab; $[y_J]$ is the minimum possible approximation of the center of the hinge J to the overframe structure.

The installation of the end tower in the working position can be performed depending on the relative spatial location of the hinge J both during the extension of the rod of the lifting hydraulic cylinder and during its return movement. Figure 12.18 shows the zones of the possible position of the center of the hinge J, which determines the direction of turning of the end tower depending on the direction of displacement of the rod.

The zone bounded by the angular points 1-d'-D'-C-K-5 determines such a position of the center of the hinge J, at which the installation of the end tower in the working position is performed during the return movement of the lifting cylinder rod. This zone is relatively small in size, which complicates the layout of the mechanism for installing and fixing the end tower. The location of the center of the hinge J in this zone at the transport position of the end tower is observed when three conditions are met simultaneously:

if $l_{ak} \geq l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}$

$$x_{J,st} > l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}, \tag{12.52}$$

$$x_{J,st} < l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{Dd}\cos(\gamma_{ts} + \gamma_{ts1}), \tag{12.53}$$

$$y_{J,st} < \frac{l_{Cc}(\cos\gamma_{ts} - \cos^{-1}\gamma_{ts}) - l_{cD}\sin\gamma_{ts}}{l_{cD}\cos\gamma_{ts} + l_{Cc}\sin\gamma_{ts}}[x_{J,st} - l_{ab} - l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD})] + \\ + l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{Cc}/\cos\gamma_{ts}, \tag{12.54}$$

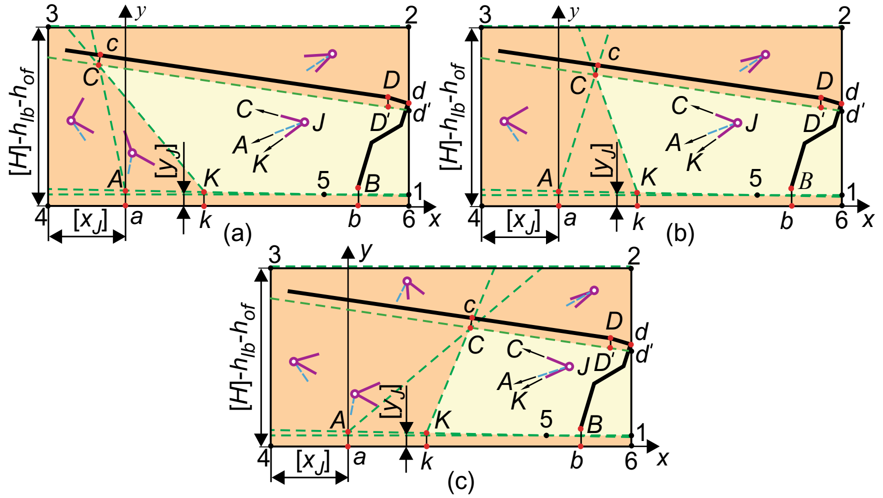


Fig. 12.18 Zones of possible location of the hinge J center with a different direction of the end tower rotation depending on the direction of the rod displacement at $x_C < x_A$ (**a**), at $x_A < x_C < x_K$ (**b**), at $x_C > x_K$ (**c**)

$$y_{J,st} > \max\begin{cases} (l_{Kk} - l_{Aa})x_{J,st}/l_{ak} + l_{Aa} \\ l_{Kk} + \frac{l_{Bb} - l_{Kk} + l_{BD}\cos(\gamma_{ts}+\gamma_{ts1}-\gamma_{BD}) + l_{cD}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts}}{l_{ab} - l_{ak} + l_{BD}\sin(\gamma_{ts}+\gamma_{ts1}-\gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}} \times (x_{J,st} - l_{ak}) \\ [y_J] \end{cases}, \tag{12.55}$$

if $l_{ak} < l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}$

$$x_{J,st} > l_{ak}, \tag{12.56}$$

$$x_{J,st} < l_{ab} + l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) + l_{Dd}\cos(\gamma_{ts} + \gamma_{ts1}), \tag{12.57}$$

$$y_{J,st} < \min\begin{cases} \frac{l_{Cc}(\cos\gamma_{ts} - \cos^{-1}\gamma_{ts}) - l_{cD}\sin\gamma_{ts}}{l_{cD}\cos\gamma_{ts} + l_{Cc}\sin\gamma_{ts}} \times [x_{J,st} - l_{ab} - l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD})] + l_{Bb} + \\ \quad + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - l_{Cc}/\cos\gamma_{ts} \\ l_{Kk} + \frac{l_{Bb} - l_{Kk} + l_{BD}\cos(\gamma_{ts}+\gamma_{ts1}-\gamma_{BD}) + l_{cD}\sin\gamma_{ts} - l_{Cc}\cos\gamma_{ts}}{l_{ab} - l_{ak} + l_{BD}\sin(\gamma_{ts}+\gamma_{ts1}-\gamma_{BD}) - l_{cD}\cos\gamma_{ts} - l_{Cc}\sin\gamma_{ts}} \times (x_{J,st} - l_{ak}) \end{cases}, \tag{12.58}$$

$$y_{J,st} > \max\begin{cases} (l_{Kk} - l_{Aa})x_{J,st}/l_{ak} + l_{Aa} \\ [y_J] \end{cases}. \tag{12.59}$$

Accordingly, the zone lying outside the zone 1-d'-D'-C-K-5 determines the position of the center of the hinge J, in which the installation of the end tower in the working position is performed when the rod of the lifting hydraulic cylinder is extended.

The location of the hinge J within the required zone 1-d'-D'-C-K-5 is achieved by choosing the length of the lower part of the folding rod l_{JK}. To do this, it must lie in the interval $l_{JK} \in (l_{JK,pr}; l_{JK,dop})$. The length $l_{JK,dop}$ must not exceed the maximum length $l_{JK,\max}$ determined by Eq. (12.25). The length $l_{JK,dop}$ is determined from the condition that the center of the hinge J must be on the straight line CD' (Fig. 12.18). To do this, it is necessary to consistently find the position of the center of the hinge J in the horizontal plane $x_{J,dop}$ using a nonlinear equation

$$\frac{x_{J,dop} - x_{C,ts}}{\cos\gamma_{ts}} - L_{sh} + \left\langle \left\{ \frac{l_{Cc}(\cos\gamma_{ts} - \cos^{-1}\gamma_{ts}) - l_{cD}\sin\gamma_{ts}}{l_{cD}\cos\gamma_{ts} + l_{Cc}\sin\gamma_{ts}} \times \right.\right.$$
$$\times [x_{J,dop} - l_{ab} - l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD})] + l_{Bb} +$$
$$\left.\left. + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - \frac{l_{Cc}}{\cos\gamma_{ts}} - l_{Kk} \right\}^2 + (x_{J,dop} - l_{ak})^2 \right\rangle^{0,5} = 0, \quad (12.60)$$

then find the position of the center of the hinge J in the vertical plane $y_{J,dop}$

$$y_{J,dop} = \frac{l_{Cc}(\cos\gamma_{ts} - \cos^{-1}\gamma_{ts}) - l_{cD}\sin\gamma_{ts}}{l_{cD}\cos\gamma_{ts} + l_{Cc}\sin\gamma_{ts}}[x_{J,dop} - l_{ab} - l_{BD}\sin(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD})] +$$
$$+ l_{Bb} + l_{BD}\cos(\gamma_{ts} + \gamma_{ts1} - \gamma_{BD}) - \frac{l_{Cc}}{\cos\gamma_{ts}}, \quad (12.61)$$

and determine the permissible length of the lower part of the folding support:

$$l_{JK,dop} = \sqrt{(x_{J,dop} - l_{ak})^2 + (y_{J,dop} - l_{Kk})^2}. \quad (12.62)$$

The lower bound $l_{JK,pr}$ of the allowable interval $l_{JK} \in (l_{JK,pr}; l_{JK,dop})$ is determined from the condition that the center of the hinge J must be on a polyline 1-5-K (Fig. 12.18) formed by intersecting lines

$$y = [y_J] \text{ and } y = \frac{l_{Kk} - l_{Aa}}{l_{ak}}x + l_{Aa}. \quad (12.63)$$

The horizontal coordinate of the intersection point of these lines (point 5 in Fig. 12.18) x_5 is determined by the equation

$$x_5 = \frac{l_{ak}}{l_{Kk} - l_{Aa}}([y_J] - l_{Aa}). \quad (12.64)$$

Since it is not known in advance on which section (1-5 or 5-K) of the 1-5-K polyline the center of the hinge J will be located, two nonlinear equations must be solved to determine the horizontal coordinate $x_{J,pr}$:

$$\sqrt{(x_{J,pr}-x_{C,ts})^2+([y_J]-y_{C,ts})^2}+\sqrt{(x_{J,pr}-l_{ak})^2+([y_J]-l_{Kk})^2}-L_{sh}=0, \quad (12.65)$$

$$\sqrt{(x_{J,pr}-x_{C,ts})^2+\left(\frac{l_{Kk}-l_{Aa}}{l_{ak}}x_{J,pr}+l_{Aa}-y_{C,ts}\right)^2}+$$
$$+\sqrt{(x_{J,pr}-l_{ak})^2+\left(\frac{l_{Kk}-l_{Aa}}{l_{ak}}x_{J,pr}+l_{Aa}-l_{Kk}\right)^2}-L_{sh}=0. \quad (12.66)$$

The value of $x_{J,pr}$ found in solving the first of these equations will be valid if the condition $x_{J,pr}\geq x_5$ is met. In this case, the vertical coordinate of the center of the hinge J will be $y_{J,pr}=[y_J]$. The value of $x_{J,pr}$ found in solving the second of these equations will be valid if the condition $x_{J,pr}\leq x_5$ is met. In this case,

$$y_{J,pr}=\frac{l_{Kk}-l_{Aa}}{l_{ak}}x_{J,pr}+l_{Aa}. \quad (12.67)$$

The length $l_{JK,pr}$ is determined by the equation

$$l_{JK,pr}=\sqrt{(x_{J,pr}-l_{ak})^2+(y_{J,pr}-l_{Kk})^2}. \quad (12.68)$$

The length $l_{JK,pr}$ should not be less than the minimum length of the lower part of the folding rod $l_{JK,\min}$, defined by the Eq. (12.34).

Figure 12.19 shows the influence of the angles of installation of the end tower in the transport γ_{ts} and working γ_{ws} positions on the characteristic sizes of the lower part of the folding rod $l_{JK,\max}$, $l_{JK,\min}$, $l_{JK,dop}$ and $l_{JK,pr}$ on the example of the installation of the end tower with a length of 10 m and a given size $l_{cD}=8$ m.

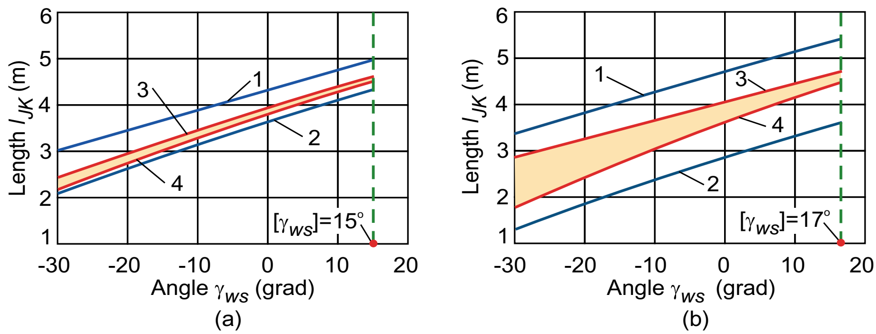


Fig. 12.19 Impact of the installation angles of the end tower in the transport and working positions on the characteristic sizes of the lower part of the folding rod at $\gamma_{ts}=9^{\circ}$ (**a**) and at $\gamma_{ts}=30^{\circ}$ (**b**): 1—$l_{JK,\max}$, 2—$l_{JK,\min}$, 3—$l_{JK,dop}$, 4—$l_{JK,pr}$

An increase in the angle γ_{ts} has a significant effect on the width of the interval of permissible lengths of the lower part of the folding rod $l_{JK} \in (l_{JK,pr}; l_{JK,dop})$ due to an increase in the size of zone 1-d'-D'-C-K-5 (Fig. 12.18). According to Fig. 12.19, the width of this interval is from 0.10 to 0.24 m at $\gamma_{ts} = 9°$ and from 0.26 to 1.2 m at $\gamma_{ts} = 30°$. This is achieved by increasing the lengths $l_{JK,\max}$ and $l_{JK,dop}$ while increasing the angle γ_{ts} and simultaneously decreasing the lengths $l_{JK,\min}$ and $l_{JK,pr}$. Angles γ_{ts} ~ 30° are characteristic of terminal units with a remote location of the end tower, and angles γ_{ts} ~ 10° are characteristic of terminal units with a terminal or central location of the end tower. Therefore, it is advisable to use a folding rod when designing the mechanism for installing and fixing the end tower in relation to the remote location of the end tower. For other structural types of terminal units, this requires great care due to the very strict requirement for the permissible length of the lower part with a sufficiently large total length of the folding rod, ranging from 6 to 18 m [8].

The conditions of the folding rod layout also impose a restriction on the maximum value of the inclination angle of the end tower in the working position γ_{ws}, which can be implemented when designing the mechanism for lifting and fixing the end tower (Fig. 12.19). As calculations show, this restriction manifests itself when the maximum possible angle $[\gamma_{ws}] >$ ~15°. This is due to the fact that at large angles γ_{ws}, it is required to use a longer folding rod, as a result of which the hinge J cannot be placed in the permissible zone 1-d'-D'-C-K-5 (Fig. 12.18) due to the large length of the lower part l_{JK} of the rod. When layout technological equipment on a self-propelled chassis at angles $\gamma_{ws} > [\gamma_{ws}]$, the center of the hinge J turns out to be lower than the broken line 1-5-K, i.e., the condition (12.59) is not met.

In the transport position, the distance between the centers of the cylindrical hinges of the lifting hydraulic cylinder bracing $(l_{AJ})_{ts}$ is

$$(l_{AJ})_{ts} = \sqrt{x_{J,ts}^2 + (y_{J,ts} - l_{Aa})^2}. \tag{12.69}$$

In the case when the center of the hinge J lies in the zone 1-2-3-C-6, the length $(l_{AJ})_{ts}$ determines the maximum distance $(l_{AJ})_{\max}$ between the hinges A and C, otherwise the minimum distance $(l_{AJ})_{\min}$ between these hinges.

In the working position, the distance between the centers of the cylindrical hinges A and C of the lifting hydraulic cylinder bracing $(l_{AJ})_{ws}$ is

$$(l_{AJ})_{ws} = \sqrt{(l_{ak} + l_{JK}\cos\gamma_{sh})^2 + (l_{Kk} - l_{Aa} + l_{JK}\sin\gamma_{sh})^2}, \tag{12.70}$$

where γ_{sh} is the inclination angle of the rod in the working (unfolded) state, determined by the equation

$$\gamma_{sh} = arctg\left[\frac{l_{Bb} - l_{Kk} + l_{BD}\sin\gamma_{BD} + l_{cD}\cos\gamma_{ws} + l_{Cc}\sin\gamma_{ws}}{l_{ab} - l_{ak} + l_{BD}\cos\gamma_{BD} + l_{cD}\sin\gamma_{ws} - l_{Cc}\cos\gamma_{ws}}\right]. \tag{12.71}$$

In the case when the center of the hinge J lies in the zone 1-2-3-C-6, the length $(l_{AJ})_{ws}$ determines the minimum distance $(l_{AJ})_{\min}$ between the hinges A and C, otherwise the maximum distance $(l_{AJ})_{\max}$ between these hinges.

Obviously, the operability of the mechanism with a folding rod will be ensured if the following ratio is observed in the working position of the end tower between the values of the inclination angle of the axis AJ of the lifting hydraulic cylinder γ_{hc} and the longitudinal axis JK of the folding rod:

$$\gamma_{hc} > \gamma_{sh}. \tag{12.72}$$

The minimum distance $(l_{AJ})_{\min}$ determines the maximum permissible length of the lifting hydraulic cylinder $L_{hc,\max}$ according to the layout condition in the transport position of the end tower:

$$L_{hc,\max} \approx (l_{AJ})_{\min}, \tag{12.73}$$

and the required stroke value of its rod when transferring the end tower from the transport position to the working position is

$$\Delta_{hc} = (l_{AJ})_{\max} - (l_{AJ})_{\min} = |(l_{AJ})_{ws} - (l_{AJ})_{ts}|. \tag{12.74}$$

Figure 12.20 shows the results of calculating the relative stroke of the hydraulic cylinder rod $\xi = \Delta_{hc}/(l_{AJ})_{\min}$, depending on the angle γ_{ws} and the size l_{cD} with the length of the lower part of the folding rod $l_{JK,\max}$. Comparing the data in Fig. 12.20 with similar data, when installing a remote end tower directly using a lifting hydraulic cylinder (Fig. 12.16), it can be seen that the required stroke of the rod is significantly less. This allows you to choose the length of the hydraulic cylinder L_{hc} not according to the condition (12.73), but a smaller one:

$$L_{hc} = (l_{AJ})/(1 + [\xi_{hc}]) < L_{hc,\max}. \tag{12.75}$$

The minimum possible length of the hydraulic cylinder can be obtained if we take $[\xi_{hc}] = \xi_{hc,\max} \sim 0.9$. In particular, for the one considered in Fig. 12.20 cases, this

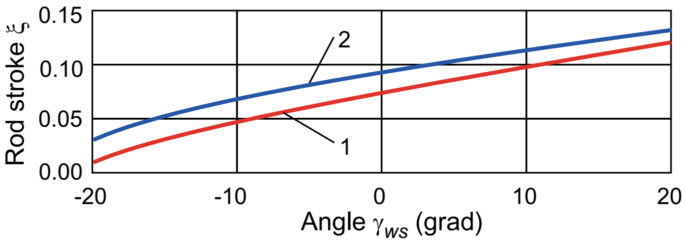


Fig. 12.20 Relative stroke of the drive hydraulic cylinder rod, which ensures the rotation of the end tower from the transport to the working position: 1—$l_{cD} = 9$ m, 2—$l_{cD} = 6$ m

allows the use of hydraulic cylinders, the length of which will be ~1.7 times less than that determined on the basis of the ratio (12.73).

12.5 Conclusion

An important condition for the successful design development of promising self-propelled tower units, providing accelerated formation of mobile single-span ropeway, is the successful layout of the main technological equipment on the load-bearing frame of multi-axle wheeled chassis of high cross-country and load-carrying capacity. To do this, it is necessary to comprehensively coordinate several regulatory and technical conditions that impose opposite requirements on the layout of the equipment—to ensure the installation of the end tower of the maximum possible length within a sufficiently limited space on the load-bearing frame of the wheeled chassis.

This technical problem can be solved during the two-stage process of designing the mechanism for installing and fixing the end tower.

At the first stage, which is a preliminary layout of the main technological equipment, the optimal inclination angles of the end tower and the minimum possible vertical overall dimension in the transport position are determined, which allow the use of maximum length end towers in the terminal unit designs, subject to the necessary regulatory requirements for the possibility of using existing general-purpose highways to move the terminal units to the location of mobile ropeways.

At the second stage, which is the final layout of the main technological equipment, the optimal overall dimensions of the lifting devices of the mechanism for installing and fixing the end tower and their connecting dimensions to the load-bearing frame of the wheeled chassis and the end tower are determined, which allow for the required turning of the end tower from the transport position to the working position and back.

The mathematical models presented in this chapter and the conclusions of the analysis of quantitative and qualitative results obtained when applying these models to the calculation of promising structural types of terminal units allow the designer to choose qualitative layout variants for the main technological equipment of mobile ropeways during the design process.

Single-span mobile pendulum-type ropeways based on autonomous self-propelled wheeled chassis with increased load capacity and cross-country ability are an innovative type of rope transport. Only in recent years, intensive theoretical research and design developments of this equipment have been initiated, aimed at creating a set of necessary methods for designing and modeling work processes. The following priority areas for further research can be noted:

- scientific substantiation of the functionality and development of recommendations for the optimal use of mobile ropeways depending on the operating conditions, the design of the terminal units, the required capacity, reliability, efficiency, etc.;

- creation of digital twins of terminal units and mobile ropeways based on a complex of interconnected geometric and informational mathematical models of structural elements and physical processes occurring at different stages of the technological equipment life cycle;
- development of an economically optimal strategy and system of maintenance, scheduled and diagnostic repairs of mobile ropeways based on simulation of the failure flow of critical structural elements.

Acknowledgements The study was supported by the grant of Russian Science Foundation (project No. 22-29-00798).

References

1. Monheim, H., Muschwitz, C., Auer, W., Philippi, M.: Urbane Seilbahnen: Moderne Seilbahnsysteme eröffnen neue Wege für die Mobilität in unseren Städten. KSV Kölner Stadt- und Verkehrsverlag, Köln, Germany (2010)
2. Alshalafah, B., Shalaby, A., Dale, S., Othman, F.M.Y.: Improvements and innovations in aerial ropeway transportation technologies: observations from recent implementations. J. Transp. Eng. **139**(8), 814–821 (2013)
3. Tiessler, M., Ricci, G.L., Bogenberger, K.: Urban cableway systems: state-of-art and analysis of the Emirates Air Line, London. In: 23rd International Conference on Intelligent Transportation Systems, pp. 1–8 (2020)
4. Hoffmann, K., Zrnić, N.: A contribution on the history of ropeways. In: Koetsier, T., Ceccarelli, M. (eds.) Explorations in the History of Machines and Mechanisms. History of Mechanism and Machine Science, pp. 381–394. Springer, Dordrecht (2012)
5. Reichenbach, M., Puhe, M.: Struggling with inertia: regime barriers opposing planning and implementation of urban ropeways. J. Urban Mobility **2**, 100023 (2022)
6. PAS 183:2017 Smart cities—Guide to establishing a decision-making framework for sharing data and information services. BSI 2017
7. Panfilov, A.V., Korotkiy, A.A, Panfilova, E.A., Lagerev, I.A.: Development of transport infrastructure of urban mobility based on cable metro technology. IOP Conf. Ser. Mater. Sci. Eng. **786**, 012067 (2020)
8. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Structures and design fundamentals of mobile transporting and overloading rope facilities. RISO BGU, Bryansk, Russia (2020)
9. Fistola, R.: The city from the wire the aerial cable transport for the urban mobility. J. Land Use Mobility Environ. **4**, 59–65 (2010)
10. Winter, J.A., Sesma, I., Funda, M.: Case study of cable-propelled transit to be an alternative application to conventional means of public transportation. In: 15th International Conference on Automated People Movers and Automated Transit Systems, pp. 262–277 (2016)
11. Pestal, E.: Seilbahnen und Seilkrane in Holz und Materialtransport. Fromme, Wien, Austria (1961)
12. Fruhstuck, H.: Die Anwendung des RopeCon® Systems fur den Transport von Bauxit. Berg- und Hüttenmännische Monatshefte **158**(8), 339–342 (2013)
13. Vuchic, V.R.: Urban Transit Systems and Technology. Wiley, Inc., New York, USA (2007)
14. Nuessgen, M.: Urban ropeways in Europe. Creating opportunities in urban development. Eurist—European Institute for Sustainable Transport, pp. 1–27 (2015)
15. Sever, D.: Some new methods to ensure harmonization of sustainable development of mountain resorts ropeway. Promet-TrafficTransp. **14**(5), 213–220 (2002)

16. Tezak, S.: Modern cableways—the base of mountain sports tourism. In: Kasimoglu, M., Aydin, H. (eds.) Strategies for Tourism Industry, pp. 297–312. Intech Open, Wien (2012)
17. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Kinematic and force analysis of the end tower positioning mechanism at mobile ropeway. In: Radionov, A.A., Gasiyarov, V.R. (eds.) The 7th International Conference on Industrial Engineering 2021, pp. 394–404. Springer, Cham (2022)
18. Dukelskiy, A.I.: Suspended cable cars and cable cranes. Mashinostroenie, Moscow, Russia (1966)
19. Scheingert, Z.: Aerial ropeways and funicular railways. Pergamon Press, Oxford, UK (1966)
20. Lagerev, A.V., Lagerev, I.A.: Designing supporting structures of passenger ropeways of minimum cost based on modular intermediate towers of discretely variable height. Urban Rail Transit. **6**(4), 265–277 (2020)
21. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Self-propelled terminal station of the mobile ropeway. Patent RU No. 200827, Filed 12 May 2020 (2020)
22. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Self-propelled terminal station of the mobile ropeway. Patent RU No. 204003, Filed 08 Dec 2020 (2021)
23. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Self-propelled terminal station of the mobile ropeway. Patent RU No. 204005, Filed 16 Dec 2020 (2021)
24. Lagerev, A.V., Lagerev, I.A., Tarichko, V.I.: Self-propelled terminal station of the mobile ropeway. Patent RU No. 206299, Filed 04 Apr 2021 (2021)
25. Lagerev, A.V., Tarichko, V.I., Lagerev, I.A.: Placement of technological equipment on the basic chassis of the mobile transportation and reloading rope complex. Nauchno-tekhnicheskiy vestnik Bryanskogo gosudarstvennogo universiteta **3**, 388–403 (2020)
26. Rao, S.S.: Engineering Optimization. Theory and Practice. Wiley, Inc., New Jersey (2009)

Chapter 13
Sustainability and Safety Challenges in Mining Transportation by Railway in India

Suchismita Satapathy, Hemalata Jena, and Sasmita Sahu

Abstract Rail infrastructure is very important for effective and economic mining transportation. Mining sectors are dependent on railway to transport their mining resources and mining technology. During transportation of coal, iron, and mining products by rail due to spread of dust, it effects environment and very hazardous for human health also. The pollution and waste is also impacts on climate change. So, sustainability in transportation policy is very vital for mining sectors. This study focuses to study and find the barriers of transportation of coal open supply chain and safety and sustainability challenges at all stages of the coal chain in India. Then, an effort is taken to find interrelation of these challenges by interpretive structural modelling (ISM).

Keywords Sustainability · Railway · Mining company

13.1 Introduction

Coal is the main source of power generation. Worldwide it plays a vital role for industrial and economic growth of the countries. But maximum air pollution is noted during transportation of coals (coal supply chain), storing with landscape damages, severe accidents, and health issues are found inside and near places of coal mines. By understanding these environmental and occupational issues, many developing countries have used fossil fuels and other renewal resources as their source of energy. NGOs and other supporting organizations are against the coal mines due to the adverse environmental impact. The negative impact of coal mines affects the water bodies, humans, animals, land fertility, air quality index, etc. But on the other hand, the coal chains are helpful in providing employment to huge communities. Coal is a precious substance that is used in almost all kinds of industries and also for electricity generation. Hence, the coal chains must follow the regulations and environmental

---

S. Satapathy (✉) · H. Jena · S. Sahu
School of Mechanical Engineering, KIIT Deemed to Be University, Bhubaneswar, Odisha 751024, India
e-mail: ssatapathyfme@kiit.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_13

rules during their mining activities and also during the transportation of the coal via trucks, wagons, trains, and ships to its final place of use. The mining sector in India is extremely helpless without transportation sector for its successive supply chain management. These mining sector pull out 99% of toxic wastes, with them brings heavy pollutants for land, air, and water. Sustainability is a most important factor in supply chain management, which uses the term green very often to clarify the social, economic, and environmental parameters [1, 2]. All most all the businesses, government organizations, industries, and consumers are very much concerned about environment and environment related challenges to cope with high level of Industrialization [3]. The development of global market and shortages of natural resources have forced organizations to think and act on supply chain strategies on the basis of environmental perspective [4]. As per [5], the causes of environmental degradation are global warming, stratospheric ozone depletion, acidification, and loss of biodiversity. Implementation of sustainability in supply chain management can reduce the effect of pollution, which can help to eradicate the risks to human health and the environment [6].

The mining sector in India is highly dependent on the transportation sector for its successive supply chain management. These mining sector extracts 99% of toxic wastes [7], which brings heavy pollutants for land, air, and water. Being an important point of discussion, the supply chain issues and their impact on the environment, society, and the economy have influenced many researchers, to start their research on this point [8]. The Indian mining industry's GDP is in the range of 2.5–2.75%, and it is 10–11% with respect to the GDP of the total industrial sector. The demand of coal mines is also very high, but the major problem is transportation of produced coal. The most important challenges of coal transportation are lack of proper transportation modes, lack of road connectivity, inter connection of transportation channels, organized transportation system, proper transportation management system, etc. Transportation tasks include the delivery of produced coal from the mines to the destinations, to export by-products to dump, and transport materials with maximum speed, minimum cost, and greater traffic safety.

13.1.1 Status of Coal Transportation in India

Railways is using 1,13,880 for coal transportation to solve the electricity crisis problem in India. Railway has used 86 per cent of its open wagons for coal transportation. 122 mining states like Jharkhand, Odisha, Chhattisgarh, and Madhya Pradesh around 3–5 wagons run altogether. For mining transportation, according to the ministry of coal, 50% of coal was transported by railways, 32% by road. But as the road transportation is not sustainable and safe hence transportation by road is reduced day by day. Road transportation of coal affects the social life of people by spreading coal dust all over roads, houses, water sources, etc. It is also the main cause of health problems like lung infection, eye irritation, etc. Road jam, accident cases are severe for road transportation. Hence, road transportation is not suitable. Compared

Table 13.1 Coal transportation by Indian Railway (Statistical 2022) [9]

Overall coal evacuation system from mining	Coal transported percentage
Merry go round system	15
Rope	0
Belt	5
Road	33
Rail	46
Others	1

to other transportation, maximum accidents are seen in road transportation. Water and rope transportation will pollute water and air severely, which will also destroy the life of water animals and forest animals. Hence, railway is considered as the best way of transportation and set environmental impact assessment for other modes of transportation. The forest rope way for mining coal transportation will create soil erosion and contamination, change in drainage pattern, generation of waste water, risk of disasters due to technical failures and increase in vulnerability during natural hazards. Road and railway transportations are criticized for air pollution; coal dust has impacts on water bodies too. Hence, Gujarat Govt. has put forth regulations for transportation of coal through road and railway. Gujarat and Odisha were the first states, those in 2010 have developed some guidelines for railway sidings to avoid pollution. Still there are many sustainability and safety challenges found for cargo railway transportation, as it is carried open and pollutes the atmosphere, which are the main cause of climate change and environmental pollution. As per Table13.1, it is evident that the share of railway transportation is 46% out of the total coal transported from the coal mines in India [9].

From Table 13.2, it is clear that the maximum coal (i.e. 605.84) MT was transported in financial year 2019 [9].

In particular, in India, 27% of railways are useful for cargo transportation in mining. The government has decided to increase the number. Coal transportation on the Indian railways is the most heavily used transportation medium. The statistics show that, in 2017, out of 574 MT of coal imported for grid electricity generation (Central Electricity Authority 2017), 341 MT, or 60%, was transported through railways (Railway Board March 2017). The railway transports coal for roughly 85% of the cost. As per Table 13.2 (Statistical 2022), it is found that the maximum coal transported in the 2019 financial year is 605.84 tons, compared to the minimum in 2009 (i.e. 363.9 tons). The table shows that the transportation rate increases, but after pandemic COVID-19, the graph is in a downward direction, but after 2022 the government stakeholder planning to improve the scenario. With some challenges and barriers in railway transportation, with the improvement of transportation methods, coal transportation will be less costly and more attractive for all mine holders. Many sustainable and safety issues, such as accidents, air pollution, water and land pollution, and so on, can be addressed by undermining transportation. But there are many barriers and challenges found in undermine rail transportation in India from a safety

Table 13.2 Coal transportation by Indian Railway (Statistical 2022) [9]

Financial year	Coal transported in (MT)
2010	396.1
2011	420.37
2012	455.81
2013	496.42
2014	508.6
2015	545.81
2016	551.83
2017	532.83
2018	555.2
2019	605.84
2020	586.87
2021	541.82

and sustainability point of view. Therefore, in this paper, an effort is made to study sustainable challenges so that the mining stakeholders and government stakeholders can benefit from revitalizing these lacunas.

1. An insufficient transportation tracking system.
2. Inadequate critical maintenance facilities.
   Inadequate technology availability for early track failure and replacement.
3. Slower haulage speeds in mines.
4. Slower production times and lower productivity for the undermine railway system.
5. Roadblocks caused by a lack of space beneath mines.
6. The water space beneath mines.
7. The possibility of ground collapse in closed mines.
8. The geometry required for the rail system is not in alignment with the mine layout.
9. Lack of proper knowledge of track design.
10. The costs of rail innovations are very high.
11. Lack of water recycling facilities to reduce pollution.
12. Landslide and earthquake research facility to save undermine.
13. Lack of a proper lighting system and facilities for interconnecting lines.
14. Railway sidings and constructing multiple railway lines need a lot of time.
15. Lack of training and education for workers, suppliers, and mine workers determines railway safety.
16. Interpretive structural modelling is implemented to find linear relations between these challenges.

13.2 Methodology of Research

A standard question is designed to collect data for sustainable challenges in the mining sector. The survey is done for cargo railways transporting coal in Odisha-based mines with yes and no types of answers. Then, ISM is implemented for selected safety and sustainable challenges. ISM is a structured method to find relationships among parameters used. This formulation has been widely used by researchers to create interrelationships or linear relations among various elements related to the issue. ISM helps to find construction as well as its components for analysing the problem from different perspectives [10]. It not only aids in identifying the relationships between variables in order to determine the complex-relationships within a system, but it also allows for the analysis of the effect of each variable in relation to other variables [11–13]. In this study, ISM is used to identify the internal inter-dependence of the variables.

13.3 Result and Discussion

A "structural self-interaction matrix (SSIM)" was traced by identifying the linear relationships between the variables. The symbols like "V, A, X, and O" were used for finding the relationship among the parameters (i, j). The symbol 'V' showed the relation between factor i and factor j; the symbol 'A' was explored when the factor j was expressed for factor i; and the symbol 'X' and 'O' were explained by factor i and j for both relations and no relation. In the same way, the SSIM was obtained by using binary relations 0 and 1, in the form of a "reachability matrix". Then, transitivity relation was shown by the * mark. Then, lastly, drive power and dependence relations are calculated and a matrix-model is obtained. The level's partitioning for the variables was done, and an ISM model was generated [14]. Figure 13.1 exhibits the steps of ISM methodology used to find the challenges of the coal supply chain as per Indian context.

From an extensive literature review, a standard questionnaire is designed to survey the challenges of the coal supply chain in India [15–17]. To study the challenges of the coal supply chain in India, the designed questionnaire is circulated by personal contact and by mail and the challenge data is collected by a yes/no type of questionnaire (Table 13.3).

A structural self-interaction matrix (SSIM) is created by finding relations between the pairs in Table 13.4. The four symbols are utilized to refer to the direction of the kinship between the elements *i* and *j* (i.e. row and column variables 1 to 16).

V = for the i–j relationship but not in both directions;
A = for the relationship between j and i but not in both directions;
X = for two-way relations: from i to j and j to i; and
O = if the relationship between the elements appears to be invalid, use.

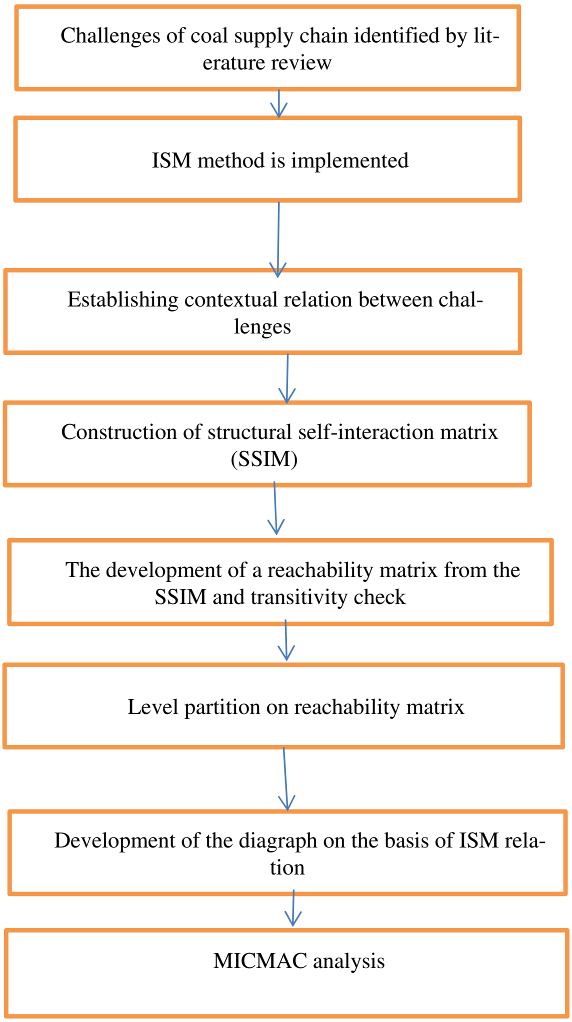


Fig. 13.1 Steps of ISM

Table 13.5 converts the entries V, A, X, and O of the SSIM 1 and 0 binary matrix, as per the following rules:

(*i*, *j*) is V, then the (*i*, *j*) entry in the reachability matrix becomes 1 and the (*j*, *i*) entry becomes 0.
(*i*, *j*) is A, then the (*i*, *j*) entry in the reachability matrix becomes 0 and the (*j*, *i*) entry becomes 1.
If I (*i*, *j*) is X, then both the (*i*, *j*) and (*j*, *i*) entries of the reachability matrix become
(*i*, *j*) is O, then both the (*i*, *j*) and (*j*, *i*) entries of the reachability matrix become 0. In Table 13.4, the M1 to M16 value is O. So M1 to M16 and M16 to M1 are both 0 in Table 13.5.

Table 13.3 Questionnaire for challenges [15–17]

Challenging-variables	Wherever applicable (yes = y, no = n)
1. An insufficient transportation tracking system	Y
2. Inadequate critical maintenance facilities	Y
3. Inadequate technology availability for early track failure and replacement	Y
4. Slower haulage speeds in mines	Y
5. Slower production times and lower productivity for the undermine railway system	Y
6. Roadblocks caused by a lack of space beneath mines	Y
7. The water space beneath mines	Y
8.The possibility of ground collapse in closed mines	Y
9. The geometry required for the rail system is not in alignment with the mine layout	Y
10. Lack of proper knowledge of track design	Y
11. The costs of rail innovations are very high	Y
12. Lack of water recycling facilities to reduce pollution	Y
13. Landslide and earthquake research facility to save undermine	Y
14. Lack of a proper lighting system and facilities for interconnecting lines	Y
15. Railway sidings and constructing multiple railway lines need a lot of time	Y
16. Lack of training and education for workers, suppliers, and mine workers undermines railway safety	Y

Table 13.6 investigates transitive relations, which means that if A is related to B and B is related to C, then A and C have a transitive relationship. In Table 13.6, drive power and dependency are calculated by taking the sum of rows and columns individually.

Table 13.7 investigates the reachability set row by row by considering entry of 1 and the antecedent set by column by finding entry of 1. The intersection set is the common variable between the reachability set and the antecedent set found level wise. The levelled variables are extracted, and the process is repeated. The level-wise selection of variables is used to build the ISM model as per their importance.

Table 13.8 shows the level-wise variables selected. As M_2, M_8, M_{10}, M_{12}, and M_{16} are selected in the first level in Table 13.7, they are removed and the processes are repeated till all the variables are selected.

Figure 13.2 shows the ISM model for coal transportation level wise. It shows the interrelation between the barriers or challenges of coal transportation. Coal mining is always developed in the natural landscape, but due to the coal mines, the climate of the natural landscape and its nearest locations are damaged. The communities

Table 13.4 Structural self-interaction matrix (SSIM)

Variables	M16	M15	M14	M13	M12	M11	M10	M9	M8	M7	M6	M5	M4	M3	M2	M1
M1	O	X	O	O	V	X	X	V	O	A	V	O	O	X	O	
M2	X	O	O	O	O	O	O	O	O	O	O	O	O	O		
M3	O	O	O	O	X	V	O	O	O	A	V	O	O			
M4	V	O	O	O	O	O	O	O	O	O	O	X				
M5	O	O	O	O	V	O	O	O	O	O	V					
M6	X	X	O	A	X	X	O	V	O	A						
M7	O	O	O	O	V	V	O	O	O							
M8	X	O	O	O	O	A	O	O								
M9	V	A	A	A	X	A	V									
M10	X	A	X	A	O	O										
M11	X	X	V	X	X											
M12	X	X	X	X												
M13	V	V	V													
M14	V	A														
M15	X															
M16																

Table 13.5 Final reachability matrix with transitivity-relationships

Variables	M_{16}	M_{15}	M_{14}	M_{13}	M_{12}	M_{11}	M_{10}	M_9	M_8	M_7	M_6	M_5	M_4	M_3	M_2	M_1
M_1	1	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0
M_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
M_3	1	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0
M_4	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1
M_5	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0
M_6	0	0	0	0	0	1	0	0	1	0	1	1	0	0	1	1
M_7	1	0	1	0	0	1	1	0	0	0	1	1	0	0	0	0
M_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
M_9	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1
M_{10}	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1
M_{11}	1	0	0	0	0	1	0	1	1	0	1	1	1	1	1	1
M_{12}	0	0	1	0	0	1	0	0	1	0	1	1	1	1	1	1
M_{13}	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1
M_{14}	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1
M_{15}	1	0	0	0	0	1	0	0	1	1	1	1	0	1	1	1
M_{16}	0	1	0	0	0	1	0	1	0	1	1	1	0	0	1	1

Table 13.6 Transitivity-relationships

Drive-power	Variables	M_{16}	M_{15}	M_{14}	M_{13}	M_{12}	M_{11}	M_{10}	M_9	M_8	M_7	M_6	M_5	M_4	M_3	M_2	M_1
8	M_1	1	0	1*	0	0	1	0	0	1	1*	1*	1	0	0	1	0
2	M_2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
5	M_3	1*	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0
3	M_4	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1
4	M_5	0	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0
6	M_6	0	0	0	0	0	1	0	0	1	0	1	1	0	0	1	1
6	M_7	1	0	1	0	0	1	1	0	0	0	1	1	0	0	0	0
2	M_8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
5	M_9	1	0	0	0	0	0	0	0	1	1*	0	1	0	0	0	1
4	M_{10}	1*	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1
10	M_{11}	1*	0	0	0	0	1	0	1	1	0	1	1	1	1	1	1
9	M_{12}	0	0	1	0	0	1	0	0	1*	0	1	1	1	1	1	1
9	M_{13}	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1
5	M_{14}	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1
9	M_{15}	1	0	0	0	0	1	0	0	1	1	1	1	0	1	1	1
	M_{16}	0	1	0	0	0	1	0	1	0	1	1	1	0	0	1	1
	Dependence	7	2	4	2	2	10	1	3	8	7	9	12	3	6	7	2

*Transitivity-relationships

Table 13.7 First-iteration

Variables	Reachability-set	Antecedent-set	Intersection-set	Level
M1	M1, M3, M6, M9, M10, M11, M12, M15	M1, M3, M7, M9, M10, M11, M15	M1, M3, M9, M11, M15	
M2	M2, M16	M2, M16	M2, M16	I
M3	M1, M3, M11, M12,	M1, M3, M7, M12	M1, M3, M12	
M4	M4, M5, M16	M4, M5	M4, M5	
M5	M3, M4, M5, M16	M4, M5	M4, M5	
M6	M6, M9, M11, M12, M15, M16	M1, M3, M5, M6, M7, M11, M12, M15, M16	M6, M11, M12, M15, M16	
M7	M1, M3, M6, M7, M11, M12	M7	M7	
M8	M8, M16	M8, M11, M16	M8, M16	I
M9	M1, M9, M10, M12, M16	M1, M6, M9, M10, M13, M14, M15, M16	M1, M9, M10, M16	
M10	M1, M10, M14, M16	M1, M9, M10, M13, M14, M15, M16	M1,M10,M14,M16	I
M11	M1, M6, M7, M11, M12, M13, M15, M16	M1, M6, M8, M9, M11, M12, M13, M14, M15, M16	M1, M6, M11, M12, M13, M15, M16	
M12	M3, M6, M9, M11, M12, M13, M14, M15, M16	M11, M12, M13	M11, M12, M13	I
M13	M6, M9, M10, M11, M12, M13, M14, M15, M16	M11, M12, M13	M11, M12, M13	
M14	M9, M10, M12, M14, M16	M10, M11, M12, M13, M14, M15	M10, M12, M14	
M15	M1, M6, M9, M11, M12, M14, M15, M16	M1, M6, M11, M12, M13, M14, M16	M1, M6, M11, M12, M14, M16	
M16	M2, M6, M8, M10, M11, M12, M14, M16	M2, M4, M6, M8, M10, M11, M12, M13, M14, M15, M16	M2, M6, M8, M10, M11, M12, M14, M16	I

Table 13.8 Iteration variables are listed in

Variables	Level
M2, M8, M10, M12, M16	I
M7, M19	II
M3, M5, M9, M11, M13	III
M1, M8	IV
M4, M6	V
M15	VI

staying near to the mines lose their land their vegetation suffer with health diseases and are even forced to take contaminated air and water. Still the sector has boomed, and due to this, the country's economy has grown a lot. But by seeing the importance and negative effects of most mining companies, society as well as the government have put pressure on the stakeholders to take the necessary steps to avoid and reduce their negative impact on the earth.

Mining companies are now under intense pressure to plan and take responsibility for minimizing the negative effects of mines on land. This study has explored the transportation of coal by rail and sustainable challenges, such as what steps can be taken to start undermining connected railway infrastructure. It also explores the challenges in India for developing undermined railway channels and finds an interrelation of parameters with these challenges. The ISM model summarizes the relevant issues like the lack of critical maintenance facilities, the potential for fall-of-ground in closed mines, lack of proper track design knowledge; lack of water recycling facility to avoid pollution; and lack of training and education for workers, suppliers, and mine workers employed with undermine railways such as fire safety are the major issues that must be addressed before the start of railway channels to reduce cost and pollution.

Micmac Analysis

From Fig. 13.3, Micmac analysis, it is found that among four clusters, the variables having less dependency and less drive power (M1, M2, M3, M4, M5, M7, M8, M9, M14) are called autonomous variables. In cluster II, M6 and M16 variables lie, whose driving power is less but whose dependency is greater. They are called dependent variables. Cluster III and IV lie (M11, M12) and M13, which are called linkage variables and independent variables, respectively. Linkage variables are high driving power and dependency, and independent variables are more driving power but less dependency.

13.4 Conclusion

Starting from digging coal to transportation, the most concerning issues are environmental, social, economic, and political. The emissions of coal dust, waste water, and dumped coal on the land highly pollute the atmosphere. So, during transportation by rail and other means on land or in ships on water or through rope ways, coal dust is emitted that pollutes the ecosystem. Hence, underground railways may not affect the environment that much, but the mining workers' lives are in danger use of automated equipment or protective devices may minimize the risk of accidents and save the workers' direct involvement in the mines. The role of coal mining companies is to take care of miners on site and also to help the local people by taking good care of nature. They must look into matters like mining operations, transport of coal and other ores, and controlling dust to avoid pollution. This can be done by guiding and training good regular practice of obeying mining rules, policies, and regulations

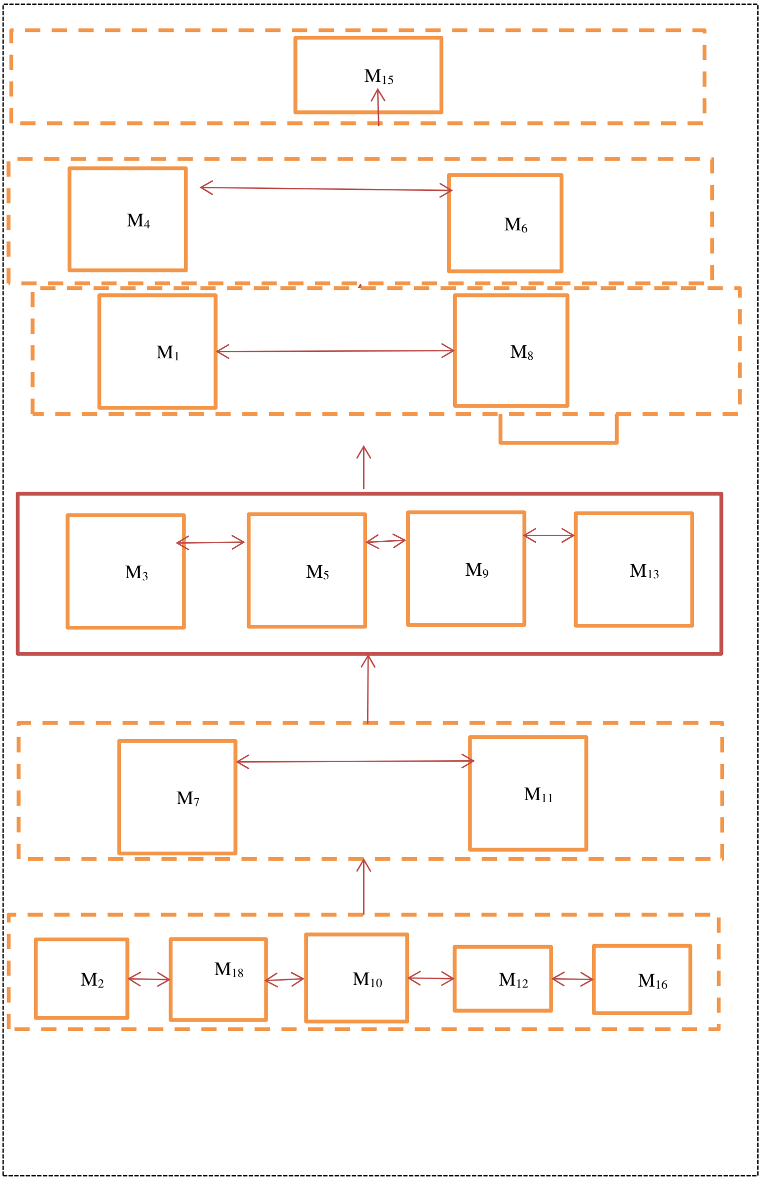


Fig. 13.2 ISM model

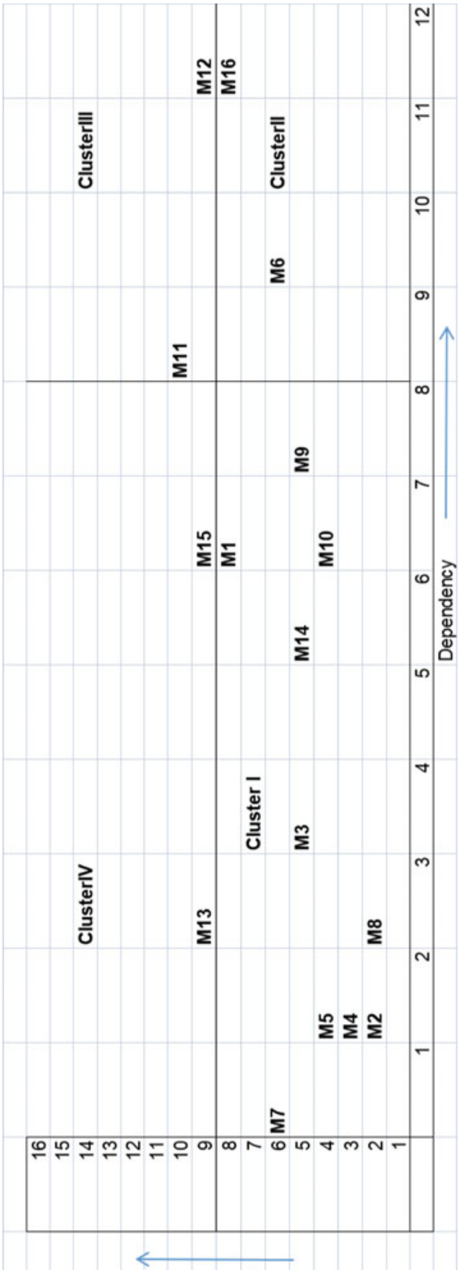


Fig. 13.3 Micmac analysis

by all the workers. The government must take action against the mining companies that are digging illegal mines and must not permit those that are not following environmental rules for logistics and transportation. With proper environmental impact assessment, advancement in technology for mining operations, and taking care of the challenges of railway transportation during transportation, the effects of pollution can be minimized.

This chapter provides an insight into the challenges of railway transportation as per the Indian perspective. The government and stakeholders must take necessary steps to eliminate the challenges of level 1 (i.e. M2, M8, M10, M12, M16) as these are first-level variables which are the basis of supply chain transportation. Variables such as (M1, M2, M3, M4, M5, M7, M8, M9, and M14) are autonomous variables that have less drive power and dependency on the model. But the variables with high dependency and drive power highly impact the coal mining supply chain. So these sensitive variables must be taken care of properly by framing policies by stakeholders for the improvement of sustainability in supply chain management of coal.

This research will select challenges as per their impact on each other. Hence, it will help technically judge to frame policies and regulations for smooth performance of the Indian coal chain.

In future, more data can be collected from coal mining sectors to design the framework to eliminate the challenges in an optimized way. The outcome may change if all coal mines in India are privatized, nationalized, or imported.

References

1. Rahimifard, S., Clegg, A.J.: Aspects of sustainable design and manufacture. Int. J. Prod. Res. **45**(18–19), 4013–4019 (2007). https://doi.org/10.1080/00207540701608511
2. Saha, M., Darnton, G.: Green companies or green con-panies: are companies really green, or are they pretending to be? Bus. Soc. Rev. **110**(2), 117–157 (2005). https://doi.org/10.1111/j.0045-3609.2005.00007.x
3. New, S., Green, K., Morton, B.: An analysis of private versus public sector responses to the environmental challenges of the supply chain. J. Public Procurement **2**(1), 93–105 (2002)
4. Mutingi, M.: Developing green supply chain management strategies. J. Indus. Eng. Manage. (2012)
5. Walker, H., Wendy, P.: Sustainable procurement: emerging issues. International Public Procurement Supply Chain Management: an International Journal Conference proceedings, 21–23 Sept Decade of the 3rd Millennium), 4–7 July, Istanbul, Turkey (2006)
6. Bolton, P.: Government procurement as a policy tool in South Africa. J. Public Procurement **6**, 193–217 (2010)
7. Adler, R., Claassen, M., Godfrey, L., Turton, A.R.: Water, mining and waste: a historical and economic perspective on conflict management in South Africa (2007)
8. Arıoğlu Salmona, M.Ö.: Comparison of urban water quality management in EU and Turkey. In: 22 nd International Housing Research Conference (Urban Dynamics & Housing Change—Crossing into the 2ndInternational Housing Research Conference (Urban Dynamics & Housing Change—Crossing into the 2nd Decade of the 3rd Millennium), 4–7 July, Istanbul, Turkey 2010
9. https://www.dgms.net/Coal%20Mines%20Regulation%202017.pdf
10. Alawamleh, M., Popplewell, K.: Interpretive structural modeling of risk sources in a virtual organisation. Int. J. Prod. Res. **49**(20), 6041–6063 (2011)

11. Dachyar, M., Yadrifil, Laili, Y.: Interpretive structural model of institutional design for increased domestic component of upstream oil and gas industry in Indonesia. Int. Sci. Index **08**(09), 776–780 (2014)
12. Gavareshk, M.H., Hosseini, S.J., Khajezadeh, M.: A case study of green supplier selection method using an integrated ISM-Fuzzy MICMAC analysis and multi-criteria decision making. Indus. Eng. Manage. Syst. **16**(4), 562–573 (2017)
13. Mishra, D., Satapathy, S.: An integrated SWARA, QFD and ISM approach for Agricultural injuries in India. Int. J. Decis. Support Syst. Technol. **12**(2), 1–24 (2020). https://doi.org/10.4018/IJDSST.2020040101
14. Dubey, R., Gunasekaran, A., Chakrabarty, A.: Ubiquitous manufacturing: overview, framework and further research directions. Int. J. Comput. Integr. Manuf. **30**(4), 381–394 (2017)
15. Dionelis, C., Giaoutzi, M.: Environmental and safety aspects in rail transport,8th nectar conference Las Palmas G.C. 2–4 June (2005)
16. Lucas, P.S., Carvalho, R.G.D., Grilo, C.: Railway disturbances on wildlife: types, effects, and mitigation measures. In: Railway Ecology, pp. 81–99. Springer, Cham (2017)
17. Raghuram, G., Verma, A.: Dedicated freight corridor: current challenges. In: World Conference on Transport Research-WCTR (2019)

Chapter 14
Performance of Ribs in Double Pass Jet Solar Air Heater: A Review

Purushottam Kumar Singh and Santosh Kumar Mishra

Abstract The present paper consists of diverse comparative study of different types of artificial roughness constituents which are used to raise the coefficient of transfer of heat accounting small cost in friction factor. Experimental works carried out by various researchers have been reviewed on passive technique by the use of artificial roughness for enhancing the rate of heat transfer. The range of parameter of this study has been taken on the basis of experimental consideration and operating condition of the systems. The Reynolds number of the order of 3000 to 21,000, height of relative roughness 0.0181–0.0363 and relative pitch roughness of 4.0–9.5 been achieved. The correlation of transfer of heat and factor of friction that developed in unsmooth channel of solar air heater have been studied and conferred.

Keywords Ribs · Solar air heater · Artificial roughness · Heat transfer coefficient · Friction factor · Reynolds number

14.1 Introduction

The thermal performance of conventional solar air heater has been found to be poor because of the low convective heat transfer coefficient from the absorber plate to the air. It leads to high absorber plate temperature and greater losses to the nature. The main thermal resistance to the heat transfer is due to the formation of a laminar sub-layer on the absorber plate heat-transferring surface. The use of artificial roughness on a surface is an effective method to increase the rate of transfer of heat to the flowing fluid in the duct. It is found that artificial roughness in the form of ribs of different geometrical shapes that has been used for increment of coefficient of heat

---

P. K. Singh
Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar 788010, India

S. K. Mishra (✉)
Department of Production Engineering, National Institute of Technology Trichy, Trichy 620015, India
e-mail: apsantoshmishra@gmail.com

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_14

transfer in heat exchanger [1–3] and on the underside of the absorber plate enhances the heat transfer coefficient between the plate and the flowing fluid (air) in solar air heater [4–6]. It has been found that an artificial roughness on the heat transfer surface in the form of projections usually creates turbulence near the wall or breaks the laminar sub-layer and thus enhance the heat transfer coefficient with a minimum pressure loss forfeit [7]. Flat plate solar air collector has been used to carry heated air at low to moderate temperature for different purposes such as space heating, water heating, timber seasoning, agricultural products drying, industrial applications.

The artificial roughness which are facilitate in the form of ribs, helps to agitate the sub-stratum of laminar. This disturbance produces the surroundings turbulence which helps to slow down heat hurdles and finally raises the rate of transfer of heat. The process of keeping the elevation of element of roughness small to the dimension of duct helps to do so. In the year 1861 J. P. Joule released a report which was explained by Bergles et al. [8] states the same.

Blower facilitates energy for causing turbulence but consumes large energy in case of producing huge upheaval. To determine elevation of artificial unsmooth surface on element we must have the knowledge of laminar sub-layer thickness.

14.2 Performance Analysis of Conventional Solar Air Heater

The efficiency of a system is accredited through the amount of input given to the output gained. To construct an effective designing of solar air heater, its heat and hydraulic performance are supposed to be analysed. Thermal performance deals with the process of transfer of heat in the accumulator whereas hydraulic performance deals with the falloff pressure. It is commonly made with steel, aluminium and Galvanized iron. The type of traditional SAH as given below in Fig. 14.1 is usually considered for manipulation of heat and hydraulic performance. Yadav et al. [9] have detailed its designing and building.

14.2.1 Heat Performance

Beckman and Duffie et al. [10] accounted the below given equation of calculating heat functioning in solar air heater which were initially formulated by Hottel–Whillier–Bliss as:

$$Q_u = A_c F_R [I(\tau\alpha)_e - U_L(T_i - T_a)] \tag{14.1}$$

Or

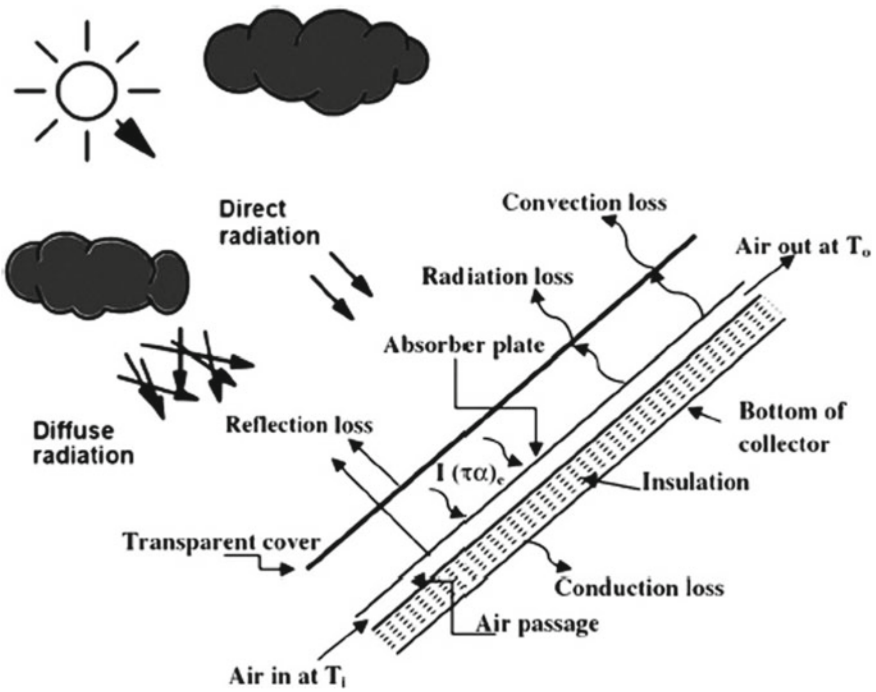


Fig. 14.1 Conventional solar air heater (Reprinted from Yadav et al. [9] with permission from Elsevier)

$$q_U = \frac{Q_U}{A_C} = F_R[I(\tau\alpha)_e - U_L(T_i - T_a)] \tag{14.2}$$

The expression below helps to find the gain of energy in solar air heater pipe:

$$Q_u = mC_p(T_O - T_i) = hAc(T_{pm} - T_{am}) \tag{14.3}$$

Duffie and Beckman et al. [10] gave an expression for determining Nusselt number [N_U]:

$$N_U = {}^{hL}/_{K} \tag{14.4}$$

Moreover, for performance of heat in SAH it is depicted as:

$$N_U = {}^{hL}/_{K} n_{th} = {}^{q_u}/_{I} F_R[(\tau\alpha)_e - U_L\left(\tfrac{T_i - T_a}{I}\right)] \tag{14.5}$$

14.2.2 Hydraulic Performance

Hydraulic performance of a solar air heater in the channel deals with falloff pressure (ΔP). Drop in pressure takes place due to the loss of energy in running fan for propelling air through the channel. This drop-in pressure is exemplified in non-dimensional form by using the equation of factor of friction (F), given by Frank and Mark et al. [11].

$$f = \frac{(\Delta P)Dh}{2\rho L V^2} \tag{14.6}$$

14.3 Methods of Producing Artificial Roughness

The following methods are used for producing artificial roughness:

1. Fixation of wire
2. Machining process
3. Wire mess
4. Protrusion shaped geometry
5. Sand blasting

14.4 Types of Rib

Roughness element plays a vital role in increasing the heat transfer characteristics of absorber plate. Various shapes of artificial geometrics used are discussed in subsequent sub-sections.

14.4.1 Transverse Continuous Ribs

Prasad et al. [12] first of all gave the concept of using wire of little diameter as an artificial roughness in lower part of an absorber plate to increase the heat functioning of solar air heater. This functioning of solar air heater is used in drying purposes. A practical examine was conducted using the parameters 0.019 as relative roughness aspect ratio, relative roughness height of 0.01–0.03 at a relative roughness pitch of 10–40 and roughness Reynolds number range of 842. An optimum value of about 71% has been reported corresponding to roughness Reynolds number of 24 (Fig. 14.2).

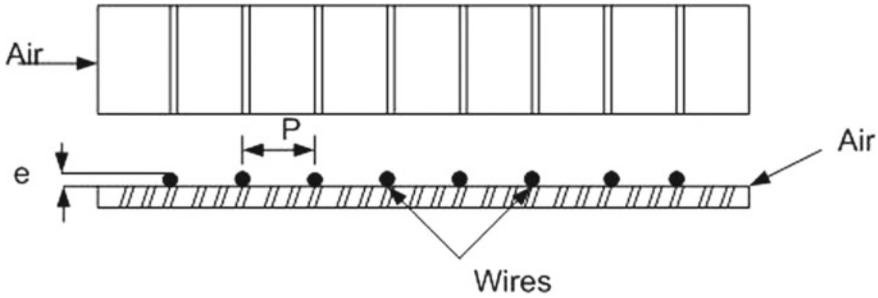


Fig. 14.2 Roughened absorber plate fixed with transverse continuous ribs (Reprinted from Verma et al. [13] with permission from Elsevier)

14.4.2 Ribs of Circular Cross-Section

Prasad et al. [4] used flow rate of high mass and 1 mm bulge out structure of wire to make the flow turbulent. Nusselt number, factor of friction and factor of plate efficiency of roughened and plane absorber plate were compared to plane corrugated and unruffled absorber plate. The bulge out structure of wire increases the rate of transfer of heat. The factor efficiency of plate and heater increases from 0.63–0.73. This results in almost 14% better execution. Moreover, Prasad and Mullick [14], Prasad and Saini [15] concentrate their study on flow and roughness data such as relative roughness and height.

In contrast to experiment [4, 14, 15] these were made for flow of fully rough condition. Gupta et al. [16] perform an experiment regarding semi scratchy stream region, normally on which every solar air heater works. He also brings out relation between Nusselt number and factor of friction.

Verma et al. [13] made an open experimental investigation regarding maximization of thermohydraulic roughness and streaming data for Reynolds number (Re) of limitation of 900–19,500, pitch relative roughness of 9–38, relative height of 0.011–0.031.

14.4.3 Ribs of Rectangular Cross-Section

Karwa et al. [17] highlighted the essence of using iterate rectangular cross-section through the factor of friction and transfer of heat. He did it for aspect channel ratio of the limitation of 7.19–7.75, pitch relative roughness of 10, height of relative roughness of 0.0467–0.050 and Reynolds number of the extension of 2800–15,000. He moreover stated that increase of factor of friction and removal of heat was because of the whirl created by the element's roughness on the far side of the laminar subtenant layer as given in Fig. 14.3.

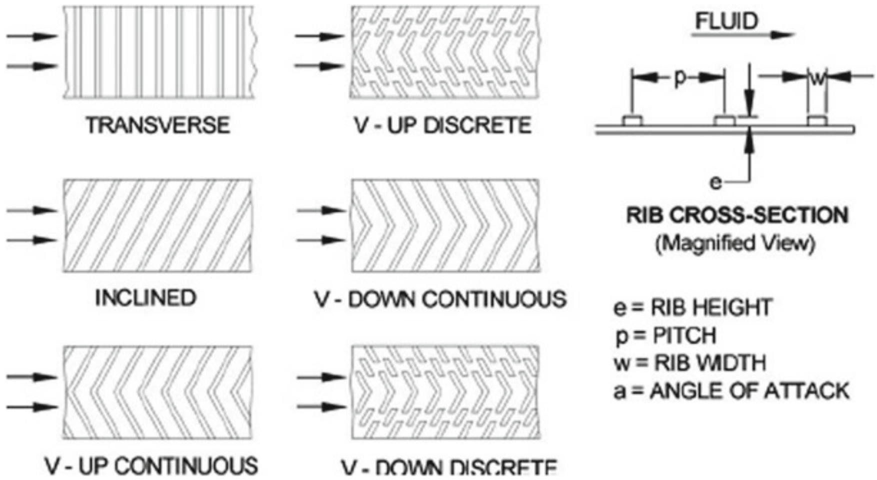


Fig. 14.3 Rectangular cross-section ribs (Reprinted from Karwa et al. [17] with permission from Elsevier)

14.4.4 Transverse Broken Ribs with Circular Cross-Section

Sahu and Bhagoria et al. [18] experimented on 90° fractured ribs for heat execution in solar air heater. He restricted height of roughness to 1.6 mm, aspect ratio of duct 7.5, pitch of the limitation of 11–31 mm and Reynolds number (Re) of 2950–12,500. It is observed that roughened nature of the absorber plate helps in increasing the coefficient of consignment of heat approximately from 1.30 to 1.45 times in comparison to plane absorber plate.

14.4.5 Inclined Continuous Ribs

Gupta and its co-author work on the basis of thermohydraulic operation study the consequence of height of relative roughness, ribs inclination with regards to direction of flow. There was an increment in relative height of roughness with decrease in Reynolds number. In the ribs of circular cross-section, the best result of thermohydraulic execution was found at Reynolds number laying 15,000 and height of roughness at 0.0234.

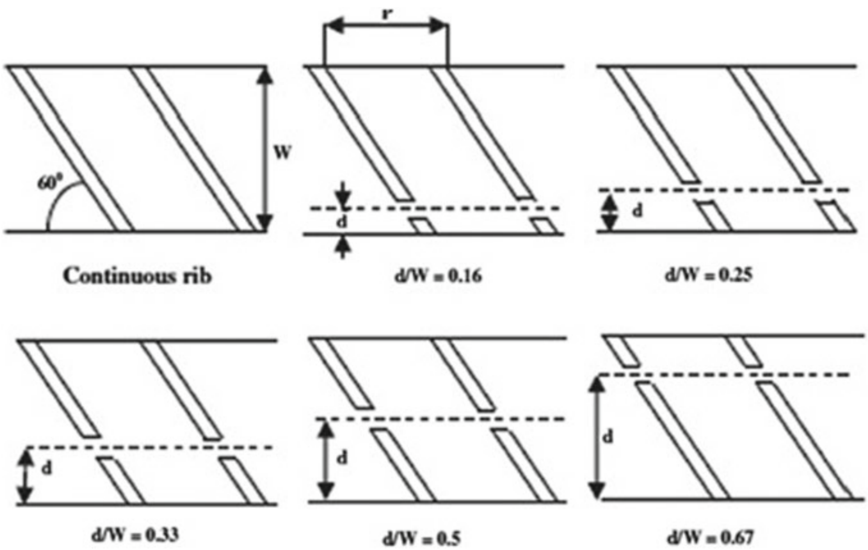


Fig. 14.4 Inclined ribs with gap (Reprinted from Aharwal et al. [19] with permission from Elsevier)

14.4.6 Inclined Broken Ribs

Aharwal et al. [19] observed and specified the essence of gap position and width in fractured inclined ribs containing square cross-section. It has square cross-section of transfer of heat and rectangular channel of characteristics of friction. The duct has an aspect ratio of 5.84; pitch relative roughness 10, relative height roughness height 0.0377 and attack angle of 60° were noticed. In addition, a relative gap width limit of 0.5–2.0 and position of gap varying from 0.1667 to 0.667 for Reynolds number 3,000–18,000 was notified as shown in Fig. 14.4.

14.4.7 V-Shaped Ribs

14.4.7.1 V-Shaped Continuous Ribs

Momin et al. [20] with help of an experiment inspected the structural characteristics of v-shaped ribs as shown in Fig. 14.5. He included Reynolds number of the range of 2450–18,500, height of roughness of 0.021–0.0341 and an attack angle of the stream of the range of 30°–90°. The increase in Nusselt number was ascertained smaller as per the enhancement in factor of friction with an increasing of Reynolds number. The availability of artificial roughness maximizes the Nusselt number and factor friction almost 2.31 and 2.85 times respectively for plane channel at an attack angle of 60°. He furthermore briefed that 0.0341 value of height of relative roughness and

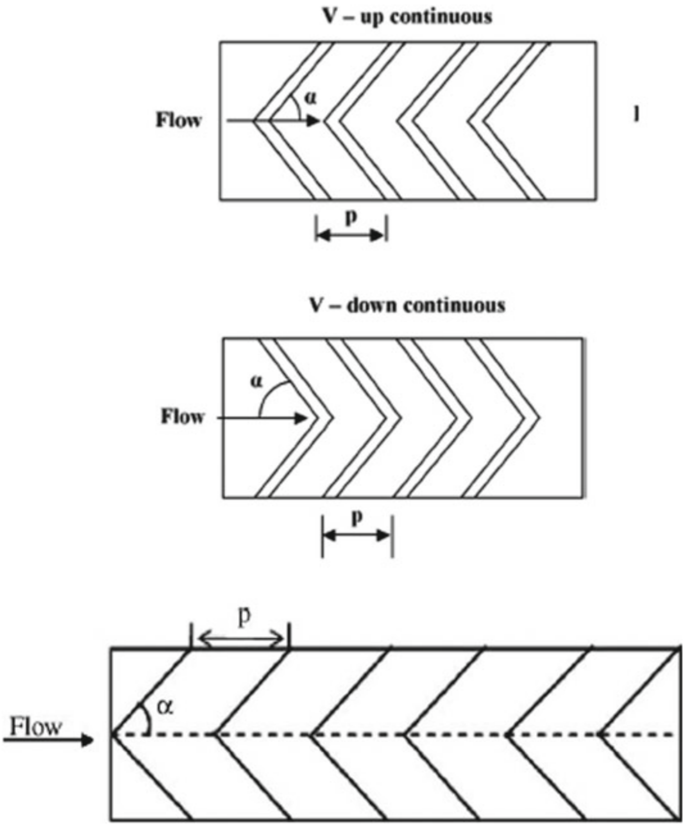


Fig. 14.5 V-shaped continuous ribs (Reprinted from Momin et al. [20] with permission from Elsevier)

Nusselt number was 1.140 and 2.310 times than inclined and plane absorber plate, respectively.

14.4.7.2 V-Shaped Staggered Discrete Ribs

Gupta et al. [21] set up a suitable design element for solar air heater of roughened nature at real climatic status. He did all for the variable height of relative roughness and pitch roughness of 10 at an angle of attack of 60°. He found maximum coefficient of transfer of heat and agent of friction at an angle of 60°.

Karwa et al. [17] has comparatively studied the augmented transfer of hotness and friction for channel of rectangular structure with continuous and discrete arrangement of v ribs. There has been an increment of 103–136, 111–146, 93–133 and 104–140% in Stanton number in comparison to smooth channel. The different structure used by Karwa is shown in Fig. 14.6.

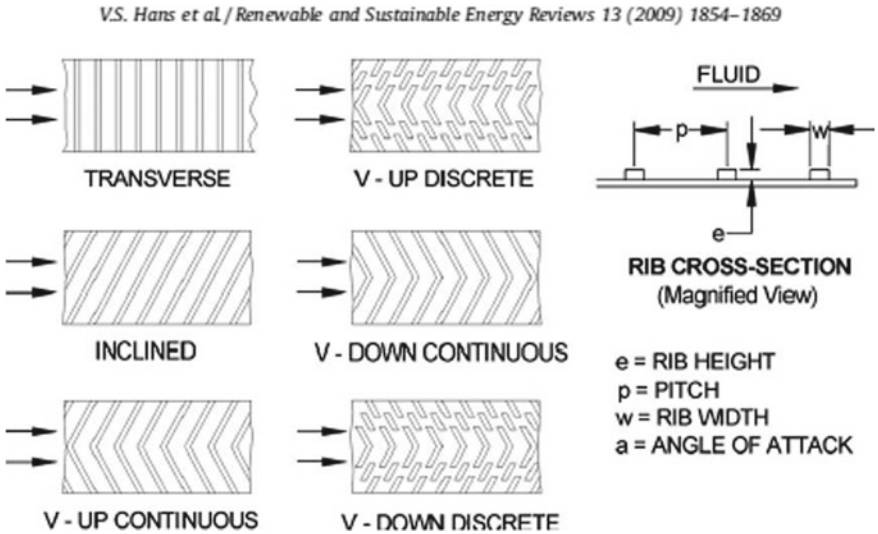


Fig. 14.6 Roughness geometry used by Karwa (Reprinted from Karwa et al. [17] with permission from Elsevier)

14.4.8 Inclined Broken Ribs

Karwa et al. [22] suggested that chamfered ribs can be used as a method to produce artificial roughness. He used different chamfered rib angles such as −15.5°, 0°, 6°, 16° for rectangular channel having various aspect ratios of 4.8, 6.1, 7.8, 9.66, etc. A Reynolds number of the ranges of 2,950–20,500 were considered.

Karwa et al. [23] moreover approached through experiment in real atmospheric situation using artificial chamfered ribs. In this he uses different data which were entirely separate from those used in Karwa et al. [24]. He got pitch relative roughness of 4.6 and 7.10, angle of ribs has been chamfered at 15° for a Reynolds number of 3,700–16,500. In this an increment of 9.5–40.5% in efficiency of heat is found on absorber plate equipped with plane channel (Fig. 14.7).

14.5 Wedge Shaped Ribs

Bhagoria et al. [25] practically work to confirmed pitch of relative roughness, height of relative roughness and angle of wedge on the transfer of heat and factor of friction in solar air heater. Apart from transfer of heat and factor of friction studied nature of flow in air heater. The inspection involved the Reynolds number of the ramble of 3,000–18,000, wedge angle of rib (θ) of 8°–12°. He informed that Nusselt number and factor of friction enhanced by 2.4–5.3 times with regards to plane channel. The figure is shown in Fig. 14.8.

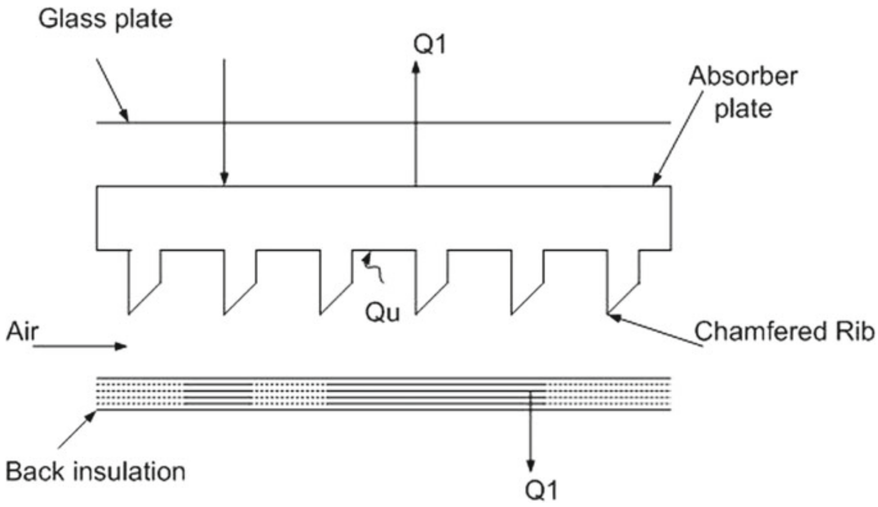


Fig. 14.7 Integral chamfered rib with fixed chamfer angle (Reprinted from Karwa et al. [24] with permission from Elsevier)

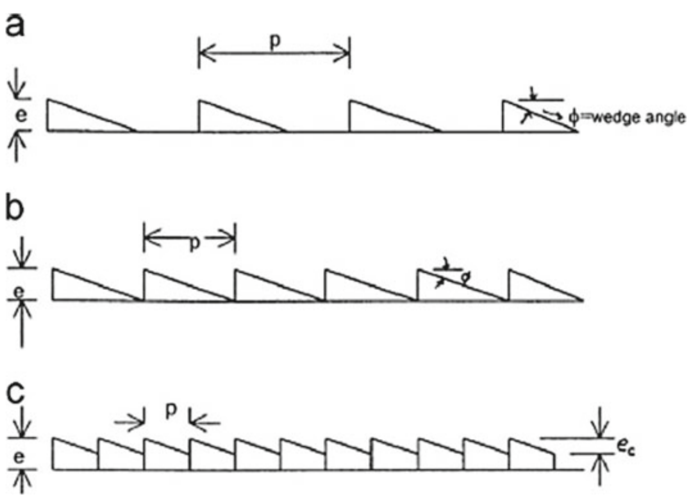


Fig. 14.8 Wedge shaped ribs (Reprinted from Bhagoria et al. [25] with permission from Elsevier)

14.6 Arc Shaped Ribs

Saini et al. [26] used arc shaped ribs for the enforcement of transfer of coefficient of heat in solar air heater. The air heater is equipped with arc shape wire which is parallel in nature as shown in Fig. 14.9. Here Nusselt number was seen increasing 3.81 times in comparison to arc angle of 0.334.

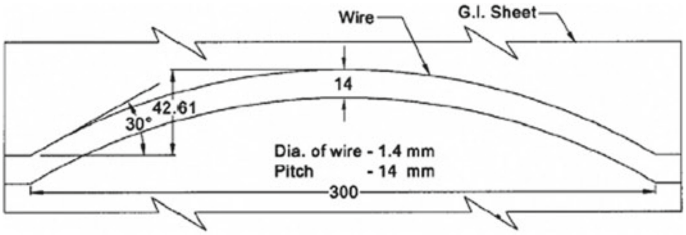


Fig. 14.9 Arc shape ribs (Reprinted from Saini et al. [26] with permission from Elsevier)

14.7 Different Combined Roughness Element

14.7.1 Rib Groove—(1)

Jaurker et al. [27] in his experimentation examine behaviour of friction and transfer of heat in roughened rectangular rib groove duct. He found factor of friction 2.70 and Nusselt number 3.60 under the availability of artificial roughness in rib groove. The transfer of heat was found utmost at relative pitch roughness of 6 and relative groove of 0.40.

14.7.2 Rib Groove—(2)

Layek et al. [28] enquired regarding transference of heat and friction in groove geometry arranged in the shape of repeated transverse compound on the absorber plate of solar air heater. He considered 4 various types of rib grooves having the position value of 0.3–0.6. He experimented this for fixed roughness height of 0.030 and pitch roughness of 10. The outcome was seen that there was an increment of 2.45–2.61 times in the Nusselt number. The friction component related to height of roughness was 0.032 and pitch roughness was 10. It is shown in Fig. 14.10.

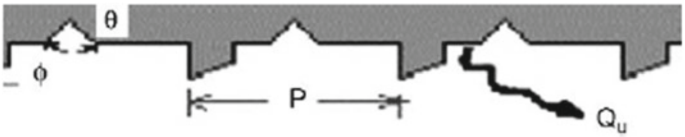


Fig. 14.10 Combination of chamfered and groove rib (Reprinted from Layek et al. [28] with permission from Elsevier)

14.8 Conclusions

This paper consists of a revised paper that has been made on the basis of study of a number of research papers. In this the effort has been made to review the work done by various scholars on artificial roughness so as to gain the consigned heat on the absorber plate. Sufficient progress in transfer of heat has been obtained at insignificant friction penalty. These papers also highlight the interrelation between transfer of coefficient of heat and factor of friction given by different scholars.

These correlations can also portend the heat and thermohydraulic performance using roughened ducts in solar air heater. Several methods of artificial roughness and experiment-based study made by various scholars has been studied and accounted. It has been detected that roughness geometry constructed artificially is a competent means of gaining heat execution in SAH. Furthermore, it is ascertained that better performance is achieved by formation of turbulence on roughened surface. But the fact that matter the most is that the process of producing artificial roughness on absorber plate, as it is a difficult job and is also economically unsuitable for applications in prominent basis. The overall review gives the following information:

1. The artificial roughness improves the functioning of solar air heater, reduces its size and maximize rate of heat transfer.
2. Different experimental as well as mathematical studies have been made for enhancement of transfer of heat and process of flow.
3. CFD technique could be utilizes for examining of transfer of heat and stream nature of unsmooth solar air heater.
4. Solar air heater applications differ from industries to industries. The type of geometry chosen depends on the requirement of energy.
5. To attain much better heat execution in solar air heater the technique of compound increment may be involved.

References

1. Webb, R.L., Eckert, E.R.G., Goldstein, R.: Heat transfer and friction in tubes with repeated-rib roughness. Int. J. Heat Mass Transf. **14**(4), 601–617 (1971)
2. Han, J.C., Park, J.S., Lei, C.K.: Heat transfer enhancement in channels with turbulence promoters. (1985)
3. Williams, F., Pirie, M.A.M., Warburton, C.: Heat transfer from surfaces roughened by ribs. In: Bergles, A., Webb, R.L. (eds.) Augmentation of Convective Heat Transfer, pp. 36–43. ASME, New York (1970)
4. Prasad, K., Mullick, S.C.: Heat transfer characteristics of a solar air heater used for drying purposes. Appl. Energy **13**(2), 83–93 (1983)
5. Li, Q., Flamant, G., Yuan, X., Neveu, P., Luo, L.: Compact heat exchangers: a review and future applications for a new generation of high temperature solar receivers. Renew. Sustain. Energy Rev. **15**(9), 4855–4875 (2011)
6. Bhushan, B., Singh, R.: Nusselt number and friction factor correlations for solar air heater duct having artificially roughened absorber plate. Sol. Energy **85**(5), 1109–1118 (2011)

7. Lanjewar, A.M., Bhagoria, J.L., Agrawal, M.K.: Review of development of artificial roughness in solar air heater and performance evaluation of different orientations for double arc rib roughness. Renew. Sustain. Energy Rev. **43**, 1214–1223 (2015)
8. Bhushan, B., Singh, R.: A review on methodology of artificial roughness used in duct of solar air heaters. Energy **35**(1), 202–212 (2010)
9. Yadav, A.S., Bhagoria, J.L.: Heat transfer and fluid flow analysis of solar air heater: a review of CFD approach. Renew. Sustain. Energy Rev. **23**, 60–79 (2013)
10. Duffie, J.A., Beckman, W.A.: Solar Engineering of Thermal Processes. Willey, New York (1980)
11. Frank, K.: SB Mark Principles of Heat Transfer. Thomson Learning Inc., Colorado (2001)
12. Prasad, B.N., Saini, J.S.: Effect of artificial roughness on heat transfer and friction factor in a solar air heater. Sol. Energy **41**(6), 555–560 (1988)
13. Verma, S.K., Prasad, B.N.: Investigation for the optimal thermohydraulic performance of artificially roughened solar air heaters. Renew. Energy **20**(1), 19–36 (2000)
14. Prasad, B.N., Saini, J.S.: Optimal thermohydraulic performance of artificially roughened solar air heaters. Sol. Energy **47**(2), 91–96 (1991)
15. Prasad, B.N., Saini, J.S.: Effect of artificial roughness on heat transfer and friction factor in a solar air heater. Sol. Energy **41**(6), 555–560 (1988)
16. Gupta, G.D., Solanki, S.C., Saini, J.S.: Thermohydraulic performance of solar air heaters with roughened absorber plates. Sol. Energy **61**(1), 33–42 (1997)
17. Karwa, R.: Experimental studies of augmented heat transfer and friction in asymmetrically heated rectangular ducts with ribs on the heated wall in transverse, inclined, V-continuous and V-discrete pattern. Int. Commun. Heat Mass Transf. **30**(2), 241–250 (2003)
18. Sahu, M.M., Bhagoria, J.L.: Augmentation of heat transfer coefficient by using 90 broken transverse ribs on absorber plate of solar air heater. Renew. Energy **30**(13), 2057–2073 (2005)
19. Aharwal, K.R., Gandhi, B.K., Saini, J.S.: Experimental investigation on heat-transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater. Renew. Energy **33**(4), 585–596 (2008)
20. Momin, A.M., Saini, J.S., Solanki, S.C.: Heat transfer and friction in solar air heater duct with V-shaped rib roughness on absorber plate. Int. J. Heat Mass Transf. **45**(16), 3383–3396 (2002)
21. Gupta, M.K., Kaushik, S.C.: Performance evaluation of solar air heater having expanded metal mesh as artificial roughness on absorber plate. Int. J. Therm. Sci. **48**(5), 1007–1016 (2009)
22. Karwa, R., Bairwa, R.D., Jain, B.P., Karwa, N.: Experimental study of the effects of rib angle and discretization on heat transfer and friction in an asymmetrically heated rectangular duct. J. Enhanc. Heat Transf. **12**(4) (2005)
23. Karwa, R., Solanki, S.C., Saini, J.S.: Heat transfer coefficient and friction factor correlations for the transitional flow regime in rib-roughened rectangular ducts. Int. J. Heat Mass Transf. **42**(9), 1597–1615 (1999)
24. Karwa, R., Solanki, S.C., Saini, J.S.: Thermo-hydraulic performance of solar air heaters having integral chamfered rib roughness on absorber plates. Energy **26**(2), 161–176 (2001)
25. Bhagoria, J.L., Saini, J.S., Solanki, S.C.: Heat transfer coefficient and friction factor correlations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate. Renew. Energy **25**, 341–369 (2002)
26. Saini, S.K., Saini, R.P.: Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness. Sol. Energy **82**(12), 1118–1130 (2008)
27. Jaurker, A.R., Saini, J.S., Gandhi, B.K.: Heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness. Sol. Energy **80**(8), 895–907 (2006)
28. Layek, A., Saini, J.S., Solanki, S.C.: Second law optimization of a solar air heater having chamfered rib–groove roughness on absorber plate. Renew. Energy **32**(12), 1967–1980 (2007)

Chapter 15
Optimising Transit Networks Using Simulation-Based Techniques

Obiora A. Nnene, Mark H. P. Zuidgeest, and Johan W. Joubert

Abstract Public transport systems play a critical role in improving mobility and access to opportunities, which is crucial for the socio-economic growth and well-being of any society. A key component of the system is the actual transit network, which usually consists of interconnected nodes and links that enable people to access the system and to travel to their chosen destinations in a smooth and efficient manner. This chapter focuses on the transit network design problem (TNDP), which deals with finding efficient network routes among a set of alternatives that best satisfies the conflicting objectives of different network stakeholders including passengers and operators. The goal of solving this problem is to improve the operational efficiency of a network, thereby reducing costs incurred by the service operator and minimising commuting costs for the commuter. A general description of the problem investigated in this chapter is given, exploring key aspects of the problem and trends in the discipline over time. This is followed by a discussion of the evolution of TNDP solution techniques, namely older mathematical solutions, a more recent meta-heuristics solution framework as well as simulation-based solutions that seem to be gaining traction currently. The chapter rounds off with a look at the future of the problem against technological advancements in transportation and significant structural changes that are likely to occur going forward.

Keywords Transit network design · Simulation · Meta-heuristics

O. A. Nnene (✉) · M. H. P. Zuidgeest
Department of Civil Engineering, University of Cape Town, Cape Town, South Africa
e-mail: obiora.nnene@uct.ac.za

J. W. Joubert
Department of Industrial Systems Engineering, University of Pretoria, Pretoria, South Africa

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_15

15.1 Introduction

Optimally designed transit networks facilitate the provision of efficient, accessible, and affordable mobility in cities. Additionally, they help to minimise the occurrence of transit-related problems such as congestion, air, and noise pollution as well as accidents. Other beneficial effects of optimally designed transit networks are seen in the reduction of transit costs that accrue to network users and service operators. This cost reduction can typically come in the form of a reduction in travel time for commuters and of operational costs for the owners. Lastly, optimised transit networks also encourage increased ridership on public transit systems, a desired outcome for public transportation planners and authorities globally.

Transit network design (TND) is a branch of transportation planning and engineering that focuses on designing public transit networks through the methodical application of documented practical guidelines like the NCHRP, or optimisation techniques namely analytical and approximate algorithms [1], though, the latter is mostly utilised in attempts to design transit network [2]. Analytical methods adopt mathematical optimisation, while approximate optimisation techniques are heuristic and meta-heuristic algorithms.

Optimisation techniques are used to identify the best among alternative solutions. However, the quality of results from the optimisation scheme are limited by how the solutions are evaluated. The difficulty of evaluating a solution in turn depends on the nature of the same. A transit network is a large stochastic system given elements like the random nature of passenger behaviour, travel demand, and transit service operations. Other elements are the unique topography of a network and the interconnectivity between the network and other external dynamic systems, like the environment [3]. These factors significantly increase the complexity of evaluating a network which in turn affects the quality of the optimised solution. In many cases, it is a futile exercise representing such systems as transit network with analytical expressions and attempting to find their closed-form solution. One reason for this is that expressions, variables, and parameters cannot adequately describe the randomness of a system. However, such systems lend themselves to simulation which can then be used to evaluate them.

Therefore, the focus of this chapter is on the design of public transport networks in a way that accounts for the stochastic behaviour of different network stakeholders. The discipline has been around since the existence of a need for efficient transportation systems. Formally, the problem is referred to as the transit network design problem (TNDP), as it involves finding the best network solution that simultaneously optimises the stated objective(s) of different transport stakeholders.

As indicated earlier, the ability to evaluate a network is a key step in solving the transit network design problem (TNDP). Historically, transit network design experts have used tools like aggregated trip-based models (TBM) for network evaluation when solving a TNDP, however, these methods are static and fail to fully describe the behaviour of various network stakeholders. Therefore, a key objective of the chapter is to show the power of simulations particular activity-based travel demand simulations in the evaluation of transits networks and how this can be integrated into the TND solution framework. This also represents the highlight of this chapter wherein a network design approach is presented that will accommodate the random decision-making of commuters and operators who seek to maximise their utility in response to network dynamics. Furthermore, another key advantage of the work is in presenting a network design approach that is not context dependent especially in terms of the service provision and network operations. Transit service operations are broadly classified as formal and informal. The former refers to services that operate according to a planned schedule while informal services, also called paratransit, are uncoordinated and less reliable [4]. Logically, the operations of the paratransit services are more arbitrary and less reliable due to actions like poor route adherence and competition with other service providers. However, even these behaviours can be described by robust simulation tools. This increases the prospect of evaluating, and thus optimising transit networks and their operations not only in the sophisticated and complex networks of developed cities but also in the uncoordinated, informal, transit networks in the developing world. The remainder of this chapter presents a broad description of the TNDP which is then followed by a discourse on the optimisation of transit networks that is based on simulations. This method will be referred to as a simulation-based optimisation network design approach. The chapter then rounds up with a reflection on the network design trends that will unfold in future.

15.1.1 The Transit Network Design Problem (TNDP)

Public transport networks play a critical role of facilitating smooth operation of transit services. The TNDP is a typical multi-objective optimisation problem with a set of discrete or continuous decision variables such as network configuration, route choice, and service headway. Other considerations are the feasibility constraints on route length, vehicle capacity, and fleet size. Usually, the network designer seeks a compromise set of networks and their operational frequency among different alternatives that address the often-conflicting objectives of different stakeholders such as network users, operators, and even the public transit authorities [5]. According to [6, 7], the network design and frequency setting activities of the TNDP are, respectively, classified as strategic and tactical, while vehicle and crew scheduling are operational activities. Network design is seen as strategic because it involves long-term planning and requires less detail. Conversely, frequency setting is considered a tactical activity as it is done within a shorter time horizon. Lastly, vehicle and crew scheduling take place in the shortest time and requires microscopic route level details (see Fig. 15.1).

The main steps usually taken to solve a TNDP include (a) generating alternative solutions given certain feasibility conditions, (b) evaluating them against an objective function, and (c) searching for the best solution. However, it should be noted that these steps may vary depending on the unique context of the problem being solved. Normally, the solution generation is aimed at creating feasible network alternatives that will constitute the problem's search space, and this is achieved with ad-hoc

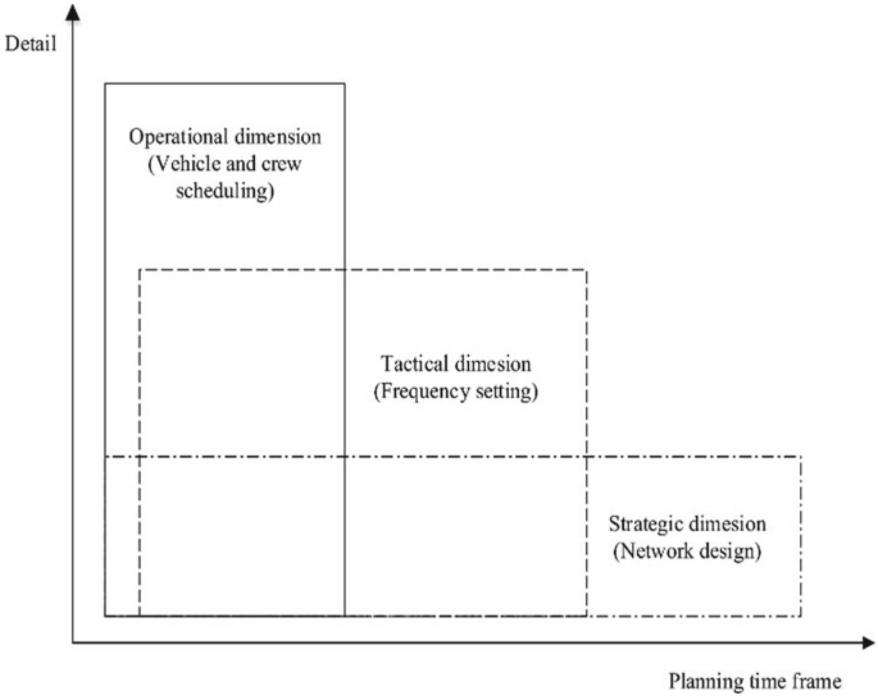


Fig. 15.1 Transport planning time horizon, adapted from Zuidgeest [8]

heuristic algorithms. On the other hand, evaluating the network solutions is done with a travel demand model with the aim of obtaining transport-related indicators used to measure the performance of each network, relative to the objective functions. After generating and evaluating solution objectives, a search procedure is adopted to find the best compromise solution among the given alternatives. Two main approaches used in the literature are (1) analytical procedures that attempt to find a closed-form solution for the TNDP and (2) meta-heuristic algorithms that can find good approximate solutions in relatively short time frames. The latter approach has been preferred by researchers in recent times because of the near impossibility of finding a closed-form solution for a very complex problem like the TNDP and the fact that meta-heuristics require fewer computing resources and are easily applied to many problem domains.

15.1.2 Components of the TNDP

As a typical optimisation problem, the main components of the TNDP are objective function(s), decision variable, feasibility constraints, and a travel demand model. These components are described briefly in the section below.

Objective Function

An objective function expresses the intended goal of an optimisation problem. Typically, it is expressed mathematically. Depending on the nature of the problem, a single objective or multiple objectives may be used in the formulation of an objective function. They are typically presented as the minimisation of a cost factor or the maximisation of a benefit or utility. In optimisation problems, the objectives are generally contradictory; hence, solving the problem is an attempt to find the best compromise solution between conflicting objectives. Most works in the literature combine minimisation of travel time and transit cost including average travel time and network length [9, 10]. Other objectives used in the literature include measures on the network coverage [11] and route directness [12].

Decision Variable

In the TNDP literature, a decision variable is a resource which the policymaker wants to optimise [13]. A feasibility condition usually defines the limits or bounds of their availability. Some of the more frequently used decision variables in the design of transit networks are route alignment, route frequency, route length, headway, service frequency, and timetables [14, 15]. Generally, a single or a combination of multiple decision variables is used.

Feasibility Constraints

These are parameters that reflect the limiting conditions of the decision variable in a transit network design problem. They generally define the feasibility of the optimisation problem and ensure that one obtain solutions within reasonable resource limitations. Some of the commonly used constraints in the literature are maximum/minimum service frequencies, maximum load factor, route length, fleet size, and operational cost. Pattnaik et al. [16] combined maximum frequencies, allowable fleet size and maximum load factor, while Cipriani et al. [17] used route length and service frequency to ensure that the length of the resulting routes and their service frequencies does not exceed an acceptable threshold. These constraints ensure that network solutions are generated within realistic limits, defined by the availability of resources or their scarcity thereof.

Travel Demand Model

The travel demand models in the TNDP usually serve as a proxy for passenger or user behaviour. They help to describe people's trip-making choices and decisions within a transit network. The four-step travel demand model has been used extensively for this purpose in the literature, especially the traffic assignment step of the model. Typical static transit assignment sub-models are the All-or-Nothing, user equilibrium (UE), and stochastic user equilibrium (SUE). However, a more advanced agent-based traffic assignment [18, 19] which assigns traffic at the level of the individual traveller is utilised in this work. The method facilitates the assignment of individual traveller's trips on a network instead of assigning aggregate travel demand as with trip-based models. Hence, it supports the simulation-based optimisation (SBO) network design approach proposed in this work.

15.1.3 Problem Formulation

Depending on the nature of the problem at hand, a TNDP may be formulated as a single or multiple objective problem. Researchers in the TNDP literature often make simplifying assumptions to reduce the computational difficulty of a multi-objective optimisation problem (MOP). One of the major differences between single and multi-objective solution algorithms is that in the former, researchers make simplifying assumptions like using a linear summation to reduce many objectives to a single objective. Understandably, the assumptions are made to reduce the complexity and intractability of the TNDP. Furthermore, weights must be defined beforehand for each objective. The obtained single results then reflect the weighted objectives. On the other hand, the outcome of multi-objective algorithms is a set of solutions representing all the possible trade-offs between the objectives of a problem. This makes it possible to obtain valuable information about the trade-offs between the objectives and sensitivity for weighting the various objectives in terms of an optimal design solution [20]. However, this, among other reasons, make the multi-objective solution approach more complex than the single objective alternative. A generalised formulation for the TNDP is therefore given as

$$\min : Z_1, Z_2 \tag{15.1}$$

$$Z_1 = \beta_{time} \sum_{r=1} t_r q_r + n_{tr} \tag{15.2}$$

$$Z_2 = \beta_{dist} \sum_{r=1} d_r f_r + \beta_{op} \sum_{r=1} t_r f_r \tag{15.3}$$

subject to the user equilibrium on the network:

$$\boldsymbol{q_t} = \tau\left[\boldsymbol{C_t}(\boldsymbol{r}, \boldsymbol{f})\right] \tag{15.4}$$

and constraints on vehicle capacity:

$$B_r = Q_j^{\max}/(f_r \cdot C) \leq B_{\max} \tag{15.5}$$

$$d_{\min} \leq d_r \leq d_{\max} \tag{15.6}$$

$$f_{\min} \leq f_r \leq f_{\max} \tag{15.7}$$

where

Z_1 = user cost objective function (−).

Z_2 = operator cost objective function (−).

β_{time} = monetary unit value for user travel time (‘000).

r = route on the network (−).

t_r = total travel time on route r including access, in vehicle and waiting times (h).

q_r = travel demand on route r (pax).

n_{tr} = transfers (−).

β_{dist} = monetary unit value for user travel time (‘000).

d_r = length of route r (km).

f_r = frequency on route r (veh/h).

β_{op} = monetary unit value for vehicle operating time (‘000).

$\boldsymbol{q_t}$ = vector of equilibrium flows on the transit network (−).

τ = user route choice model function (−).

$\boldsymbol{C_t}$ = vector of generalised route cost on the transit network (−).

$\boldsymbol{r}$ = vector of routes on the transit network (−).

$\boldsymbol{f}$ = vector of frequencies (−).

B_r = load capacity of route r and B_{max} is its maximum value (−).

Q_j^{max} = maximum passenger volume on any link of route r (−).

d_{min} = minimum route length (km).

d_{max} = maximum route length (km).

f_{min} = minimum allowed frequency.

f_{max} = maximum allowed frequency.

The objective functions, in Eq. 15.1, represent the costs that accrue to commuters and operators of the transit network. Equation 15.2 expresses the user cost objective, and operator’s cost objective is seen in Eq. 15.3. Transit users generally view the cost in terms of their total travel time (access, waiting, and in-vehicle travel times plus transfers where applicable). On the other hand, operators are concerned with the total operational costs comprising of the total distance and time operated. Operational distance is the cost that accrues from the wear and tears of the vehicle fleet as they traverse the designated routes to meet passenger demand, it is typically measured in kilometres. However, the operational time consists of personnel cost element like salaries that accrue throughout operations. Therefore, by minimising these objective functions, the total cost incurred on the network will be optimised for both stakeholders. The objectives are subject to the UE model (Eq. 15.4), which describes people's travel behaviour. The feasibility constraints for the model are those on vehicle capacity (Eq. 15.5) which introduces a load factor constraint, route length in Eq. 15.6, which is introduced to define the upper and lower bounds outside which it would be illogical to operate a bus service and Eq. 15.7 which represents the minimum and maximum operable frequency on each route within the bus network. It is usually dependent on the available fleet size and transit demand for each route.

These constraints are used to set the allowed limiting conditions for the allocation of resources on the transit network.

15.1.4 Solution Procedures for the TNDP

The primary distinction between analytical and approximate solution methods for the TNDP is in the way they solve the TNDP. Analytical methods utilise exact algorithms such as the branch and bound, branch and cut or the A* algorithm. They attempt to find the closed form of an objective function in the search for a unique solution to the problem. Instances of research done with analytical solutions in the literature are [21–23]. Conversely, heuristic techniques use approximate algorithms which can find good solution(s) within a reasonable time. Some examples of such research works are [24–26].

The major criticism of analytical methods is that by nature, the TNDP is non-convex [27, 28] and NP-hard [29, 30]. This implies that their equivalent decision problem is NP-complete. Hence, there is no verifiable efficient algorithm that exists to solve them in polynomial time [31, 32]. Therefore, it is almost impossible to derive a closed-form expression for its objective function. To this end, researchers use simplifying assumptions at the risk of rendering the solution unrealistic. The other criticism of analytical solution methods is their limited scope of application to idealistic or small-sized problems. This implies that applying them to more realistic TNDP would require almost infinite computational resources, which is unrealistic. More recently, the earlier mentioned criticism has led to the development of a type of heuristic algorithms known as meta-heuristics. Their main advantage over general heuristic is that they are not problem-dependent [33]. Hence, they are amenable to a broader array of problems spanning various knowledge domains than ordinary heuristics. Dréo et al. [34] highlights the fact that when the number of objectives in the MOP exceeds two, meta-heuristics are best suited for the problem. In terms of the TNDP, meta-heuristic algorithms can be applied to large scale or realistic problems since they can find acceptable network solutions within a limited period.

15.1.5 Review of Relevant Literature

This review focuses on solution models that have previously been used by researchers to solve the TNDP problem. Some notable review articles on the subject area are those by [5, 7, 35, 36]. In these papers, the authors give a detailed classification for the TNDP. Three prominent categories in the articles are optimisation objective(s), solution techniques and parameters like decision variables, demand pattern, network structure, among others. Besides earlier mentioned review articles, the section also describes the works of other notable authors in the literature. The reviewed works span five decades, since the first TNDP research was documented. They are grouped into two main publication periods, which occur before and after the year 2000.

Pre-2000

The work of Lampkin and Saalmans [37] is the first documented research in the TNDP literature. The central theme of the work was to redesign an existing bus network in a city in England, for improved efficiency. Since the loss of patronage/traffic to private cars was the primary motivation for the work, the specific optimisation objectives were to maximise the overall network utilisation and minimise travel time subject to available fleet size. They defined route spacing and frequency as the problem's decision variables. For their travel demand sub-model, the authors used the generation, distribution, and assignment steps of a typical four-step model. Lastly, the authors used a heuristic solution model based on a greedy search algorithm to find the most efficient network of routes. In the three decades between when the work of Lampkin and Saalmans [37] was published, and the year 2000, most of the documented research works in literature have implemented heuristic and analytical solution techniques or a combination of both. Ordinary heuristics have mostly been used to generate feasible network or route alternatives, while the optimisation problem is solved with an analytical model. A deviation from this trend is the work of Pattnaik et al. [16], who implemented a genetic algorithm (GA)-based meta-heuristic solution.

A hybrid two-stage model was proposed by Dubois et al. [38], which comprised both route network design and frequency setting. The route configuration and service frequency parameters were used as the decision variables, while the optimisation objective was to minimise the generalised time of travel subject to constraints on investment cost. The solution involved choosing a set of routes and their corresponding bus lines with a modified version of Lampkin and Saalmans [37]'s link insertion technique. In the second step of the model, transit line frequencies were calculated using an analytical model. The author assumed a variable demand context to get the optimal frequency.

The work by LeBlanc [39] also proposed an analytical transit network solution model, which had an operating frequency as its only decision variable. The author's optimisation objective was to minimise the operator's cost and maximise transit usage with constraints on operating cost. A simultaneous modal split—traffic assignment model was used to consider the frequency of every transit line because the changes in modal split on some transit lines affected the service frequency of others. The solution model was used to design a public transit network in North Dallas, Texas. Finally, in Constantin and Florian [40], the authors proposed an analytical solution approach based on a sub-gradient algorithm. The objective of their model is to minimise waiting time and total travel time, while, satisfying fleet size constraints. Route frequency served as the decision variable in their model, while a multipath traffic assignment model was used to assign travel demand on the network. This solution approach was used to improve a sample transit network in the USA.

Post-2000

Since the 2000s, meta-heuristic algorithms have been used more often as solution models for the TNDP. This indicates that in more recent times, meta-heuristic solutions have gained more acceptance. One reason for their widespread acceptance is their relatively simple adaptation to optimisation problems even when large and extensive case studies are to be solved. Further, advances in the fields of operations research and computational science in the last two decades have made the implementation and use of meta-heuristic procedures relatively straight forward. Some notable works that have used meta-heuristic solutions from the year 2000 till date include [41–45]. Furthermore, the TNDP has been applied to studies on transit network improvement which is exemplified in the work of Cipriani et al. [17]; route network optimisation and frequency setting done by Szeto and Wu [24]. In addition, an investigation of the bus transit network design problem with variable transit demand was done by Lee and Vuchic [46]. Other research works conducted on the TNDP has dwelt on transit emissions management [47], optimal network routing and intersection signal setting [48], and rail frequency optimisation [49].

Notably, all the mentioned research works adopt single objective optimisation algorithms in their solutions, even though the TNDP is essentially a multi-objective problem. In the literature, when a TNDP is solved with multi-objective solution models, it is called a multi-objective transit network design problem (MTNDP). Fewer of these works exist in the literature when compared to those solved with single objective optimisation procedures. Some prominent MTNDP works are in vehicular emissions minimisation [50, 51], transit network improvement [9], and minimising traffic externalities [20].

15.2 Simulation-Based Optimisation

Simulation-based optimisation (SBO) involves a synthesis of both simulation and optimisation models to solve decision-based problems like the TNDP. The discipline is a relatively new academic discipline that has only gained traction in the operations research literature in the last two decades [52]. An optimisation algorithm is generally used to find a unique or acceptable solution to a problem, given a set of alternatives. Simulations, on the other hand, through experimentation, can describe the complex behaviour of an entity within a system. They replicate large-scale, real-life systems as a means of gaining a better understanding of the system's performance under different scenarios. Notably, both models exhibit complementary limitations in their functionality. Optimisation algorithms can find solutions but do not fare well in analysing systems—especially large stochastic ones. Conversely, simulations may explain the latter but cannot optimise them. This complementary behaviour allows using both phenomena in achieving the aims of this research. The development of techniques such as simultaneous perturbation for non-linear optimisation [53] and reinforcement learning for dynamic programming have advanced the evolution of optimisation methods that are compatible with simulation models and the modification of older optimisation algorithms to integrate with simulation more easily [54]. Furthermore, advancements in computational science have aided the overall growth in this field, making it possible to process larger models in much less time. In a typical TNDP, the problem search space comprises networks with varying configurations and their corresponding operational schedules. Each network solution is evaluated by simulating travel demand on it. At the end of the simulation, the performance indicators are used to rank the networks. This process continues repeatedly until an efficient solution for the problem is found. This implies that optimisation is being achieved through the agency of a simulation.

Travel demand models and simulations

Travel demand models afford us a systematic way to investigate how people's demand for public transport services in response to system dynamics [55]. Such models replicate the behavioural interactions of agents within the transportation system. The discipline grew out of the need to correctly predict future travel volumes, which served as an essential design parameter in the development of highway systems being constructed at the time [56]. Since then, two dominant modelling philosophies have evolved in transportation planning, namely trip-based modelling (TBM) and activity-based modelling (ABM). TBMs are so named because the trip is the basic unit of analysis. They represent travel demand in terms of aggregated interzonal trips. Hence, they are also known as aggregated travel demand models and are more suited for regional and sub-regional public transport analysis. The ABM uses people's activities as the dominant unit of analysis. Therefore, trips are modelled as the connection between activities. ABMs are disaggregated models because they are implemented with microsimulation frameworks, using data that reflect the travellers' choice and decision-making in microscopic details. Other classifications for travel demand models are static and dynamic. This deals with how the models assign travel demand on a network in the temporal dimension. TBMs are static and are only able to capture average performance indicators for a specific time snapshot on a transit network. On the other hand, ABMs are dynamic as they can capture time-dependent phenomena on the network, particularly at the level of passenger activities like boarding or alighting a transit vehicle [57]. The ABM is of interest in this work, particularly a class of these models known as activity-based simulations (ABS).

In general, a simulation is an experiment-based method of studying and analysing the behaviour of the variables and parameters of a model [58]. It is used to gain a better understanding of a natural system or phenomenon. When the simulation is in the form of a computational model, it is called a simulation model. In public transport planning, simulations help us analyse the detailed interactions of users, drivers, and other stakeholders. They give a better understanding of how these entities interact within the transportation system under different prescribed scenarios. The lessons learnt may inform decision-making when providing transit solutions. The insights and information received can also be used during network upgrades and other activities that help to improve the attractiveness of a public transportation system. Simulations have been used to study pedestrian movement in public transit infrastructure [59], bus priority system planning [60], bus passenger behaviour at stops [61], and passenger response to service disruptions [62]. Different types of simulations in the literature include discrete event, continuous system, agent-based, Monte Carlo, and hybrid simulations. More details regarding simulations are available in White and Ingalls [58] and Schruben [63]. The type of simulation utilised in this research is known as ABS. The next section discusses ABS in the context of public transport planning.

Activity-based Simulation

Understanding the concept of agents is central to grasping how ABS work. An agent is an autonomous entity that possesses some attributes and exhibits specific behaviour within a modelled environment. They are autonomous because they receive information from their environment and change their state or behaviour in response. Furthermore, agents do not require human intervention to act. They operate on their thread of execution within the model, and they interact with other agents and their environment. A model that replicates a real-life system, using an abstraction built around agents is called an agent-based model. Such a model must specify the rules that govern the attributes, behaviours, and environment of the agent. Hence, agent-based modelling aims to search for analytical insight into the collective behaviour of agents that obey simple rules, especially in natural systems [64].

According to Heath and Hill [65], the theoretical foundations of ABS were laid by researchers like [66] who attempted to understand the occurrence of emergent behaviour in systems. This was done by studying individual agents and using them as the catalysts for the characteristic patterns observed in the system. Emergent behaviour refers to actions and behaviours that are observed among the agents when they react and adapt to system changes within their environment [67]. Such behaviour is not part of the original rules that define the agents' actions [68] asserts that this emergent phenomenon results from the input variables of the simulation and the agent's interaction with other agents. Emergent behaviour, which is at the heart of ABS, was first observed in the cellular automata game, (game of life), developed by John Conway (Weimer et al. [69]). In the game, checker-like objects replicate themselves and form patterns on a grid, to observe the way complex patterns emerge from the execution of straightforward rules.

In this work, activity-based travel demand simulation (ABTDS) is used as a component of the proposed SBO network design approach. In an ABTDS, the agents include network users, operators, vehicles, and other entities. One assumption is that an individual's decision to travel depends on their need to engage in an activity (travel

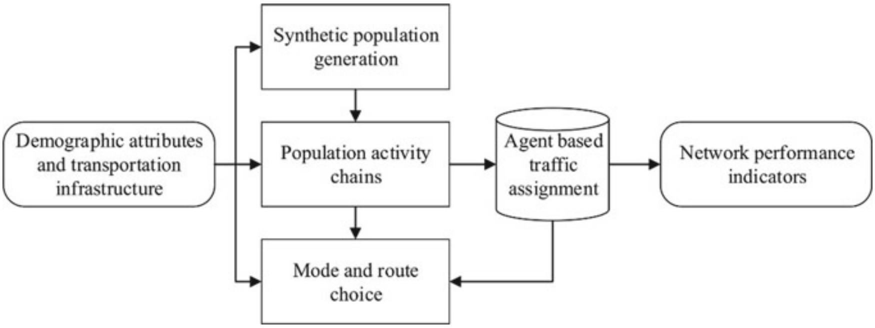


Fig. 15.2 Activity-based travel demand simulation flowchart, adapted from Zheng et al. [70]

demand is a derived need). The activity depends on the agent or decision-maker, a set of activity options or choice sets, and specific heuristic rules that govern the sets and define the boundaries outside which they become unrealistic. The major components of the model are activity-based demand generation and agent-based traffic assignment. These are discussed, respectively, in the next two sections, while a flow chart for the ABTDS can be found in Fig. 15.2.

Activity-based demand generation

- Generate agent population: in this step, a synthetic population of agents is generated, using a concept of random realisation described in Balmer et al. [71]. This involves creating a virtual population that has the same demographic attributes and structure as that of a real population census. Essentially, if one takes from the synthetic population, within statistical limits, it should return the real census. Additionally, the synthetic population is composed of spatially located households, which have specified attributes such as a street address, car ownership, and household income. The households are then assigned individuals having attributes like gender and age.
- Generate individual activity schedules: this step consists of generating activity schedules for each respective agent in the synthetic population. Activity here is defined simply as a physical engagement of an individual in something that satisfies his personal and/or family needs [72]. A daily schedule reflects the pattern of activities to be engaged in by the agent as well as information like start and end times of activities, duration of activity, and the activity location.
- Passenger mode choice: in this last step, mode choices are made by the commuters for each trip. This is like the third step in the four-step model (mode choice), but it does not only distribute the trips based on modal characteristics. Instead, modes are also selected based on the demographic attributes of the travellers. An instance is that only families with car ownership as an attribute will have the option of selecting that mode for their trips.

Agent-based traffic assignment

In a transit network, people choose their travel route based on the cost associated with the network's routes. Hence, the user behaviour witnessed on a network largely depends on the attendant cost of travelling on that network. This behaviour, which is reflected in the traveller's route choice, in turn, changes the network's state relative to congestion and delays. The new conditions on the network, subsequently, affects the route choices of the traveller, which again changes the state of the network. When this cycle progresses to a point where the route choice of the traveller can no longer affect the network as to improve their travel experience, a point of UE has been attained [73]. One assumption used in Wardrop's UE is that the travellers always have a perfect and uniform valuation of all route costs. Hence, they will always choose the least expensive route [74]. However, this is not realistic, owing to the stochastic and sometimes irrational nature of human decision-making. It implies that people will not always choose the shortest travel path. Therefore, the UE model has been extended to account for the randomness associated with people's decision-making [75]. The principle guiding this modification is that each user perceives travel costs differently, and their perception guides their choice of least expensive route(s). Therefore, their choices lead to a distribution of routes with the most attractive route having the highest demand. This extended model is known as the SUE assignment model. The critical limitation of the SUE is that, behaviourally, the model only accounts for the route choice of the traveller. This limitation makes them insufficient to fully describe the microscopic behaviour of agents on transit networks. Furthermore, the Wardrop's and stochastic UE models consider static traffic assignment and are typically represented with a structure as (origin, destination). This is because they do not account for time-dependent variations of travel demand and travel costs on a transit network. To this end, Kaufman et al. [76] and Friedrich and Hofsaß [77] propose some improvements to the static assignment that account for temporal variations. The enhanced model is known as Dynamic Traffic Assignment (DTA). It incorporates an additional dimension for departure time in its structure: (origin, departure time, and destination). Its major contribution is the ability to generate time-dependent traffic or link volumes. Therefore, the agent-based traffic assignment model is a direct extension of the DTA [78].

Multi-objective optimisation

The TNDP has earlier been characterised as a typical multi-objective optimisation problem (MOP). Problems of this nature have at least two conflicting objectives that need to be resolved simultaneously. Therefore, solving an MOP requires making certain trade-off decisions to obtain an efficient solution that is acceptable [79]. Many real-life optimisation problems fall into this category. A general mathematical statement for MOPs can be seen in Eqs. 15.8–15.11.

$$\min : f(x) = [f_1(x),\ f_2(x),\ f_3(x), \ldots,\ f_N(x)]^T \tag{15.8}$$

$$g_j(x) \geq 0 \quad \forall j = 1, \ldots, J \tag{15.9}$$

$$h_k(x) \geq 0 \quad \forall k = 1, \ldots, K \tag{15.10}$$

$$x_i^{Lower} \leq x_i \leq x_i^{Upper} \tag{15.11}$$

where N is the number of objective functions ($N \geq 2$), J and K are the number of inequality and equality constraints, respectively. x_i^{Lower} and x_i^{Upper} symbolise the lower and upper bounds of the decision variable. If a solution x_i satisfies the $J + K$ constraints, it is said to be feasible. The set of all feasible solutions constitute the feasible search space. The case above is framed as a minimisation problem. However, it can be converted to a maximisation by multiplying each objective function by -1 and transforming the constraints based on the principles of duality, highlighted in Deb [80]. The result of an MOP is a set of trade-off solutions known as a Pareto set or frontier which normally contains a set of non-dominated solutions.

Like the algorithms that solve single optimisation, multi-objective optimisation solution algorithms are also classified as exact and approximate. Exact or analytical optimisation algorithms are more effective for solving problems with small search spaces. Dréo et al. [34] highlights the fact that when the number of objectives in an MOP exceeds two, approximate solution methods are more suitable for the problem. This is because of the hardness of such problems and their multiple-objective frameworks. However, an approximate solution algorithm cannot guarantee that a Pareto optimal solution set will be found. Instead, they ensure that a good approximation of the Pareto optimal solution can be obtained in a reasonable time frame. Heuristic and meta-heuristic procedures are typical approximate optimisation algorithm. A class of meta-heuristics that is particularly amenable to multi-objective problems is the multi-objective meta-heuristics. An instance of this is the multi-objective evolutionary algorithm (MOEA). The latter is a type of meta-heuristics that are designed, based on biological principles [81–83]. They have been extensively researched because of their ability to generate good approximations of the Pareto sets in many multi-objective optimisation problem scenarios and disciplines. A typical MOEA is known as the non-dominated sorting genetic algorithm (NSGA-II).

15.2.1 A Simulation-Based Optimisation Framework for Transit Network Design

The interaction between MOP and ABS lies in translating the optimisation model's solution (network) into a format that is readable by the simulation. There would also be a need to reconfigure the simulation's output into a scheme the optimisation can use to rank the network solution. It is this interaction between the optimisation and simulation models that make the proposed solution model a SBO of public transit networks. This is because the optimisation is being achieved through the agency of a simulation. A graphical representation of a conceptual framework for the proposed

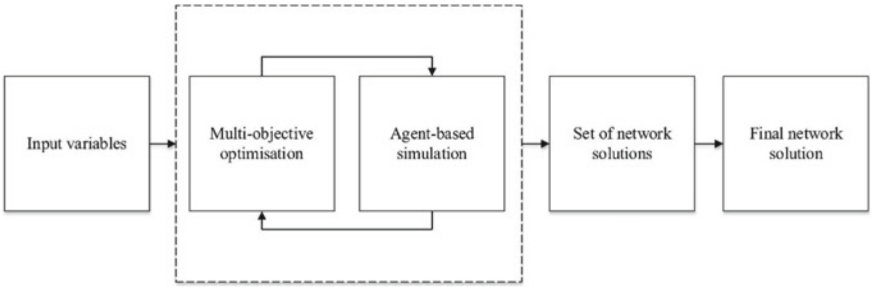


Fig. 15.3 Steps in the SBO framework [84]

SBO solution model is shown in Fig. 15.3. The framework details the steps taken to achieve the goals of this research.

Multi-objective public transit network design

Three main steps are involved in network design, namely network generation, network evaluation, and lastly, a procedure used to search for an optimised network.

- **Network generation**: In this stage of the model, computer-based heuristic algorithms would be used to create a population of feasible solutions for the network design problem. Feasibility criteria like network size and route length guide the process. This pool of feasible networks is then initialised within the SBO solution algorithm.
- **Network analysis**: This involves calling the ABS to evaluate the network solutions initialised in the generation stage. The scores and other indicators obtained from evaluating the solutions, then serve as input for the model's final stage.
- **Search for optimised solution**: In this final stage, the integration between simulation and optimisation occurs. The results of the network analysis (simulation) are used alongside other sub-process of the optimisation to rank and compare the solutions. The best solutions are then used to create newer solutions. This process continues iteratively until a predefined termination criterion is satisfied.

Agent-based Travel Demand Simulation

- **Initial demand generation**: In this step, a synthetic population of public transit users are created by sampling from a real population. The individuals in the synthetic population are then assigned demographic and other attributes based on the census data of the transport area under consideration. Subsequently, a daily plan comprising all the activity locations and trip chains in the transport area is created. The trip chains are created by organising sequentially the trips embarked on by the travellers within a 24-h modelling timeframe.
- **Iterative demand optimisation**: This stage comprises three sub-steps. In the first sub-step called execution, plans generated by agents in the demand generation are simulated using an agent-based traffic assignment. The next sub-step is called scoring. Here, the executed plans are evaluated and assigned a score, using a

scoring or utility function. The scores are then used to measure the performance of a plan and if it should be adjusted or not. The last step, known as replanning, is a process that allows every individual to recalculate their current plan based on how satisfactory they find the present network conditions. Replanning facilitates the correct simulation of passenger behaviour, such as choosing a different route when the initial one they select is congested.

- **Result analysis**: At the end of the simulation, various performance indicators relating to the specific objectives of the study may be collected and analysed to gain insight into the travel demand and behaviour of agents within the study area.

15.2.2 A Simulation-Based Transit Network Design Model (SBTNDM)

A so-called simulation-based transit network design model (SBTNDM) is discussed here. The key components of the model are the ABS called multi-agent transport simulation (MATSim) and the MOEA called non-dominated sorting algorithm (NSGA-II). These are discussed below.

Multi-agent transport Simulation (MATSim)

MATSim is a model used to simulate travel demand in this work is a typical agent-based model that can simulate the microscopic activities of people on a public transportation network over a 24-h duration. Conceptually, a MATSim simulation consists of two layers, characterised as physical and mental in Nicolai [85] and Rieser [86]. The physical layer is also called a mobility or traffic flow simulation and represents the tangible parts of a transit system, like agents or travellers, their activity plans, activity locations, vehicle fleet, network infrastructure, and other concrete elements of the system. On the other hand, the mental layer represents the abstract part of a transit network system and describes how agents receive and process information from the network environment and how this affects their decisions and choices on the network, with the goal of improving their overall travel experience.

MATSim input data

The input data required in MATSim consists of a transit network, transit schedules, vehicle fleet, agent plan or daily activity chain and configuration settings. These are saved as extensible markup language (XML) [87] files. The agent's plan files are extracted from automated fare collection (AFC) data set, while the transit network, operational schedules are obtained by converting the Google transit feed specification (GTFS) [88] feed to the network and operational schedules. The data extraction is done with the aid of ad-hoc or heuristic algorithms developed for that purpose. Lastly, a configuration file is created, which contains parameters and their values that are needed to control the simulation.

Transit network simulation in MATSim

MATSim organises public transit system data in a format that is commonly used by transit services worldwide [18]. The transit network modelled in MATSim will comprise two or more transit routes. The route itself is a sequence of road links that facilitate the service's route operation. Each route serves one direction of travel and enables buses to move to and from the depot at the end and beginning of a day, respectively. The routes also have as an attribute the list of departures, which gives information about the time a vehicle starts at the first stop on that route. Furthermore, a route includes a sequential list of transit stops that are served, alongside operating timetables, which indicate when vehicles arrive or leave a stop. The times are specified as offsets in time units from the departure at the first stop. At each subsequent stop, the offset is added to the initial departure time at the first stop. Each departure contains a vehicle's start time on the route and a reference to the vehicle. As the timing information is part of the route, it becomes possible to have routes with identical stop sequences but different time offsets. Stop locations are described by their coordinates and an optional name or id. They must be assigned to unique lines of the network for the simulation.

A typical simulation loop in MATSim has five steps namely initial demand generation, execution, scoring, replanning, and termination. These steps are shown in Fig. 15.4 below. In the first step, the socio-economic, demographic, and travel behaviour data are used to create agent plans. In this work, this step is achieved with the AFC data. The next step is to execute or simulate the agent plans; thereafter, the plans are scored using inbuilt utility functions. This is followed by replanning in which agents are allowed to modify their travel plans and route choice depending on prevailing network conditions. Lastly, the simulation is terminated.

Non-dominated sorting Genetic Algorithm (NSGA-II)

The NSGA-II is a MOP developed by Deb et al. [89] for solving optimisation problems. Its operations start with initialising a population of solutions, or chromosomes that serves as the first parents. Subsequently, the solutions are scored or evaluated against the objective functions. Thereafter, a non-dominated sorting procedure [90]

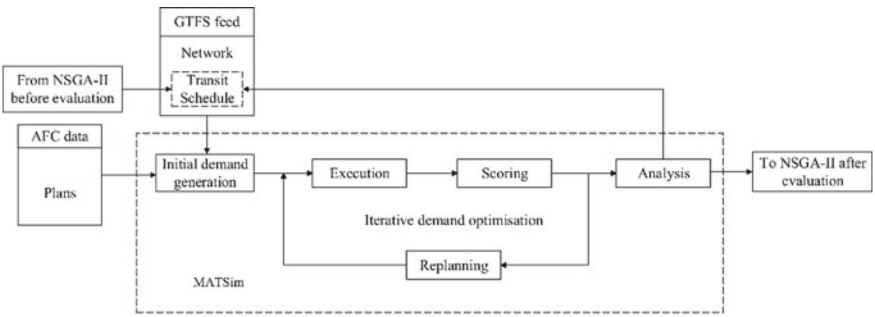


Fig. 15.4 Interactions between sub-models [84]

is used to rank the population into different Pareto fronts or solutions set. Fitness values equivalent to their ranking are then assigned to each front in ascending order, with the best front ranked as 1 and the next front ranked as 2. After this, binary tournament selection operator and a crowded comparison operator are used to select parents that will be used to reproduce the offspring. The binary tournament selection randomly chooses two solutions, determines the fitter of both solutions, then adds that one to the mating pool. The next step involves using the crossover and mutation operators to create a population of children/offspring of a size equivalent to that of the first parent. Thereafter, the procedure is slightly different from the first generation. The generated offspring and parent are merged to form a population that is twice the size of the original population in every subsequent generation. The merged population is evaluated and again ranked according to the non-dominance and crowding distance criteria. The better performing half of the merged populations are selected as the new parent population. This process then goes on iteratively until a specified termination condition is satisfied. Elitism is introduced in the algorithm by archiving a small percentage of the best performing or elite solutions from both the parents and offspring populations during successive generations. These are reused as part of the parent population in the next generation.

In designing public transport networks with the NSGA-II, the initial population is a set of feasible network alternatives. The networks generally have different configurations and other attributes. Therefore, the task is to find a network and its attributes among the alternatives, which best addresses the stated optimisation goals. Furthermore, each chromosome possesses a gene. Routes in each network solution represent genes in this context. The best performing chromosome or network in the population represents a globally optimum solution. However, for very difficult problems like the TNDP, it is not feasible to know if a solution is the global optimum. This is especially true in a multi-objective context where one seeks a set of non-dominated solutions (Pareto optimal front) rather than a single solution. Therefore, an efficient, locally optimal front that is obtained within a reasonable time frame is generally considered acceptable. Figure 15.4 shows the integration between MATSim and NSGA-II within an SBO framework.

15.2.3 Case Study

Base Network

The case study network is the MyCiTi bus rapid transit (BRT) network in Cape Town, South Africa (see Fig. 15.5). The network consists of 472 nodes and about 46 operational routes. The service began its operations in 2010 as part of a nationwide rollout of BRT services across South Africa. In Cape Town, the service is expected to be a significant component of the integrated public transit network (IPTN) which is a transit network planned in anticipation of the future effect of urban growth on travel demand in the city. The plan involves a significant expansion of the city's current public transportation network. This is logical given the expected growth of the city's population by approximately 11% in 2032 when the IPTN is scheduled to be fully functional. According to the TDA [91], a vital objective of the IPTN is to ensure that at least of the inhabitants in Cape Town, will live within 500 m of a BRT trunk or rail line by the target year of 2032. The MyCiTi is expected to be the backbone of the IPTN. The system utilises recent technologies like automated fare collection (AFC), closed transfer facilities and level boarding platforms. It will be rolled out in four stages, with the full system ready for service in about twenty years. The first phase routes of the service were launched officially in 2011. Since then, new routes have been incrementally developed to expand the service's coverage within the city.

Solution Procedure

The steps taken in the design of the MyCiTi BRT are discussed below.

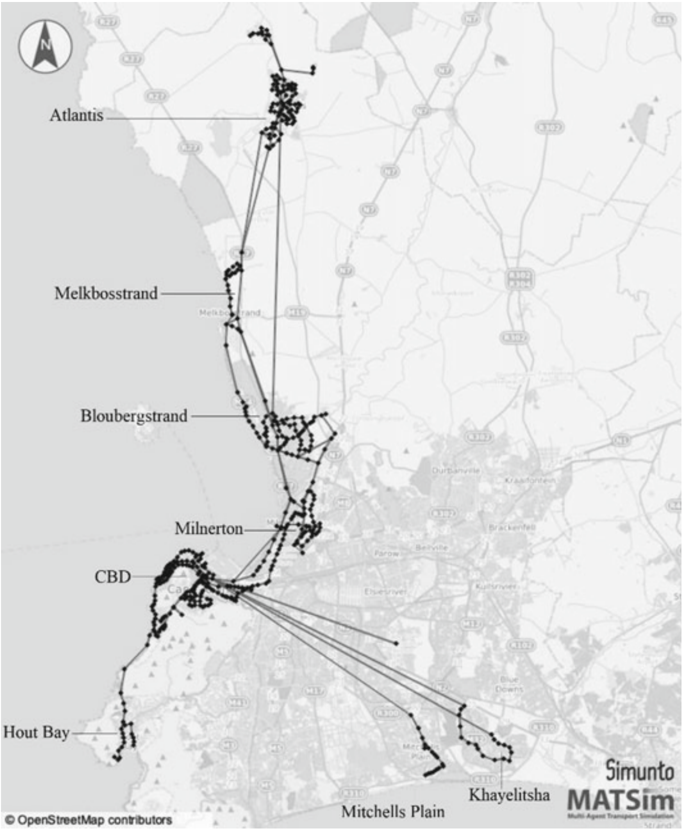


Fig. 15.5 Map of the MyCiTi BRT network, adapted from Nnene [84]

Network Generation Algorithm

This is the first stage of the SBTNDM. It starts by creating a pool of feasible transit networks, from which the first population of solutions will be initialised in the model's optimisation framework. An ad-hoc heuristic algorithm was developed for the network generation exercise. Its inputs include the MyCiTi, network and its constituent routes, the network size parameter (the number of routes), and feasibility criteria for route length r_{len}, route directness r_{dir} (minimum deviation from the shortest path), and route overlap $r_{overlap}$ (maximum coincidence between the links of a route and that of the shortest path). These parameters will be used to define the feasibility conditions for acceptable routes. A network generation heuristic based on the Java programming language [92] was developed for the work; this was combined with JGrapht an open-source graph creation and manipulating the programme by Michail et al. [93] and the XML. The transit network input data is extracted from the GTFS feed of the MyCiTi BRT. The network is then converted into a GraphML file [94], which is a unique XML format for graphs. The conversion makes it possible to read the network as a graph with its nodes, links, and their attributes. Subsequently, the graph can be manipulated with the JGrapht tool and graph theory operations.

Network Evaluation Procedure

This step of the model involves using the MATSim simulation tool to evaluate the generated network solutions. It requires setting up public transit scenario for the problem in MATSim, which is called by the SBTNDM during the evaluation process. Inputs for the scenario include (a) the initialised population of network alternatives, (b) a synthetic population of agents and their travel demand (24-h activity plan), which is created from the AFC data, (c) an initial schedule of transit operations on the routes of the network, comprising a timetable with its detailed fleet schedule and vehicle departures, and (d) a fleet of transit vehicles that will operate the schedules. MATSim is called each time a new solution is to be evaluated. Before evaluating a new solution, the subsisting transit schedule data file is overwritten since it would have been altered during the previous run of the NSGA-II. The MATSim simulation process then begins with executing the users' initial demand and optimising them. At the end of the simulation, the resulting events file are analysed. The obtained score is then assigned to the current network solution which is then returned to the optimisation module for further processing. An image depicting the SBTNDM procedure is shown in Fig. 15.6.

Search for optimised network solution

This stage of the model describes how the network optimisation progresses and how a Pareto set of transit network solutions is realised. The main inputs used here are the outputs of the NGA and NEP, respectively, namely the feasible candidate solutions and objective function scores from simulating each solution with MATSim. This implies that at different stages of its operation, the procedure will call both subroutines. The generated network routes are converted to MATSim transit schedule files in XML format, which contains both the transit routes and their schedules.

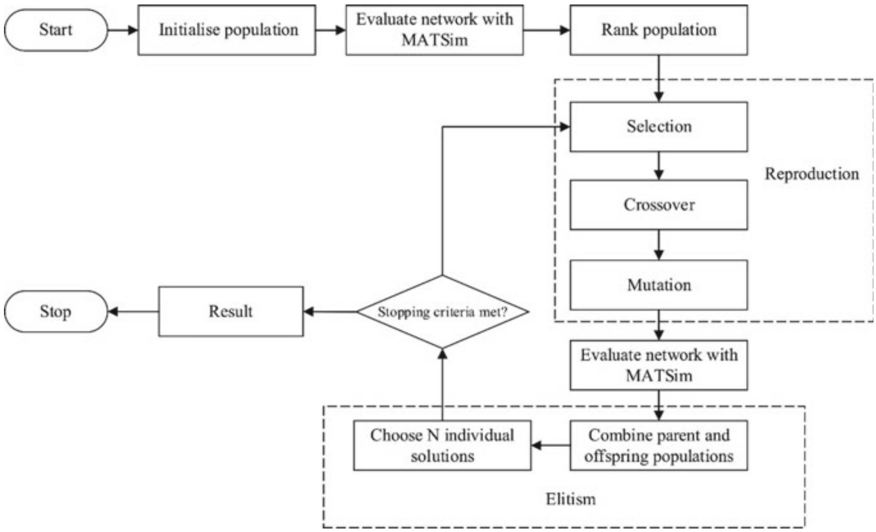


Fig. 15.6 Simulation-based transit network design model [84]

Hence, this is utilised in the work as the NSGA-II's chromosome. An important step in evolutionary algorithms is to encode the gene-level operation of each solution. To this end, the transit Schedule file, which is initially in XML format is converted to a JavaString object notation data (JSON) format [95]. This facilitates the efficient and straightforward manipulation of the transit schedule with the genetic operators (selection, crossover, and mutation) during the reproduction process. However, this encoding scheme then makes it necessary to customise the NSGA-II operators to enable them to manipulate the JSON format. The major advantage of this approach is that it accommodates the encoding of each network with a detailed operational schedule. It also facilitates the simultaneous handling of the route network design and frequency setting sub-problems of the TNDP. At the end of this process, a Pareto set of solutions is obtained for the problem.

15.2.4 Results of Case Study

Figure 15.7 shows the result obtained from the network design case study. The Pareto frontier obtained after the 15, 30, and 50 generations of the SBTNDM are shown in the image. An observation of the plot reveals that the solutions obtained after 15 generations are spreads out further across the search space (along the x-axis) than the front obtained after 30 generations. Similarly, the Pareto frontier after 30 generations is spread out further than that obtained after 50 generations. This implies an in-depth exploration of the search space has been done, which is indicative of a good diversity among the obtained solutions. As better solutions are found in each

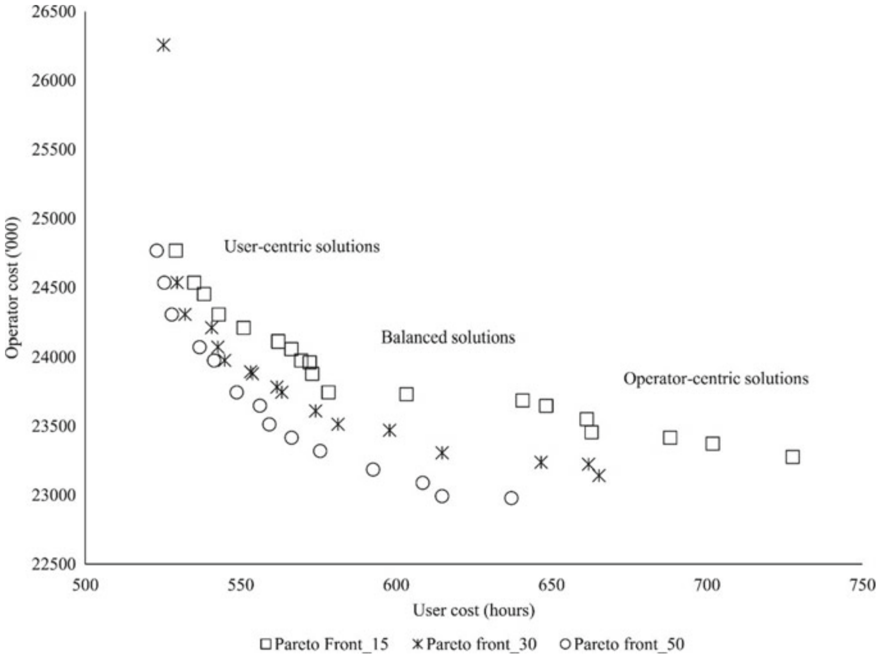


Fig. 15.7 Pareto frontier after 15, 30, and 50 evaluations [84]

generation, the algorithm need not search parts of the search space where these results have previously been found. Furthermore, the fact that there are fewer solutions as the algorithm runs progress shows that worse solutions are being eliminated. This is a sign of convergence in the results. Lastly, it can also be observed that the Pareto front after 50 generations has lower objective function values for both the user and operator cost functions. This is in line with the expected behaviour of minimisation problems.

Further visual observation of the plot reveals that the network with the highest travel time also has the least operator cost and vice versa. This is indicative of the trade-off between both the users' and operators' perspectives. Users prefer direct trips that reduce their travel time, while operators prefer longer and slightly more circuitous routes that increase the volume of demand they can potentially satisfy while reducing their average service costs in the process. The balanced network solutions occur within the marked cluster in the middle of the plot in Fig. 15.7. In the context of this work, the networks are seen as balanced as they exhibit the least conflict between the earlier mentioned objectives. In other words, they are the best compromise solutions between the objectives. These solutions are therefore regarded as efficient network solutions. Table 15.1 shows the objective function scores for the solutions in the Pareto front.

In the table, network 1 has the least user cost or objective 1 score and will be referred to as the user-centric solution. This network also has the highest operator

Table 15.1 Raw objective function values

Network (−)	User cost Z_1 (hours)	Operator cost Z_2 ('000)
1	522.9	24,767.52
2	525.41	24,536.12
3	527.82	24,304.72
4	536.75	24,073.32
5	541.43	23,976.82
6	548.73	23,745.42
7	556.13	23,648.92
8	559.23	23,514.02
9	566.34	23,417.52
10	575.54	23,321.01
11	592.58	23,186.12
12	608.58	23,089.61
13	614.80	22,993.11
14	637.07	22,979.07

cost or objective 2 score. On the other hand, network 14 has the least operator cost and will be called the operator-centric solution. However, network solution 8 shows the least difference in the normalised values of both objectives. Hence, it may be considered as the best compromise or balanced network solution, since it shows the least conflict between the perspectives of the commuter and operator. To depict this clearly, the above objective scores are normalised and ordered to facilitate plotting them on similar scales. Subsequently, the normalised scores are ordered and plotted against one another. Figure 15.8 shows a plot of the normalised objective(s) function scores.

15.2.5 Conclusion

The objective of this work is to develop a transit network design technique that searches for efficient network solutions. This goal is achieved by integrating an activity-based simulation with multi-objective optimisation. The proposed model is then tested with the transit network in the city of Cape Town, South Africa. The results show that the so-called simulation-based transit network design model can indeed design logical and efficient transit networks that reflect the perspective of different network stakeholders like commuters and operators. Furthermore, the results highlight the potentially important role simulation models can play in the transit network design discipline owing to their ability to describe and thus evaluate the stochastic behaviour of different stakeholders on a network. As a decision support tool, the SBTNDM will also be useful to guide policymakers to develop effective policy decisions that are relevant to the transportation realities of today. In terms of the future

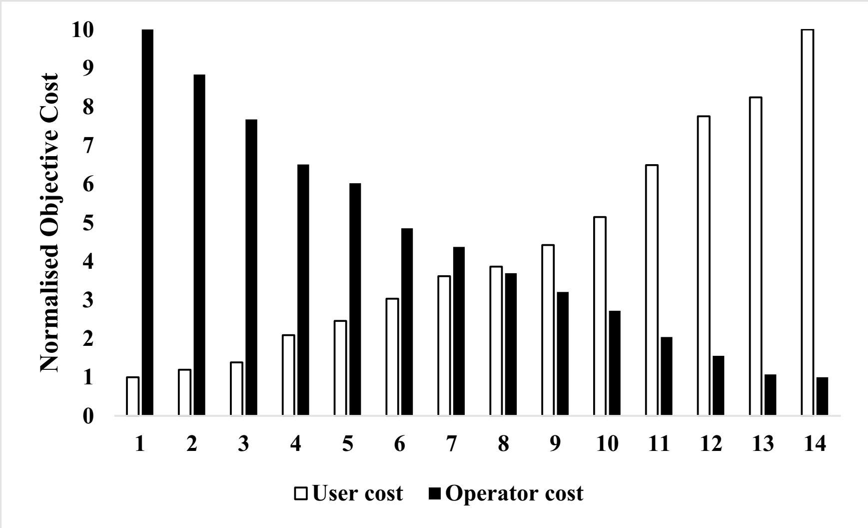


Fig. 15.8 Network solutions showing compromise between the user and operator cost objectives

research directions that may extend from this work, the primary consideration is to extend the application of the SBTNDM to a hybrid network context, to improve modal integration in Cape Town.

References

1. Ceder, A.: Public Transit Planning and Operation: Theory, Modelling and Practice, 1st edn, p. 626. Elsevier, Burlington, MA (2007)
2. Kepaptsoglou, K., Karlaftis, M.: Transit route network design problem: review. J. Transp. Eng. **135**(8), 491–505 (2009)
3. Rodrigue, J., Comtois, C., Slack, B.: The Geography of Transport Systems, 3rd edn, p. 432. United Kindom, Routledge (2013)
4. Ferro, P.S., Golub. R.B.A.: Planned and Paratransit Service Integration Through Trunk and Feeder Arrangements: An International Review, pp. 604–618 (2012)
5. Buba, A.T., Lee, L.S.: A differential evolution for simultaneous transit network design and frequency setting problem. Expert. Syst. Appl. **106**, 277–289 (2018)
6. Ceder, A.: Public Transit Planning and Operation: Modeling, Practice and Behavior, 2nd edn, p. 716. CRC Press (2015)
7. Ibarra-Rojas, O.J., Delgado, F., Giesen, R., Muñoz, J.C.: Planning, operation, and control of bus transport systems: a literature review. Transp. Res. Part B Methodol. **77**(3), 38–75 (2015)
8. Zuidgeest, M.H.P.: Sustainable Urban Transport Development: A Dynamic Optimisation Approach. University of Twente, Enschede (2005)
9. Heyken Soares, P., Mumford, C.L., Amponsah, K., Mao, Y.: An adaptive scaled network for public transport route optimisation. Public Transp. **11**(2), 379–412 (2019)
10. Yang, J., Jiang, Y.: Application of modified NSGA-II to the transit network design problem. J. Adv. Transp. **2020**(i), (2020)

11. Cadarso, L., Marin, Á.: Rapid transit network design considering risk aversion. Electron. Notes Discret. Math. **52**, 29–36 (2016)
12. Suman, H.K., Bolia, N.B.: Improvement in direct bus services through route planning. Transp. Policy **81**, 263–274 (2019)
13. Curtin, K.M.: Operations research. In: Kempf-Leonard, K. (ed.) Encyclopedia of Social Measurement, pp. 925–931. Elsevier, Texas (2004)
14. Ngamchai, S., Lovell, D.J.: Optimal time transfer in bus transit route network design using a genetic algorithm. J. Transp. Eng. **129**(October), 510–521 (2003)
15. Shih, M., Mahmassani, H.: A Design Methodology for Bus Transit Networks with Coordinated Operations. Texas (1994)
16. Pattnaik, S.B., Mohan, S., Tom, V.M.: Urban bus transit route network design using genetic algorithm. J. Transp. Eng. **124**(4), 368–375 (1998)
17. Cipriani, E., Gori, S., Petrelli, M.: Transit network design: a procedure and an application to a large urban area. Transp. Res. Part C Emerg. Technol. **20**(1), 3–14 (2012)
18. Horni, A., Nagel, K., Axhausen, K.W.: The multi-agent transport simulation MATSim. Multi-Agent Transp. Simul. MATSim 662 (2016)
19. Nagel, K., Flötteröd, G.: Agent-based traffic assignment: going from trips to behavioral travelers. Int. Conf. Travel. Behav. Res. 1–26 (2009)
20. Possel, B., Wismans, L.J.J., Van Berkum, E.C., Bliemer, M.C.J.: The multi-objective network design problem using minimizing externalities as objectives: comparison of a genetic algorithm and simulated annealing framework. Transp. (Amst) **45**(2), 545–572 (2018)
21. Daganzo, C.F., Ouyang, Y.: A general model of demand-responsive transportation services: from taxi to ridesharing to dial-a-ride. Transp. Res. Part B Methodol. **126**, 213–224 (2019)
22. Chen, J., Wang, S., Liu, Z., Wang, W.: Design of suburban bus route for airport access. Transp. A Transp. Sci. **13**(6), 568–589 (2017)
23. Ouyang, Y., Nourbakhsh, S.M., Cassidy, M.J.: Continuum approximation approach to bus network design under spatially heterogeneous demand. Transp. Res. Part B Methodol. **68**(18), 333–344 (2014)
24. Szeto, W.Y., Wu, Y.: A simultaneous bus route design and frequency setting problem for Tin Shui Wai Hong Kong. Eur. J. Oper. Res. **209**(2), 141–155 (2011)
25. Nikolić, M., Teodorović, D.: A simultaneous transit network design and frequency setting: computing with bees. Expert. Syst. Appl. **41**(16), 7200–7209 (2014)
26. Nnene, O.A., Joubert, J.W., Zuidgeest, M.H.P.: Transit network design with meta-heuristic algorithms and agent based simulation. IFAC-PapersOnLine **52**(3), 13–18 (2019)
27. Newell, G.F.: Some issues related to the optimal design of bus routes. Transp. Sci. **13**(1), 20–35 (1979)
28. Fusco, G., Gori, S., Petrelli, M.: A heuristic transit network design algorithm for medium size towns. In: Proceedings of 9th Euro Working Group on Transportation, Bari, pp. 652–656. http://www.iasi.cnr.it/ewgt/13conference/116_fusco.pdf (2002)
29. Fan, W., Machemehl, R.B.: Optimal transit route network design problem with variable transit demand: genetic algorithm approach. J. Transp. Eng. **132**(1), 40–51 (2006)
30. Nnene, O.A., Zuidgeest, M.H.P., Beukes, E.A.: Application of metaheuristic algorithms to the improvement of the MyCiTi BRT network in Cape Town. J. S. Afr. Inst. Civ. Eng. **59**(4), 56–63 (2017)
31. Talbi, E.: From Design to Implementation [Internet], vol. 2009. Main (2009). http://onlinelibrary.wiley.com. https://doi.org/10.1002/9780470496916.fmatter/summary
32. Fan, W., Machemehl, R.B.: Optimal Transit Route Network Design Problem: Algorithms, Implementations, vol. 7. Texas (2004)
33. Fan, W., Machemehl, R.B.: Optimal Transit Route Network Design Problem: Algorithms, Implementations, and Numerical Results, vol. 7. Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College, Texas (2004)
34. Dréo, J., Pétrowski, A., Siarry, P., Taillard, E.: Metaheuristics for Hard Optimization: Methods and Case Studies, p. 369. Springer (2006)

35. Durán-Micco, J., Vansteenwegen, P.: A survey on the transit network design and frequency setting problem. Public Transp. **14**, 155–190 (2022)
36. Johar, A., Jain, S.S., Garg, P.K.: Transit network design and scheduling using genetic algorithm–a review. Int. J. Optim. Control Theor. Appl. **6**(1), 9–22 (2016)
37. Lampkin, W., Saalmans, P.D.: The design of routes, service frequencies, and schedules for a municipal bus undertaking: a case study. J. Oper. Res. Soc. **18**(4), 375–397 (1967)
38. Dubois, D., Bel, G., Llibre, M.: A set of methods in transportation network synthesis and analysis. J. Oper. Res. Soc. [Internet] **30**(9), 797–808. http://link.springer.com (1979). https://doi.org/10.1057/jors.1979.190. [cited 2017 Aug 15]
39. LeBlanc, L.J.: Transit system network design. Transp. Res. Part B Methodol. 22B(No 5), 383–90 (1988)
40. Constantin, I., Florian, M.: Optimizing frequencies in a transit network: a nonlinear bi-level programming approach. Int. Trans. Oper. Res. **2**(2), 149–164 (1995)
41. Huang, D., Liu, Z., Fu, X., Blythe, P.T.: Multimodal transit network design in a hub-and-spoke network framework. Transp. A Transp. Sci. **14**(8), 706–735 (2018)
42. An, K., Lo, H.K.: Robust transit network design with stochastic demand considering development density. Transp. Res. Procedia **7**(852), 300–319 (2015)
43. Nnene, O.A., Joubert, J.W., Zuidgeest, M.H.P.: An agent-based evaluation of transit network design. Procedia Comput. Sci. **151**, 757–762 (2019)
44. Arbex, R.O., da Cunha, C.B.: Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm. Transp. Res. Part B Methodol. **81**, 355–376 (2015)
45. Madadi, B., Nes, R., Snelder, M., Arem, B.: A bi-level model to optimize road networks for a mixture of manual and automated driving: an evolutionary local search algorithm. Comput. Civ. Infrastruct. Eng. 1–17 (2019)
46. Lee, Y.J., Vuchic, V.R.: Transit network design with variable demand. J. Transp. Eng. 131(1), 1–10 (2005)
47. Beltran, B., Carrese, S., Cipriani, E., Petrelli, M.: Transit network design with allocation of green vehicles: a genetic algorithm approach. Transp. Res. Part C Emerg. Technol. **17**(5), 475–483 (2009)
48. Gallo, M., D'Acierno, L., Montella, B.: A meta-heuristic approach for solving the urban network design problem. Eur. J. Oper. Res. **201**(1), 144–157 (2010)
49. Gallo, M., Montella, B., D'Acierno, L.: The transit network design problem with elastic demand and internalisation of external costs: an application to rail frequency optimisation. Transp. Res. Part C Emerg. Technol. **19**(6), 1276–1305 (2011)
50. Brands, T., van Berkum, E.: Performance of a genetic algorithm for solving the multi-objective, multimodal transportation network design problem. Int. J. Transp. **2**(1), 1–20 (2014)
51. Sharma, S., Ukkusuri, S.V., Mathew, T.V.: Pareto optimal multiobjective optimization for robust transportation network design problem. Transp. Res. Rec. **2090**, 95–104 (2009)
52. Gosavi, A.: Simulation-Based Optimization: Parametric Optimization Techniques and Reinforcement Learning, 2nd edn, p. 554. Springer, New York (2015)
53. Bhatnagar, S., Prasad, H.L., Prashanth, L.A.: Stochastic Recursive Algorithms for Optimization, 1st edn. In: Lecture Notes in Control and Information Sciences, vol. 434, p. 280. Springer, London (2013)
54. Gosavi, A.: Background, 2nd edn. In: Simulation Based Optimization: Parametric Optimization and Reinforcement Learning, pp. 1–12. Springer, New York (2015)
55. Castiglione, J., Bradley, M., Gliebe, J.: Activity-Based Travel Demand Models: A Primer. SHRP 2 Report. Transportation Research Board of the National Academies, Vermont (2015)
56. Bates, J.: History of demand modelling. In: Hensher, D.A., Button, K.J. (eds.) Handbook of Transport Modelling, p. 11–33. Emerald Group (2000)
57. Duell, M., Amini, N., Chand, S., Saxena, N., Grzybowska, H., Waller, T.: Deploying a dynamic traffic assignment model for the Sydney region. Australas. Transp. Res. Forum 2015 Proc. (September), 1–14 (2015)

58. White, K.P., Ingalls, R.G.: The basics of simulation. In: Proceedings-Winter Simulation Conference, pp. 38–52. Washington, DC (2016)
59. Bohari, Z.A., Bachok, S., Osman, M.M.: Simulating the pedestrian movement in the public transport infrastructure. Procedia Soc. Behav. Sci. [Internet] **222**, 791–799 (2016). https://doi.org/10.1016/j.sbspro.2016.05.167
60. Papageorgiou, G., Damianou, P., Pitsillides, A., Aphamis, T., Ioannou, P.: Modelling and simulation of transportation systems: planning for a bus priority system. 6th EUROSIM Congr. Model Simul. (EUROSIM 2007) **2**, 325–335 (2007)
61. Cortés, C.E., Burgos, V., Rodrigo, F.: Modelling passengers, buses and stops in traffic microsimulation: review and extensions. J. Adv. Transp. [Internet] **47**(June 2010), 512–25 (2011). http://onlinelibrary.wiley.com. https://doi.org/10.1002/atr.144/full
62. Yin, H., Han, B., Li, D., Wu, J., Sun, H.: Modeling and simulating passenger behavior for a station closure in a rail transit network. PLoS One **11**(12), 1–28 (2016)
63. Schruben, L.: Model is a verb. In: Tolk, A., Fowler, J., Shao, G., Yücesan, E. (eds.) Advances in Modeling and Simulation [Internet], pp. 17–25. Springer, Cham (2017) [cited 2019 Feb 9]. http://link.springer.com.https://doi.org/10.1007/978-3-319-64182-9_2
64. Uhrmacher, A.M., Weyns, D. (eds.): Multi-Agent Systems: Simulation and Application, 541 p. CRC Press (2009)
65. Heath, B.L., Hill, R.R.: Some insights into the emergence of agent-based modelling. J. Simul. **4**(3), 163–169 (2010)
66. Hebb, D.O.: The organisation of behaviour: a neuropsychological theory. Wiley (1952)
67. Bonabeau, E.: Agent-based modeling: methods and techniques for simulating human systems. Proc. Natl. Acad. Sci. [Internet] **99**(suppl. 3), 7280–7287. http://www.ncbi.nlm.nih.gov/pubmed/12011407 (2002)
68. Siebers, P.O., Macal, C.M., Garnett, J., Buxton, D., Pidd, M.: Discrete-event simulation is dead, long live agent-based simulation! J. Simul. [Internet] **4**(3), 204–210 (2010). http://link.springer.com. https://doi.org/10.1057/jos.2010.14
69. Weimer, C.W., Miller, J.O., Hill, R.R.: Agent-based modeling: an introduction and primer. In: Roeder, T.M.K., Frazier, P.I., Szechtman, R., Zhou, E., Huschka, T., Chick, S.E. (eds.) Proceedings of the 2016 Winter Simulation Conference, p. 65–79. Washington DC (2016)
70. Zheng, H., Son, Y.J., Chiu, Y.C., Head, L., Feng, Y., Xo, H., et al.: A Primer for Agent-Based Simulation and Modeling in Transportation Applications. Development Springfield (2013)
71. Balmer, M., Axhausen, K.W., Nagel, K.: An agent based demand modeling framework for large scale micro-simulations. In: 85th Annual Meeting of the Transportation Research Board, p. 43. Washington, DC (2006)
72. Vuk, G.: Activity Based Travel Demand Modelling-A Literature Study. Danmarks Transport Forskning (2001)
73. Wardrop, J.G.: Some theoretical aspects of road traffic research. In: Proceedings of the Institution of Civil Engineers Part II, pp. 325–62 (1952)
74. de Dios, O.J., Willumsen, L.G.: Modelling Transport, 4th edn., p. 580. Wiley & Sons, Sussex, UK (2011)
75. Sheffi, Y.: Urban transportation networks: equilibrium analysis with mathematical programming methods. Transp. Res. Part A Gen. [Internet] **20**(1), 76–7 1986. https://doi.org/10.1016/0191-2607(86)90023-3
76. Kaufman, D.E., Smith, R.L., Wunderlich, K.E.: An iterative routing/assignment method for anticipatory real-time route guidance. In: Vehicle Navigation and Information Systems Conference, 1991, pp. 693–700. IEEE, Ann Arbor, MI (1991)
77. Friedrich, M., Hofsaß, I.: A Dynamic traffic assignment method for planning and telematic applications. In: Proceedings of Seminar K, European Transport Conference, pp. 29–40. University of Stuttgart, Cambridge (2000).
78. Chiu, Y.C., Bottom, J., Mahut, M., Paz, A., Balakrishna, R., Waller, T., et al.: Dynamic Traffic Assignment: A Primer [Internet]. Transportation Research E-Circular. Washington, DC. https://onlinepubs.trb.org/onlinepubs/circulars/ec153.pdf (2011)

79. Elarbi, M., Bechikh, S., Ben Said, L., Datta, R.: Multi-objective optimization: classical and evolutionary approaches. In: Bechikh, S., Datta, R., Gupta, A. (eds.) Recent Advances in Evolutionary Multi-objective Optimization, pp. 1–30. Springer, Cham (2017)
80. Deb, K.: Multi-Objective Optimization Using Evolutionary Algorithms, 1st edn, p. 518. Wiley & Sons (2001)
81. Branke, J., Deb, K., Miettinen, K., Słowiński, R.: Multiobjective Optimization-Interactive and Evolutionary Approaches, 1st edn, p. 470. Springer-Verlag, Berlin (2008)
82. Rangaiah, G.P., Bonilla-Petriciolet, A. (eds.): Multi-Objective Optimization in Chemical Engineering, 512 p. Wiley & Sons Ltd., Oxford, UK (2013)
83. Elarbi, M., Bechikh, S., Ben Said, L., Datta, R.: Multi-objective optimization: classical and evolutionary approaches. In: Bechikh, S., Datta, R., Gupta, A. (eds.) Recent Advances in Evolutionary Multi-objective Optimization, pp. 1–30. Cham, Springer (2017)
84. Nnene OA. Simulation-based optimisation of public transport networks [Internet]. Faculty of Engineering and the Built Environment; 2020. Available from: https://open.uct.ac.za/handle/11427/32308
85. Nicolai, T.W.: MATSim for UrbanSim: integrating an urban simulation model with a travel model. Ph.D. (2013)
86. Rieser, M.: Adding transit to an agent-based transportation simulation. Ph.D. (2010)
87. Bray, T., Jean, P., Sperberg-McQueen, C.M., Maler, E., Yergeau, F., Cowan, J.: Extensible Markup Language (XML) 1.1, 2nd edn. In: W3C Recommendation. W3C (2006)
88. McHugh, B.: Pioneering open data standards: the GTFS story. In: Beyond Transparency-Open Data and Future of Civic Innovation, pp. 125–136 (2013)
89. Deb, K., Agrawal, S., Pratap, A., Meyarivan, T.: A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II. In: Schoenauer, M., Deb, K., Rudolph, G., Yao, X., Lutton, E., Julian, J., et al. (eds.) Parallel Problem Solving from Nature PPSN VI PPSN 2000 Lecture Notes in Computer Science, vol. 1917, pp. 849–858. Springer-Verlag, Berlin (2000)
90. Talbi, E.: Common concepts for metaheuritics, 2nd edn. In: Talbi, E., Zomaya, A.Y. (eds.) Metaheuristics: From Design to Implementation. Wiley and Sons, USA (2009)
91. TDA. Integrated Public Transport Network 2032: Network Plan (2014)
92. Arnold, K., Gosling, J.: The Java Programming Language, p. 595. Addison-Wesley (2000)
93. Michail, D., Kinable, J., Naveh, B., Sichi, J.V.: JGraphT—a java library for graph data structures and algorithms, p. 27 (2019)
94. Brandes, U., Eiglsperger, M., Herman, I., Himsolt, M., Marshall, M.S.: GraphML progress report structural layer proposal. In: Mutzel, P., Jünger, M., Leipert, S. (eds.) Graph Drawing GD 2001 Lecture Notes in Computer Science, vol. 2265, pp. 501–512. Springer, Berlin (2002)
95. Crockford, D.: Introducing JSON. https://www.json.org/ (2011)

Chapter 16
A Survey of Various 2,5-Furandicarboxylic Acid-Based Renewable Polyesters

Kartikeya Shukla, Karuppan Muthukumar, and Santosh Kumar Mishra

Abstract The limited fossil resources availability and their consumption for the production of plastics and other petroleum products have severe environmental impacts due to carbon emissions and incredibly long degradation time. 2,5-furandicarboxylic acid (FDCA)-based polyesters have the potential to supplant petroleum-based plastics, especially for packaging applications. Derived from biomass, FDCA-based polyesters are renewable and more environment friendly. This study provides an overview on synthesis methodologies, novel catalysts used and the properties of polyesters produced using different di-alcohols. The study focuses on the comparison between mechanical and thermal properties of each system, and in turn this provides an insight into tunable nature of FDCA-based polyesters which can then be optimized for its end application. A summary on the biodegradability studies performed gives a direction for the future research in this area to maximize the eco-friendliness of FDCA-based bio-plastics and make it as a viable option.

Keywords 2,5-furandicarboxylic acid · Polyester · Renewable · Esterification · Overview

16.1 Introduction

Due to the depletion of fossil resources, utilization of renewable resources has been a choice for the synthesis of value-added products [1]. Among various value-added products, polymers hold an important place. Hence, efforts to synthesize polymers from renewable resources are significant since last decade. One of the best applications of biopolymer is the utilization of cellulose ester for the vulcanization of

K. Shukla (✉) · K. Muthukumar
Department of Chemical Engineering, National Institute of Technology Tiruchirappalli, Tamil Nadu, Tiruchirappalli 620015, India
e-mail: shukla@nitt.edu

S. K. Mishra
Department of Production Engineering, National Institute of Technology Tiruchirappalli, Tamil Nadu, Tiruchirappalli 620015, India

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_16

natural rubber [2]. With various chemical modifications, the resins derived from natural resources became more and more popular.

Polyesters are the most important member of the polymer family due to their unique properties like fiber forming ability, potential biodegradability, and biocompatibility. Monomers of biopolyesters are easily accessible; hence, biopolyesters are quite biocompatible. Polyesters from various sources find various applications in packaging, fibers, photographic films, recording tapes, etc. Renewable and biodegradable polyesters are two categories of polyesters which are environment friendly. Renewable polymers are the polymers which are derived from bioresources and are not dependent on fossil resources. Biodegradable polymers are the polymers which are naturally degradable under certain conditions.

The market for polyester from petrochemical-based monomers is a huge as their applications have been increased since last few decades. Among various polyesters, poly (ethylene terephthalate) (PET) is a well-known polymer which has a largest market volume of greater than 50 million tons annually [3]. It is also the mostly researched terephthalic acid (TA)-based polyester as compared to its analogs like poly (propylene terephthalate) (PPT) and poly (butylene terephthalate) (PBT). There are various efforts to make bio-based PET, using bioderived ethylene glycol (EG) [4]. However, it still requires a lot of effort. To make a polymer fully renewable, a bio-based alternative to Terephthalic acid (TA) must developed. Although many renewable building blocks are commercially available like renewable polyols, succinic acid, and lactic acid, the need of rigid building block having more T_g and T_m still prevails. 2,5-furandicarboxylic acid (FDCA) is a building block which can be a renewable substitute for TA. There are various methods for FDCA production which include 5-hydroxymethylfurfural oxidation or furfural oxidation to 2-furoic acid which can be latter converted to FDCA in presence of Lewis acid catalyst (Fig. 16.1). FDCA can also be synthesized from electrochemical oxidation of 5-hydroxymethylfurfural (HMF) or by thermocatalytic oxidation of HMF.

FDCA can be converted to polyester by either esterification or transesterification reaction. Esterification reaction is shown in Fig. 16.2 where alcohol reacts with TA to get polyester. For transesterification reaction, FDCA has to be converted to salt by reacting it with methanol as shown in Fig. 16.3. Then, the salt of FDCA react with-alcohol to synthesize polyester. It has been reported that transesterification reaction is more efficient to get better conversion as compared to esterification reaction.

There are various studies reported on FDCA-based polyesters and their findings. Although various reviews have been already reported on FDCA-based polyesters, this chapter systematically summarizes the findings in the studies reported on FDCA-based polyesters. It also highlights various process conditions under which the polyesters had been prepared. Table 16.1 summarizes the FDCA-based studies reported and their properties.

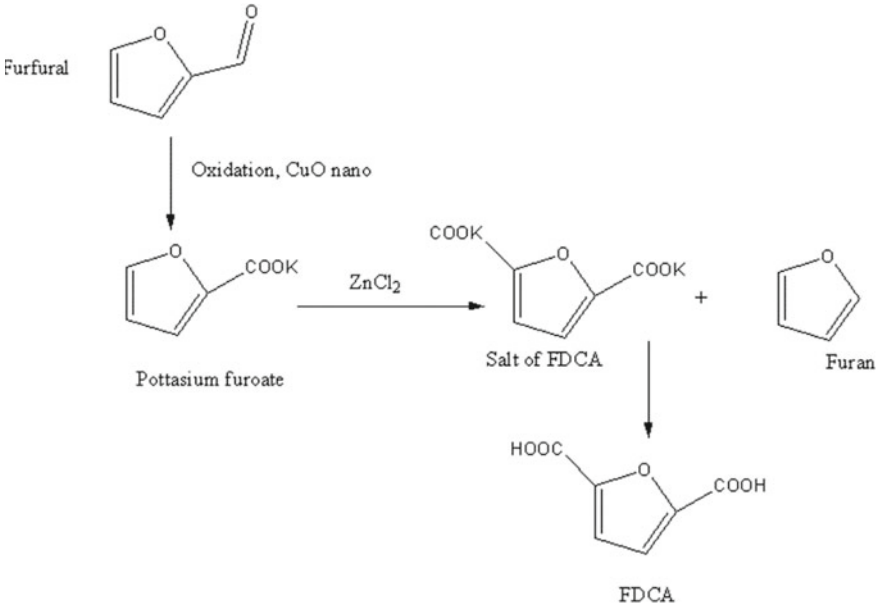
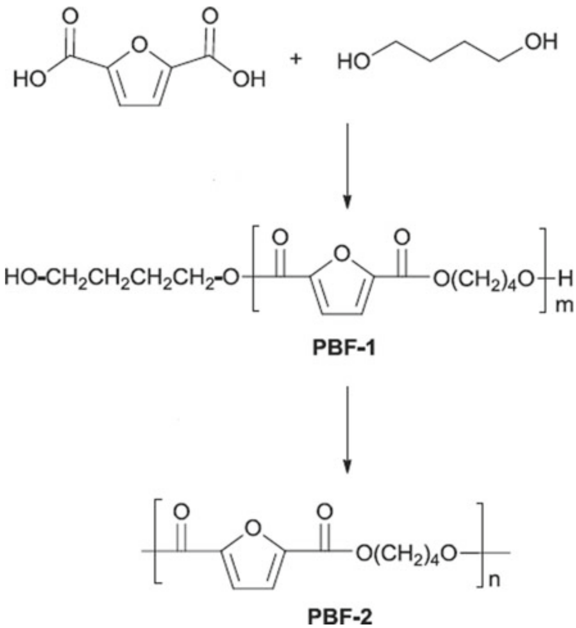


Fig. 16.1 Synthesis of FDCA from furfural

Fig. 16.2 Synthesis of polyesters from FDCA by esterification reaction



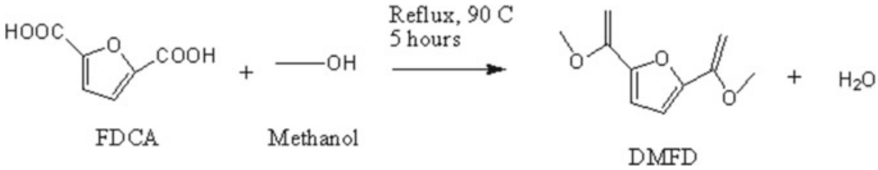


Fig. 16.3 Transesterification of FDCA and methanol

16.2 FDCA-Based Renewable Polyesters

Moore and Kelly, 1977 derived polyesters from FDCA and 1,6-hexanediol at lower temperatures. The polymerizations were conducted at relatively low temperatures because they are too vulnerable to aerobic oxidation at these temperatures. Thermal study reveals that the pure furan-based polymer had low glass transition temperature (T_g) whenever the diol and the diacid were both in the cis configurations [5].

Likewise, the synthesis of various furan-based monomers was carried out by Gandini and co-workers. These studies were a thrust in the rise of synthesis of FDCA-based polyesters. Gandini et al. synthesized poly (ethylene 2,5-furandicarboxylate) (PEF) using polycondensation of ethylene glycol (EG) and dichloride salt of FDCA [6]. It was characterized and properties of PEF were compared with PET. The thermal properties of PEF obtained were similar to PET. PEF was reported to be of crystalline nature. Antimony oxide (Sb_2O_3) was used as the catalyst but due to the toxicity of catalyst, researchers explored other materials as the catalyst.

16.2.1 Various Types of Catalysts Reported

Various studies have been reported to screen out the catalyst for the synthesis of FDCA-based polyester [7]. The synthesis of PBF was carried out by using 45 catalysts at different reaction conditions. It was found that on increasing the concentration of Titanium in the catalyst, molecular weight of polyesters does not increase; however, its polydispersity index (PDI) was found to be increased. It was also found that on increasing the concentration of Sn in catalyst, higher molecular weight of the polyester was reported. While, when triphenyl phosphate was used as the catalyst, reduction in coloration of polyester was found. The study also concluded that film reactor was efficient with the mass transfer limiting reactions.

There are some other catalysts reported for the synthesis of PEF. During the synthesis of PEF, due to poor solubility of FDCA in ethylene glycol, the molar ratio of ethylene glycol and FDCA would have to be high. Due to which formation of diethylene glycol is inevitable. Banella et al. [8] synthesized PEF using zinc acetate (ZnAcO) and aluminum acetylacetonate $(Al(acac))_3$ as the catalyst [8]. The catalysts were found to be effective as the final PEF was found to be of low discoloration due

Table 16.1 Various FDCA-based polyesters and their properties

Monomers	Catalyst	Method	Young's modulus	T_m (°C)	T_g (°C)	References
Ethylene glycol, FDCA	Aqueous hydrochloric acid	Transesterification followed by poly transesterification	–	210–215	75–80	[6]
Ethylene glycol and FDCA	Tetra butyl titanate	Direct esterification method	–	21.8–89.9	148.2–210.4	[21]
FDCA and 1,4-butanediol	–	Polycondensation	–	170	31	[7]
FDCA and 2,3-butanediol	Titanium (IV) n-butoxide (TiBO), tin (IV) ethylhexanoate ($Sn(Oct)_2$), or zirconium (IV) butoxide (ZrBO)	Esterification/transesterification	–	270–300	71–131	[11]
FDCA, ethylene glycol, and 1,4-butylene glycol	$Ti(OC_4H_9)$	Polytransesterification	–	169	36	[23]
FDCA and methanol	Thionyl chloride	Transesterification	–	214	77	[24]
FDCA, bis(2-hydroxyethyl) terephthalate (BHETP), ethylene glycol (EG, 99.8%)	Sb_2O_3	Polytransesterification	–	255.3	75.4	[12]
FDCA and glycerol	Sb_2O_3	Polycondensation	–	–	–	[25]
FDCA and methanol anhydrite	Sulfuric acid	Esterification and polycondensation	–	253	87	[14]
FDCA and vanillic acid	Zn $(AcO)_2$		–	193	42	[10]
FDCA and methanol anhydrite	Sulfuric acid	Polycondensation and transesterification	–	69.8	173–196	[29]
FDCA and methanol	Sulfuric acid	Esterification–polycondensation	–	–	–	[30]

(continued)

Table 16.1 (continued)

Monomers	Catalyst	Method	Young's modulus	T_m (°C)	T_g (°C)	References
FDCA, 1,4-butanediol (BDO) and 1,4-cyclohexanedimethanol (CHDM)	Tetra butyl titanate	Esterification–polycondensation reaction	–	140.1–251.9	45.7–74.4	[15]
FDCA, succinic acid, and 1,3-propanediol	Potassium hydroxide (KOH, 85%)	Polycondensation reaction	–	–	87–104	[37]
FDCA, poly (ethylene glycol), isosorbide	Pyridine	Polycondensation reactions		40	168	[38]
FDCA and anhydrous methanol	Sulfuric acid	Polycondensation method	–	–		[39]
FDCA, itaconic acid (IA), succinic acid (SA), and 1,3-propanediol	p-Toluene sulfonic	Direct polycondensation	–	–	73.5−141.7	[40]
5-(methoxycarbonyl) furan-2-carboxylic acid, NaOH, methanol	Thionyl chloride	Polycondensation	–	–	26 °C	[41]
1,4-butanediol, FDCA	Antimony trioxide (Sb_2O_3, 99%)	Transesterification and polycondensation	–	170.3	38.7	[20]
1,3-propanediol, 1,4-cyclohexanedimethylene (CHDM), and FDCA	Sulfuric acid	Transesterification and polycondensation	–	201–211	82–89	[33]
5-hydroxymethylfurfural (HMF), and FDCA	–	Electrochemical oxidation	–	–		[42]
FDCA, 1,6-hexanediol, and 1,2-propanediol	Tetra butyl titanate	Transesterification and polycondensation	–	210.4	89.9	[31]

(continued)

Table 16.1 (continued)

Monomers	Catalyst	Method	Young's modulus	T_m (°C)	T_g (°C)	References
2,4-furandicarboxylic acid (2,4-FDCA), ethylene glycol (EG, 99.8%),	$(Ti(OiPr)_4$	Polyesterification reactions	2070–2450 MPa	210–215 °C	75–80 °C	[16]
2,4-furandicarboxylic acid (2,4-FDCA), ethylene glycol (EG, 99.8%),	$Al(acac)_3$	Transesterification reaction	–	–	83.3	[8]
FDCA and methanol	Tetrabutyltitanate (TBT)	Transesterification and polycondensation	–	–	88–90 °C	[19]
The dimethyl esters of 2,5- and 2,4-furandicarboxylate, ethylene glycol (EG)	$Ti(OiPr)_4$	Transesterification and polycondensation	–	215 ± 1	82.4 ± 1.8	[27]
FDCA, 1,4-butanediol, 2,6-naphthalate-co-butylene furandicarboxylate	–	Transesterification and polycondensation	–	242.2	98.2	[17]
FDCA, 2,6-naphthalate-co-butylene furan dicarboxylate, 1,3-propanediol	–	Transesterification and polycondensation	–	193.8, 200.3	81	[32]
2,5-thiophenedicarboxylic acid and methanol	Sulfuric acid	Esterification	–	–	≤ 50	[43]
Terepthalic acid, ethylene glycol	–	–	2950	255	67	[44]

to presence of diethylene glycol. The characteristics of PEF gave a hint of their applications in packaging industry.

Some studies have suggested the use of transesterification of salt of FDCA and alcohol for the synthesis of polyesters. Cruz-Izquierdo et al. synthesized furan-based polyesters by transesterification of dimethyl furan-2,5-dicarboxylate (DMFD) and aliphatic diols [9]. Aliphatic diols were of variable carbon length (C_2–C_{12}). The reaction was conducted using lipase B. The carbon chain length was found to be primary determinant of cyclic oligoester formation.

16.2.2 Properties of FDCA-Based Polyesters

This section highlights the major findings and progress made by the researchers in the area of properties of FDCA-based polyesters. Various studies, based on several copolyesters of FDCA, have been reviewed to give an outline of the progress made.

Since FDCA-based polyesters are characterized by poor thermal properties, which needs further improvement. Since last decade, extensive research has been published in the area of liquid crystalline polymers due to its excellent mechanical, thermal properties, and chemical properties. Wilsens et al. [10] synthesized aromatic thermotropic polyesters based on FDCA and vanillic acid [10]. Similar to TA, FDCA monomer exhibits poor solubility and reactivity in the melt condensation. Due to its poor solubility, the time required to make FDCA soluble was quiet high in order to be properly incorporated into the polymer backbone. Successful copolymerization lowers the melting point and suggests that there is a window for the production of FDCA-based polymers at melt polycondensation temperatures below 300 °C. The study also reported the scale up of the process to 100 g.

FDCA polyesters have been facing a drawback of poor thermal properties and this has made several researchers to work over it. Gubbels et al. synthesized novel polyesters from FDCA and 2,3-butanediol. The molecular weights were found to be quite high, indicating its suitability for coating applications [11]. These polyesters were found to have T_g (T_g) between 70 and 110 °C, and they were thermally stable up to 270–300 °C. Moreover, it was proposed that the polyester with a high molecular weight and T_g of 113 °C might be appropriate for hot-fill applications. Similarly, another effort was made by Sousa et al. [12], where bio-based copolyesters derived from TA, and FDCAs were developed [12]. These monomers were combined in various stoichiometric ratios, and the properties of resulting copolyesters were studied. The PET-PEF containing 20% FDCA was found to be the most pertinent copolyester. The polyester was found to possess T_g of 62.4 °C with high thermal stability up to 260 °C, and the copolyester displayed characteristics that were similar to those of commercial PET. The dynamic mechanical analysis also showed the properties of synthesized polyester to be close to PET. Another study by Thiyagarajan et al. [13], where FDCA-based polyesters from medium to high molecular weight polyesters were synthesized [13]. It was found that all the polyesters have molecular weights between 34000 and 65000 $gmol^{-1}$ as well as polydispersities very close to

2.0. The novel polyesters exhibit comparable or even greater thermal stability when compared to pure FDCA polyesters. It was interesting to note that the glass transition temperatures (T_g) of polyesters generated from 2,4-furandicarboxylic and FDCA isomers were identical. Another study to improve the thermal properties of FDCA-based polyester was reported by Diao et al. [15], where 1,4-cyclohexanedimethanol (CHDM) was used as a monomer to improve the thermal properties of polyesters. The polyester was synthesized using FDCA, 1,4-butanediol (BDO), and CHDM [15]. It was found that on raising CHDM concentration, thermal stability parameters like T_g, T_m, and $T_{d,max}$ were improved. Most importantly the resultant polyesters qualify as a new form of thermoplastic engineering plastic due to their increased T_g and T_m. Incorporation of CHDM increased the thermal stability of the polyester, and it was found that the polyesters could be used for food packaging materials.

Few studies have directly compared FDCA based polyesters properties with the polyesters commercially used for packaging application, poly(ethylene naphthalate) (PEN). Papageorgiou et al. [14] synthesized FDCA-based and compared their properties PET and PEN [14]. It was reported that PEF demonstrated slower crystallization rates than PEN and PET. PEF was found to be thermally stable. Compared to PET or PEN, these levels were found to be a bit lower.

The polyesters from FDCA are facing a problem of decolorization due to the presence of diethylene glycol. For this, some studies have been reported. Zaidi et al. developed transparent films from PET and 2,4-FDCA [16]. It was reported that on adding this furan monomer content, the characteristics could be adjusted and controlled. For instance, the copolyesters were semi-crystalline up to a concentration of 15 mol%, but beyond a concentration of 50 mol%, they became amorphous in nature. The amorphous polymers displayed exceptional thermal stability above 400 °C.

Some studies have also been reported on improvement of mechanical properties of the polyesters, which are also very important for the packaging applications. Wang et al. [17] synthesized a polyester from FDCA, 2,6-naphthalenedicarboxylic acid (2,6-NDCA), and 1,3-propanediol [17]. Investigations were made to study the mechanical, thermal, and crystallization properties. The polyesters had molecular weight up to 28,000 $gmol^{-1}$, and their polydispersity indices ranged from 2.1 to 2.7. PPF and PNF were reported to be semi-crystalline, whereas other PPNFs were reported to be amorphous in nature. The initial temperature of considerably increased as FDCA content was increased. When the FDCA level was 74 mol%, the polyester had favorable mechanical properties.

The drawback of poor conversion due to poor solubility of FDCA and formation of diethylene glycol was addressed in some studies. Rosenboom et al. [18] synthesized PEF by ring opening polymerization [18]. The melting point of such a mixture of cyclic oligomers was found to be higher than the temperature at which PEF melts. This issue was suggested to be resolved by starting the procedure in the presence of a liquid plasticizer that is inert, removable, and high boiling. At a temperature of roughly 220 °C, the produced polymer itself melts. This theory generates the polymers with high molecular weight in a diffusion-limited polymer system.

To enhance the thermal stability of the polyesters, one of the well-known methods is blending of polymers. This method, for FDCA-based polyesters, was reported by Poulopoulou et al. where he developed blends of furan-based polyesters with the well-known polyesters [19]. It was found that PEF and PBF found to form homogeneous blend, while PPF does not mix well. It was concluded that mixing improved the thermal properties.

Hu et al. [20] synthesized bio-based copolyester from poly (butylene furandicarboxylate) and poly(ethylene glycol) [20]. Regarding their mechanical, thermal, and structural qualities, the resultant polymers were assessed. Furthermore, important hydrolytic degradation tests are conducted for the uses of copolymers in various conditions. The copolymers crystallize more quickly than PBF at melting temperatures over 120 °C, according to isothermal crystallization tests. Tensile experiments unambiguously demonstrate that PEG concentration causes elongation at break to grow dramatically, up to 5 times more than PBF. After impact testing, the majority of the samples exhibited remarkable impact toughness.

16.2.3 Other Renewable Polyesters

Some other renewable polyesters were also derived from FDCA. Jiang et al. synthesized polyesters from FDCA and different diols [21]. It was reported that direct esterification procedure was worthwhile and successful for producing these furan-aromatic-based polyesters with suitable thermal and mechanical properties. Likewise, Gomes et al. [22] synthesized novel polyesters from FDCA and other renewable resources [22]. The polyesters were reported to pursue structures, molecular weights, and qualities that are quite equivalent to aromatic-aliphatic homologs produced from fossil resources, making them entirely viable as macromolecular materials. The study gave the close resemblance of properties of PEF with properties of PET; hence, it was established that PEF has the potential to replace PET.

The kinetic assessment of the polymerization was carried out by Ma et al. and in this study furan-based copolyesters were synthesized from FDCA with alcohols like ethylene glycol and butylene glycol [23]. The reactivity of the diol comonomers with FDCA acid was determined. From the kinetic experiments, it was found that the length of the carbon chain improved the reactivity of diols with FDCA. It was also found that the diol comonomer molar ratio inside the copolyester can also affect the thermal characteristics of the copolyesters as synthesized.

The study on decoloration of polyesters was carried out by Knoop et al. [24], where high molecular weight PEF was synthesized and characterized by studying mechanical properties [24]. It was also seen that low color materials with high molecular weights can be synthesized, which included PEF, PPF, and PBF. It was found that PEF can be processed similar to PET.

Another renewable resource for the synthesis of polyesters can be glycerol, which is a well-known polyol. Amarasekara et al. [25] synthesized polyester from glycerol and FDCA [25]. It was found that FDCA and glycerol combine to form a branched polyester resin having yield up to 70% using Sb_2O_3 as catalyst. This tough resin was found to be hardly soluble in trifluoroacetic acid and is insoluble in all popular organic solvents.

It is already well known that poly (butylene adipate terephthalate) is a biodegradable polyester. Hence, the effect of incorporation of adipic acid into FDCA-based polyester was studied by Wu et al. [26], where high quality copolyesters derived from FDCA, adipic acid, and 1,4-butane diol were synthesized [26]. The thermal stability of PBAF was found to be outstanding. Crystallizab and T_m decrease with increase in adipic acid composition from 0 to 30 mol%. It was reported that polyesters involving 1,4 butane diol and adipic acid, 1,4 butane diol and FDCA are crystalline in nature. However, polyester PBAFs were nearly amorphous. PBAFs exhibited excellent mechanical properties like high-elastic deformation and remarkable rebound resilience.

FDCA can also be synthesized by Henkel type reaction, disproportionation of salt of 2-furoic acid into two isomers of salt of FDCA. Hence, these salts were directly explored for polyesters. Thiyagarajan et al. [27] reported the polyesters from isomers of FDCA [27]. Through this method, high molecular weight homopolymers and copolymers were produced that also had strong thermal stability, wide processing latitudes, and a thermal behavior that could be adjusted for both the glass transition temperature and crystallinity.

Wang et al. [17] developed bio-based copolyesters FDCA [28]. The level of randomness ranged from 0.92 to 1.08, indicating that the distribution of BN and BF units was unpredictable. With increasing FDCA content, the T_g value steadily fell. PBN and PBNF25 have a high crystallization rate. However, PBNF50, PBNF75, and PBF crystallize at incredibly slow rates. All polyesters had $T_{d,max}$ values of 390 °C, respectively.

16.2.4 Decomposition of FDCA-Based Polyesters

The thermal degradation of FDCA-based polyesters is also explored in some studies. This include Tsanaktsis et al. where three novel aliphatic–aromatic polyesters, namely PEF, PPF, and PBF, were synthesized. The decomposition of three polyesters, such as PEF, PPF, and PBF, has been studied [29]. According to TGA, PBF and PPF have the lowest decomposition temperatures, and PEF has the maximum thermal stability because it contains the fewest methylene units. These data and the decomposition kinetics results from pyrolysis-GC/MS were used to determine that the decomposition behavior of the polyesters. According to a pyrolysis-GC/MS analysis, all three polyesters disintegrate in the second stage mostly via the scission of hydrogen bonds, which results in the production of vinyl compounds and derivatives of FDCA. Similarly, Terzopoulou et al. synthesized polyesters using transesterification of DMFD with diols [30]. These renewable polyesters were also studied their thermal degradation behavior. All polyesters were shown to degrade in a similar way, mostly through β-hydrogen bond scission.

16.2.5 Other Applications of FDCA-Based Polyesters Reported

There are various other applications also for which FDCA-based polyesters are explored. This section includes those studies too. Geng et al. synthesized novel bio-based copolyesters busing FDCA and alcohols like 1,6-hexanediol and 1,2-propanediol [31]. It was proposed that these polyesters had the properties required for 3D-printing. The 3D-printed PHPF exhibited good mechanical characteristics determined by tensile testing and dependable microstructure shown by SEM. The fact that PHPF outperformed polylactide, the currently most popular bio-based 3D-printed polymer, in terms of both heat stability and mechanical qualities showed that PHPF is a potential 3D-printing material.

Wang et al. [32] synthesized polyester from dimethyl thiophene-2,5-dicarboxylate and alcohols like ethylene glycol, 1,3-propanediol, 1,4-butanediol, and 1,6-hexanediol [32]. According to the findings, it was found that all polyesters possessed good crystallizability, satisfactory tensile strength, and modulus. Additionally, compared to PET , all TDCA-based polyesters showed significantly greater CO_2 and O_2 permeability, demonstrating outstanding gas barrier characteristics. It was proposed that polyester synthesized might be the most promising biopolymer for packaging properties.

Jia et al. synthesized a series of FDCA, 1,3-propanediol, and 1,4-cyclohexanedimethylene (CHDME) [33]. Nuclear magnetic resonance was used to determine the PPCF's chemical makeup, composition, and sequence distribution (^{1}H NMR and ^{13}CNMR). It was reported that PPF's gas barrier qualities diminished on increasing the content of CHDME. However, gas barrier properties of synthesized polyester were still found to be better than poly (ethylene naphthalate).

González et al. [34] developed FDCA-based polyesters for polyurethane coatings using glycerine, 1,3 propane diol, and succinic acid [34]. The coating obtained was found to be more hydrophilic character.

16.2.6 Degradation of FDCA-Based Polyesters

Although many degradation studies have been reported for FDCA-based polyesters. This includes soil burial test, hydrolysis test, and PBS test. This section includes the important studies which have been reported on degradation studies. Haernvall et al. studied the degradation of FDCA-based polyesters, obtained from different polyols [35]. Additionally, the capability of thermobifida cellulosilytica cutinase 1 (Thc Cut1) to enzymatically hydrolyze these FDCA-based polyesters was investigated. It was found that the enzymatic activity increased fourfold when the linear diol 1,3-propanediol used instead of branched. The enzyme's activity was doubled as expected when ethoxy units were added to the polyester chain, in this example by switching 1,5-pentanediol for the proper ether, diethylene glycol.

Peng et al. [36] studied the synthesis and degradation of poly(butylene adipate-co-butylene furandicarboxylate) (PBAF), and poly(butylene succinate-co-butylene furandicarboxylate) (PBSF), from hydrolytic and compost degradation [36]. The study reported polyesters with butane diol, and FDCA content around 40–60%. The polyesters were hydrolyzed in acidic and alkaline environments, as well as they were effectively degraded in compost. As compared to neutral conditions, acidic and alkaline hydrolytic degradation was faster. It was reported that direct correlation between composition and crystallinity and compost breakdown was there. However, copolyesters with higher butane diol and FDCA concentrations showed slow biodegradation. Moreover, 90% biodegradation in 180 days was shown by all of the copolyesters.

The hydrolytic degradability of PBAF and PBSF copolyesters with copolymer compositions (BF unit molar fraction, BF) of 40–60% was evaluated in this work at 25 °C in PBS buffer solution of 7.0 pH. While about 1–2% of the bulk was lost, after the reaction, the intrinsic viscosity dropped by 35–44% exponentially.

16.3 Conclusions

This study highlights the major findings reported in the literature relevant to FDCA-based polyesters. Although substantial progress has been made in the area of renewable polyesters derived from FDCA, improvements in thermal properties and mechanical strength are required. The exploration of various materials for better activity and conversion must be sought. For packaging applications, gas barrier properties have to be improved. Although several polyesters are degradable too, however, some efforts still are required in this aspect. The economic analysis of production of FDCA also needs to be addressed.

References

1. Shahzad, U.: The need for renewable energy sources. Energy **2**, 16–18 (2012)
2. Connors, S.A.: Chemical and Physical Characterization of the Degradation of Vulcanized Natural Rubber in the Museum Environment, pp. 1219–1219. Queen's University at Kingston (1999)
3. Nisticò, R.: Polyethylene terephthalate (PET) in the packaging industry. Polym. Test. **90**, 106707 (2020)
4. Siracusa, V., Blanco, I.: Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly (ethylene terephthalate) (Bio-PET): recent developments in bio-based polymers analogous to petroleum-derived ones for packaging and engineering applications. Polymers **12**(8), 1641 (2020)
5. Moore, J.A., Kelly, J.E.: Polyesters derived from furan and tetrahydrofuran nuclei. Macromolecules **11**(3), 568–573 (1978)

6. Gandini, A., Coelho, D., Gomes, M., Reis, B., Silvestre, A.: Materials from renewable resources based on furan monomers and furan chemistry: work in progress. J. Mater. Chem. **19**(45), 8656–8664 (2009)
7. M Gruter, G.J., Sipos, L., Adrianus Dam, M.: Accelerating research into bio-based FDCA-polyesters by using small scale parallel film reactors. Comb. Chem. High Throughput Screen. **15**(2), 180–188 (2012)
8. Banella, M.B., Bonucci, J., Vannini, M., Marchese, P., Lorenzetti, C., Celli, A.: Insights into the synthesis of poly (ethylene 2, 5-furandicarboxylate) from 2, 5-furandicarboxylic acid: steps toward environmental and food safety excellence in packaging applications. Ind. Eng. Chem. Res. **58**(21), 8955–8962 (2019)
9. Cruz-Izquierdo, Á., van den Broek, L.A., Serra, J.L., Llama, M.J., Boeriu, C.G.: Lipase-catalyzed synthesis of oligoesters of 2, 5-furandicarboxylic acid with aliphatic diols. Pure Appl. Chem. **87**(1), 59–69 (2015)
10. Wilsens, C.H., Noordover, B.A., Rastogi, S.: Aromatic thermotropic polyesters based on 2, 5-furandicarboxylic acid and vanillic acid. Polymer **55**(10), 2432–2439 (2014)
11. Gubbels, E., Jasinska-Walc, L., Koning, C.E.: Synthesis and characterization of novel renewable polyesters based on 2, 5-furandicarboxylic acid and 2, 3-butanediol. J. Polym. Sci. Part A Polym. Chem. **51**(4), 890–898 (2013)
12. Sousa, A.F., Matos, M., Freire, C.S., Silvestre, A.J., Coelho, J.F.: New copolyesters derived from terephthalic and 2, 5-furandicarboxylic acids: a step forward in the development of biobased polyesters. Polymer **54**(2), 513–519 (2013)
13. Thiyagarajan, S., Vogelzang, W., Knoop, R.J., Frissen, A.E., van Haveren, J., van Es, D.S.: Biobased furandicarboxylic acids (FDCAs): effects of isomeric substitution on polyester synthesis and properties. Green Chem. **16**(4), 1957–1966 (2014)
14. Papageorgiou, G.Z., Tsanaktsis, V., Bikiaris, D.N.: Synthesis of poly (ethylene furandicarboxylate) polyester using monomers derived from renewable resources: thermal behavior comparison with PET and PEN. Phys. Chem. Chem. Phys. **16**(17), 7946–7958 (2014)
15. Diao, L., Su, K., Li, Z., Ding, C.: Furan-based co-polyesters with enhanced thermal properties: poly (1, 4-butylene-co-1, 4-cyclohexanedimethylene-2, 5-furandicarboxylic acid). RSC Adv. **6**(33), 27632–27639 (2016)
16. Zaidi, S., Thiyagarajan, S., Bougarech, A., Sebti, F., Abid, S., Majdi, A., Silvestre, A.J., Sousa, A.F.: Highly transparent films of new copolyesters derived from terephthalic and 2, 4-furandicarboxylic acids. Polym. Chem. **10**(39), 5324–5332 (2019)
17. Wang, G., Yu, J., Jiang, M., Wang, R., Liang, Y., Zhou, G.: Bio-based copolyesters poly (butylene 2, 6-naphthalate-co-butylene furandicarboxylate) derived from 2, 5-furandicarboxylic acid (FDCA): synthesis, characterization, and properties. Polym. Test. **91**, 106771 (2020)
18. Rosenboom, J.G., Hohl, D.K., Fleckenstein, P., Storti, G., Morbidelli, M.: Bottle-grade polyethylene furanoate from ring-opening polymerisation of cyclic oligomers. Nat. Commun. **9**(1), 1–7 (2018)
19. Poulopoulou, N., Smyrnioti, D., Nikolaidis, G.N., Tsitsimaka, I., Christodoulou, E., Bikiaris, D.N., Charitopoulou, M.A., Achilias, D.S., Kapnisti, M., Papageorgiou, G.Z.: Sustainable plastics from biomass: blends of polyesters based on 2, 5-furandicarboxylic acid. Polymers **12**(1), 225 (2020)
20. Hu, H., Zhang, R., Sousa, A., Long, Y., Ying, W.B., Wang, J., Zhu, J.: Bio-based poly (butylene 2, 5-furandicarboxylate)-b-poly (ethylene glycol) copolymers with adjustable degradation rate and mechanical properties: synthesis and characterization. Eur. Polymer J. **106**, 42–52 (2018)
21. Jiang, M., Liu, Q., Zhang, Q., Ye, C., Zhou, G.: A series of furan-aromatic polyesters synthesized via direct esterification method based on renewable resources. J. Polym. Sci. Part A Polym. Chem. **50**(5), 1026–1036 (2012)
22. Gomes, M., Gandini, A., Silvestre, A.J., Reis, B.: Synthesis and characterization of poly (2, 5-furan dicarboxylate)s based on a variety of diols. J. Polym. Sci., Part A: Polym. Chem. **49**(17), 3759–3768 (2011)
23. Ma, J., Pang, Y., Wang, M., Xu, J., Ma, H., Nie, X.: The copolymerization reactivity of diols with 2, 5-furandicarboxylic acid for furan-based copolyester materials. J. Mater. Chem. **22**(8), 3457–3461 (2012)

24. Knoop, R.J., Vogelzang, W., van Haveren, J., van Es, D.S.: High molecular weight poly (ethylene-2, 5-furanoate); critical aspects in synthesis and mechanical property determination. J. Polym. Sci., Part A Polym. Chem. **51**(19), 4191–4199 (2013)
25. Amarasekara, A.S., Razzaq, A., Bonham, P.: Synthesis and characterization of all renewable resources based branched polyester: poly (2, 5-furandicarboxylic acid-co-glycerol). Int. Sch. Res. Not. (2013)
26. Wu, B., Xu, Y., Bu, Z., Wu, L., Li, B.G., Dubois, P.: Biobased poly (butylene 2, 5-furandicarboxylate) and poly (butylene adipate-co-butylene 2, 5-furandicarboxylate) s: from synthesis using highly purified 2, 5-furandicarboxylic acid to thermo-mechanical properties. Polymer **55**(16), 3648–3655 (2014)
27. Thiyagarajan, S., Meijlink, M.A., Bourdet, A., Vogelzang, W., Knoop, R.J., Esposito, A., Dargent, E., Van Es, D.S., Van Haveren, J.: Synthesis and thermal properties of bio-based copolyesters from the mixtures of 2, 5-and 2, 4-furandicarboxylic acid with different diols. ACS Sustain. Chem. Eng. **7**(22), 18505–18516 (2019)
28. Wang, J., Liu, X., Zhu, J., Jiang, Y.: Copolyesters based on 2, 5-furandicarboxylic acid (FDCA): effect of 2, 2, 4, 4-tetramethyl-1, 3-cyclobutanediol units on their properties. Polymers **9**(9), 305 (2017)
29. Tsanaktsis, V., Papageorgiou, G.Z., Bikiaris, D.N.: A facile method to synthesize high-molecular-weight biobased polyesters from 2, 5-furandicarboxylic acid and long-chain diols. J. Polym. Sci., Part A Polym. Chem. **53**(22), 2617–2632 (2015)
30. Terzopoulou, Z., Tsanaktsis, V., Nerantzaki, M., Papageorgiou, G.Z., Bikiaris, D.N.: Decomposition mechanism of polyesters based on 2, 5-furandicarboxylic acid and aliphatic diols with medium and long chain methylene groups. Polym. Degrad. Stab. **132**, 127–136 (2016)
31. Geng, Y., Wang, Z., Hu, X., Li, Y., Zhang, Q., Li, Y., Wang, R., Zhang, L.: Bio-based polyesters based on 2, 5-furandicarboxylic acid as 3D-printing materials: design, preparation and performances. Eur. Polymer J. **114**, 476–484 (2019)
32. Wang, J.G., Zhang, X.Q., Shen, A., Zhu, J., Song, P.A., Wang, H., Liu, X.Q.: Synthesis and properties investigation of thiophene-aromatic polyesters: potential alternatives for the 2, 5-furandicarboxylic acid-based ones. Chin. J. Polym. Sci. **38**(10), 1082–1091 (2020)
33. Jia, Z., Wang, J., Sun, L., Liu, F., Zhu, J., Liu, X.: Copolyesters developed from bio-based 2, 5-furandicarboxylic acid: synthesis, sequence distribution, mechanical, and barrier properties of poly (propylene-co-1, 4-cyclohexanedimethylene 2, 5-furandicarboxylate)s. J. Appl. Polym. Sci. **136**(13), 47291 (2019)
34. García González, M.N., Börjesson, P., Levi, M., Turri, S.: Development and life cycle assessment of polyester binders containing 2, 5-furandicarboxylic acid and their polyurethane coatings. J. Polym. Environ. **26**(9), 3626–3637 (2018)
35. Haernvall, K., Zitzenbacher, S., Amer, H., Zumstein, M.T., Sander, M., McNeill, K., Yamamoto, M., Schick, M.B., Ribitsch, D., Guebitz, G.M.: Polyol structure influences enzymatic hydrolysis of bio-based 2, 5-furandicarboxylic acid (FDCA) polyesters. Biotechnol. J. **12**(9), 1600741 (2017)
36. Peng, S., Wu, L., Li, B.G., Dubois, P.: Hydrolytic and compost degradation of biobased PBSF and PBAF copolyesters with 40–60 mol% BF unit. Polym. Degrad. Stab. **146**, 223–228 (2017)
37. Sousa, A.F., Fonseca, A.C., Serra, A.C., Freire, C.S.R., Silvestre, A.J.D., Coelho, J.F.J.: New unsaturated copolyesters based on 2, 5-furandicarboxylic acid and their crosslinked derivatives. Polym. Chem. **7**(5), 1049–1058 (2016)
38. Sousa, A.F., Coelho, J.F., Silvestre, A.J.: Renewable-based poly ((ether) ester) s from 2, 5-furandicarboxylic acid. Polymer **98**, 129–135 (2016)
39. Terzopoulou, Z., Tsanaktsis, V., Nerantzaki, M., Achilias, D.S., Vaimakis, T., Papageorgiou, G.Z., Bikiaris, D.N.: Thermal degradation of biobased polyesters: Kinetics and decomposition mechanism of polyesters from 2, 5-furandicarboxylic acid and long-chain aliphatic diols. J. Anal. Appl. Pyrol. **117**, 162–175 (2016)
40. Dai, J., Ma, S., Teng, N., Dai, X., Shen, X., Wang, S., Liu, X., Zhu, J.: 2, 5-Furandicarboxylic acid-and itaconic acid-derived fully biobased unsaturated polyesters and their cross-linked networks. Ind. Eng. Chem. Res. **56**(10), 2650–2657 (2017)

41. Shen, Y., Yao, B., Yu, G., Fu, Y., Liu, F., Li, Z.: Facile preparation of bio-based polyesters from furandicarboxylic acid and long chain diols via asymmetric monomer strategy. Green Chem. **19**(20), 4930–4938 (2017)
42. Nam, D.H., Taitt, B.J., Choi, K.S.: Copper-based catalytic anodes to produce 2, 5-furandicarboxylic acid, a biomass-derived alternative to terephthalic acid. ACS Catal. **8**(2), 1197–1206 (2018)
43. Wang, G., Hou, M., Jiang, M., Wang, R., Liang, Y., Zhou, G.: Poly (propylene naphthalate-co-propylene 2, 5-furandicarboxylate) s derived from bio-based 2, 5-furandicarboxylic acid (FDCA): synthesis, characterization and thermo-mechanical properties. Polym. Degrad. Stab. **179**, 109244 (2020)
44. Zhi-Yu, Y., Yi-Ling, C., Hao-Chun, Y., Chin-Wen, C., Rwei, S.P.: Synthesis and characterization of thermoplastic poly (Ester Amide) s elastomer (TPEaE) obtained from recycled PET. J. Renew. Mater. **9**(5), 867 (2021)

Chapter 17
Recycling of Platinum Group Metals and Alternative Catalysts for Catalytic Converters

M. K. Shukla, Balendra V. S. Chauhan, Thallada Bhaskar, Atul Dhar, and Ajitanshu Vedratnam

Abstract Platinum group metals (PGM) are used as a catalyst in the automotive catalytic converters to curb engine emissions. The modern catalytic converter (three-way) executes oxidation of CO and unburnt HC, and reduction of NO using its large active surfaces containing PGM, which are precious metals with high cost all over the world. Due to the high cost of the PGM, researchers are working on efficient methods for extracting and reusing these valuable metals from catalytic converters. Pyrometallurgy and hydrometallurgy are the most common ways for the extraction of the PGMs among other methods. Alternative to platinum, materials like titanium dioxide and other metal-based oxides can be used for carrying out redox reactions of toxic vehicular emissions. The use of such alternative catalysts can help in reducing the increasing demands and cost of PGMs. This chapter focuses on the possibilities of recycling the PGMs from catalytic converters and also of reducing the ever-increasing requirement of PGMs in the manufacturing of autocatalysts in the catalytic converters. The chapter reports the recent global trends of PGM recycling and its demand for use as autocatalysts, alternative materials ~~of~~ to PGMs in catalytic converters and alternative methods for emission reduction. Further, the engine-related challenges and research on future directions of replacing PGM's as autocatalysts has been performed; it includes some experimental results of direct decomposition of

M. K. Shukla
Automotive Fuels and Lubricants Application Division, CSIR-Indian Institute of Petroleum, Dehradun, India

B. V. S. Chauhan (✉)
Centre of Earth Observation Science, School of Applied Sciences, University of Brighton, Brighton BN24GJ, UK
e-mail: b.chauhan@brighton.ac.uk

T. Bhaskar
Material Resource Efficiency Division, CSIR-Indian Institute of Petroleum, Dehradun, India

A. Dhar
School of Engineering, Indian Institute of Technology, Mandi, India

A. Vedratnam
Invertis University, Rajau Paraspur, India

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_17

NOx using non-noble metal catalysts such as Cu-COK12, Cu-Nb_2O_5, Cu-YZeolite, and Cu-ZSM5. The article should also provide a quicker understanding of research on development of low-cost non-noble metal-based alternative autocatalysts.

Keywords Alternative catalysts · Autocatalysts · Demand · PGM · Recycling · Supply

17.1 Introduction

The harmful gas emissions from the engine exhausts contributes to air pollution and imposes a great threat to environment [1–7]; thus, the automotive industries are much inclined to counter the engine emissions. Hence, catalytic converters are applied after the exhaust pipe to reduce the emission levels from the engine exhaust [8–10]. These catalytic converters consist of an active surface of platinum group metals (palladium, platinum, and rhodium), also sometimes denoted as PGM. PGMs are preferred due to their catalytic ability for the conversion of the exhaust gases into less harmful oxides [11]. The PGM's are called the state-of-the-art Industries' Vitamin because of its exceptional characteristics like resistance toward corrosion, catalytic activity, stability (thermal and electrical), and inertness [12–16]. By employing catalytic converters, the engine exhaust emissions are controlled to be in the permitted range set by the emission controlling body.

The automobiles are used extensively in the modern world; they have now been basic daily need of an individual. But apart from all the advantages automotives have, we are paying a huge cost in the form of environmental damage, as they emit large amount of NO_x, CO, unburnt hydrocarbons, Particulate matter emissions (also known as Soot), and other toxic gases. There are many regulatory bodies around the globe who have made laws, norms and emission regulations, standards according to the country's environmental conditions and extent of air pollution. The catalytic converter serves as leading aid to fulfill such regulations, so their demand has become obvious in today's world. With the growing demand of catalytic converters, the demand of their main ingredient's such as PGM has of course increased and they are under extensive research. Carrying the fact of increased demand of PGM in such amounts, has led to beat the supply or yield globally [17–19], and consequently making them "precious and costlier metals". Table 17.1 shows the cost increment of PGMs over consecutive years.

Table 17.1 Average costs of PGM globally (in the units of U.S. dollars per kg) for 4 consecutive years [20]

Costs in →	2018	2017	2016	2015
Platinum metal	28 935.67	30 575.36	31 797.08	33 951.18
Palladium metal	31 829.23	28 131.90	19 837.01	22 344.76
Rhodium metal	67 516.56	35 783.78	22 409.07	30 703.96

Figure 17.1 depicts the data of Platinum Group Metal's Demand Vs Supply for 5 consecutive years for various sectors. From the above graphical representation, it can be observed that supply of PGM has been lesser as compared to its demand since these last 5 years. The following Table 17.2 presents the platinum group metals' percentage of change among total demand and supply for 5 consecutive years.

Additionally, the demand of PGMs as autocatalysts in the automobile industries for some countries around the globe is as shown in Fig. 17.2.

Moreover, this study further reviews the difference in usual usage or demand of platinum group metals as compared to its demand in the automobile industry (as autocatalysts), is shown in Fig. 17.3.

A comparison of the total gross demand of PGMs with the demand for its use as autocatalysts is given in Fig. 17.3.

Figure 17.3 and Table 17.3 reflects that good percentages of the demand of platinum group metals in automotive industry as autocatalysts with respect to its demand in global market. The platinum metal has proved its dependence in the jewelries and ornaments, so a huge percentage of platinum goes in the global market as compared to its demand as autocatalysts.

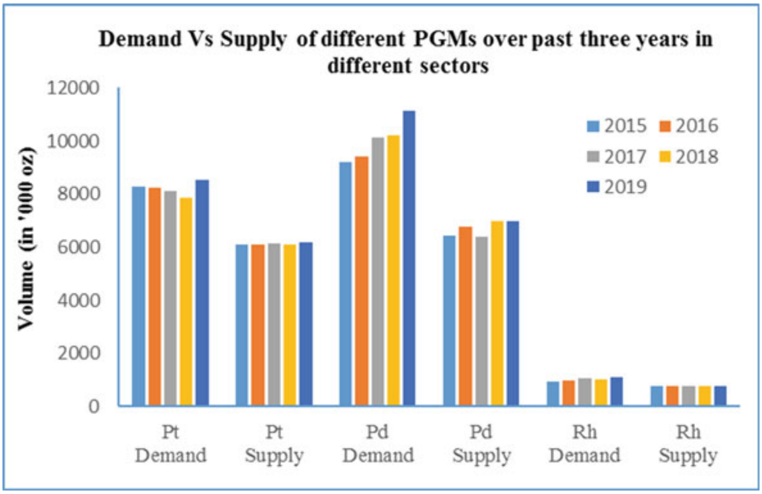


Fig. 17.1 Data of Platinum Group Metal's Demand Vs Supply for 5 consecutive years for various sectors [21]

Table 17.2 Platinum Group Metals' percentage of change among total demand and supply for 5 consecutive years

	2015	2016	2017	2018	2019	Average
Platinum	26	28	30	32	33	29.5
Palladium	30	33	34	37	35	33.8
Rhodium	29	23	26	28	30	27.2

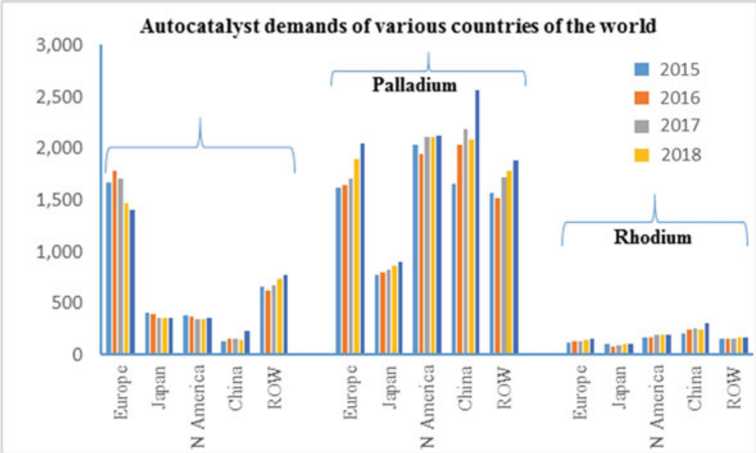


Fig. 17.2 Demand of PGMs as autocatalysts around the globe (ROW in the graph refers to the "rest of world") [21]

The huge requirements of PGMs convey that, if by any possibility we can reduce the demand of platinum group metals in the automotive industry, the global prices will be reduced significantly. Recycling of platinum group metals has been in consideration since a long time, and it has been proved as a good practice in view of scenario of increasing cost and demand of PGMs. Researchers are investigating new materials and techniques as the alternatives to PGMs to reduce exhaust emissions in more efficient ways [22]. However, due to the superior activity and results by the PGMs, the most used metals for the catalytic conversion are platinum, palladium, and rhodium [13, 23–26].

17.1.1 History of Emission Control Research

Please note that the first paragraph of a section or subsection is not indented. The first paragraph that follows a table, figure, equation, etc., does not have an indent, either.

Subsequent paragraphs, however, are indented.

In 1975, after beginning of emission control research in the US, the investigations directed that palladium and platinum as most suitable oxidation catalyst. While the iridium, rubidium, and osmium showed their oxides are volatile [27]. From 1975 to the 1980s, researchers were working actively to control emissions; the other challenge was to finalize a catalyst to reduce NO_x. For the very first time, a two-bed converter came into the picture; in the primary bed, reduction of NO_x took place, and in the secondary bed, HC and CO were treated and oxidized. But the main discrepancy in this came when NH_3 formed into the primary bed went to the second one to again

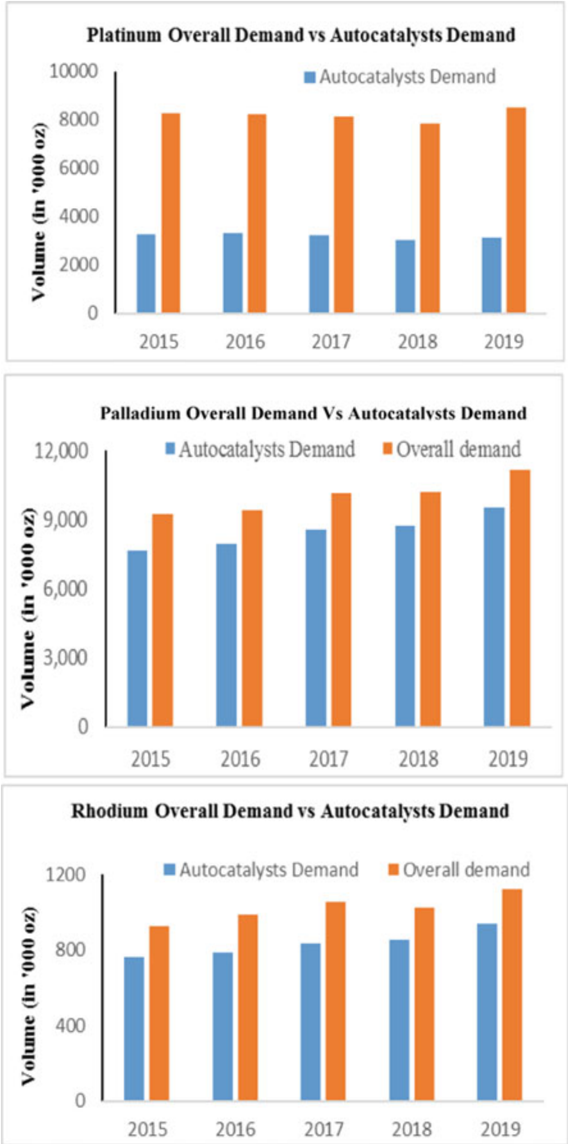


Fig. 17.3 Representation of demand of PGMs in all sectors as compared to automotive sector [21]

Table 17.3 Percentage of the demand of PGM in the automobile industry as autocatalysts from total demand of PGMs in the global market [21]

	2015	2016	2017	2018	2019	Average
Platinum	39	40	41	40	42	40.4
Palladium	83	81	80	82	81	81.4
Rhodium	82	81	83	84	82	82.4

form NOx into the secondary bed. Moreover, ruthenium (even while readily forming volatile oxides) was also tested and seen as a possible catalyst, and its chemical properties were tested in many different studies [28–36], but they were not preferred for further production because they did not serve the purpose as they not only proved to be an inefficient reducing agent for NO, but also showed higher selectivity toward NH_3. Additionally, rhodium was taken into consideration for reduction of NO_x, as they shown good NO_x reducing nature with lesser selectivity toward NH_3.

Eugene Houndry, a French-based mechanical engineer is the inventor of catalytic converter [37–39]. However, it was further developed by Carl D. Keith and John J. Mooney in the year 1973, where it was produced for the very first time. After 5 years of its production, the three-way catalyst was also studies for indispensable reduction of NOx [40–45]. The platinum group metals are considered as a group of highly valued and rarely available transition metals that consists of platinum, palladium, rhodium, iridium, osmium, ruthenium, (all are periodic table's d-block elements). They are all white silvery metals that are unreactive, having almost the same chemical and physical characteristics, and are also found at the same place together in mineral deposits. There is a nice history behind using Pt, Pd, and Rh as autocatalysts [46]. Due to difficulties in availability and the high costs of noble metals, in the mid-1970s the research was focused on non-noble metal-based catalysts. But after some extent of the research, it was found that non-noble metals with their oxides, for example, cobalt oxide, nickel oxides, manganese oxide, copper oxide, and chromium oxide, etc., proved to have less durability, less abatement activity toward automotive emissions [22, 27, 46–48]. So, the research was moved forward on the catalysts with noble metals due to their exceptional capabilities of higher temperature stability and lesser likeliness to react or interact with the material of support. Pardiwala et al., in their study for the USA and Japan, stated that the catalytic converter has the ability to abate the lethal emissions in forms of CO_2, H_2O, O_2, and N_2, and it has become a compulsory for every vehicle [38]. Researches also stated the same for Indian government has also made catalytic converters obligatory, and strict regulations are there for harmful emission prevention [39–41]. In 1970s, Japan and the United States of America are the countries, which made catalytic converter to be mandatory, and further, this rule was also implemented in Asia, Europe, and Australia after 10 years; additionally, later on other countries such as India, Brazil, and Mexico took 10 more years to make it mandatory for all vehicles [49].

In the same scenario for the manufacturers, platinum group metal-containing catalytic converter production became a must requirement. The position of catalytic converter as shown in Fig. 17.4, is on rear side of vehicle, inside the exhaust pipe, so that all kind of exhaust gases produced by engine combustion can pass through it and they can be dealt in the Platinum group metal-containing catalytic converter [37]. Additionally, researchers have also worked on the placement of catalysts concerning the engine and explored interesting behaviors in the reduction of emissions. For example, with the increase in distance of placement, the non-methane hydrocarbon emissions increased [50]. However, they also used another factor of palladium loading in their research and showed higher palladium loading results in lesser non-methane hydrocarbon emissions.

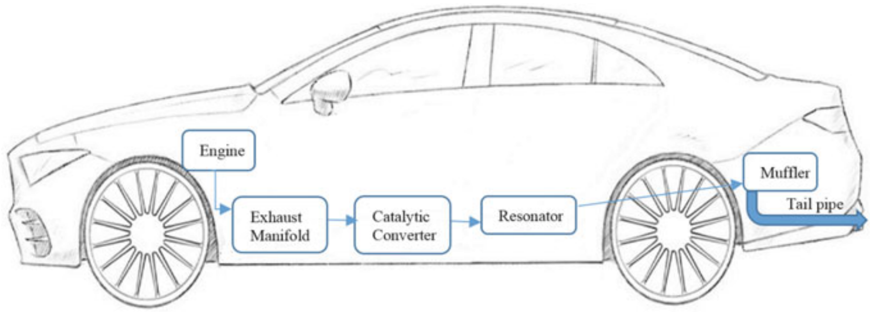


Fig. 17.4 Schematic of the placement of a catalytic converter in a car

17.1.2 Requirement of PGMs in the Catalytic Converters

PGMs are coated on the monolith substrate inside the catalytic converter so as to deal with lethal exhaust emissions; the coated surface remains active and redox reactions take place on it [5]. The catalytic converters can be further studied as two-way (where HC and CO get oxidized to H_2O and CO_2) and three-way catalytic converters (including function of converting HC and CO), it also reduces nitrogen oxides into O_2 and N_2 [2]. Researchers studied some potential candidates similar to PGMs such as Cr_2O_3, TiO_2, NiO, CeO_2, Fe_2O_3, and ZrO_2. But in 1980s, PGM was established well and found efficient in their role in the catalytic converters [2].

17.1.3 The Different Aspects of Platinum Group Metals

As discussed in the previous sections, the exhaust emissions undergo redox reactions which is the primary goal of a catalytic converter, contributing to reduce the lethal emissions [40]. The palladium metal and the platinum metal are mostly used as oxidizing agent for unburnt hydrocarbons and carbon monoxide to convert them into H_2O and CO_2, respectively, as shown in the following reactions.

$$CO + O_2 \rightarrow CO_2$$

$$CxHx + O_2 \rightarrow CO_2 + H_2O$$

However, rhodium is deployed to break NO into the N_2 and also steam reforming [51, 52]. Figure 17.5 shows a typical three-way catalytic converter.

The alumina washcoat which is porous in structure helps for distribution of platinum, palladium, and rhodium on the substrate's surface. The washcoat is made up of γ-Al_2O_3. It provides a greater contact area for the interaction of exhaust gases and active phases and a greater heating stability. In some cases, it may happen that

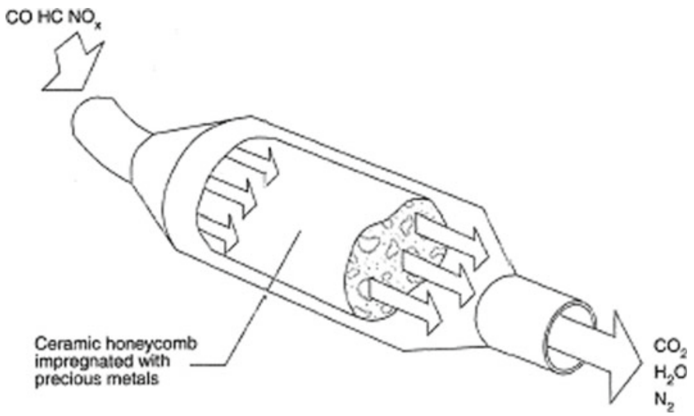


Fig. 17.5 Typical three-way catalytic converter [53]

if temperature rises, the surface area of γ-Al_2O_3 may get decreased; for this reason, metal oxides like CeO_2, La_2O_3, BaO, and ZrO_2 are used as stabilizing agents [54]. Furthermore, to assist the distribution of PGM on the substrate, a traditional additive (mixture of ZrO_2 with CeO_2) is used; this combination also helps in oxidation reactions and promotes catalytic activity [55].

17.1.4 Availability of PGMs

The maximum supply of PGM in the world market is accomplished by South Africa. Following Tables 17.4, 17.5, and 17.6 represents the supply chain of platinum, palladium, and rhodium separately from some regions around the globe.

The data in Tables 17.4, 17.5, and 17.6 clearly specifies that PGMs are immensely being used as a autocatalysts; there is a very high demand. The purpose of these tables is to give an idea that there is a need of PGM recycling and reuse and focus that recycling should be done as much as possible.

As shown in the Sect. 17.1, the current research inculcates the numbers of demand and supply of PGM metals and focuses on the need of recycling of such precious

Table 17.4 Platinum's supply available in units of '000 oz in last successive years [21]

	South Africa	North America	Russia	Others
2019	4565	385	668	956
2018	4467	372	687	959
2017	4450	370	720	953
2016	4347	369	652	153
2015	4571	318	670	149

Table 17.5 Palladium's supply available in units of '000 oz in last successive years [21]

	South Africa	North America	Russia	Others
2019	2744	983	2792	1460
2018	2543	950	2976	1458
2017	2547	960	2452	1409
2016	2571	922	2487	126
2015	2684	864	2434	142

Table 17.6 Rhodium's supply available in units of '000 oz in last successive years [21]

	South Africa	North America	Russia	Others
2019	652	52	73	67
2018	618	43	69	70
2017	611	37	78	70
2016	593	24	80	54
2015	611	23	80	50

noble metals. There is ample amount of research already available on the topic of PGM recycling and reuse, the current research reviews the developments made in the methods of recycling, reuse, and alternative catalysts tested in place of PGMs. The current study also presents experimental results of catalytic activity of alternative catalysts such as Cu-COK12, Cu- Nb_2O_5, Cu-YZeolite, and Cu-ZSM5 using $DeNO_x$ (Direct decomposition of NO_x) technology.

17.2 Current Scenario of the Use and Recycling of PGMs from Catalytic Converters

As discussed in the earlier sections that the demand of PGM are higher than supply, hence the idea of recycling the PGMs would be great. Figure 17.6 shows the trends of demand volume and PGMs recycling volume being performed in recent times.

Figure 17.6 shows that the amount of PGMs obtained from the recycling of autocatalysts is very small as compared to their total demand in the autocatalysts industry. This low fraction of the extraction of PGMs from the autocatalysts adds more to its demand and supply gap. This percentage needs to be increased so that the maximum possible share of demand as autocatalysts gets fulfilled by recycling the old autocatalysts from discarded automobiles.

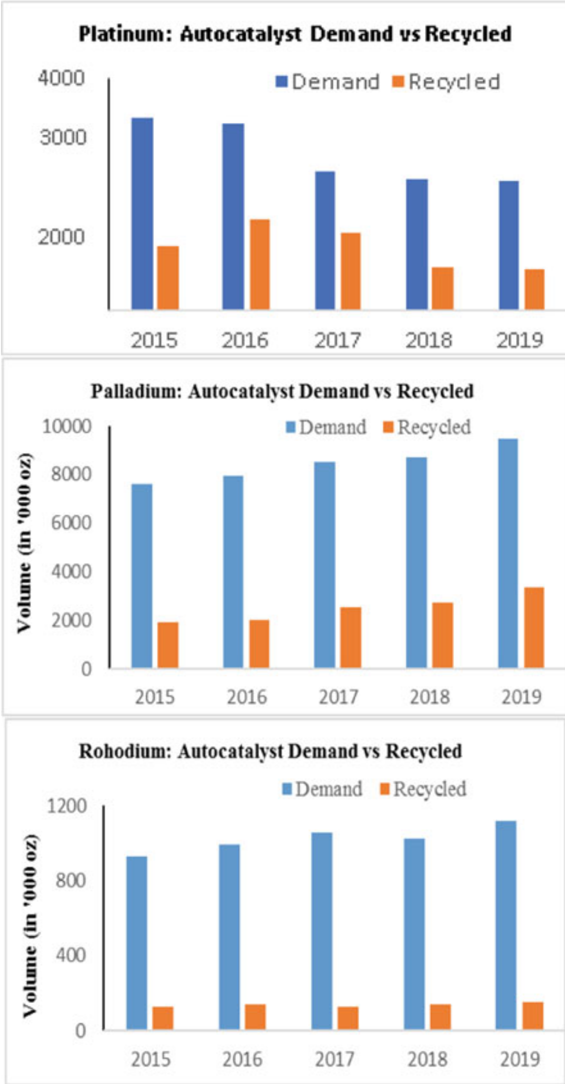


Fig. 17.6 Trends of demand volume and PGMs recycling volume, being performed in recent times [21]

17.3 Methods of PGM Recycling

The recycling of PGMs in catalytic converters has been of particular interest to many researchers [10, 56–61]. It is considered that the recycling of autocatalysts from the catalytic converter takes less effort than to purify or separate them as compared to the ones taken out directly from mineral ores. Additionally, it is also a fact that the content of PGM is higher when recycled from spent autocatalysts as compared to the ones extracted directly from the earth [51]. Figure 17.7 gives a flowchart of the

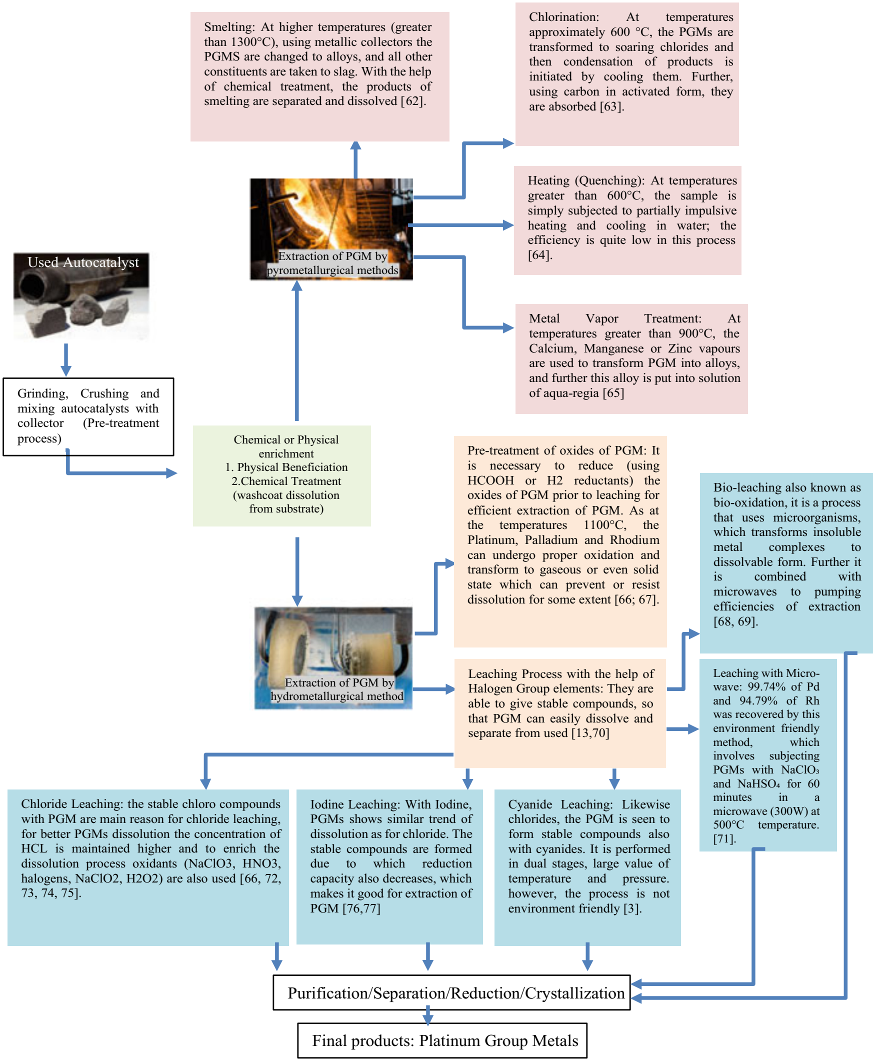


Fig. 17.7 Flowchart of the steps involved in common techniques of extraction of Platinum group metals from the catalytic converters

steps involved in common techniques of extraction of platinum group metals from the catalytic converters.

17.3.1 HydroMetallurgy

Hydrometallurgy is the most basic and common metallurgical process of PGM extraction from the autocatalysts. In this process, the catalytic carrier is first immersed into a solution of chlorides, nitrates, aqua regia, etc. Consequently, PGMs get converted into their respective chlorides (MCl6-2). The obtained solution is then concentrated and separated by electrolytic decomposition of the metal chloride complexes.

Dissolving PGMs in common acids is not easy, as they show high chemical inertness. Hence, aqua regia solution (firmly acidic) is availed to dissolve PGMs. The presence of nitric acid helps as a reducing agent as the reducing potentials for the formation of the chloride complexes of the PGMs is quite high. About 90% of the PGMs used in a car's catalytic converter get extracted by this process. However, processing takes considerable time due to slow phenomenon of PGMs dissolution in solution of aqua regia. Also, a lot of liquid waste gets created in this process which may be hazardous due to the presence of strong metals [67].

17.3.2 PyroMetallurgy

It is second most used common way for the extraction of PGMs from the catalytic converters. In this method, the catalyst carrier is first ground to break up its surface. It is then melted with additional metal collectors, forming PGMs alloys and metal collector, together with the slag. Further, the metal alloys are purified to yield pure PGMs, and the slag is removed simultaneously.

For the choice of collector metal, several properties like melting point, mutual solubility, and chemical properties between PGMs and collectors have to be considered thoroughly. Mostly copper, nickel, lead, and iron are considered good collector. This technique has many advantages like a lesser investment, low melting temperature, a simple refining process, and simple operation. However, it has a disadvantage of low extraction of rhodium and also by the formation of lead oxide, as it is a toxic waste added into the environment [13].

17.3.3 Pressure Cyanidation

The use of pressure cyanidation is a potential way of extracting PGMs from the automotive catalytic converters. In this method, the spent catalyst is first pre-treated with pressure alkaline leaching. The metal concentrate so obtained is then once again treated with two stages of pressure cyanide leaching. It is then followed by the zinc cementation process giving out concentrates of the respective precious metals. And ultimately, the PGMs are separated by electrolytic decomposition of the metal concentrates [3]. Although it can be categorized under the hydro-metallurgical process, the pressure cyanidation process is, however, more complex and advanced. Firstly, the selective dissolution of base metals by the acidic leaching process was done with elevated pressure conditions, keeping nearly all the precious metals in residue of iron. However, its results were not very satisfactory, partly due to the uncertainty of extraction of PGM, high reagent consumption, lesser rhodium recoveries, and severe pollution, etc. The organization of the United States Bureau of Mines consequently executed investigations on convalescing the platinum group metals by cyanide leaching at high temperatures. The recoveries reported were not much high and also the cyanide exhaustion was quite high in the process of leaching. Thus, a conclusion was made that new pertinent pre-treatment methods are much needed. Chen et al. [6] suggested a new method of pre-treatment, where followed by the 2 stages of leaching of pressure cyanide, the automotive catalysts are pre-treated with pressure alkaline leaching. This leads to a very high number of recoveries of platinum, palladium, and rhodium [3].

17.3.4 Industries Involved in Recycling

The art of recycling catalytic converters has now become well known and gained the focus of industrialists globally. Some used catalytic converters are shown in Fig. 17.8. The processes discussed above in Sect. 17.3 are employed to extract PGMs from them and use them to make fresh catalytic converters.

Different companies have now begun works to recycle the old, discarded autocatalysts used in automobile vehicles to extract these metals back. Currently, most of the companies that have been involved for production of PGMs are also actively growing a facility for the recycling of catalytic converters to extract back the used PGMs. Some companies are listed in Table 17.7.

Among the above-listed companies, the Umicore Autocatalysts recycling is the most established name in the entire world that works to extract back the PGMs from the used autocatalysts with its plants in Germany, Brazil, the U.S.A., Belgium,

Fig. 17.8 Some used catalytic converters before process of PGM extraction [59]

Table 17.7 List of few PGM recycling companies around the world

Stillwater mining company	USA
Umicore Autocatalysts Recycling	Belgium
Alpha Recycling	USA
Power Metal Recycling	USA
Environmental Solutions (Asia) Pte Ltd	Singapore
Evciler	Turkey
Sufimet spa	Italy
Duesmann & Hensel Recycling	Germany
European Metal Recycling Ltd	England

etc. Moreover, researchers have studied to substitute PGMs with different noble and non-noble metal catalysts as discussed in the next section.

17.4 Alternatives of Platinum Group Metals as Autocatalysts in Catalytic Converters

some potential catalysts, to replicate PGMs in the catalytic converters. Following Table 17.8 shows the work of researchers since many years for the development of reliable and low-cost solution for exhaust gas treatment. Selected PGM alternatives are discussed in this section.

17.5 Alternative Methods/Techniques

17.5.1 Selective Catalytic Reduction (SCR)

The selective catalytic reduction can control the nitrogen oxides emissions, and the technology involves a reducing agent coupled with catalyst which needs to be injected in the exhaust gas flow stream [100]. Anhydrous ammonia, liquid ammonia, and urea can be used as the reagent for the reduction of NO_x. The use of liquid ammonia is preferred over anhydrous ammonia, as it is safer to store and is not toxic [101]. The initially manufactured SCR catalyst system was comprised of TiO_2 anatase containing active components (mostly V_2O_5 & WO_3). However, toxicity of vanadium and need of catalyst activity at elevated temperatures gave an idea to focus on another type of research, for example, the highly active metal zeolites [102].

Nowadays, catalysts are generally metal-based zeolites like iron, copper, chromium, etc. The NO_2 is generated at just the center of metals on these metal exchanged zeolites, whereas the selective catalytic reduction reaction occurs inside zeolite lattice. On these metal-exchanged zeolites, the NO_2 is produced at the

Table 17.8 Studies performed by researchers regarding alternatives for platinum group metals

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
Au-TiO_2	FTIR, BET	Catalyst Used: 1% Au-TiO_2, Gas Used: CO for 30 min at 300 K, Conversion of CO: 50–70%, Time: 3–15 h	For CO oxidation at normal room temperature, Ti-based gold catalysts show good activity. Pretreatment (calcination/high and low temperature reduction) of Au impregnated TiO_2 shows good catalytic activity	[78]
Cu-ZSM5	XRD, BET	Experimental method: direct and continuous decomposition of NO_x. Harda et al., used pulsating heating in presence of water vapor	Conversion of NO is focused in this research, and CuZSM5 catalyst is explained as a potential catalyst for nitrogen oxide decomposition	[79–82]
$K/A^{2+}B_2^{3+}O_4^{2-}$	TGA, XRD	Sample used: Soot Catalyst Mixture, Catalyst Used: K_2CO_3, K_2Mn_2Od, and KO_2, Experimental Method: TGA, Temperature Range = 200–600 C, Gas Used: Balanced oxygen is used at flow rates of 80 and 120 ml/min. Catalyst Amount = Ratio of 1 g soot and 9 g of catalyst is used and TGA was performed, it was observed that for every run the combustion of only 0.5 mg took place	Spinel kind oxides, if doped with alkali metals, they enhances the reactivity of these oxides to some extents. The K_2CO_3, K_2Mn_2O8, and KO_2 catalysts were subjected to the stability tests, and due to potassium sublimation a potassium degradation was observed while undergoing the soot combustion	[83]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
$La_{0.8}Sr_{0.2}$ 'X'O_3	XRD, BET	Sample used: catalysts used involved 'X' = Co, Mn, Fe, Cr, Cu in different concentrations in the catalyst. Experimental Method: passed the NO balance He gas at 15 ml/min, through flow reactor. The catalyst was placed in the reactor, and Gas chromatography machine was used to determine the reactivity of catalysts	It was observed that the catalytic activity was dependent on the concentration and composition of catalysts, oxide ion vacancies, and cation sites. It was concluded that oxides of Co-based pervoksites are potential catalysts for NO abatement	[84]
Co, K/MgO	BET, TPR, FTIR, XRD, XPS	Sample Used: Soot Catalyst Mixture, Catalyst Used: Co, K/MgO, Experimental Method: TPO, Temperature Range = 200–450 C, Gas Used: 6% O_2 in N_2, Catalyst Amount = 7 mg. Potassium Content Used: (1.5, 4.5 and 7.5 wt%)	At the temperature of 400 °C, the 1.5 wt%, 4.5 wt%, 7.5 wt% of K, and 12 wt% of Co were calcined for diesel soot combustion. The catalyst combination calcined at 700 °C, comprising of 7.5 wt% of K, sustain more to show good catalytic activity; the CO conversion into CO_2 was effective using Co, K/MgO at soot burning temperatures	[85]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
MoO_3/support; V_2O_5/support	TPR, CHN analysis	Type of Soot: size of 28 mm particle carbon black; BET for SA: 80 m^2/g; The Carbon, Nitrogen, and Hydrogen analysis found that C = 97.99 wt.%, N = 0.06 wt.%, H = 1.12 wt.%) were present, Gas Used: 10% O_2 + 1000 ppm NO_2 + 100 ppm SO_2 + 7% H_2O in N_2, Flow Rate = 500 ml/min, Temperature Range: 80–750 C, Experiment: Fixed Bed Reactor	TPR analysis was performed on supports like ZrO_2, MCM-41, HZSM-5, Al_2O_3, SiO_2, SnO_2, Cordierite, and Nb_2O_5. The O_2 and NO_2 were used as oxidants. It was observed that higher reactivity was achieved with the help of oxides with high vapor pressures and low values of melting point. The research concluded that among all the catalysts (V_2O_5/support and MoO_3/support) tested, the most reactive were V_2O_5/MCM-41 and MoO_3/SiO_2 catalysts	[86]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
Metal Chlorides (such as CuCl, $PbC1_2$, Pb, OCl, FeOCl, and BiOCl)	TGA	Soot Used: Printex-U soot, Sample Used: 4 milli gram catalyst, 2 milli gram soot and 54 milli gram SiC, Gas Used: 21 vol percent Oxygen balance Nitrogen, Flow rate: 50 ml/min, Soot Conversion: 20–60%, Catalyst Used: CuCl, $PbC1_2$, Pb, OCl, FeOCl and BiOCl, Temperature = 550 K (CuCl), 610 K (PbCl, Pb, OCl) and 645 K (FeOCl, BiOCl)	TGA analysis was performed to see the oxidation of soot (in loose contact). Most active metal oxychlorides were of Bi, Cu, Fe, and Pb. Metal chlorides like CoCl2, $BaCl_2$, NiCl2, and CaCl2 showed less catalytic activity because of high melting point. HgCl2 (or other highly volatile metal chlorides have shown zero or no catalytic activity. Using metal chlorides for oxidation of soot is in question as due to decomposition or evaporation, there is an activity loss and instability is also present	[87]
MnOx-CeO_2	TGA, FTIR, XRD	Soot Used: collected the carbon black from tail pipe of EURO II diesel, Catalyst Used = MnOx-CeO_2, Gas Used = 10 percent Oxygen, 5% H_2O, 1000 ppm NO, balance N_2, Flow Rate: 140 ml/min, Experiment: TPO, TG-FTIR and flow reactor experiment	Observed soot oxidation activity of catalysts was higher for 330–400 °C. Higher activity was observed when content of cerium was higher in the catalysts. At SO_2 trap downstream, these catalysts find their applicability as they are prone to sulfur poisoning	[88]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
$K/CuFe_2O_4$	XRD, XPS, TPR	Soot Used: <5 weight percent of SOF dry soot was used. Experimental Method: TPR, Gas Used: Helium balanced 0.5% NO $\pm$ 5% O_2 Catalyst Amount: 5% weight of soot in the catalyst	For the abatement of diesel soot and NO_x, adding K on $CuFe_2O_4$ was found effective, and in the same scenario if platinum, Vanadium, and some other alkali metals, the catalytic activity was not enhanced. Amount of potassium doping was crucial in the catalytic reactivity of $Cu_{1-x}K_xFe_2O_4$	[89]
La-K-Mn-O perovskite-type oxide	TPR, XRD, BET	Catalyst Used: La–K–Mn–O, Experiment: NOx–soot removal reaction, Method: TPR, Catalyst Amount: 5% weight of soot in the catalyst. Gas: Helium balanced 0.5% NO $\pm$ 5% O_2. Flow Rate: 20 ml/minute on TCD Gas Chromatograph	XRD analysis of $La_{1-x}K_xMnO_3$, and solubility limit of K was found in range of 0.20–0.25. As a byproduct of processing pervoksites La-K-Mn-O, the $K_2Mn_4O_8$ was found, which is also a potential candidate for diesel soot and NO_x abatement. Analysis concluded that oxides of La-K-Mn-O are favorable for diesel soot and NO_x abatement	[90]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
Cu/K/Mo/Cl	XRD	Catalyst Used: Cu/K/Mo/Cl catalyst (K, Cu, (MOO, 3)) with model soot (Printex-U), Composition: 10.3 weight percent of Cu, 8.3 weight percent of MO and 6 weight percent of K. Experimental Analysis: DRIFT and XRD	In the ball mill, the catalysts in tight contact with soot performed well and highly active within the temperature range of 665–720 K, and for oxidation of soot in loose contact or 'mixture with spatula', this temperature goes high to 790 K. Specifically, for tight contact the oxidation of soot occurs at the 683 K	[91]
CuO-CeO_2	XRD, BET, TPO	Catalyst Used: Mixed oxides such as Cu–Ce–Zr; Cu–Ce; Ce–Zr, and CeO_2. Soot: Printex-U (Degussa), Experimental Method: TPO, Catalyst Amount: 1:10 ratio of soot and catalyst. Experimental Setup: Placed in reactor with 1000 ppm gas of nitrogen oxide and 9.5% of oxygen in nitrogen at a flow rate of 500 cm^3/min	The 'aging (air flow for 20 h' time)' experimental investigation of CuO-CeO_2 at the temperature of 800 °C, the rate of oxidation of diesel soot due to this catalyst in both forms the loose and tight contact, reached maximum at 419 °C and 321 °C respectively. The catalyst CuO-CeO_2 seems good candidate for oxidation of soot and nitrogen oxides removal, as selectivity for production of CO_2 reached to approximately 100%	[92]

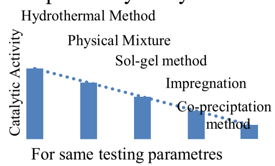
(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
MnO_x-CeO_2-Y_2O_3	XRD, N2 adsorption-desorption, Raman Spectroscopy, H_2-TPR, NO-TPO, X-ray Photoelectron spectroscopy, Soot TPO, BET	The Y doping in the different weight percentages (0, 1, 3, 6, and 10 wt%) was done in MnOx-CeO_2-Y_2O_3. The mixture was kept into dry air flow in observation for 12 h at a temperature of 800 °C. Gas: 800 ppm of Nitrogen oxide with 10% balanced oxygen/nitrogen (500 cm^3 min^{-1}, at a Gas Hourly Space Velocity of 30000 per hour) Experimental Method: TPO, Catalyst Amount: 1:10 mixture of soot and catalyst	The maximum oxidation of soot is observed at weight percentages of 6 and 10%	[93]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
$Ce_{0.5}Fe_{0.3}Zr_{0.2}O_2$	XRD, RAMAN, H2-TPR	Sample Used: Soot and catalyst mixture, Soot used: Printex-U (Degussa), Catalyst used: CeO_2-ZrO_2-Fe_2O_3 mixed oxide catalysts, Experiment method: TPO, Soot Amount: 15 mg, Catalyst Amount: 150 mg, Temperature Range: 25–600 C, Gas Used: 10% O_2/N_2	For combustion of soot, the maximum stability and activity were achieved for aging sample for 10 h at a temperature of 800 °C, which is due to good oxygen concentration vacancy of ferric oxide and its property of having surface reducibility. The prepared catalysts implemented different methods of preparation, and the activity of catalyst was comparatively analyzed as follows: 	[94]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
K/$Ce_{0.65}Zr_{0.35}O_2$/cordierite	BET, XRD, SEM, XPS, LRS	Sample used: Soot Catalyst Mixture, Soot Used: Found from vessel of glass after igniting diesel sample. Catalyst Used: Potassium-promoted $Ce_{0.65}Zr_{0.35}O_2$ monolithic catalysts, Experiment method: TPO, Gas Used: N2, Temperature Range (catalytic combustion of soot by Nitrogen oxide/Oxygen): 25–600 C	Studied the combustion of spatular mixture of catalyst and soot by repetetive TPO runs. After ten runs, due to loss of potassium at high temperatures, authors quoted a deactivation, whereas activation was observed when potassium was not present in the mixture. In the presence of NO/O_2 with K/CeO_2/cordierite (comparatively more active) and K/$Ce_{0.65}Zr_{0.35}O_2$/cordierite, the soot burning hiked. In tight contact the $Ce_{0.65}Zr_{0.35}O_2$ activity was greater as compared to CeO_2	[95]
FSP-Mn_3O_4	XRD, PXRD, SEM, NH_3-TPD, H_2-TPR, NDIR, TPO, TPD	Sample Used: Soot and Catalyst mixture, Catalyst Used: Flame spray pyrolysis is used to originate the catalysts such as Mn_2O_3, Mn_3O_4, and MnO_2 Experiment method: TPO, Temperature Range: 25–750 C, Gas Used: 10 volume percent Oxygen and 90 volume percent Nitrogen	TPO was employed to check the activity of catalyst and soot mixture in loose and tight contact. Among all catalysts samples investigated, FSP-Mn_3O_4 performed best. FSP-Mn_3O_4 was later coated on DPF, the oxidation of soot occurred at the temperature of 350 °C, prooving the catalyst a potential candidate for real-time continuous diesel soot oxidizer	[96]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
Alkali doped Fe_3O_4	XRD, FTIR, TPO	Sample used: 0.006 g soot (type: Degussa Printex80) and 0.050 g catalyst, Catalyst used: Fe_3O_4 (more than 98% Aldrich) with carbonate alkali (alkali metals = Li, Na, k, Cs), Experiment method: TPO, Temperature Range: 25–700 C, Gas used: 5% O_2 in He, Catalyst amount: ratio of 1 g soot to 8 g catalyst	It is observed that controlled alkali doping can increase the catalytic ability of magnetite for the combustion of soot. Li < Na < K < Cs is the sequence in which the alkali promoters increases promotional effects (coherent with the ionic radiis of these promoters)	[97]
K-doped manganese and iron spinels	XRD, ATR-FTIR, RAMAN, TPO	sample used: 0.006 g soot (type: Degussa Printex80) + catalyst, Catalyst used: iron doped K_2SO_4, KOH, CH_3COOK, KNO_3 and K_2CO_3 KOH, K_2CO_3, KNO_3, CH_3COOK, and K_2SO_4 with manganese spinels, Experiment method: TPO, Temperature Range: 25–700 C, Gas used: 5% O_2 in He, Catalyst amount: 1:8 of soot and catalyst	The increase in activity of combustion was observed when KNO_3, KOH, and K_2CO_3 was used. But a decreasing activity was observed for K_2SO_4 (shown as $\Delta T50\% \approx 25$ °C). Additionally, $\Delta T50\% \approx 150$ °C was observed for KNO_3 and $\Delta T50\% \approx 80$ °C for K_2CO_3, and for CH_3COOK and KOH and CH_3COOK, it was $\Delta T50\% \approx 40$ °C. It was also observed that higher the K content, higher is the potential for soot combustion	[98]

(continued)

Table 17.8 (continued)

Catalysts used	Characterizations performed	Experimental conditions	Remarks/findings	References
Nanostructured $Ce_{0.7}Mn_{0.3}O_2{-}\delta$ (CM) and $Ce_{0.7}Fe_{0.3}O_2{-}\delta$ (CF) solid solutions	Raman, XRD, TEM, ICP-OES, TGA-DTA, SEM-EDX, FT-IR, H_2-TPR, UV-vis DRS, HRTEM, BET, XPS	Sample used: Soot Catalyst Mixture, Catalyst Used: $Ce_{0.7}Mn_{0.3}O_{2-1}$(CM) and $Ce_{0.7}Fe_{0.3}O_{2-1}$(CF), Experimental Method: TG-DTA, Temperature Range = 573–1073 K, Gas Used: nitrogen atmosphere(50 ml min^{-1}), Catalyst amount: 15 mg	Soot oxidation capability of $Ce_{0.7}Mn_{0.3}O_2$ (CM) and $Ce_{0.7}Fe_{0.3}O_2$ (CF) was compared with CeO_2-ZrO_2 (CZ)'s catalytic activity. It was observed that Fe and Mn in ceria solution resulted in increased soot oxidation activity. As compared to ceria in pure form the $Ce_{0.7}Mn_{0.3}O_2{-}\delta$ (CM) and $Ce_{0.7}Fe_{0.3}O_2{-}\delta$ (CF) found more thermally stable. The research concluded CM as best catalyst among tested ones	[99]

metal centers, while the SCR reaction itself takes place within the zeolite framework. Because the NO_2 is destroyed as soon as it is produced in the SCR method, it doesn't appear as gas-phase NO_2 [103].

The main reactions for this process are:

$$2NO + 2NH_3 + {}^1/_2O_2 \rightarrow 2N_2 + 3H_2O$$

$$NO_2 + NO + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

17.5.2 NO_x Traps

NO_x traps or absorbers are applied to reduce the NO_x emissions from the automotive exhausts. Various metal-based Zeolites were employed as adsorbents in this study, and their unique characteristics in a variety of applications such as ion exchange, adsorbents, and catalysts have piqued the interest of automotive industry makers [104, 105].

Das et al. [106] developed iron-exchanged X-zeolite and investigated it in real-time exhaust of SI engine. For NO_x, the conversion efficiency of 55.8% was achieved, and the conversion of 57.4% was reported for CO. A numerical mathematical equation model for assessing the actions of a catalytic converter incorporating the Fe-X catalyst was also created [107].

17.5.3 $DeNO_x$ (Direct Decomposition of NO_x)

The direct decomposition of NO_x has been in research since a long time due to its easy applicability to break NO into nitrogen and oxygen with the help of catalysts. The direct decomposition of NO_x method do not employ a reducing agent and deals in temperature less than 1000 °C while decomposing the NO, hence known to me thermodynamically favorable method [108]. The method includes conversion of NO to Nitrogen and Oxygen (as shown in reaction below) at the catalyst's surface, with N desorbing as N_2 and O remaining strongly attached at surface of catalyst.

$$2NO \rightarrow N_2 + O_2$$

The dissolution and absorbance of NO occur efficiently on surface of transition metal. The direct decomposition of NOx has widely been studies for PGM metals. There's also an article there in 1920s that stated that at a temperature of approximately 800 °C, $DeNO_x$ progressed on the surface of platinum metal [109], and though research that time in this area slowed due to lack in activity of catalyst and necessary catalysts just weren't readily available to recompense platinum metal. Also in early 1990s, the studies shown that Cu-ZSM-5, Ag/Co_3O_4, Pd/$MgAl_2O_4$ and perovskite-type oxides shown good activity for decomposition of nitrogen oxides, so researchers focused on the rare earth metals and the compounds of the oxides of pyrochlore [110–115].

17.6 Future Scope and DeNO$_x$ Results Using Non-noble Metal Catalysts

The use of emission control techniques is however depends on particular characteristics associated with different engines. Certain modifications in the discussed techniques might improve the control of the engine exhaust emissions. For example, for lean-burn Spark Ignition (SI) and Compression Ignition (CI) engines, the three-way catalyst system is not effective for reducing NO_x emission. This is because the reducing catalyst is used up in reducing the high level of O_2 in diesel exhaust gases. To overcome this problem, other techniques such as Selective Catalytic Reduction (SCR), in which ammonia is used as a reductant and metal oxides as an oxidizer [101], are applied. Also, NO_x traps or NO_x adsorbers are applied, in which different metal-based zeolites are used as an adsorbent [104].

Authors have conducted a study for direct decomposition of NOx using alternative catalyst to PGMs. The experimental tests were based on the development of non-noble metal-based catalysts in order to provide a low-cost solution. The catalysts Cu-COK12, Cu- Nb_2O_5, Cu-YZeolite, and Cu-ZSM5 were prepared by the standard wet impregnation method, the supports ZSM-5, Y-Zeolite and Nb_2O_5 were obtained from Zeolyst International, the Netherlands, and COK12 support was prepared in the laboratory of CSIR-Indian Institute of Petroleum, Dehradun, India. Furthermore, the reactivity tests of prepared catalysts toward NO decomposition were performed with the help of a quartz glass fixed bed reactor setup. This experimental setup at the laboratory of EATA, AFLAD, and CSIR-Indian Institute of Petroleum consists of quartz reactor, thermocouples, mass flow controllers (MFCs), furnace, gas shut ON/OFF valves, gas regulators, and temperature control units. Helium and nitrogen gases were simultaneously used as purging agents to remove the impurities in the gas lines and fixed bed reactor. The prepared catalyst (of amount 250 mg) was placed on the quartz wool (fixed bed) and NO gas was made to pass through the fixed bed reactor; this fixed bed reactor was placed in a furnace to maintain the temperature of the reaction from 200 to 600 °C. For this case, the flow rate of NO was maintained (using mass flow controllers) at 100 ml/min. Similarly, for each catalysts, the tests were performed at a NO flow rate of 100 ml/min, and temperature of furnace was varied from 200 to 600 °C. The reacted NO gas coming out of quartz fixed bed reactor was then taken into DANI Master Gas Chromatography machine, equipped with the thermal conductivity detectors, and the output was seen in the form of voltage signals with the help of Clarity software attached with the DANI Master GC.

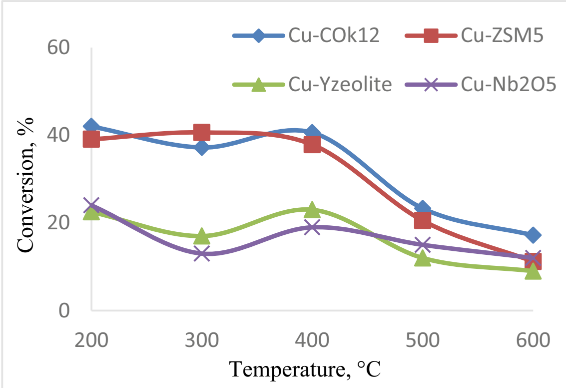


Fig. 17.9 Percentage conversion of NO by catalysts at 100 ml/min flow rate

The interpreted results are hence plotted for the percentage conversion versus the temperature as shown in Figure 17.9.

Figure 17.9 shows the catalytic activity of Cu-COK12, Cu- Nb_2O_5, Cu-YZeolite, and Cu-ZSM5 at the NO flow rate of 100 ml/min. The reactivity of Cu-COK12 and Cu-ZSM5 remains approximately 40% at lower temperatures and falls down with subsequently higher temperatures; but, the reactivity of Cu-YZeolite and Cu-Nb_2O_5 remains low. Moreover, in order to enhance the catalytic activity and to accomplish the aim to get comparable reactivity with platinum group metals, the further investigations are planned to vary the flow rates of NO and the non-noble metal catalyst weight. In the future, it is planned to calculate the dependence of NO decomposition activity of catalysts in terms of space velocities. This study can be extended for developing the diesel oxidation catalysts for the abatement of HC, CO, and particulate matter emissions.

17.7 Conclusions

Platinum, palladium, and rhodium, have powerful catalytic abilities. Additionally, platinum metals are naturally beautiful, which elevates their value as jewelery in many cultures. The automotive sector is anticipated to have a substantial impact on future PGM demand, while important Asian nations like China are anticipated to have significant rise in jewelery market for platinum. Along with the expansion of the world economy, there is also anticipated growth in the demand for platinum metals for industrial uses. These metals, which are utilized in electronic components and automotive catalytic converters, are increasingly being recycled because of recent increases in PGM costs. PGM recycling often begins with scrap refiners, which gather scrap materials such used catalytic converters and electronic components that contain PGMs to recover the precious metals. To further improve the quality of the recycled material, other refiners often purchase the recovered PGM material.

Technological developments that rely on the catalytic capabilities of PGMs, such as fuel cells, become more extensively employed across the globe, the market for recycled platinum metals is anticipated to rise over the upcoming years. The study highlights the following conclusions:

- The high demands of the PGMs emphasize the need to recycle the catalytic converters for the chemical extraction of these precious metals used as autocatalysts.
- The gap between total gross supply and total gross demand of PGMs is around 30%; this is what it makes them precious.
- Only about 32% of the demand for PGMs as an autocatalysts gets fulfilled by recycling from used catalytic converters. This percentage should be increased with a target to achieve above 90% recycling.
- The use of PGMs in catalytic converters can be reduced by replacing them with other materials and techniques like nickel oxide, titanium dioxide, CeO_2 composite catalysts, Cu/Cr Oxide Catalysts, zeolites, selective catalytic reduction, NOx traps, etc.
- A direct decomposition of engine exhaust is possible using alternative catalyst to PGMs with comparable reactivity with platinum group metals.
- The current research showed an experimental investigation on NO decomposition activity using Cu-based non-noble metal-based catalysts through $DeNO_x$ technology. The maximum reactivity achieved was for Cu-COK12 and Cu-ZSM5, it remains approximately 40% at lower temperatures.

In the future, the plan will be to find ways to increase the reactivity of the catalysts, so that we can add to the research of alternative catalysis. Using non-noble metal catalysts instead of PGMs would be a great breakthrough in this area of research.

Acknowledgements The work was supervised by Dr. Atul Dhar, School of Engineering, Indian Institute of Technology Mandi, H.P., India. The research was performed with the collaboration of CSIR-Indian Institute of Petroleum, Dehradun, U.K., India, Indian Institute of Technology Mandi, H.P., India, and Centre of Earth Observation Science, School of Applied Sciences, University of Brighton, Brighton, BN24GJ, United Kingdom.

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this chapter.

Credit Author Statement M.K. Shukla: Conceptualization, Methodology, Visualization, Writing- Original draft preparation; **Balendra V.S. Chauhan**: Investigation, Draft preparation, Writing and Editing; **Dr. Thallada Bhaskar**: Data curation, Visualization and Supervision; **Dr. Atul Dhar**: Validation, Supervision, Reviewing and Editing; **Dr. Ajitanshu Vedratnam**: Visualization, Draft preparation, Editing.

Abbreviations

ATR-FTIR	Attenuated total reflectance-Fourier transform infrared
BET	Brunauer–Emmett–Teller
CHN	Carbon Hydrogen Nitrogen analysis
CI	Compression ignition
CO	Carbon monoxide
$DeNO_x$	Direct decomposition of NOx
DPF	Diesel particulate filter
FSP	Flame spray pyrolysis
FTIR	Fourier Transform Infrared Spectroscopy
H2-TPR	Hydrogen-temperature programmed reduction
HC	Hydrocarbons
HRTEM	High-Resolution Transmission Electron Microscopy
ICP-OES	Inductively coupled plasma—optical emission spectrometry
LRS	Laser Raman spectroscopy
MFC	Mass flow controller
N_2O	Nitrous oxide
NDIR	Nondispersive infrared sensor
NH_3-TPD	Ammonia-Temperature programmed desorption
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO-TPO	Nitrogen oxide- Temperature programmed oxidation
NOx	Nitrogen oxide gases
PGM	Platinum group metals
PM	Particulate matter
PXRD	Powder X-ray diffraction
ROW	Rest of World
SA	Surface Area
SCR	Selective catalytic reduction
SEM	Scanning electron microscope
SEM-EDX	Energy-dispersive X-ray spectroscopy
SI	Spark ignition
TEM	Transmission electron microscopy
TGA	Thermogravimetric analysis
TGA-DTA	Thermal gravimetric analysis -Differential thermal analysis
TPD	Temperature programmed desorption
TPO	Temperature programmed oxidation
TPR	Temperature programmed reduction
UHC	Unburnt hydrocarbons
USA	United States of America
UV vis DRS	UV–vis diffuse reflectance spectroscopy
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

References

1. Ambroziak, T., Gołębiowski, P., Pyza, D., Jacyna-Gołda, I., Merkisz-Guranowska, A.: Identification and analysis of parameters for the areas of the highest harmful exhaust emissions in the model EMITRANSYS. J. KONES **20**(3), 9–20 (2013)
2. Agarwal, A.K.: Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog. Energy Combust. Sci. **33**(3), 233–271 (2007)
3. Gritsuk, I., Volkov, V., Mateichyk, V., Gutarevych, Y., Tsiuman, M., Goridko, N.: The evaluation of vehicle fuel consumption and harmful emission using the heating system in a driving cycle. SAE Int. J. Fuels Lubr. **10**(1), 236–248 (2017)
4. Thiyagarajan, S., Geo, V.E., Ashok, B., Nanthagopal, K., Vallinayagam, R., Saravanan, C.G., Kumaran, P.: NO_X emission reduction using permanent/electromagnet-based fuel reforming system in a compression ignition engine fueled with pine oil. Clean Technol. Environ. Policy **21**(4), 815–825 (2019)
5. Watson, A.Y., Bates, R.R., Kennedy, D.: Assessment of human exposure to air pollution: methods, measurements, and models. In: Air Pollution, The Automobile, and Public Health. National Academies Press (US) (1988)
6. Chen, J., Huang, K.: A new technique for extraction of platinum group metals by pressure cyanidation. Hydrometallurgy **82**(3–4), 164–171 (2006)
7. Reşitoğlu, İA., Altinişik, K., Keskin, A.: The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technol. Environ. Policy **17**(1), 15–27 (2015)
8. Abitha, J.: Prevention of exhaust from gasoline and diesel engines. J. Adv. Mech. Eng. Sci. **2**(3), 21–28 (2016)
9. Gao, J., Tian, G., Sorniotti, A., Karci, A.E., Di Palo, R.: Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. Appl. Therm. Eng. **147**, 177–187 (2019)
10. Saternus, M., Fornalczyk, A.: Possible ways of refining Precious Group Metals (PGM) obtained from recycling of the used auto catalytic converters. Metalurgija **52**(2), 267–270 (2013)
11. Farrauto, R.J., Heck, R.M.: Catalytic converters: state of the art and perspectives. Catal. Today **51**(3–4), 351–360 (1999)
12. Panda, R., Jha, M.K., Pathak, D.D.: March. Commercial processes for the extraction of platinum group metals (PGMs). In: TMS Annual Meeting & Exhibition, pp. 119–130. Springer, Cham (2018)
13. Dong, H., Zhao, J., Chen, J., Wu, Y., Li, B.: Recovery of platinum group metals from spent catalysts: a review. Int. J. Miner. Process. **145**, 108–113 (2015)
14. Jha, M.K., Lee, J.C., Kim, M.S., Jeong, J., Kim, B.S., Kumar, V.: Hydrometallurgical recovery/recycling of platinum by the leaching of spent catalysts: a review. Hydrometallurgy **133**, 23–32 (2013)
15. Mpinga, C.N., Eksteen, J.J., Aldrich, C., Dyer, L.: Direct leach approaches to Platinum Group Metal (PGM) ores and concentrates: a review. Miner. Eng. **78**, 93–113 (2015)
16. Afolabi, A.S., Nkobane, M.P., Abdulkareem, A.S.: Development of PGMs and chrome extraction circuit from UG-2 ore. In: Proceedings of the World Congress on Engineering, vol. 3 (2012)
17. Leman, A.M., Jajuli, A., Feriyanto, D., Rahman, F., Zakaria, S.: Advanced catalytic converter in gasoline engine emission control: a review. In: MATEC Web of Conferences, vol. 87, p. 02020. EDP Sciences (2017)
18. Renner, H., Schlamp, G., Kleinwächter, I., Drost, E., Lüschow, H.M., Tews, P., Panster, P., Diehl, M., Lang, J., Kreuzer, T., Knödler, A.: Platinum group metals and compounds. Ullmann's Encyclopedia of Industrial Chemistry, pp. 1–73 (2000)
19. Kondo, S., Takeyama, A., Okura, T.: A study on the forecasts of supply and Demand of Platinum Group Metals. J.-Min. Mater. Process. Inst. Jpn. **122**(8), 386 (2006)

20. Loferski, P.J.: Platinum-Group Metals Statistics and Information. US Geological Survey, February. http://minerals.usgs.gov/minerals/pubs/commodity/platinum (2015). Last accessed 13 Apr 2015
21. Matthey, J.: PGM market report, November 2016 (2019). www.platinum.mathey.com
22. Kummer, J.T.: Catalysts for automobile emission control. Prog. Energy Combust. Sci. **6**(2), 177–199 (1980)
23. Matsuda, S., Kato, A.: Titanium oxide based catalysts-a review. Appl. Catal. **8**(2), 149–165 (1983)
24. Angelidis, T.N.: Development of a laboratory scale hydrometallurgical procedure for the recovery of Pt and Rh from spent automotive catalysts. Top. Catal. **16**(1), 419–423 (2001)
25. Atkinson, G.B., Kuczynski, R.J., Desmond, D.P.: US Department of the Interior. Cyanide leaching method for recovering platinum group metals from a catalytic converter catalyst. U.S. Patent No. 5,160,711 (1992)
26. Yakoumis, I., Moschovi, A.M., Giannopoulou, I., Panias, D.: Real life experimental determination of platinum group metals content in automotive catalytic converters. In: IOP Conference Series: Materials Science and Engineering, vol. 329, no. 1, p. 012009. IOP Publishing (2018)
27. Kummer, J.T.: Use of noble metals in automobile exhaust catalysts. J. Phys. Chem. **90**(20), 4747–4752 (1986)
28. Shelef, M., Gandhi, H.S.: The reduction of nitric oxide in automobile emissions. Platin. Met. Rev. **18**(1), 2–14 (1974)
29. Gandhi, H.S., Stepien, H.K., Shelef, M.: Optimization of ruthenium-containing, stabilized, nitric oxide reduction catalysts. Mater. Res. Bull. **10**(8), 837–845 (1975)
30. Gandhi, H.S., Stepien, H.K., Shelef, M.: Paper No. 750177. Society of Automotive Engineers (1975)
31. Voorhoeve, R.J.H., Remeika, J.P., Trimble, L.E.: Perovskites containing ruthenium as catalysts for nitric oxide reduction. Mater. Res. Bull. **9**(10), 1393–1404 (1974)
32. Yao, H.C., Japar, S., Shelef, M.: Surface interactions in the system $RhAl_2O_3$. J. Catal. **50**(3), 407–418 (1977)
33. McCabe, R.W., Usmen, R.K., Ober, K., Gandhi, H.S.: The effect of alumina phase-structure on the dispersion of rhodium/alumina catalysts. J. Catal. **151**(2), 385–393 (1995)
34. Wong, C., McCabe, R.W.: Effects of high-temperature oxidation and reduction on the structure and activity of $RhAl_2O_3$ and $RhSiO_2$ catalysts. J. Catal. **119**(1), 47–64 (1989)
35. Chen, J.G., Colaianni, M.L., Chen, P., Yates, J.T., Fisher, G.B.: Thermal behavior of a rhodium/alumina model catalyst: disappearance of surface rhodium upon heating. J. Phys. Chem. **94**(12), 5059–5062 (1990)
36. Beck, D.D., Capehart, T.W., Wong, C., Belton, D.N.: XAFS characterization of Rh/Al_2O_3 after treatment in high-temperature oxidizing environments. J. Catal. **144**(1), 311–324 (1993)
37. Pundir, B.P.: Engine Emissions: Pollutant Formation and Advances in Control Technology. Alpha Science International, Limited (2007)
38. Pardiwala, J.M., Patel, F., Patel, S.: Review paper on catalytic converter for automotive exhaust emission. In: International Conference on Current Trends in Technology, pp. 382–481. NUiCONE (2011)
39. Bera, P., Hegde, M.S.: Recent advances in auto exhaust catalysis. J. Indian Inst. Sci. **90**(2), 299–325 (2010)
40. Heck, R.M., Farrauto, R.J.: Automobile exhaust catalysts. Appl. Catal. A **221**(1–2), 443–457 (2001)
41. Shelef, M., McCabe, R.W.: Twenty-five years after introduction of automotive catalysts: what next? Catal. Today **62**(1), 35–50 (2000)
42. Traa, Y., Burger, B., Weitkamp, J.: Zeolite-based materials for the selective catalytic reduction of NO_x with hydrocarbons. Microporous Mesoporous Mater. **30**(1), 3–41 (1999)
43. Nishita, Y., Mizuki, J., Tanka, H., Uenishi, M., Kimura, M.: Self regeneration of palladium-perovskite catalysts in modern automobile. J. Phys. Chem. Solids **66**, 274–282 (2005)
44. He, H.X.D.H., Dai, H.X., Au, C.T.: An investigation on the utilization of perovskite-type oxides $La_{1-x}Sr_xMO_3$ ($M = Co_{0.77}Bi_{0.20}Pd_{0.03}$) as three-way catalysts. Appl. Catal. B Environ. **33**(1), 65–80 (2001)

45. Taylor, K.C.: Why rhodium in three way catalysts? Catal. Rev.-Sci. Eng. **35**(4), 457–481 (1993)
46. Gandhi, H.S., Graham, G., McCabe, R.: Automotive exhaust catalysis. J. Catal. **216**(1–2), 433–442 (2003)
47. Shelef, M., Otto, K., Otto, N.C.: Poisoning of automotive catalysts. In: Advances in Catalysis, vol. 27, pp. 311–365. Academic Press (1979)
48. Heck, R.M., Farrauto, R.J.: Breakthrough catalytic technologies: the future. Catal. Air Pollut. Control. Commer. Technol. 71–112 (1995)
49. Fornalczyk, A., Saternus, M.: Removal of platinum group metals from the used auto catalytic converter. Metalurgija **48**(2), 133–136 (2009)
50. Zammit, M., Wuttke, J., Ravindran, P., Aaltonen, S.: The effects of catalytic converter location and palladium loading on tailpipe emissions. No. 2012-01-1247. SAE Technical Paper (2012)
51. Trinh, H.B., Lee, J.C., Suh, Y.J., Lee, J.: A review on the recycling processes of spent auto-catalysts: towards the development of sustainable metallurgy. Waste Manage. **114**, 148–165 (2020)
52. Hickey, N., Boscarato, I., Kaspar, J.: Air pollution from mobile sources: formation and effects and abatement strategies. In: Current Environmental Issues and Challenges, pp. 15–43. Springer, Dordrecht (2014)
53. Arcoumanis, C. (ed.): Internal Combustion Engines. Elsevier (2012)
54. Kašpar, J., Fornasiero, P., Hickey, N.: Automotive catalytic converters: current status and some perspectives. Catal. Today **77**(4), 419–449 (2003)
55. Ozawa, M.: Role of cerium–zirconium mixed oxides as catalysts for car pollution: a short review. J. Alloys Compd. **275**, 886–890 (1998)
56. Kirichenko, A.S., Seregin, A.N., Volkov, A.I.: Developing a technology for recycling automotive exhaust-gas catalysts. Metallurgist **58**(3), 250–255 (2014)
57. Hagelüken, B.C.: Recycling the platinum group metals: a European perspective. Platin. Met. Rev. **56**(1), 29–35 (2012)
58. Rumpold, R., Antrekowitsch, J.: September. Recycling of platinum group metals from automotive catalysts by an acidic leaching process. In: Proceedings of the 5th International Platinum Conference, Sun City, South Africa, The Southern African Institute of Mining and Metallurgy, pp. 695–713 (2012)
59. Tekper, I., Lewballah, J.K., Quaisie, J.K., Adzabe, F.J.K., Osei, E.Y., Asamoah, E., Baidoo, P., Danquah, A.: An Investigation into the Comparisons of Exhaust Emissions Through Catalytic Converters Installed on a Kia Sportage Lx (Exhaust System) (2020)
60. Benson, M., Bennett, C.R., Harry, J.E., Patel, M.K., Cross, M.: The recovery mechanism of platinum group metals from catalytic converters in spent automotive exhaust systems. Resour. Conserv. Recycl. **31**(1), 1–7 (2000)
61. Kizilaslan, E., Aktaş, S., Şeşen, M.K.: Towards environmentally safe recovery of platinum from scrap automotive catalytic converters. Turk. J. Eng. Environ. Sci. **33**(2), 83–90 (2010)
62. Hoffmann, J.E.: Recovery of platinum-group metals from gabbroic rocks metals from auto catalysts. JOM **40**(6), 40–44 (1988)
63. Kim, W., Kim, B., Choi, D., Oki, T., Kim, S.: Selective recovery of catalyst layer from supporting matrix of ceramic-honeycomb-type automobile catalyst. J. Hazard. Mater. **183**(1–3), 29–34 (2010)
64. Sasaki, H., Maeda, M.: Zn-vapor pretreatment for acid leaching of platinum group metals from automotive catalytic converters. Hydrometallurgy **147**, 59–67 (2014)
65. Liu, G., Tokumaru, A., Owada, S.: Separation of PGMs bearing alumina phase from cordierite in spent automobile catalyst by thermal shock. Resour. Process. **60**(1), 28–35 (2013)
66. Trinh, H.B., Lee, J.C., Srivastava, R.R., Kim, S.: Total recycling of all the components from spent auto-catalyst by NaOH roasting-assisted hydrometallurgical route. J. Hazard. Mater. **379**, 120772 (2019)
67. Paiva, A.P., Piedras, F.V., Rodrigues, P.G., Nogueira, C.A.: Hydrometallurgical recovery of platinum-group metals from spent auto-catalysts–focus on leaching and solvent extraction. Sep. Purif. Technol. **286**, 120474 (2022)

68. Schippers, A., Hedrich, S., Vasters, J., Drobe, M., Sand, W., Willscher, S.: Biomining: metal recovery from ores with microorganisms. Geobiotechnology **I**, 1–47 (2013)
69. Yong, P., Rowson, N.A., Farr, J.P.G., Harris, L.R., Macaskie, L.E.: A novel electro biotechnology for the recovery of precious metals from spent automotive catalysts. Environ. Technol. **24**(3), 289–297 (2003)
70. Kriek, R.J.: Leaching of selected PGMs: a thermodynamic and electrochemical study employing less aggressive lixiviants. Master's thesis (2008). University of Cape Town
71. Wang, S., Chen, A., Zhang, Z., Peng, J.: Leaching of palladium and rhodium from spent automobile catalysts by microwave roasting. Environ. Prog. Sustain. Energy **33**(3), 913–917 (2014)
72. Tyson, D.R., Bautista, R.G.: Leaching kinetics of platinum and palladium from spent automotive catalysts. Sep. Sci. Technol. **22**(2–3), 1149–1167 (1987)
73. Lanaridi, O., Platzer, S., Nischkauer, W., Betanzos, J.H., Iturbe, A.U., Del Rio Gaztelurrutia, C., Sanchez-Cupido, L., Siriwardana, A., Schnürch, M., Limbeck, A., Konegger, T.: Benign recovery of platinum group metals from spent automotive catalysts using choline-based deep eutectic solvents. Green Chem. Lett. Rev. **15**(2), 404–414 (2022)
74. Harjanto, S., Cao, Y., Shibayama, A., Naitoh, I., Nanami, T., Kasahara, K., Okumura, Y., Liu, K., Fujita, T.: Leaching of Pt, Pd and Rh from automotive catalyst residue in various chloride based solutions. Mater. Trans. **47**(1), 129–135 (2006)
75. Puvvada, G.V.K., Sridhar, R., Lakshmanan, V.I.: Chloride metallurgy: PGM recovery and titanium dioxide production. JOM **55**(8), 38–41 (2003)
76. Karim, S., Ting, Y.P.: Recycling pathways for platinum group metals from spent automotive catalyst: a review on conventional approaches and bio-processes. Resour. Conserv. Recycl. **170**, 105588 (2021)
77. Meng, X., Han, K.N.: Recovery of platinum and palladium from spent automobile catalytic converters by leaching with solutions containing halogen salts, ammonium and oxidants (No. CONF-951105-). Minerals, Metals and Materials Society, Warrendale, PA (United States) (1995)
78. Bollinger, M.A., Vannice, M.A.: A kinetic and DRIFTS study of low-temperature carbon monoxide oxidation over Au—TiO_2 catalysts. Appl. Catal. B **8**(4), 417–443 (1996)
79. Harada, S., Ohnishi, T., Ogura, M.: Two-step catalytic system using pulsatile heating to achieve NO decomposition in the presence of water vapor. Chem. Lett. **45**(11), 1283–1284 (2016)
80. Iwamoto, M., Furukawa, H., Mine, Y., Uemura, F., Mikuriya, S.I., Kagawa, S.: Copper (II) ion-exchanged ZSM-5 zeolites as highly active catalysts for direct and continuous decomposition of nitrogen monoxide. J. Chem. Soc. Chem. Commun. **16**, 1272–1273 (1986)
81. Ziolek, M., Sobczak, I., Decyk, P., Nowak, I.: NO adsorption and decomposition on Cu-containing mesoporous molecular sieves-comparison with CuZSM-5, vol. 125. In: Studies in Surface Science and Catalysis, pp. 633–640. Elsevier (1999)
82. Hasna, A.M.: Reduction of NO_x gases using copper zeolite catalyst, vol. 1. In: Proceedings of the World Congress on Engineering (2009)
83. An, H., McGinn, P.J.: Catalytic behavior of potassium containing compounds for diesel soot combustion. Appl. Catal. B **62**(1–2), 46–56 (2006)
84. Teraoka, Y., Fukuda, H., Kagawa, S.: Catalytic activity of perovskite-type oxides for the direct decomposition of nitrogen monoxide. Chem. Lett. **19**(1), 1–4 (1990)
85. Querini, C.A., Cornaglia, L.M., Ulla, M.A., Miro, E.E.: Catalytic combustion of diesel soot on Co, K/MgO catalysts. Effect of the potassium loading on activity and stability. Appl. Catal. B: Environ. **20**(3), 165–177 (1999)
86. Liu, S., Obuchi, A., Uchisawa, J., Nanba, T., Kushiyama, S.: An exploratory study of diesel soot oxidation with NO_2 and O_2 on supported metal oxide catalysts. Appl. Catal. B **37**(4), 309–319 (2002)
87. Mul, G., Kapteijn, F., Moulijn, J.A.: Catalytic oxidation of model soot by metal chlorides. Appl. Catal. B **12**(1), 33–47 (1997)
88. Tikhomirov, K., Kröcher, O., Elsener, M., Wokaun, A.: MnOx-CeO_2 mixed oxides for the low-temperature oxidation of diesel soot. Appl. Catal. B **64**(1–2), 72–78 (2006)

89. Shangguan, W.F., Teraoka, Y., Kagawa, S.: Promotion effect of potassium on the catalytic property of $CuFe_2O_4$ for the simultaneous removal of NO_x and diesel soot particulate. Appl. Catal. B **16**(2), 149–154 (1998)
90. Teraoka, Y., Kanada, K., Kagawa, S.: Synthesis of La K Mn O perovskite-type oxides and their catalytic property for simultaneous removal of NO_x and diesel soot particulates. Appl. Catal. B **34**(1), 73–78 (2001)
91. Mul, G., Neeft, J.P., Kapteijn, F., Makkee, M., Moulijn, J.A.: Soot oxidation catalyzed by a Cu/K/Mo/Cl catalyst: evaluation of the chemistry and performance of the catalyst. Appl. Catal. B **6**(4), 339–352 (1995)
92. Wu, X., Liang, Q., Weng, D., Lu, Z.: The catalytic activity of CuO–CeO_2 mixed oxides for diesel soot oxidation with a NO/O_2 mixture. Catal. Commun. **8**(12), 2110–2114 (2007)
93. Zhang, H., Wang, J., Cao, Y., Wang, Y., Gong, M., Chen, Y.: Effect of Y on improving the thermal stability of MnOx-CeO_2 catalysts for diesel soot oxidation. Chin. J. Catal. **36**(8), 1333–1341 (2015)
94. Zhenhua, G., Xiuli, S., Hua, W., Kongzhai, L.: Structure and catalytic property of CeO_2-ZrO_2-Fe_2O_3 mixed oxide catalysts for diesel soot combustion: effect of preparation method. J. Rare Earths **32**(9), 817–823 (2014)
95. Neyertz, C.A., Banús, E.D., Miró, E.E., Querini, C.A.: Potassium-promoted $Ce_{0.65}Zr_{0.35}O_2$ monolithic catalysts for diesel soot combustion. Chem. Eng. J. **248**, 394–405 (2014)
96. Wagloehner, S., Nitzer-Noski, M., Kureti, S.: Oxidation of soot on manganese oxide catalysts. Chem. Eng. J. **259**, 492–504 (2015)
97. Legutko, P., Jakubek, T., Kaspera, W., Stelmachowski, P., Sojka, Z., Kotarba, A.: Soot oxidation over K-doped manganese and iron spinels—how potassium precursor nature and doping level change the catalyst activity. Catal. Commun. **43**, 34–37 (2014)
98. Legutko, P., Kaspera, W., Stelmachowski, P., Sojka, Z., Kotarba, A.: Boosting the catalytic activity of magnetite in soot oxidation by surface alkali promotion. Catal. Commun. **56**, 139–142 (2014)
99. Venkataswamy, P., Jampaiah, D., Rao, K.N., Reddy, B.M.: Nanostructured $Ce_{0.7}Mn_{0.3}O_{2-\delta}$ and $Ce_{0.7}Fe_{0.3}O_{2-\delta}$ solid solutions for diesel soot oxidation. Appl. Catal. A **488**, 1–10 (2014)
100. Busca, G., Lietti, L., Ramis, G., Berti, F.: Chemical and mechanistic aspects of the selective catalytic reduction of NO_x by ammonia over oxide catalysts: a review. Appl. Catal. B **18**(1–2), 1–36 (1998)
101. Grossale, A., Nova, I., Tronconi, E.: Study of a Fe–zeolite-based system as NH_3-SCR catalyst for diesel exhaust aftertreatment. Catal. Today **136**(1–2), 18–27 (2008)
102. Brandenberger, S., Kröcher, O., Tissler, A., Althoff, R.: The state of the art in selective catalytic reduction of NO_x by ammonia using metal-exchanged zeolite catalysts. Catal. Rev. **50**(4), 492–531 (2008)
103. Cheung, T., Bhargava, S.K., Hobday, M., Foger, K.: Adsorption of NO on Cu exchanged zeolites, an FTIR study: effects Of Cu levels, NO pressure, and catalyst pretreatment. J. Catal. **158**(1), 301–310 (1996)
104. Hepburn, J.S., Thanasiu, E., Dobson, D.A., Watkins, W.L.: Experimental and modeling investigations of NO_x trap performance. SAE Transactions, pp. 1987–2009 (1996)
105. West, B., Huff, S., Parks, J., Lewis, S., Choi, J.S., Partridge, W., Storey, J.: Assessing reductant chemistry during in-cylinder regeneration of diesel lean NO_x traps. SAE Transactions, pp. 1975–1985 (2004)
106. Das, R.K., Bhattacharyya, S., DuttaGupta, M., Ghosh, B.B.: Theoretical and experimental analysis of iron-exchanged X-zeolite catalyst for SI engine emission control. Exp. Therm. Fluid Sci. **19**(4), 214–222 (1999)
107. Putrasari, Y.: Preparation of nio catalyst on fecral substrate using various techniques at higher oxidation process. Doctoral dissertation, Universiti Tun Hussein Onn Malaysia (2011)
108. Imanaka, N., Masui, T.: Advances in direct NO_x decomposition catalysts. Appl. Catal. A **431**, 1–8 (2012)
109. Green, T.E., Hinshelwood, C.N.: CCXXIV—the catalytic decomposition of nitric oxide at the surface of platinum. J. Chem. Soc. (Resumed) **129**, 1709–1713 (1926)

110. Iwamoto, M., Yahiro, H., Tanda, K., Mizuno, N., Mine, Y., Kagawa, S.: Removal of nitrogen monoxide through a novel catalytic process. 1. Decomposition on excessively copper-ion-exchanged ZSM-5 zeolites. J. Phys. Chem. **95**(9), 3727–3730 (1991)
111. Hamada, H., Kintaichi, Y., Sasaki, M., Ito, T.: Silver-promoted cobalt oxide catalysts for direct decomposition of nitrogen monoxide. Chem. Lett. **19**(7), 1069–1070 (1990)
112. Teraoka, Y., Torigoshi, K.I., Yamaguchi, H., Ikeda, T., Kagawa, S.: Direct decomposition of nitric oxide over stannate pyrochlore oxides: relationship between solid-state chemistry and catalytic activity. J. Mol. Catal. A Chem. **155**(1–2), 73–80 (2000)
113. Ogata, A., Obuchi, A., Mizuno, K., Ohi, A., Aoyama, H., Ohuchi, H.: Enhancement effect of Mg^{2+} ion on direct nitric oxide decomposition over supported palladium catalysts. Appl. Catal. **65**(2), L11–L15 (1990)
114. Imanaka, N., Masui, T., Masaki, H.: Direct decomposition of nitric oxide over C-type cubic $(Gd_{1-x-y}Y_xBa_y)_2O_{3-y}$ solid solutions. Adv. Mater. **19**(21), 3660–3663 (2007)
115. Zhang, H.M., Shimizu, Y., Teraoka, Y., Miura, N., Yamazoe, N.: Oxygen sorption and catalytic properties of $La_{1-x}Sr_xCo_{1-y}Fe_yO_3$ perovskite-type oxides. J. Catal. **121**(2), 432–440 (1990)

Chapter 18
Two-Wheeler Electric Vehicles Purchase Policy

Apoorva Kashyap, Anshuman Bajpai, and Ram Krishna Upadhyay

Abstract The global crescent concern about climate change caused by automotive greenhouse gas emissions and the environmental destruction of natural resources is pushing world economies to adopt an innovative alternative fuel technology. Electric vehicles are being posed as a green and sustainable, innovative technology which has the potential to empower a streamlined transition to a low-carbon transportation system while preserving natural resources. Numerous nations have made extraordinary attempts to help the utilization of electric vehicles as of late; for instance, modern nations together with Norway and the Netherlands in Europe and the USA have strengthened individuals' desire to utilize electric vehicles through appropriate appropriations and concealment of private vehicles. In Asia, Taiwan has been fostering the arrangement of supplanting fossil fuel-based traditional two-wheeler vehicles with two-wheeler electric vehicles (TWEVs) and reinforcing the approach by supplanting countless old TWEVs and sponsoring the acquisition of TWEVs. This study was conducted on college-going students, as they were the likely main category to purchase TWEVs. Their idea of natural manageability can be molded for developing vehicle use propensities. This study uses a survey form to investigate the factors influencing the purchase of traditional two-wheeler and factors that will prompt a college student to purchase a two-wheeler electric vehicle in the near future. Factor analysis is conducted on the Likert scale data obtained through a questionnaire survey to club the various variables into a few factors for more straightforward interpretation. This study used Statistical Package for the Social Sciences (SPSS) software to analyze factors. Later, a comparative assessment is carried out of the factors affecting the purchase intention of fossil fuel-based traditional two-wheeler and two-wheeler electric vehicles.

Keywords Electric vehicles · Adoption · Management · Correlation

---

A. Kashyap · A. Bajpai · R. K. Upadhyay (✉)
School of Engineering and Applied Sciences, National Rail and Transportation Institute, Vadodara, Gujarat, India
e-mail: ram.upadhyay@gsv.ac.in

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_18

18.1 Introduction

The 17 Sustainable Development Goals, declared under the 2030 Agenda for Sustainable Development, were adopted by all members of the United Nations in 2015. The goals were an urgent call for action by all countries through global partnership. One of the major focuses of these sustainability goals is to create a sustainable way of living while actively battling the rapid climate change caused by humans. These intentions are highlighted in the following Goals [1]:

- Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
- Make cities and human settlements inclusive, safe, resilient, and sustainable.
- Take urgent action to combat climate change and its impacts.

The function of transportation in sustainable development was initially highlighted during the United Nations' Earth Summit in 1992, and it was reaffirmed in Agenda 21, the summit's conclusion document. During the nineteenth Special Session in 1997, the United Nations General Assembly conducted a five-year review of Agenda 21 implementation, noting that transportation is expected to be the primary driving force behind a growing global demand for energy over the next twenty years. As predicted, it is now the largest user of energy in developed countries and the fastest-growing one in most developing countries. Furthermore, the significance of transportation was once again captured in the final document of the 2002 World Summit on Sustainable Development—the Johannesburg Plan of Implementation (JPOI).

There has been a renewed focus on sustainable transportation worldwide in recent years. During the United Nations Conference on Sustainable Development (2012) (Rio +20), world leaders unanimously agreed that transportation and mobility are critical to long-term development. Economic growth and accessibility can both benefit from sustainable mobility. The UNFCCC perceives the significance of transportation for environmental activity; the vehicle area will assume an incredibly significant part in accomplishing the Paris Agreement, considering that transportation represents almost a fourth of all energy-related worldwide ozone-harming substance discharges, and these outflows are supposed to fill altogether in the years to come [2].

In its attempt to achieve the Goals, India has been trying to cut down its Carbon Emissions by signaling the onset of a new era of mobility. The focus on electrification of transportation as the major technical avenue to achieve this transition has been driven by global technology trends and India's fast-rising economy. This junction offers India a powerful but fleeting potential to become a global leader in innovative mobility solutions and battery manufacturing, putting the country on track for long-term economic growth and global competitiveness. India is uniquely positioned to deploy electric vehicles (EVs) at scale, leapfrogging old mobility paradigms that perpetuate traffic congestion, air pollution, and oil import dependency while driving down battery costs even faster than current predictions anticipate through economies of scale [3].

With the announcement of the PM Gati Shakti Master Plan emphasizing the significance of high-quality multi-modal transportation in achieving total cost competitiveness through sustainable means, it becomes necessary to take a step back and look at the varied implementation of the electric vehicle, its adoption pan India and primarily the youth.

18.1.1 Global Trends in Greenhouse Gas Emissions

China (26%) is the world's largest GHG emitter, accounting for 13% of global emissions, followed by the USA (13%), the European Union (more than 8%), India (7%), Russia Federation (5%), and Japan (2%) (~3%). These countries are also responsible for the highest CO_2 emissions [4].

18.1.2 Pollution Levels in India

Over the last few decades, India's increasing urbanization, population, and wealth growth have significantly impacted its residents' mobility.

Since 1980, India's transportation demand has increased by about eight times more than any other Asian economy. This rapid expansion has benefited the country in various ways, including establishing a booming auto sector and related economic prosperity. However, there are several obstacles to overcome. A recent WHO survey shows fourteen Indian cities are among the world's top fifteen most polluted cities [5]. This problem causes enormous health and welfare losses, which the World Bank estimates to be 7.7% of India's GDP (PPP adjusted). Furthermore, major Indian cities are now frequently ranked among the most congested cities in the world. In some metros, the average vehicle speed is as low as 17 km/h. Congestion costs a lot of money in terms of lost productivity and wasted fuel; a high-level estimate of the economic loss from congestion in our top four metros is over USD 22 billion per year [6].

The many contaminations from the emission usually contaminate the air when they mix with it, posing a risk to people and the environment. Because car emissions occur at such a low altitude, automotive pollution is difficult to avoid. It is the level of the environment in which people live and breathe. CO, CO_2, nitrogen oxides, and particulate matter are the primary polluting pollutants released by vehicles and are responsible for air pollution.

The following list is a brief introduction to various contaminants and their impact on individual health:

- **Carbon monoxide** is one of the most severe contaminants found in automobile exhaust. Due to a lack of adequate oxygen supply, it is a dangerous gas framed in the burning council of cars. Fuel motors and forest fires account for roughly 90% of CO in the atmosphere. CO has a negative impact on people's health; when someone is exposed to CO, their blood's oxygen-carrying capacity drops, which can lead to headaches, respiratory problems, and even death.
- **Nitrous Oxides (NO) and Nitric Oxides (NO_2)** are two types of nitrogen oxides. Vehicle emissions are responsible for half of all global nitrogen oxide emissions. Because of the extreme traffic volumes in cities, these oxides have a negative impact. Individual health is often unaffected by inhaling nitric acid, but NO_2 can be dangerous to humans if inhaled in larger amounts. These vehicle toxins can irritate the lungs and weaken the body's defenses against respiratory infections such as pneumonia and flu. They also contribute to the production of ozone and particle pollution. In many urban areas, nitrogen oxide pollution accounts for 33% of the fine particulate pollution that can be seen all over.
- **Carbon Dioxide:** The increase in the size of CO_2 in the atmosphere results from many human activities. In the current condition, the vehicular outflow is responsible for 25% of total CO_2 increases worldwide. CO_2 is now the primary cause of global warming. According to many studies, the earth's temperature rises by 1 °C every thirty years due to the rapid increase in the CO_2 in the atmosphere.
- **Particulate Matters** are solid particles such as dust, dirt, smoke, and liquid droplets. Wind, fires, and automobile construction procedures can emit these particles into the atmosphere.

India accounted for roughly 7.2% of global greenhouse gas emissions and 6.9% of global CO_2 emissions in 2018 [4]. With 23.5% CH_4, 5.7% N_2O, and 0.9% F-gas emissions, total greenhouse gas emissions were 70% CO_2 and 30% non-CO_2, mostly methane. India's annual GDP growth has been around 7% for more than a decade, and in 2018, it was around 8%. With a 7.0% increase, the trend continued. On the other hand, the annual change in greenhouse gas emissions shows that emissions had a more variable character, with many falling between 2 and 4%. In 2018, India's greenhouse gas emissions increased by about 5.5% to 3.7 billion tons of CO_2, up from 3.7 billion tons of CO_2 in 2017 [4].

The large increases of 8.7% in coal consumption, 8.1% in natural gas consumption, and 5.1% in oil consumption contributed to the 7.3% increase in CO_2 emissions in 2018 [4]. In 2018, India's electric power production increased by 6.2% to 1.56 Gigawatt hours (GWh), making it the country's largest source of CO_2 emissions with a 50% share. Coal-fired power plants provided three-quarters of total electricity in 2018, with natural gas accounting for 5%, renewable energy at 16.7%, and nuclear power accounting for 2.5%. Coal power accounted for nearly two-thirds of the total power increase in 2018, with hydropower accounting for 4%, other renewable power accounting for 28% (primarily wind and solar energy), and nuclear power accounting for a 2% increase in total power.

18.1.3 Conventional and Electric Two-Wheelers: Status Quo of the World

In many parts of the world, two-wheelers with combustion engines, such as scooters, and motorcycles, play an important role in transportation. Two-wheelers account for a large portion of the passenger vehicle population in South and Southeast Asia, with 72% in India, 87% in Indonesia, and 95% in Vietnam [7]. In several Asian countries, the fleet is growing at a rate of up to 10% per year. Powered two-wheelers account for 12% of all registered vehicles in Europe, though nearly half of these are of more than 250 cc and are frequently used for touring and sports rather than utility mobility. Motorcycles account for 26% of the vehicle population in Brazil but only 3% in North America. Two-wheelers accounted for more than a quarter of overall passenger transport activity (measured in passenger-km) in China and Southeast Asia in 2015, more than any other mode [8].

Two- and three-wheelers are simple to electrify due to their lightweight and smaller driving distances, which necessities small batteries with fewer charging issues from power systems. In some areas, electrification already makes economic sense in terms of the total cost of ownership. Two/three-wheelers are today's most electrified road transport segment, accounting for more than 20% [9]. Electric two/three-wheelers are projected to be the enormous EV armada among all transport modes. Development is, for the most part, in Asia, where two/three-wheelers are predominant. The worldwide supply of electric two/three-wheelers in the Stated Policies Scenario increments from north of 290 million in 2020 to in excess of 385 million by 2030, to account for 33% of the complete stock in 2030 [9]. Deals of electric two/three wheelers increment from around 25 million in 2020 to 50 million in 2030, representing the greater part, everything being equal. In the Sustainable Development Scenario, the worldwide supply of electric two/three-wheelers comes to more than 490 million by 2030, around 40% of the complete stock for two/three-wheelers. This compares to more than 60 million in 2030, representing practically 75% of all deals, a 25% increment compared with the Stated Policies Scenario [9].

On the other hand, motorcycles are important contributors to air pollution, noise, and CO_2 emissions and are involved in many traffic accidents. Motorcycles are the primary means of transportation for a considerable portion of the population in many Asian cities [10]. In congested cities like Hanoi, motorbike accessibility to jobs is higher than any other means [11]. It has a higher status than a bicycle and is thought to be handier, especially in hot and humid weather. Motorcycles are generally inexpensive and accessible to most households, making them an equitable method of transportation.

Motorcycle mode share is frequently low in European cities but has recently increased. Amsterdam is a good example, with mopeds and scooters accounting for roughly 2% of all journeys in 2016, up from 2% in 2008. Despite intentions and widespread popular support to prohibit mopeds and scooters from utilizing bicycle lanes, these vehicles are still permitted to use all bike lanes. They are not required to wear helmets as of mid-2018. The users are diversified, encompassing people of various ages and income levels.

At the same time, electric two-wheelers are becoming more popular, and in some countries, such as China (7%) and Denmark, the Netherlands, and Japan (2–4%), they already have a sizeable modal share [12]. China dominates E2W sales with over 30 million units sold and a stock of about 250 million, followed by Europe with 2.3 million units sold and the rest of the globe with roughly 1 million units sold in 2015 [13].

In China, petrol-fueled motorcycle prohibitions began in several cities in the early 2000s, beginning with a sales ban in Shanghai in 1996, resulting in a huge and rapid uptake of e-bikes, particularly scooter-style e-bikes, with a 15–25% trip mode share in important cities [7]. They have also become popular in cities where traditional motorcycles are still permitted. E-bikes have pedals and are classified as non-motorized vehicles, which means they do not need a helmet or a license and can ride in bike lanes. In a small, medium, and big cities, e-bikes are used by a diverse spectrum of user groups, as well as a method of public transportation. Lower-income groups, on the other hand, are more likely to ride two-wheelers [7].

Vietnam has the most significant percentage of motorcycles in its vehicle fleet, but e-bikes are not yet widely used. Those who do not have access to motorcycles are the primary users. Students are a prominent user group, as they find these handier than bicycles because they do not require a license, registration, or helmet, as motorbikes do. E-bikes are frequently of a sort that is a combination of scooter-style and bicycle-style e-bikes. Although they have pedals, they are rarely used. In some cities, two-wheeler lanes exist, but they must share the road with other vehicles in most cases. No explicit policies are in place to encourage the use of electric two-wheelers.

18.1.4 Two-Wheelers in India

Two-wheelers are one of India's most widely used forms of motorized personal transport. India is the world's second-largest motorized two-wheeler market, trailing only China, and its market share is increasing as the country increasingly urbanizes. According to estimates from 2001, two-wheelers accounted for 60–70% of registered vehicles in major cities, according to research conducted by the Ministry of Urban Development (MoUD) in 30 Indian cities [14, 15]. In the same period, the percentage of urban families owning a two-wheeler climbed from 11.6 to 33%, while household automobile ownership increased from 1.2 to 6.5%. Since the 1970s, the expansion of motorized two-wheelers in the country has surpassed that of automobiles. While private car ownership climbed sevenfold between 1981 and 2002, two-wheeler ownership increased 16-fold [16]. Nearly, 14 million two-wheelers were sold in 2012–13, more than five times the number of automobiles sold in the same year. Given the recent increase in urban population and vehicle ownership, existing mode shares may favor private motor vehicles even more (cars and two-wheelers). However, two-wheelers are the most common means of transportation in most cities.

The most significant modal share of two-wheelers is seen in mid-sized cities like Pune, Ahmedabad, Chennai, and Hyderabad, with populations ranging from 3.8 million in the Pune Metropolitan Region to 6.6 million in Chennai [16].

18.1.5 Indian EV Programs and Policies

The focal and state legislatures and nodal organizations driving the arrangement switches are consistently viewed as essential partners in improving another innovation or area. With electric mobility, the focal and state legislatures and nodal organizations should distinguish the arrangement and administrative obstructions to work with private area interests in the area. Along these lines, the partners should distinguish ways of advancing the progress of the current auto industry by taking on more up-to-date advancements, safeguarding occupations, and keeping up with its financial commitments. The government should likewise proactively distinguish what's in store patterns of the quickly changing area to advance the reception of the best and most proficient advancements [17].

The accessibility of EV innovation has progressively expanded in India. The laid-out players across esteem chains have contributed more than five years to foster EV-related advancements. The vehicle business is focused on advancements to expand the reach, abbreviate the charging time, and make electric vehicles available at reasonable prices for the masses. As a result, technology and supply may not be as challenging as a demand if we look at the global EV market. This is because India is a price-sensitive market. Once demand picks up, battery and EV prices are expected to fall even further, bringing them on par with other competing technologies. On the other hand, policy and regulatory initiatives are required to boost supply and demand-side stakeholders. This includes completing the necessary standards, regulations, and incentives to improve supply-side readiness. In addition, initiatives to increase demand aggregation are required. State governments are likely to act as enablers by making land available for the construction of EV infrastructure [17].

While many countries have made electric vehicles a part of their transportation policies, their responses have varied depending on their economic growth stage, energy resource endowments, technological capabilities, and political priorities for climate change responses. A unique set of circumstances in India has presented an opportunity for quicker adoption of EVs over ICE vehicles, allowing for a more sustainable mobility paradigm. These are the following:

- A relative abundance of renewable energy resources can be exploited.
- Ample qualified labor and technology in manufacturing and IT software are readily available.
- Infrastructure and consumer transformation allow for technology applications to leapfrog developmental stages.
- A worldwide culture accepts and encourages asset and resource sharing for the most significant benefit.

In light of these circumstances, India should pursue an EV policy that systematically assures that India's EV program keeps pace with the global scale since large economies appear to be making significant progress toward vehicle electrification. India's growth prospects open the possibility of achieving EV leadership in specific segments. This way, the policy will encourage a route that begins with India's unique traits and initiatives in the auto sector and progresses to global relevance and applicability. The following are the main goals of the EV policy [18]:

- Reduce transportation's use of primary oil.
- Encourage customers to buy electric and alternative-fuel automobiles.
- Encourage the use, application, study, and development of cutting-edge technology in India.
- Enhance public transit for both personal and commercial purposes.
- Make cities less polluted.
- Develop global scale and competitive electric vehicle production capacity.
- Encourage job creation in the early morning industry.

Policies at Central Level. Owing to these factors, the Ministry of Road Transport and Highways, the Department of Heavy Industry, the Department of Industrial Policy and Promotion, the Ministry of Finance, the Ministry of Housing and Urban Affairs, the Ministry of Power, the Ministry of New and Renewable Energy, the Department of Science and Technology, and NITI Aayog have all been involved in supporting the electric mobility transition at the national level. Furthermore, 27 states have developed strategies for transforming their mobility systems, and several states have developed or are developing EVs [3]. The efforts and initiatives undertaken by various ministries are discussed in brief below:

- **Ministry of Power (MoP)**: MoP has clarified that charging electric vehicles is considered a service rather than a sale of electricity, which means that no license is required to operate EV charging stations. Also published a policy on charging infrastructure to encourage the use of electric vehicles. Private charging at houses and offices is allowed under the policy as long as the charge for supplying power to an EV charging station does not exceed the average supply cost plus 15%.
- **Ministry of Road Transport and Highways (MoRTH)**: MoRTH has declared that green license plates will be issued to battery-operated cars, both private and commercial (GSR 749 (E)). Also said that it will make it easier to import 2,500 electric vehicles that meet international standards without the necessity for homologation (GSR 870 (E)). According to another announcement, all battery-operated, ethanol-powered, and methanol-powered transport vehicles will be excluded from the need for licenses (SO 5333(E)). They have also revised the Central Motor Vehicles Rules (CMVR) of 1989 to allow drivers between the ages of 16 and 18 to operate gearless electric scooters and motorcycles with batteries up to 4 kWh (GSR 1225 (E)).
- **Department of Science and Technology (DST)**: DST has launched a Grand Challenge to create an Indian Electric Vehicle Charging Infrastructure Standards.

In addition, the Bureau of Indian Standards (BIS) has issued generic EV charging specifications based on the CCS and CHAdeMO charging standards.

- **Indian Space Research Organization**: The Indian Space Research Organization (ISRO) has released a request for a quotation (RFQ) document to commercialize lithium-ion battery technology developed in India. So far, ten companies have been shortlisted for technology transfer.
- **Ministry of Housing and Urban Affairs (MoHUA)**: MoHUA has published an amendment to the building code and municipal planning rules to allow for installing electric vehicle charging stations in private and commercial structures.
- **NITI Aayog**: Through the Operating Expenditure (OPEX) model, NITI Aayog has released a concessionaire agreement for various public–private partnerships in the operations and maintenance of electric buses in cities. The upfront capital requirement would be reduced because the lease would be executed on a per-kilometer basis. The Cabinet approved the National Mission on Transformative Mobility and Battery Storage, and it will promote clean, connected, shared, sustainable, and holistic mobility activities. The Mission intends to establish a five-year Phased Manufacturing Program (PMP) to help India build large-scale, export-competitive integrated battery and cell manufacturing mega facilities and localize production across the entire electric vehicle value chain.
- **Ministry of Finance**: To assist Make in India and encourage the adoption of electric vehicles, the customs duty on all categories of vehicles, battery packs, and cells has been reduced (Notification no. 03/2019-Customs).
- **Department of Heavy Industries**: FAME II, the Cabinet authorized the second phase of the scheme for faster adoption and manufacturing of (hybrid and) electric vehicles in India. The initiative has a budget of Rs 10,000 crores, which will be utilized to provide upfront incentives for electric vehicle purchases and promote the development of charging infrastructure. The program will be implemented over three years, beginning on April 1, 2019.

Policies at State Level. As indicated by a new report by the Federation of Automobile Dealers Associations (FADA), in February, India's electric vehicle fragment saw a 58% development when contrasted with January and around 297% increment when contrasted with the earlier year [19]. The information shows that among Indian states, Uttar Pradesh tops the rundown with 2,55,770 enlisted EVs, followed by Delhi with 1,25,347 and Karnataka with 72,544, respectively, Bihar with 58,104, and Maharashtra with 52,506 eV enrollments [19].

Even amid a worldwide pandemic, the expansion in EV deals isn't credited to the approaching climb in fuel costs alone but to the expanded mindfulness and switching public cognizance toward seeing clean energy. The focal government and different state legislatures have been empowering the reception and assembling of electric vehicles by presenting a few arrangements and expense derivations.

Table 18.1, which is listed below, gives a brief overview of the various policies enacted by States at their level to encourage the adoption and, in some cases, manufacturing of electric vehicles. Apart from the states listed below, many other states

Table 18.1 State policies for electric vehicles [3, 20]

State	Policy	Key policy elements/targets
Andhra Pradesh	Electric Mobility Policy, 2018–2023	The goal of ten lakh EVs by 2024 • The goal of one lakh fast and slow EV charging stations by the year 2024 • In the upcoming capital city of Amravati, government plans to stop the registration of petrol and diesel vehicles by 2024 • All government vehicles, including boards, corporations, and government ambulances, must be electric vehicles by 2024
NCT of Delhi	Draft Electric Vehicle Policy, 2018	• Aims to increase EV registrations to 25% of all vehicle registrations by 2023 • It aims to convert 50% of its public transport to electric vehicles by 2023 • Proposes a feebate to fund a high proportion of incentives • Encourages the reuse and recycling of EV batteries that have their end of life
Karnataka	Electric Vehicles Manufacturing Policy, 2018	• 100% of three- and four-wheeler moving goods will be encouraged to transition to electric by 2030 • Incentives for first 100 fast chargers • Encourages start-ups to develop business models focused on supporting economic applications for EVs
Kerala	Electric Vehicle Policy, 2018	• The target of bringing 1 million EVs to the state by 2022 • By 2022, the state aims to pilot a fleet of 20,000 two-wheelers, 50,000 three-wheelers, 1,000 goods carriers, 3,000 buses, and 100 ferry boats

(continued)

Table 18.1 (continued)

State	Policy	Key policy elements/targets
Maharashtra	Electric Vehicle and Related Infrastructure Policy, 2018	• Target to increase the number of EV registrations in Maharashtra to 5 lakhs • Generate an investment of Rs 25,000 crores for the manufacturing of EVs • Create jobs for 1 lakh people
Telangana	Electric Vehicle Policy Draft, 2017	• Telangana State Transport Corporation to set a target of 100% electric buses by 2030 for intra-city, inter-city, and inter-state transport • Telangana Government will set up the first 100 fast charging stations in GHMC and other cities in a phased manner
Uttar Pradesh	Electric Vehicles Manufacturing Policy, 2018	• The goal of 1,000 electric buses deployed in the state by 2030 • The target of achieving 100% electrification of auto rickshaws, cabs, school buses/vans, etc., by 2030 in five cities: GB Nagar, Lucknow, Kanpur, Varanasi, and Ghaziabad
Uttarakhand	EV Manufacturing, EV Usage Promotion and Related Services Infrastructure Policy, 2018	• It aims to make Uttarakhand a preferred destination for investment in EV manufacturing capacity • Particular focus on developing green highways in Dehradun, Haridwar, Rishikesh, Haldwani, Rudrapur, and Kashipur • Term loans from One hundred million to Rs. 500 million will be provided to micro, small, and medium enterprises interested in manufacturing EVs

have already begun formulating effective policies for electric vehicle adoption and encouragement.

Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) Scheme

FAME scheme encourages the adoption of electric and hybrid vehicles. It incentivizes the manufacturers and infrastructure providers of electric vehicles through subsidies. The first phase (phase I) started in 2015 and ended in March 2019. Phase II of the scheme is operational from April 2019 to March 2024.

Phase II of the FAME scheme has been authorized by the government, with a budget of Rs 10,000 crore for three years beginning April 1, 2019. About 86% of overall budgetary support has been set aside for the Demand Incentive, which aims to increase demand for EVs throughout the country. This phase will support 7000 e-buses, 5 lakh e-3 wheelers, 55,000 e-4 wheeler passenger cars (including Strong Hybrid), and 10 lakh e-2 wheelers to build demand. However, because provision has been made for inter- and intra-segment fungibility, these data may fluctuate depending on the off-take of different categories of EVs [21].

The system will only incentivize sophisticated batteries and registered automobiles. The scheme will be applied primarily to cars used for public transportation or those registered for commercial reasons in the e-3W, e-4W, and e-bus segments, with a greater emphasis on providing economical and environmentally friendly public transportation options for the masses. However, as a mass segment, privately owned registered e-2Ws are also covered by the scheme.

Originally scheduled to take effect on April 1, 2019, for three years, it will now be in effect until March 31, 2024. This extension came just two weeks after the Department of Heavy Industries boosted the demand incentive for electric two-wheelers (e2W) from Rs 10,000/KWh km to Rs 15,000/KWh, a move that the EV sector applauded because it allowed them to lower model costs by Rs 7,000–20,000. Two major changes to the original scheme were predicted, given that it had been criticized for failing to increase the share of electric vehicles in the Indian market. According to current data, just 5% of the allocated Rs 10,000 crore, or roughly Rs 500 crore, has been invested thus far to make green mobility affordable. Only 58,613 e2Ws were sold under the scheme till June 2021, compared to a target of 10 lakh by March 2022 [22].

The total cost for the Rs 10,000 crore FAME-II plan is divided into Rs 8,596 crore for request motivating force, Rs 1,000 crore for charging foundation, and equilibrium for organizational framework and severe use in FAME-I [23]. Almost 200,000 vehicles have been upheld under the FAME-II plan. Endowments for the last three monetary years absolute Rs 900 crore for electric two- and three-wheelers. Karnataka has the most significant number of recipients under the FAME scheme, trailed by Tamil Nadu, Maharashtra, Rajasthan, and Delhi, on account of likewise extra state-level motivating forces [23].

Research Area and Scope. Despite the allocation of more than 900 crores under the FAME-II scheme and various concessions and incentives at the state level (mentioned in Table 18.1), the adoption rate of two-wheeler EVs remains low. As per a new report by the Federation of Automobile Dealers Associations (FADA), in February, India's electric vehicle fragment saw a 58% development compared with January and around 297% increment when contrasted with the earlier year of 2020 [19]. However, despite the rise shown in numbers, only 1.32% of all vehicle sales in the financial year 2021–2022 were electric [24]. This number is far too low to be considered a satisfactory result of a 900 crore program and points toward certain missing factors that have caused hindrances to adopt electric vehicles, especially when two- and three-wheeler electric vehicles have become almost as cost-competitive as traditional ones.

In order to understand this disparity, this research has been carried out. The research was aimed at understanding the perception of a two-wheeler electric vehicle from a potential consumer's perspective. It listed several characteristics of both electric vehicles and traditional fossil fuel-based vehicles and asked the respondents to rate them according to their preferences.

The target audience for this research data was college students from various states across India. The basic idea behind this decision was to keep in mind the demographics of the Indian populace and highlight the potential customers of the electric manufacturers in the next two to three years. As per the census of 2011, the population in the age group of 15–34 years had reached 430 million [25]. India is one of the most youthful countries on the planet, with over 62% of the populace in the functioning age bunch (15–59 years) and over 54% of the whole populace under 25 years old [26]. In addition, the youth are also considered to be the early adopters of technology worldwide. In order to incorporate this young populace, the youth were targeted as respondents for this research project.

The decision to focus on only two-wheeler electric vehicles for this research project was taken while keeping in focus that two-wheelers are the most widely used means of private transportation in India. They are also relatively cheap and the most accepted and affordable means of transportation. This point has been discussed adequately under Sect. 1.4.

Therefore, our final research question was "What features/characteristics are considered important by the youth of India (college-going students) while buying or switching over to an electric two-wheeler?".

18.2 Methodology

The research study conducted was quantitative in nature. It involved collecting data through a customized questionnaire and then analyzing it to fulfill the objectives of this research. We used a theory-based descriptive research design for the purpose of this research.

18.2.1 Data Collection

The primary data-gathering approach used in this study was online surveys to investigate the factors influencing college students' decision to purchase a two-wheeled electric car. For data gathering, we adopted a non-probabilistic sampling approach. Finding all the college students who could be interested in buying a two-wheeler electric car is challenging, time-consuming, and expensive. As a result, we adopted a non-probabilistic sampling approach called purposive sampling. For data collection, we created a questionnaire using several adoption scales and metrics that have already been stated in the literature review and have been used by multiple other authors when conducting similar surveys.

- Section 1 had questions related to the socioeconomic characteristics of users. It contained all the participants' personal information, such as their gender, age, education, family income, and current city of residence.
- Section 2 included questions about their current travel choices, such as their average daily commuting distances, current modes of transportation, and the purpose of the major number of trips they undertook.
- Section 3 had questions related to factors that affect traditional two-wheeler purchases. The factors were the following: 1. initial buying cost, 2. maintenance cost, 3. cost of spare parts and accessories, 4. look at the bike, 5. mileage, 6. engine capacity, 7. top speed, 8. pick up, and 9. reselling value. This section also included the question through which we tried to understand the college student's perception of the drawbacks of fossil fuel-based two-wheelers. The question was framed as follows: What do you feel is the biggest drawback of fossil fuel-based two-wheelers? Furthermore, the option given was 1. contributes to environmental pollution, 2. rising prices of fuel, and 3. maintenance costs.
- Section 4 had questions about electric vehicle awareness and its positive environmental impact. This section also included some hypothetical scenarios such as how likely attributes like government subsidies, on-road prices, Range of vehicle, charging infrastructure, maintenance cost, cost of spare parts and accessories, top speed, recharge time, battery replacement/rental prices, battery warranty, environmental contribution (clean energy) and adoption by peer group affect their purchase of two-wheeled electric vehicles. Questions related to two-wheeler electric vehicle manufacturers and government policies related to electric vehicles were asked to understand their electric vehicle awareness.

The questionnaire used for this research is mentioned in Appendices 1 and 2.

Most of the questions asked in the survey were in the form of a 5-point Likert Scale and ranged in ascending order of significance/familiarity. This can be seen mainly in Sections 3 and 4, which asked users to list their preferences on the Likert scale for traditional fossil fuel-based two-wheelers and two-wheeled electric vehicles.

18.2.2 Data Analysis Methods

Most of the questions asked in the questionnaire were based on the Likert Scale and generated ordinal data on a scale of 1 to 5. This scale was assigned values based on familiarity, awareness, or significance levels. This data was primarily used to understand the contribution of the variables asked about in the questionnaire.

Various approaches were taken to analyze the variables. These were often variable-specific and were implemented while considering the impact and the underlying idea behind introducing the variables in the questionnaire.

Variables such as those related to the respondents' demographic data were converted to frequency tables. They were used to analyze the diversity of the data obtained and the survey respondents. The demographics were tried to be kept as varied as possible to reflect the diversity found among the population of India. The data obtained in response to these questions has been compiled and represented as a table in the discussion section.

The variables that reflected the present travel choices of the respondents were taken as such, and descriptive analysis was applied to them to gain fundamental insights into their preferences. This data was then represented as graphs to provide quick insights into the respondents' preferences to the readers.

Some of the variables that were obtained from the user were divided into two major sections: characteristics that influenced buying a traditional two-wheeler and characteristics that influenced buying a two-wheeler EV. These variables were then reduced into factors, and these factors were then compared.

The respondents also gave an insight into how they perceived the policies initiated by the government—both at central and state levels. This ordinal data was obtained in the form of a Likert Scale. These were then analyzed in an introductory manner, and their graphs were illustrated to provide better insights.

The data obtained from the survey was used anonymously, and no personal identifiers have been used in this project.

18.3 Discussions

The data for this research project was gathered through online surveys to determine the elements influencing college students' decision to acquire a two-wheeler electric vehicle in India. We used the questionnaire method and received 185 valid responses between March 28 and April 15, 2022.

Table 18.2 Demographic data of the respondents

Demographic attributes		Frequency	Percentage
Gender	Male	152	82.20%
	Female	31	6.80%
Age	16 years and below	0	Nil
	17–25 years	178	96.20%
	25–30 years	6	3.20%
Educational qualification	Bachelors	163	88.58%
	Masters	20	10.8%
	Ph.D.	1	0.54%
Annual family income	Below 2.5 lacs	48	26.10%
	Between 2.5 and 5 lacs	33	17.90%
	Between 5 and 7.5 lacs	30	16.30%
	Between 7.5 and 10 lacs	30	16.30%
	Above ten lacs	43	23.40%

18.3.1 Respondent's Socioeconomic Data

The sample profile of the respondents in this survey is given in Table 18.2. Male participants provided more responses than female participants, and 96.2% of the sample was between the ages of 17 and 25.

In addition to the demographic diversity illustrated in Table 18.2, we received responses from students belonging to more than 15 states in India. Therefore, the dataset generated was diverse in nature and reflected the broad diversity found in a country like India. Thus, although generated through non-probabilistic sampling, the dataset covers the diversity found in any major cosmopolitan city in India.

18.3.2 Present Travel Choices

This section in the questionnaire highlighted the current choices of the respondents with respect to the journeys they undertook daily. The aim of this was to understand the causes and distances of the trips made by college students. The respondents were also asked to highlight the current mode of transportation they preferred to use.

Mode of Transportation. Figure 18.1 illustrates the following patterns:

1. Seventy-seven respondents preferred to use auto rickshaws or e-rickshaws as a means of connectivity between two locations.

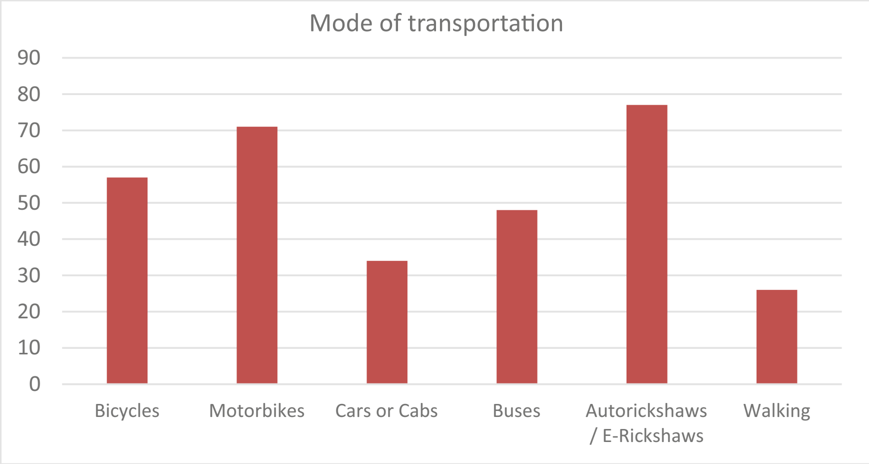


Fig. 18.1 Mode of transportation (E represents 'E-rickshaw')

2. This was closely followed by using motorbikes as a means of transportation. Seventy-one respondents preferred this.
3. Fifty-seven respondents admitted using bicycles for the trips they undertook.
4. Forty-eight respondents used public transportation services like buses to move from one location to another.
5. Thirty-four respondents preferred the comfort of cars or cabs.
6. Twenty-six respondents preferred walking to their destinations.

These patterns provide exciting insights into the means of last-mile connectivity. Some people prefer using a single transportation means like cars, cabs, or auto rickshaws that drop them on the doorsteps. Other people, who were the majority, preferred to use multi-modal transportation options to complete their journey. A vast majority of people preferred using two-wheelers, as evident from Fig. 18.1. This confirms our initial assumptions and the data from the literature review that most of personal Indian transportation choices hinge around two-wheelers.

Purpose of Trips. The question aimed to understand the reason for the number of trips undertaken by the respondents in various capacities. The respondents were free to choose from several given options or add their reasons to the list. The results are displayed in the form of a bar graph and a pie chart in Figs. 18.2 and 18.3.

The significant results can be summarized as follows:

- One hundred seven respondents mostly traveled while hanging out with friends.
- Ninety respondents mostly traveled to college.
- Eighty-six respondents had to make trips to fulfill household errands.
- Ten respondents had to travel to work, study, or shop majorly.

Figure 18.3 illustrates the number of trips made for a particular purpose as a percentage of the total trips made by the respondents.

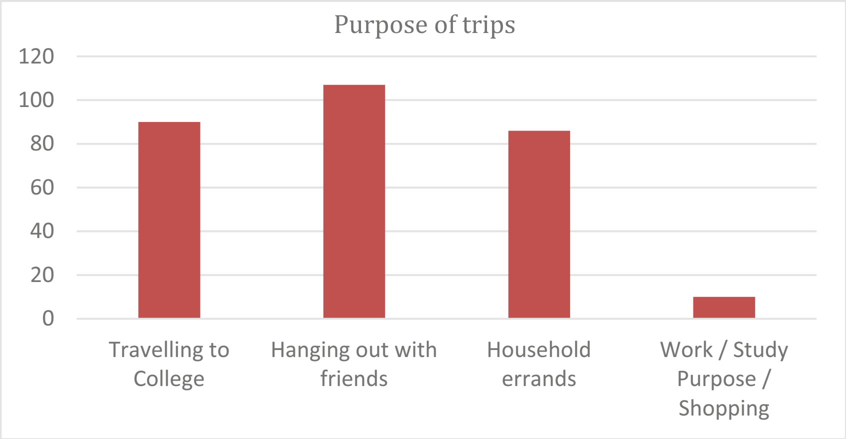


Fig. 18.2 Purpose of trips (bar graph)

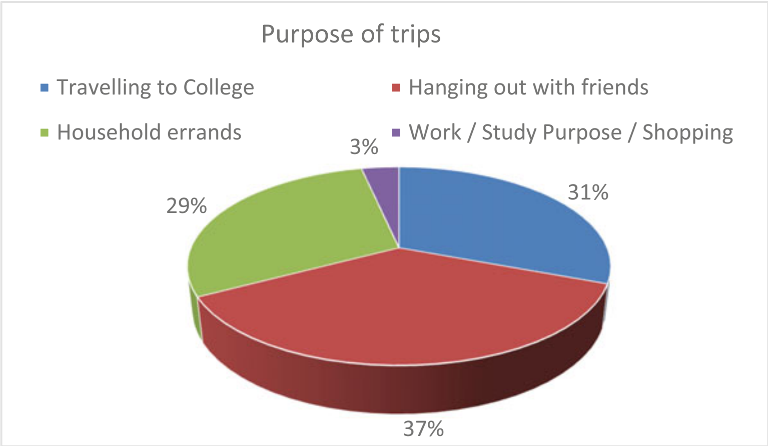


Fig. 18.3 Purpose of trips (pie chart)

Average Daily Commuting Distance. The survey also asked the people about their daily average commuting distance. This question was to ascertain the impact of range anxiety of EVs among the Indian populace and the practical effect and relevance. Figure 18.4 illustrates the traveling pattern of the respondents.

The findings can be summarized in the following manner:

- 39.1% of the respondents reported that they traveled less than 2 km in a day on average.
- 37.5% of the respondents reported that they traveled between 2 and 5 km a day on average.

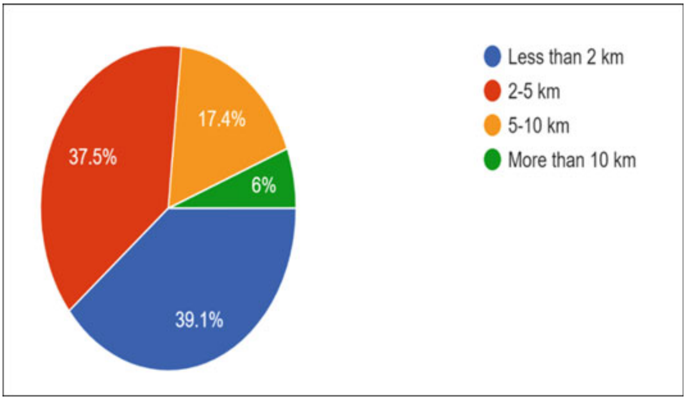


Fig. 18.4 Average daily commuting distance

- 17.4% of the respondents reported traveling between 5 and 10 km a day.
- Only 6% of the respondents had a daily average commuting distance of more than 10 km.

On analyzing the obtained dataset, it can be noted that more than 75% of the trips amount to less than 5 km per day on average. This is consistent with the previous studies and highlights one of the most essential positive aspects contributing to the easy adoption of electric vehicles in India—fewer traveling requirements for the Indian populace. It can be safely understood that range anxiety is not a significant issue in India, as the average commuting distance is less than 10 km per day. Only 23.4% of the respondents had an average traveling distance of more than 10 km per day on average.

18.3.3 Characteristics of Fossil Fuel-Based Two-Wheeler EV

This section of the questionnaire survey focused on the characteristics and features of the respondents' two-wheeler vehicles currently being used. They were asked about various economic features such as buying cost, maintenance cost, and features like mileage, pickup speed, look of the two-wheeler, etc. The results of these survey questions are discussed further.

Drawbacks of Fossil Fuel-based Two-Wheeler. The respondents were asked to provide what they identified as a drawback of fossil fuel-based two-wheelers from a given set of options. Figure 18.5 illustrates the data obtained as a bar graph.

The findings can be summarized as follows:

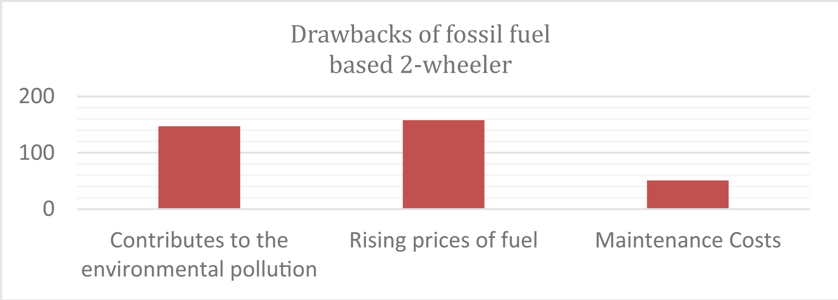


Fig. 18.5 Drawbacks of fossil fuel-based two-wheeler

- One hundred forty-seven respondents believe that two-wheelers contribute to environmental pollution and that this is a significant drawback of the traditional fossil fuel-based two-wheelers.
- One hundred fifty-eight respondents highlighted the rising fuel prices as a major drawback of traditional two-wheelers.
- Fifty-one respondents highlighted maintenance costs to be a major issue.

Thus, rising fuel prices cause worry among the respondents and may also prove elementary in them turning toward electric two-wheelers when coupled with the lesser environmental impact of the electric wheelers.

Factors influencing Buying Preferences of Traditional Two-Wheelers. This part of the questionnaire was focused on the characteristics that the youth of India favored in a vehicle when they went to buy a two-wheeler vehicle that ran on fossil fuel. A total of nine variables were defined, and the respondents were asked to rate each of them according to the significance they allotted to each variable. The variables, along with their abbreviations, are listed in Table 18.3.

Table 18.3 Characteristics of traditional two-wheeler

Variable name	Abbreviation
Initial buying cost	IBC
Maintenance cost	MC
Cost of spare parts and accessories	CSA
Look of the bike	LB
Mileage	M
Engine capacity	EC
Top speed	TS
Pickup	PU
Reselling value	RV

The individual significance allotted to each of these variables is depicted in Fig. 18.6. The figure represents the data obtained in the form of a graph on the Likert Scale. The data obtained is then analyzed using further tests.

The data was then fed into IBM SPSS, and a correlation matrix was generated for each variable. The correlation matrix is represented in Table 18.4. It is a correlation matrix of variables influencing the purchase of traditional two-wheelers. The matrix has plenty of moderate to high correlations, suggesting that the analysis is appropriate. Since there is no overly high correlation, we can continue with the output.

Kaiser–Meyer–Olkin's measure of sampling adequacy is 0.760 (Table 18.5), which is more than the required value of at least 0.6. This shows that the level of data among the factors crosses over extraordinarily/with the presence of a solid partial correlation. Subsequently, leading factor analysis is conceivable. We have used Bartlett's test of sphericity to test the null hypothesis that the correlation matrix is an identity matrix [27]. Here, an identity matrix signifies unrelated variables, and factor analysis is unsuitable. Since the significance value is less than 0.001, which is ultimately less than 0.05, we reject the null hypothesis, confirming that factor analysis can be carried out smoothly.

The commonality value for all the variables is more than 0.5 (Table 18.6), which is good enough and shows that the variables are well explained.

For the rotation component matrix (Table 18.7), we used variable maximization (Varimax) with the Kaiser Normalization rotation method in SPSS. We used this method to transfigure the initial factors into factors that are easier to interpret. Now, it has only one cross-loading, so we will take the factor which is explained by this variable more.

The variables can thus be clubbed under three factors. The categorization of these variables into factors is given in Table 18.8.

The factors identified can be defined as follows:

- Pricing of the Vehicle: This factor deals with the variables involving the pricing of the two-wheelers and their spare parts.
- Characteristics of the Vehicle: This factor deals with the vehicle's characteristics. This factor dealt with variables like the look of the vehicles, engine capacity, top speed, and pickup.
- Economical Value of the Vehicles: This part dealt with how economical the vehicle was. It considered variables like mileage and the reselling value of the vehicle.

18.3.4 Awareness About EVs

This section of the questionnaire dealt with general awareness levels about two-wheeler EVs. It had questions about familiarity with electric vehicle manufacturers, state and central policies, and EVs' environmental impacts.

Awareness of the EV Manufacturers. The respondents were asked about the manufacturers of two-wheeler EVs they knew from the given list of top manufacturers in

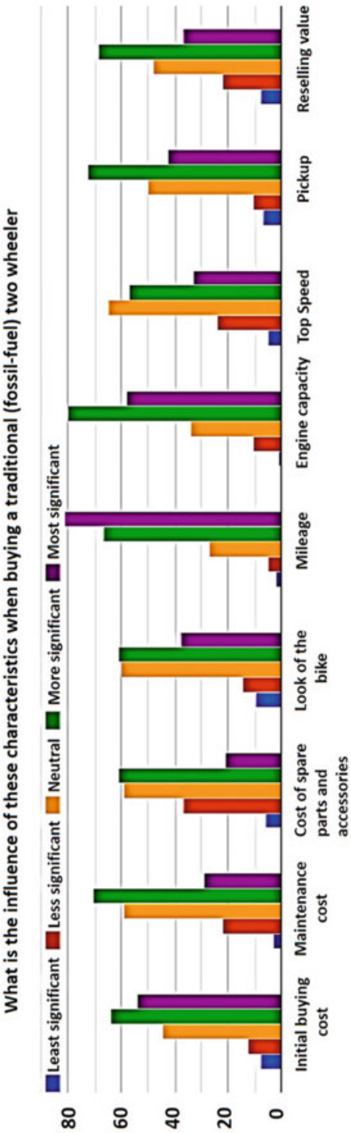


Fig. 18.6 Variables influencing the purchase of a traditional two-wheeler

Table 18.4 Correlation of variables influencing traditional two-wheelers

Correlation		IBC	MC	CSP	LB	M	EC	TS	PU	RV
	IBC	1.000	0.518	0.338	0.261	0.411	0.306	0.070	0.215	0.266
	MC	0.518	1.000	0.454	0.159	0.246	0.193	0.161	0.221	0.309
	CSP	0.338	0.454	1.000	0.192	0.176	0.234	0.219	0.278	0.328
	LB	0.261	0.159	0.192	1.000	0.113	0.318	0.420	0.296	0.080
	M	0.411	0.246	0.176	0.113	1.000	0.434	0.182	0.258	0.384
	EC	0.306	0.193	0.234	0.318	0.434	1.000	0.495	0.531	0.306
	TS	0.070	0.161	0.219	0.420	0.182	0.495	1.000	0.648	0.219
	PU	0.215	0.221	0.278	0.296	0.258	0.531	0.648	1.000	0.261
	RV	0.266	0.309	0.328	0.080	0.384	0.306	0.219	0.261	1.000
Sig. (1-tailed)	IBC		<0.001	<0.001	<0.001	<0.001	<0.001	0.172	0.002	<0.001
	MC	0.000		0.000	0.015	0.000	0.004	0.014	0.001	0.000
	CSP	0.000	0.000		0.004	0.008	0.001	0.001	0.000	0.000
	LB	0.000	0.015	0.004		0.063	0.000	0.000	0.000	0.139
	M	0.000	0.000	0.008	0.063		0.000	0.007	0.000	0.000
	EC	0.000	0.004	0.001	0.000	0.000		0.000	0.000	0.000
	TS	0.172	0.014	0.001	0.000	0.007	0.000		0.000	0.001
	PU	0.002	0.001	0.000	0.000	0.000	0.000	0.000		0.000
	RV	0.000	0.000	0.000	0.139	0.000	0.000	0.001	0.000	

Table 18.5 KMO and Bartlett's test

KMO and Bartlett's test		
Kaiser–Meyer–Olkin measure of sampling adequacy		0.760
Bartlett's test of sphericity	Approx. Chi-Square	465.167
	df	36
	Sig	<0.001

India. They were also given the option to add their responses in case of any significant manufacturer was missing from the list. The data obtained has been shown as a bar graph in Fig. 18.7.

The data can be summarized as follows:

- Hero Electric was the most recognized manufacturer, and 154 out of 185 respondents were familiar with it.
- Ather Energy was the second most recognized manufacturer. However, there was a steep drop in familiarity, with only 74 people familiar with the manufacturer.
- Sixty-five people recognized Okinawa, and 57 people recognized Revolt Motors.
- Thirty-four respondents recognized Ampere Vehicles.
- Seventeen respondents recognized Ola Electric.

Table 18.6 Communality values

Communalities		
	Initial	Extraction
IBC	1.000	0.621
MC	1.000	0.706
CSP	1.000	0.569
LB	1.000	0.558
M	1.000	0.725
EC	1.000	0.675
TS	1.000	0.774
PU	1.000	0.684
RV	1.000	0.518

Extraction Method: Principal Component Analysis

Table 18.7 Rotated component matrix

Rotated component matrix[a]			
	Component		
	1	2	3
IBC		0.704	
MC		0.823	
CSP		0.720	
LB	0.654		
M			0.833
EC	0.622		0.531
TS	0.872		
PU	0.772		
RV			0.654

Extraction Method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalization
[a]Rotation converged in six iterations

While Hero Electric was the most recognized manufacturer, other manufacturers are still far off. There was a steep decline between the top two manufacturers.

Awareness about Government Policies. This question focused on the awareness of the policies (Fig. 18.8) enacted by the various state governments and the central government. The respondents were primarily asked about their familiarity with the policies of their state and central government, some of which are listed in Table 18.1. The responses obtained are discussed further.

The data obtained can be expressed as follows:

- About 21% of the respondents expressed no level of familiarity with the topic.
- 20% of respondents were vaguely familiar with the policies.

Table 18.8 Factors influencing traditional two-wheeler buying preferences

Factors	Variables
Pricing of the vehicle	Initial buying cost
	Maintenance costs
	Cost of spare parts and accessories
Characteristics of the vehicle	Look of the vehicle
	Engine capacity
	Top speed
	Pickup
Economical value of the vehicle	Mileage
	Resell value

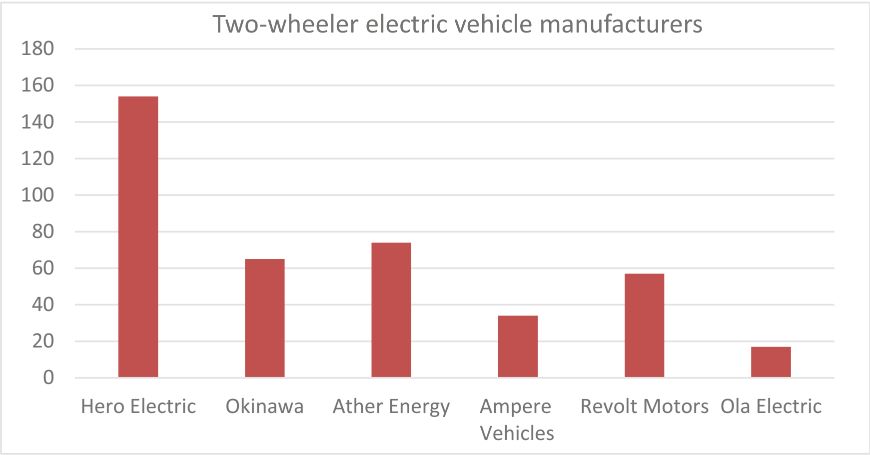


Fig. 18.7 Two-wheeler EV manufacturers

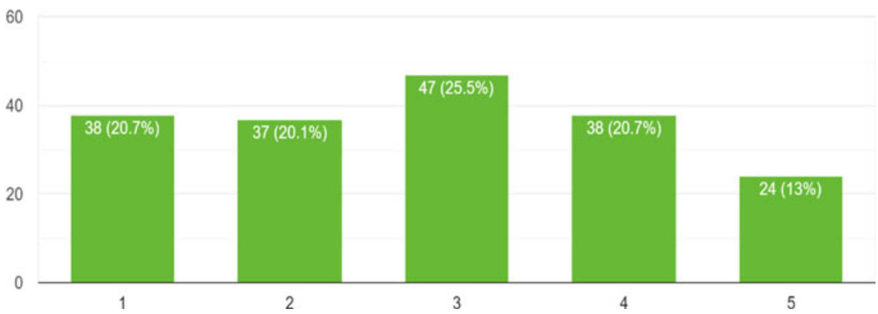


Fig. 18.8 Familiarity with government policies related to two-wheeler EV

- 25.5% of respondents said that they knew about the enacted measures.
- 20.7% of the people surveyed had a good idea about the various policies.
- 13% of the people said they had been closely following the topic and were well-read about the measures.

On analyzing the obtained data, it is observed that only 33.7% of the respondents knew substantial information about the various policies and measures implemented in their state to encourage the adoption of electric vehicles.

Awareness about FAME Programs. The Faster Adoption and Manufacturing of Electric Vehicles (FAME) Programs, implemented by the Government of India under FAME I and FAME II, focus on boosting the electric vehicle industry and encouraging its adoption. The finer details of this scheme have been discussed under Section 1.5.3. This part of the questionnaire wanted to test the awareness levels of the public about this Government of India-led scheme. Figure 18.9 illustrates the data obtained in a bar graph format.

The data obtained can be expressed as follows:

- Sixty-two respondents, who made up about 34% of the total, had no clue about these programs.
- Thirty respondents, amounting to 16% of the total responses, had only a vague idea about these programs.
- Twenty-nine respondents had heard about the program and knew something about it.
- Thirty-five respondents were familiar with the FAME program, amounting to 19% of the total responses.
- Twenty-eight respondents were very familiar with this program.

It can be observed that the familiarity level of one of the major driving forces of India's EV Industry is relatively low, and only a meager 34% of the respondents were adequately familiar with the FAME schemes.

Awareness about the Positive Environmental Impact of EVs. This section of the questionnaire was focused on understanding the level of positive environmental benefits of a two-wheeler EV that the user perceived. The question was based on

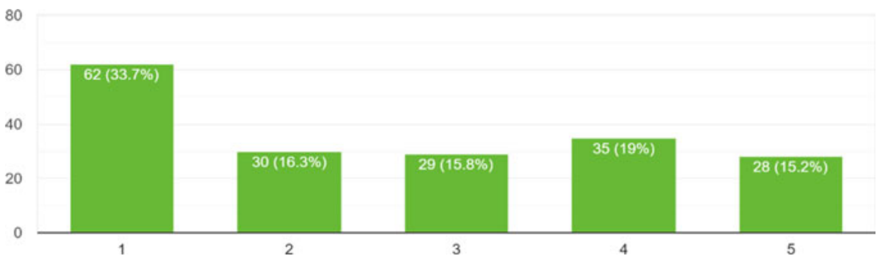


Fig. 18.9 Familiarity with FAME programs

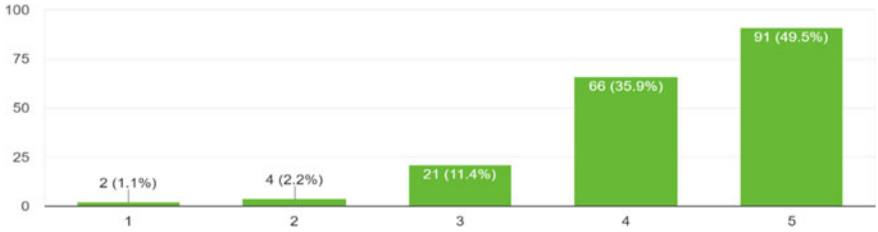


Fig. 18.10 College students' familiarity with the positives of two-wheeler electric vehicles

the Likert Scale and asked the respondents to fill in their responses. The results have been discussed below and illustrated in Fig. 18.10.

The results can be summarized as follows:

- Ninety-one respondents, who made up around 50% of the total responses, were very familiar with the positive impact.
- Sixty-six respondents, comprising 36% of responses, had a good idea of the positive impacts.
- Twenty-two respondents held a neutral outlook toward the positive impact of electric vehicles.
- Only six respondents had little to no belief in the positive impact that the adoption of two-wheeler electric wheelers could generate.

A vast majority of the respondents believed in the positive impact that the adoption of two-wheeler electric vehicles could generate.

Probability of Seeing an EV Daily. The respondents were asked to indicate how likely they were to see or use an EV daily. The main objective of this question was to understand the daily penetration of electric vehicles in Indian lives. The results obtained are illustrated in Fig. 18.11.

The results can be expressed as follows:

- Twenty-one respondents reported a meager chance of seeing an EV daily.
- Forty-eight respondents reported that they would be lucky to see an EV daily.
- Forty-three respondents were reasonably confident about seeing an EV on a daily basis.

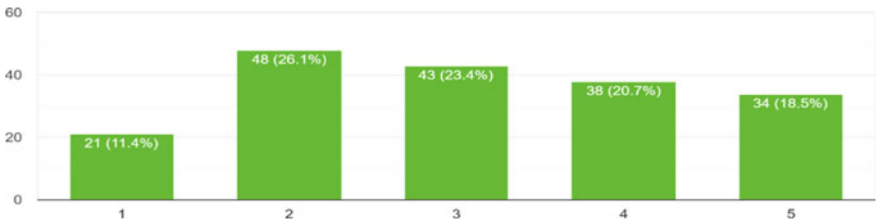


Fig. 18.11 Likeliness of seeing an EV daily

- Thirty-eight respondents reported that seeing an EV was quite a common sighting.
- Thirty-four respondents were pretty sure about seeing an EV and that it had become a regular occurrence.

A total of 72 respondents reported a good confidence level that they can see electric vehicles daily. These comprise about 39% of the total responses obtained.

18.3.5 Characteristics of Electric Vehicles

This part of the questionnaire focuses on the characteristics that the respondents looked for or wanted in an electric two-wheeler vehicle to consider it worth buying. It aimed to explore the various features that a potential customer would look for in a two-wheeler and would also consider while switching to newer technology with an alternative and unconventional source of propulsion. This section also tried to evaluate these characteristics and the various factors they contribute toward.

Favored Characteristics of Electric Vehicles. This survey section focused on the Indian youth who had bought or were considering buying an electric two-wheeler. An aggregate of twelve factors was characterized, and the respondents were approached to rate every one of them as indicated by the importance they allotted to every variable. The variables and abbreviations that indicate them are listed in Table 18.9.

The singular importance assigned to every one of these factors is portrayed in Fig. 18.12. The figure addresses the information obtained as a chart using the Likert Scale. The information obtained is then investigated utilizing further tests.

The information obtained was then subjected to Kendall's test, whose results are discussed below. Table 18.10 shows the mean rank values of variables affecting the purchase of two-wheeler EVs. It shows that there is less agreement between

Table 18.9 Variables affecting purchase

Variable name	Abbreviation
Government subsidies	C
On-road prices	ORP
Range of vehicle	Range
Charging infrastructure	CI
Maintenance cost	MC
Cost of spare parts and accessories	CSA
Top speed	TS
Recharge time	RT
Battery replacement/rental prices	BP
Battery warranty	BW
Environmental contribution (clean energy)	EC
Adoption by peer group	PG

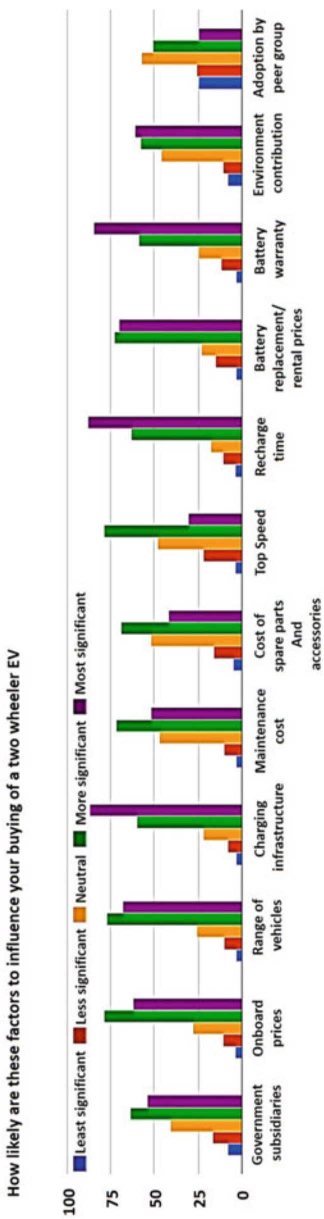


Fig. 18.12 Characteristics of a two-wheeler EV

Table 18.10 Mean ranks

Ranks	
	Mean rank
C	5.96
ORP	6.86
CSA	7.11
CI	7.84
MC	6.35
Range	5.73
TS	5.45
RT	7.67
BP	6.99
BW	7.49
EC	6.29
PG	4.26

Table 18.11 Kendall's W test statistics

Test statistics	
N	185
Kendall's W[a]	0.121
Chi-Square	246.828
df	11
Asymp. Sig	<0.001

[a] Kendall's Coefficient of Concordance

respondents on the choice of factors that affect their purchase intention of two-wheeler electric vehicles. Kendall's W test statistics is 0.121, which is clearly given in Table 18.11. Since this value is deficient, it fails to show any particular pattern.

The data, to obtain further insights, was fed into IBM SPSS, and fundamental factor analysis was run on it. Table 18.12 lists each dataset variable's mean and standard deviation with a sample size of 185.

KMO is a test directed to analyze the strength of the fractional connection (how the elements make sense of one another) between the factors. KMO esteems nearer to 1.0 are considered ideal, while values under 0.5 are inadmissible. Recently, most researchers contended that a KMO of no less than 0.80 are sufficient for factor examination to begin [28]. In our case, we had a KMO value of 0.850 (Table 18.13). This shows that the level of data among the factors crosses over extraordinarily/with the presence of a solid partial correlation. Subsequently, leading factor analysis is conceivable. We have used Bartlett's test of sphericity to test the null hypothesis that the correlation matrix is an identity matrix. Here, an identity matrix signifies that variables are unrelated and factor analysis is unsuitable. Since the significance value

Table 18.12 Descriptive statistics

Descriptive statistics			
	Mean	Std. deviation	Analysis N
C	3.76	1.107	185
ORP	4.01	0.964	185
CSA	4.08	0.935	185
CI	4.24	0.938	185
MC	3.88	0.944	185
Range	3.70	1.008	185
TS	3.61	0.978	185
RT	4.20	0.988	185
BP	4.05	0.991	185
BW	4.15	0.994	185
EC	3.84	1.091	185
PG	3.14	1.221	185

Table 18.13 KMO and Bartlett's test

KMO and Bartlett's test		
Kaiser–Meyer–Olkin measure of sampling adequacy		0.850
Bartlett's test of sphericity	Approx. Chi-Square	1151.879
	df	66
	Sig	<0.001

is less than 0.001, which is ultimately less than 0.05, we reject the null hypothesis, showing that factor analysis can be done.

Table 18.14 contains the correlation matrix of variables influencing the purchase of two-wheeler electric vehicles. There are enough correlations between variables in the moderate to high range, which confirms the appropriateness of the analysis. It also shows that most of the variables are somewhat correlated with every other variable.

Figure 18.13 represents a scree plot in which the y-axis represents the eigenvalue, and the x-axis shows the number of factors. In this curve, the point from where the curve starts to become steady after falling indicates the number of factors that would be generated. Here, the curve starts to level off at point 3, which shows the number of factors (which is 3) generated by the analysis.

The components matrix tells the **Pearson correlation** (Table 18.15) between the variables and components [29]. These are called factor loadings. Here, we expect that one variable should measure only one component. But in the above-given component matrix, variable C measures two components, which is called cross-loading. So, to avoid this situation, we take the help of rotation based on mathematical rules in which

Table 18.14 Correlation matrix of variables affecting the two-wheeler EV purchase

		C	ORP	CSA	CI	MC	Range	TS	RT	BP	BW	EC	PG
Correlation	C	1.000	0.658	0.532	0.438	0.211	0.368	0.255	0.377	0.417	0.285	0.256	0.214
	ORP	0.658	1.000	0.542	0.479	0.323	0.432	0.187	0.433	0.444	0.345	0.207	0.193
	CSA	0.532	0.542	1.000	0.611	0.448	0.336	0.318	0.531	0.524	0.531	0.342	0.191
	CI	0.438	0.479	0.611	1.000	0.555	0.486	0.376	0.715	0.636	0.531	0.293	0.207
	MC	0.211	0.323	0.448	0.555	1.000	0.651	0.371	0.434	0.518	0.535	0.297	0.293
	Range	0.368	0.432	0.336	0.486	0.651	1.000	0.415	0.416	0.510	0.447	0.281	0.366
	TS	0.255	0.187	0.318	0.376	0.371	0.415	1.000	0.542	0.384	0.469	0.338	0.365
	RT	0.377	0.433	0.531	0.715	0.434	0.416	0.542	1.000	0.662	0.655	0.318	0.130
	BP	0.417	0.444	0.524	0.636	0.518	0.510	0.384	0.662	1.000	0.727	0.314	0.156
	BW	0.285	0.345	0.531	0.531	0.535	0.447	0.469	0.655	0.727	1.000	0.429	0.170
	EC	0.256	0.207	0.293	0.293	0.297	0.281	0.338	0.318	0.314	0.429	1.000	0.474
	PG	0.214	0.193	0.207	0.207	0.293	0.366	0.365	0.130	0.156	0.170	0.474	1.000

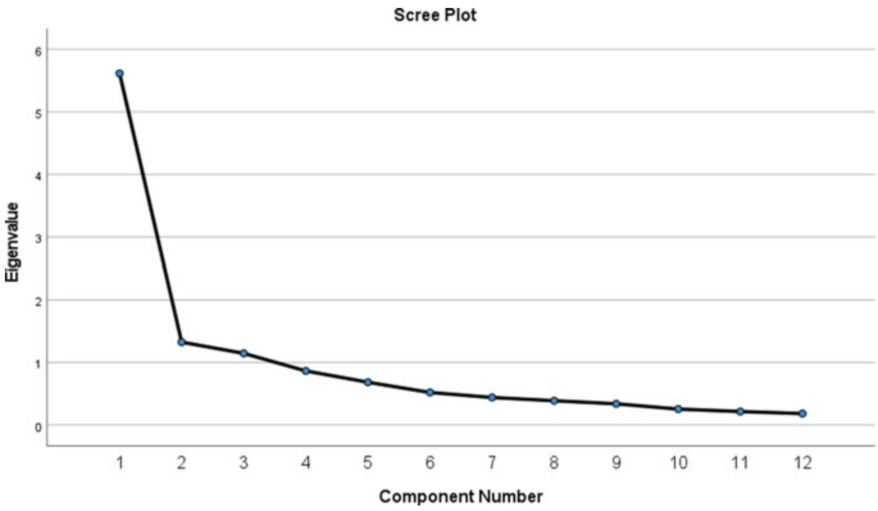


Fig. 18.13 Scree plot

Table 18.15 Component matrix

Component matrix			
	Component		
	1	2	3
C	0.606		0.551
ORP	0.645		
CSA	0.738		
CI	0.802		
MC	0.701		
Range	0.698		
TS	0.603		
RT	0.791		
BP	0.801		
BW	0.775		
EC	0.522		
PG		0.665	

Extraction Method: Principal Component Analysis
[a] Three components extracted

factor loading is redistributed over the factors [29]. We used the principal component analysis extraction method to extract the component matrix.

The explanation of the proportion of the variability of each variable by the factors is common. It is nothing but an r-squared value. It shows how well a factor explains a variable. So, if the communality value is closer to 1, the factor explains the variable

Table 18.16 Communality values

Communalities	
	Extraction
C	0.796
ORP	0.783
CSA	0.632
CI	0.693
MC	0.570
Range	0.525
TS	0.530
RT	0.731
BP	0.729
BW	0.729
EC	0.560
PG	0.814

Extraction Method: Principal Component Analysis

well. In the upper given case (Table 18.16), communalities are primarily high enough for all the variables, indicating the excellent representation of variables by the three factors.

We used variable maximization (Varimax) for the rotation component matrix with the Kaiser Normalization rotation method in SPSS. We used this method to transfigure the initial factors into factors that are easier to interpret. Now, it has no cross-loadings, which makes it easier to interpret. Table 18.17 shows the resulting rotated component matrix.

A total of three factors were identified, stemming from twelve variables that we had defined earlier. The factors are listed in Table 18.18.

The factors identified can be defined as follows:

- Pricing of the Vehicle: This factor deals with the financial aspects of buying an electric vehicle. It involved aspects such as government subsidies, on-road prices, and the cost of spare parts and accessories.
- Characteristics of the Vehicle: This factor involves the vehicle's characteristics. It involves aspects like charging infrastructure, top speed, range of the vehicles, etc.
- Social Contributions of the Vehicle: This factor comprises the positive environmental impact of electric vehicles and how adoption by peer groups affects their buying intention.

Preferred Mode of Charging. The respondents were asked about their preferred mode of charging an electric vehicle if they ever came under the ownership of one such vehicle. They were provided with three options: either charge their batteries at home or electric charging stations or swap the batteries whenever they were drained out. The responses obtained are illustrated with the help of a pie chart in Fig. 18.14.

Table 18.17 Rotated component matrix

Rotated component matrix			
	Component		
	1	2	3
C		0.864	
ORP		0.847	
CSA		0.605	
CI	0.709		
MC	0.669		
Range	0.516		
TS	0.553		
RT	0.806		
BP	0.790		
BW	0.826		
EC			0.692
PG			0.893

Extraction Method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalization
[a] Rotation converged in seven iterations

Table 18.18 Factors affecting purchase of electric two-wheelers

Factors	Variables
Pricing of the vehicle	Government subsidies
	On-road prices
	Cost of spare parts and accessories
Characteristics of the vehicle	Range of the vehicle
	Charging infrastructure
	Maintenance costs
	Top speed
	Recharge time
	Battery replacement/rental prices
	Battery warranty
Social contributions of the vehicle	Environmental contribution
	Adoption by peer group

The data can be summarized as follows:

- One hundred four respondents were happy with charging their batteries at home. This formed the majority of responses, with 56% of the respondents voting in its favor.

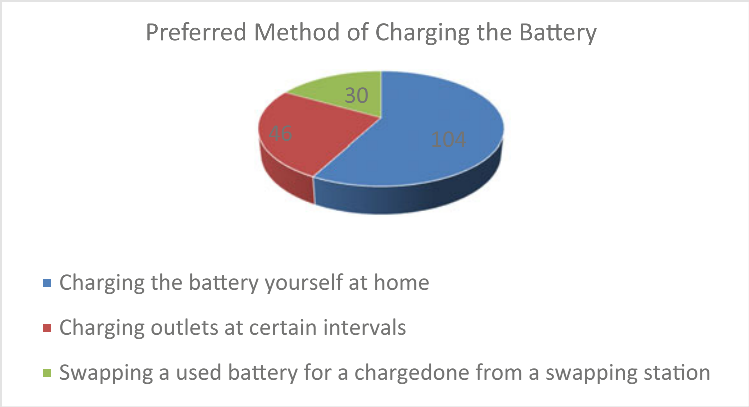


Fig. 18.14 Preferred method of charging

- Forty-six respondents, who comprised about 25% of the total respondents, preferred using charging outlets like petrol pumps today.
- Swapping a drained battery for a fully charged one was the least preferred method of obtaining the propulsion factor. Only 30 respondents, amounting to 16% of the total respondents, preferred its use.

As per the data obtained, it is charging at home seems to be the most favorable option for using an electric vehicle.

The likeliness of Switching to an EV. The respondents were finally asked to rate their likeliness of adopting an electric two-wheeled vehicle shortly. They were asked to express their likeliness on the Likert Scale, ranging from least likely to highly likely. The data obtained is expressed as a bar graph highlighting the responses obtained on a Likert Scale in Fig. 18.15.

The data obtained can also be expressed as

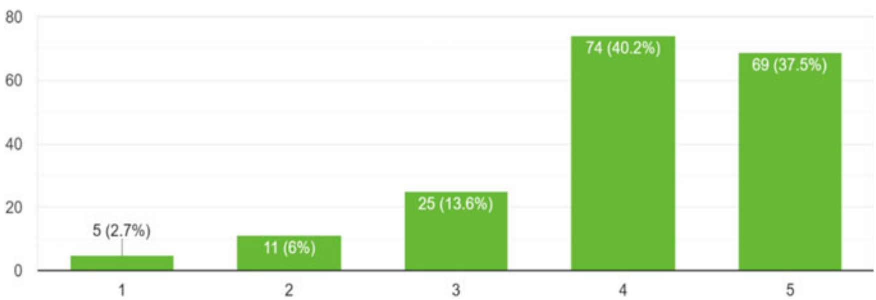


Fig. 18.15 College students' willingness to switch to two-wheeler electric vehicles

- Forty percent of the people surveyed expressed a tremendous interest in adopting an electric two-wheeler in the recent future.
- 37.5% of the respondents expressed a high probability of adopting an electric two-wheeled vehicle in the recent future.
- Only about 9% of the people surveyed expressed little to no interest in adopting a two-wheeled electric vehicle in the recent future.
- 13.6% of the people responded with a neutral outlook toward this issue.

The respondents showed a tremendous amount of interest in adopting an electric vehicle, with about 77.5% of the respondents responding in the affirmative.

18.4 Conclusions and Recommendations

Electric vehicles are slated to play an essential role in the upcoming years and will completely change how we travel from origin to destination. This study attempted to understand the growing and ever-changing landscape of electric vehicle adoption in India and its various government programs. It gave a brief overview of the characteristics that an average Indian youth would consider while opting for a brand-new electric two-wheeler.

Most youths in India preferred to travel using paratransit, closely followed by motorized two-wheelers. Non-motorized two-wheelers like bicycles were also a popular choice. Most of the trips made by this section of the Indian population are under 5 km and are mainly due to the reasons like hanging out with friends and traveling to the respective colleges.

One of the exciting insights was that despite being one of the most avid users of motorized two-wheelers, India's youth are much aware of the environmental pollution it causes. This was the second most crucial drawback of the traditional motorized two-wheelers, the first being concerns over the rapidly rising fuel prices.

The factors related to adopting both traditional and electric vehicles were also studied. The factors influencing the purchase of traditional two-wheelers were price, characteristics, and the vehicle's economic value. The factors influencing the adoption of electric two-wheelers were pricing, vehicle characteristics, and social contribution. The variable that emerged as the most influential was mileage in the case of traditional two-wheelers. The youth of India were worried more about the charging infrastructure before purchasing an electric two-wheeler.

The respondents also showed an excellent level of familiarity with the manufacturers of electric two-wheelers. Out of the given choices, Hero Electric was the most recognized brand. In stark contrast, however, they were hugely unaware of the initiatives the central government and the state governments took, especially the FAME programs. Even then, a large number of them believed in the positive impact that the adoption of two-wheeler electric vehicles could cause. Most of them reported a good confidence level in seeing an EV daily. According to the survey data, most respondents also expressed an avid interest in switching to an electric two-wheeler.

More data could be collected, and hypotheses could be formed and tested to explore further relations between the variables. Tests could also be conducted to explore the relationship between the factors and the quantitative impact each factor would have on the total outcome. Analysis methods like confirmatory factor analysis or principal component analysis could be carried out on this data.

Appendix 18.1: Research Questionnaire

Two-Wheeler EV Purchase Intention of College Students

*Required

1. Email *

2. Age Group *

   Mark only one oval.

   - 16 years and below
   - 17 - 25 years
   - 25 - 30 years
   - 30 years and above

3. Gender *

   Mark only one oval.

   - Male
   - Female
   - Prefer not to say
   - Other: ____________

4. Your Current City *

5. Your Current Program *

Mark only one oval.

- ◯ Bachelors
- ◯ Masters
- ◯ PhD
- ◯ Other: ____________________

6. What is your annual family income? *

Mark only one oval.

- ◯ Below 2.5 Lacs
- ◯ Between 2.5 - 5 Lacs
- ◯ Between 5 - 7.5 Lacs
- ◯ Between 7.5 - 10 Lacs
- ◯ Above 10 Lacs

Current Travel Choices

7. What is your average daily commuting distance? *

Mark only one oval.

- ◯ Less than 2 km
- ◯ 2-5 km
- ◯ 5-10 km
- ◯ More than 10 km

8. What is your current mode of transportation? *

Tick all that apply.

- ☐ Bicycles
- ☐ Motorbikes
- ☐ Cars or Cabs
- ☐ Buses
- ☐ Autorickshaws / E-Rickshaws
- Other: ☐ ____________________

9. What is the purpose of major number of trips? *

Tick all that apply.

- [ ] Travelling to College
- [ ] Hanging out with friends
- [ ] Household errands

Other: [ ] ______________________

Factors Affecting Traditional 2W Purchase

10. What is the influence of these characteristics when buying a traditional (fossil-fuel based) two wheeler? *

Mark only one oval per row.

	Least significant	Less significant	Neutral	More Significant	Most Significant
Initial Buying cost	◯	◯	◯	◯	◯
Maintenance Cost	◯	◯	◯	◯	◯
Cost of Spare Parts and Accessories	◯	◯	◯	◯	◯
Look of the bike	◯	◯	◯	◯	◯
Mileage	◯	◯	◯	◯	◯
Engine Capacity	◯	◯	◯	◯	◯
Top Speed	◯	◯	◯	◯	◯
Pickup	◯	◯	◯	◯	◯
Reselling Value	◯	◯	◯	◯	◯

11. What do you feel is the biggest drawback of fossil-fuel (like petrol) based two wheelers? *

Tick all that apply.

- [ ] Contributes to the environmental pollution.
- [ ] Rising prices of fuel.
- [ ] Maintenance Costs.

Other: [ ] ______________________

Factors Influencing 2W EV Adoption

12. How likely are you to switch to a 2W EV in the near future? *

Mark only one oval.

	1	2	3	4	5	
Least Likely						Most Likely

13. How familiar are you with the positive environmental impact of Electric Vehicles? *

Mark only one oval.

	1	2	3	4	5	
No idea						Quite Familiar

14. How likely are these factors to influence your buying of a two wheeler EV? *

Mark only one oval per row.

	Least significant	Less significant	Neutral	More Significant	Most Significant
Government Subsidies					
OnRoad Prices					
Range of Vehicle					
Charging Infrastructure					
Maintenance Cost					
Cost of Spare Parts and Accessories					
Top Speed					
Recharge Time					
Battery Replacement/Rental Prices					
Battery Warranty					
Environmental Contribution (Clean Energy)					
Adoption by Peer Group					

15. Which of the following is more preferred method of charging your battery? *

Mark only one oval.

- Charging the battery yourself at home .
- Charging outlets at certain intervals.
- Swapping a used battery for a charged one from a swapping station.

16. How likely are you to see an Electric Vehicle daily? *

Mark only one oval.

	1	2	3	4	5	
Least Likely	◯	◯	◯	◯	◯	Most Likely

17. Which of the following 2 wheeler electric vehicle manufacturers do you know about? *

Tick all that apply.

- ☐ Okinawa
- ☐ Hero Electric
- ☐ Ather Energy
- ☐ Ampere Vehicles
- ☐ Revolt Motors

Other: ☐ ____________________

18. How familiar are you with the subsidy policies of your state government and the central government with regard to 2 wheeler EV? *

Mark only one oval.

	1	2	3	4	5	
No idea	◯	◯	◯	◯	◯	Quite Familiar

19. How familiar are you with the FAME programs? *

Mark only one oval.

	1	2	3	4	5	
No idea	◯	◯	◯	◯	◯	Very Familiar

Feedback / Comments

20. Any suggestions / comments?

____

____

____

Appendix 18.2: Respondent Feedback

"Government and Electric Vehicles companies need to work a lot towards spreading awareness about the vehicles, their impact on the environment, and the owner's pocket."

"Cost and subsidies will follow in more number if the production of the units starts in India."

"I do not think EVs are the future of the nation... Instead, modifying, upgrading, and promoting public and mass transportation methods will make a bigger difference. Someone rightly said, 'A developed country is not where the poor have cars. It is where the rich use public transportation.'"

"The EV industry in India would likely take some time to design their vehicles according to Indian roads, hot summer heat, and other conditions that are only prevalent in India, so I am waiting for companies to adjust well to Indian conditions and then decide; to buy myself one."

"For government: Make an environment for Electronic vehicles by schemes. For EV companies, find the significant gap/needs and work on it.

"Two-wheeler EV is suitable for college students, but still, I would prefer college students to buy cycles rather than EVs (even if college is far from your home) because, in my opinion, India is not yet so developed to have EV vehicles on roads....it not the right time for it (because if Indian roads and some other factors)."

"EVs are better than other vehicles in many aspects like pollution-free, low maintenance, and the most important is their source of charging is readily available everywhere. One suggestion from my side to the government is to decrease the cost price of EV vehicles."

"Since childhood, we have been taught to use public transport to curb environmental pollution. However, it is not always possible. So, using an alternative two-wheeler or personal transport is as good as public transport in case of pollution."

References

1. Sustainable Development [Internet] [cited 2022 May 5]. https://sdgs.un.org/#goal_section
2. Sustainable Transport: Sustainable Development Knowledge Platform [Internet] [cited 2022 April 14]. https://sustainabledevelopment.un.org/topics/sustainabletransport
3. Singh, A., Saxena, A., Srivastava, A., Bhandari, A., Sanjeevi, H.K., Teja, J., et al.: India's Electric Mobility Transformation: Progress to Date and Future Opportunities 58 (2019)
4. Trends in global CO_2 and total greenhouse gas emissions: 2019 Report 70
5. Air pollution 2021 Full List: These were the 15 most polluted cities in India, Pakistan [Internet] [cited 2022 May 15]. https://www.timesnownews.com/mirror-now/in-focus/air-pollution-2021-full-list-these-were-the-15-most-polluted-cities-in-india-pakistan-article-90376307
6. Transforming India's mobility: a perspective [Internet]. NITI Ayog and Boston Consulting Group, p. 39 (2018). http://movesummit.in/files/BCG.pdf
7. Bakker, S.: Electric two-wheelers, sustainable mobility and the city. In: Almusaed, A., Almssad, A. (eds.) Sustain Cities—Authent Ambition Dream [Internet]. IntechOpen; 2019

[cited 2022 April 11]. https://www.intechopen.com/books/sustainable-cities-authenticity-ambition-and-dream/electric-two-wheelers-sustainable-mobility-and-the-city
8. Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems. Energy Technol. 418 (2016)
9. Global EV Outlook 2021 101 (2021)
10. Global EV Outlook 2018 141 (2018)
11. Nguyen, N.Q., Zuidgeest, M., van Maarseveen, M.: Using accessibility indicators to investigate urban growth and motorcycles use in Ha Noi City, Vietnam. Proc. East Asia Soc. Transp. Stud. **20** (2013)
12. A-Global-High-Shift-Cycling-Scenario_Nov-2015.pdf
13. Fishman, E., Cherry, C.: E-bikes in the mainstream: reviewing a decade of research. Transp. Rev. **36**, 72–91 (2016)
14. Society of Indian Automobile Manufactures [Internet] [cited 2022 April 23]. https://www.siam.in/statistics.aspx?mpgid=8&pgidtrail=14
15. Study on Traffic and Transportation Policies and Strategies in Urban Areas in India [Internet]. Ministry of Urban Development (2008). https://mohua.gov.in/upload/uploadfiles/files/final_Report.pdf
16. Two and Three Wheelers in India [Internet]. Innovative Transport Solution (iTrans) Pvt. Ltd., TBIU, IIT Delhi, New Delhi (2009). https://theicct.org/sites/default/files/publications/2_and_3_wheelers_in_India.pdf
17. 2019—EY to BEE—Technical study on EVs & Charging Infrastructure.pdf [Internet]. Ernst & Young LLP, p. 328. https://beeindia.gov.in/sites/default/files/2019%20-%20EY%20to%20BEE%20-%20Technical%20study%20on%20EVs%20%26%20Charging%20Infrastructure.pdf
18. Zero Emission Vehicles (ZEVs): Towards a Policy Framework [Internet]. NITI Aayog & World Energy Council (2018). http://movesummit.in/files/EV_report.pdf
19. These 11 States Are Leading India's Transition to EVs With Key Policy Initiatives [Internet] [cited 2022 May 12]. https://www.thebetterindia.com/280360/ev-in-india-leading-state-policy-for-electric-vehicles-delhi-karnataka-maharashtra/
20. Coinmen Electric Vehicles-Sector Incentives-Concessions [Internet]. Coinmen Consultants LLP. https://www.coinmen.com/wp-content/uploads/2021/09/Coinmen_Electric-Vehicles-Sector_Incentives-Concessions.pdf
21. AboutUs: National Automotive Board (NAB) [Internet] [cited 2022 April 23]. https://fame2.heavyindustries.gov.in/content/english/1_1_AboutUs.aspx
22. Fame-2 incentive scheme for electric vehicles extended by two more years [Internet]. New Indian Express [cited 2022 April 23]. https://www.newindianexpress.com/business/2021/jun/26/fame-2-incentive-scheme-for-electric-vehicles-extended-by-two-more-years-2321671.html
23. Shyam, A.R., Thakkar, K., Chaliawala, N.: Govt increases allocation for EV subsidy threefold. Econ Times [Internet] (2022, February 4) [cited 2022 May 5]. https://economictimes.indiatimes.com/industry/renewables/govt-increases-allocation-for-ev-subsidy-threefold/articleshow/89324472.cms?from=mdr
24. e-AMRIT [Internet] [cited 2022 May 13]. https://www.e-amrit.niti.gov.in/home
25. State of the Urban Youth 2012/2013. UN Habitat (2012)
26. newindia301634_1504694260.pdf [Internet]. My Gov [cited 2022 May 14]. https://www.mygov.in/newindia/wp-content/uploads/2017/09/newindia301634_1504694260.pdf
27. KMO and Bartlett's test of sphericity [Internet]. Anal. INN. 2020 [cited 2022 May 13]. https://www.analysisinn.com/post/kmo-and-bartlett-s-test-of-sphericity/
28. Watkins, M.W.: Exploratory factor analysis: a guide to best practice. J. Black Psychol. **44**, 219–246 (2018). SAGE Publications Inc.
29. SPSS Factor Analysis—Absolute Beginners Tutorial [Internet] [cited 2022 May 14]. https://www.spss-tutorials.com/spss-factor-analysis-tutorial/

Chapter 19
Adaptability of Management in Transportation Systems

Archana Santosh Mishra and Sandipkumar G. Prajapati

Abstract Transport has grown to be a crucial component of long-distance movement. Links along management, global supply chains, and communications are made possible by transportation. Future generations' alternatives for arranging the supply, utilization, and dissemination of goods and services may be seriously limited by such rigid structures and systems. The inadequate focus has been devoted to learning and research on the connection between durability and mobility. In the industry, logistical factors have always been strategically important. Wholesale and retail businesses understand that location in proximity to marketplaces or supply chains is one of the most important variables in a company's success, going beyond inventory control and shipping. Logistics among industries is concerned with issues as fundamental as plant site, input materials procurement, and service to clients. Companies of all sizes have recently been obliged to pay extra close attention to how this function interacts with others due to changes in the business environment. Federal regulations, the condition of the country's transport networks, energy constraints, and technology advancements are all crucial factors to take into account when developing a corporate plan.

Keywords Transportation · Management · Supply chain

19.1 Management and Transportation

A transportation management system (TMS) is a platform for logistics that makes use of technology to assist businesses in the planning, carrying out, and optimising of the physical movement of goods, both incoming and outgoing, as well as in ensuring that the shipment is willing to comply and that the utilized to prepare is available. Such a system frequently forms a component of a broader supply chain management (SCM) system. A TMS, usually referred to as a transportation management

A. S. Mishra (✉) · S. G. Prajapati
Department of Commerce and Business Management, Faculty of Commerce, The Maharaja Sayajirao University of Baroda, Vadodara 390020, Gujarat, India
e-mail: archanamishra446@gmail.com

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_19

system or transportation management software, offers insight into daily transportation operations, documentation and information on trade compliance, and assurances regarding the prompt delivery of freight and commodities. In addition to streamlining the shipping process, transportation control systems help firms manage and optimise all aspects of their transportation operations, whether they include ground, wind, or sea transportation.

The phrase "sustainable transport" refers to modes of transportation and systems of transportation planning that are congruent with broader sustainability issues. It evolved logically from the phrase "sustainable development." There are several meanings for sustainable transportation as well as the related phrases sustainable mobility [1]. A sustainable transportation system, according to the European Union Council of Ministers of Transport, is one that: fosters fairness within and between succeeding generations while making it possible to safely and sustainably meet the fundamental access and development requirements of people, businesses, and society. It is affordable, operates fairly and efficiently, offers a choice of transport mode, and supports a competitive economy, as well as balanced regional development.

A sustainable transportation system is defined as one that: Enables society's fundamental access and growth requirements to be satisfied securely and in a way that is compatible with the safety of humans and the environment, while also promoting fairness between and among reproduction is inexpensive, runs fairly and effectively, provides a variety of modes of transportation, and promotes a prosperous society and equitable territorial growth. Inhibits waste and carbon dioxide emissions to the planet's capacity for taking in them, uses recycled materials at or below their rates of production, and uses finite resources at or below the rates of creation of sustainable alternatives, all while reducing the impacts on farmland and noisy output [2, 3].

The Institute for Public Policy Research said in 2021 that driving must decline in the UK while the usage of active and public transportation should increase. In response, the Department for Transport said that it will invest 2 billion pounds—more than ever—in active transportation, including greening the trains in England and the rest of the UK [4]. There were many policies, we have to work on it but according to situations and recent trends, it should apply over in its sustainability and adaptability of management in transportation systems.

19.2 Transportation and Supply Chain

Transport systems management affects every supply chain step, from planning and procurement to logistics and lifecycle management. A strong system's wide-ranging and comprehensive visibility enables more effective transportation management and coordination, which raises service quality. More sales result from it, which helps firms expand. We operate and live in such a volatile international trade world; therefore, it is critical to have a system that will help you effectively traverse the challenging procedures associated with trade conformance and rules. Businesses that often ship, move, and receive products, such as the following, typically utilize transportation systems management: suppliers, distributors ecommerce businesses, commercial establishment businesses that offer logistical services, such as third-party logistics (3PL) and fourth-party logistics (4PL) providers (LSPs).

Transportation system management is used by companies in almost every sector, from construction to the life sciences. However, because of the availability of cloud-based TSM or TMS systems, it is now more feasible for organizations to benefit from integrating a transportation management system into their supply chain. The main customers are companies who spend $100 million or more annually on freight.

TMS or TSM services: Businesses can purchase a hold transport management technology linked with their current enterprise resource planning (ERP) applications and SCM systems, whether they are hosted in the cloud or on-premises. The global trade management (GTM) program can be used with your TMS or some TMS systems that feature trade documentation capabilities. Other TMSs or TSMs, often with fewer features, are offered as modules inside ERP and SCM packages. Organize, carry out, and enhance for the prompt shipment of goods.

Businesses may gain a lot from TSMs and modern transportation management in general. The following are some of the greatest aspects: lower costs for the generalization of supply chain operations across regions and countries, mechanisms, and wireless providers; automation of business functions for quicker and more accurate invoicing and paperwork; improvements in accessibility and safety, particularly in transit, the efficiency of mechanical approaches, resulting in fewer hold-ups and faster delivery times, stronger security and fresh business insights enable quicker decision-making and practical completion.

The durability of a transportation system is the capacity to anticipate, tolerate, integrate, and modify shocks and to quickly and effectively rebound from their effects [5–15]. Rail transportation is distinguished by relatively significant concentrations of surveillance and oversight in contrast to, say, automobile transportation. While these elements help the system function effectively under typical circumstances, they also make it more susceptible to interruptions. Time-sensitive responses like diverting trains and changing timetables are frequently challenging to implement.

The (technology) and (resources) layers may be thought of as the system's supply side and the (customers) as its demand side from a financial viewpoint. There are the parties in charge of organizing, running, and maintaining the public infrastructure as well as controlling how supply and demand interact. Specific goals, such as lowering travel times and improving timeliness, are often centered on the demand layer from the management's perspective, while the available actions are mostly devoted to the supplier layers, including major funds, repair, traffic monitoring, etc. The infrastructure investment consists of things like trains, ports, tunnels, and transportation. The infrastructure has services placed on tops of it, such as train departure times and routes. The users, or travelers and shippers, manifest as journeys and shipments within the system. Rail tickets purchased before the end of March were returned, income and expense concerns were transferred from carriers to the authorities for a period of six months, and the continued operation of many rail networks of factors that are likely was ensured. Specifically, the transport modes system was given $25 billion USD in funding, while the national rail industry got support. Sweden has set aside the equivalent of $300 million USD to assist public transit. Private train operators are not particularly assisted, although they are eligible to ask for general government assistance (WSP 2020) [5].

Different nations sponsored rail travel during COVID-19 in different ways. According to a global poll, the majority of the investigated nations support urban rail transportation, according to WSP (2020). Despite this, long-distance rail transportation is rarely given the same direct assistance as aviation gets in any of the analyzed nations. In the UK, the money of 37 million dollars has been set aside to assist trams and metros in certain locations. The functioning of several regionally significant rail lines was guaranteed [6].

A TSM's enhanced value in the cloud: Many of the same commercial advantages that other cloud solutions offer, such as increased economies of scale, a reduced total cost of ownership, the absence of upgrade fees, and a quicker return on investment, also apply to cloud-based transportation management systems (ROI). A cloud-based TSM offers further advantages for IT in the form of quicker deployments, less training and installation hours required, automated upgrades with the newest capabilities, and enhanced security [7].

The way business is conducted today is no longer successful in the evolving transportation industry. In the past, significant capital projects like lane additions, new interchange construction, and road construction were primarily used to overcome physical restrictions like bottlenecks and congestion. These expansion plans were mostly based on traffic numbers that were foreseen long into the future. Operational enhancements were frequently a last-minute consideration after the new infrastructure had been integrated into the system. With fewer resources and available space, transportation organizations today must deal with issues like expanding urbanization that increases travel demand. We are no longer able to construct our way out of congestion as a result.

Today's trends include limited resources: The federal gas tax, which has not been altered since 1993, serves as the main government revenue source for the nation's transportation system. Since then, governmental entities have faced tighter budget restrictions: Inflation—the price of constructing roads and bridges has gone up.

Fuel economy: Since today's cars can go further between fill-ups, gas stations' income is reduced. The purchasing of fuel has decreased as well due to the rising popularity of electric and plug-in hybrid vehicles.

Organizations are in a difficult position because of digital improvements in the commercial landscape. Businesses need to buckle up for a lot of things in order to keep up with the growing chaos and satisfy customer demands for same-day delivery, including modernizing operations to reduce inventory problems, managing warehouse operations effectively, and improving order and fulfillment management to get goods to customers quickly. Organizations in the logistics and transportation sector will need to adopt cutting-edge technology now in order to develop and maintain supply chain solutions for the future by 2021. In light of this, the following five developments will have a significant impact on the logistics and transportation sector in 2021:

1. Automated mechatronics workflow, 2. Machine intelligence, 3. Predators, 4. Self-driving vehicles, and 5. IoT drives sustainability [8].

The management of transportation operations includes all forms and facets, such as monitoring and controlling every aspect of equipment maintenance, petroleum costing, tracking and cartography, material handling, connectivity, electronic data interchange deployments, baggage handling, carrier process selection, and even financial reporting. In supply chains, transportation management solutions are essential. Deep visibility is provided by an efficient transport management system to guarantee more successful transportation planning and execution. This invariably leads to greater client pleasure, which generates more sales and propels business expansion [9, 10].

Advantages of putting in place a transport management system: increased cash flow efficiency, better mechanism for tracking, more cost reductions, increases productivity in the warehouse, decrease in inventories, and precise instructions [11].

Despite increased demand on communities to build more efficient motorways and highways, smart infrastructure is critical for modernisation. Smart roads based on IoT and ICT can enable towns and different agencies to gather and analyse data to enhance day-to-day traffic control. Smart transport network may also assist cities in adapting to long-term smart mobility requirements. Metadata from IoT sensors, cameras, radar, and 5G-enabled technology may be processed in adjacent time and utilised to enhance traffic flow on crowded highways. Data may also be transferred to the cloud for long-term study, offering important information for projects like CO_2 reduction. Edge computing brings up a plethora of new options for smart and connected roadways. It allows for reduced speed for predictive analytics and artificial intelligence (AI) that power smart road infrastructure such as adjustable traffic signals and interconnected highways. Signals, for instance, that constantly vary their frequency depending on wearable sensors might improve traffic flow or modify indicators to assist safeguard others on the road from risky vehicles.

Several factors to recognize in integrating an innovation. New technology must prioritize higher discernibility and reliability. Analyze your options, pay attention to the ROI, think about information security, focus on completing tasks, pay attention to brief strategic edge, enhance your client's understanding, and imagine the revolutionary effects [12].

19.3 Technology Advancements

Transportation organizations may use technology to create answers to congestion problems. Privately held mobility services, however, have grown in popularity due to consumer technology advancements (smartphones, apps, GPS, etc.). (Uber, Lyft, etc.). The growing funding gap for transportation necessitates a strengthening in the advancement, checking, and expanding of eco-friendly alternatives to the petrol tax as distance travelled rise and petrol tax revenues continue to be reduced by improved fuel efficiency and the rising popularity of powered mobility. Although most of the technology issues relating to road user charges have been resolved, more attention has to be paid to the regulatory issues relating to data-sharing, cybersecurity, and privacy. The switch from gasoline to electric vehicles represents a profound technological as well as social shift. Transportation leaders and ecosystem partners should concentrate on finding solutions to the EV charging connectivity challenge and resolving a potential skill's shortage in the EV industry since the US industry is on the approach of an EV explosion [5].

As consumer demands and interests evolve, there is an increasing desire for government bodies to be held accountable for spending public money in the most efficient way possible to enhance the performance of the transportation system. As a result, "performance-based" programs are becoming more popular. The general traveling population is also losing patience with unforeseen journey delays brought on by accidents, inclement weather, construction zones, and special events. Both drivers and businesses may find such delays to be inconvenient. Regardless of the form of transportation or who owns the road, the traveling public expects to get to their destinations on time. There is a higher need for connection and multimodal choices in metropolitan areas. It is necessary to have a good handle on whatever creates bottlenecks.

According to an investigation, amid the typical dawn and evening peak times may contribute to some congestion, non-recurring events like accidents, breakdowns, construction zones, poor weather, and special events account for a sizable portion of it. Roadway capacity is frequently lost because of these unanticipated incidents rather than bottlenecks or capacity limitations. There could be a chance to swiftly implement low-cost upgrades that are directed at these particular reasons to lessen their effects.

Currently, the transportation management system, to complete same-day transports, TMS or TSM must respond more quickly in response to rapid bookings placed on e-commerce sites with a condensed planning window. Huge technology corporations like SAP and OTM would need to drastically modify their platform to manage last-mile operations, from forecasting TEUs to reacting quickly [13].

The TMS or TSM systems would also need to be ready to develop creative costing solutions. As the method of scheduling transports shifts from physical agreements to premium service deliveries known as TaaS, logistic organizations soon will have their charges lesser pre-negotiated based on size or weight-linked pricing and more dependent on subscriptions (transport as service). The logistical industry has recently undergone "Amazonization" since digitalization has become the buzzword that has swept the globe. Amazon is credited for changing operations and transportation, raising customers' requirements to include relatively similar arrival, free delivery with monitoring, and extremely simple online transactions. Without a doubt, the B2B transportation sector shares these concerns. For instance, if there are not enough passengers on a train, the coach might be stocked with boxes for logistical transfer in order to reduce the cost of transportation. This form of shift requires the transportation system to be adaptive.

Convoy pickups are a possibility since drivers may keep in touch and communicate resources about their driver's side movement and current capacity for a speedier arrival. The utilization of these capabilities and the ability to monitor all of their transportation from a single cockpit, even delayed arrivals, will soon be required of shipping services.

In the cellphone and smart device era, these themes are key topics. The tracking of the package or container will become standard practice. Companies like CMA-CGM have already made investments in smart canister businesses like TRAXENS, which offer real information on the mobility, warmth, and geolocation of the box within the container. The transportation sector can follow the full origin of the supply chain, from the creation of the commodity to the preservation of heat during transportation, thanks to block chain technology. The subsequent generation of TMS would need to be ready to offer built-in solutions for geo-fencing, analytics, and collaboration with the subsequent generation of innovations.

The infrastructure of the transportation complex and the efficient delivery of transport services are crucial for the growth of the economy, maintaining economic stability, and addressing the demands of business entities and the public in terms of passenger and cargo transportation. Although since the start of the industrial revolution, advancements in transportation have been associated with expanding economic prospects. A specific transport technology has been created or modified at every stage of the growth of the worldwide economy, with a variety of effects. Economic cycles affect the prospects for production, distribution, and consumption through being linked to a range of developments, particularly infrastructure. The timeframe and expenses necessary to take the intended journey will limit how much of the desire to travel really materialises as tourism. Expenses and journey times vary on: The availability of convenient transportation options, as well as characteristics affecting speed, quality, and comfort (such as capacity, dependability, and accessibility); the cost (or price) of the services; and impressions of the services [14].

The logistics and transportation sector is undergoing a rapid digital transition. In a COVID world where the bulk of purchases are conducted online, consumer expectations for product delivery and quickness are rising sharply. This is having a significant impact on how logistics and transportation service providers manage their supply chains and adopt trends designed to improve fleet management, warehouse operations, and freight costs.

The logistics and transportation industry is being overrun by new technology; therefore, it is a good idea to embrace innovations that can improve supply chain efficiency. Industry-changing developments including robotic process automation, artificial intelligence, drones, autonomous cars, and IoT are expected to arrive in 2021. Organizations will be able to build on the promise of a changing supply chain landscape while satisfying consumer needs—today and every day—by embracing these trends [15].

Optimizing the spatial structure and layout of an urban aggregation calls for a more comprehensive comprehension of urban spatial interaction. We create a crawler software to gather online large data for an examination of urban spatial connectivity. In contrast to other research, the study of urban connectivity uses vectorial, accurate, and large information with excellent spatial and temporal quality from intercity bus traffic flows. Metropolis exchange a diversity of resources with one another, including economic, electricity, technology, mobility, and emigration. Urban spatial interaction is a phenomenon that allows cities to link with one another and come together to form an intricate city network system is considering that UA is known for having a higher capacity for combining people, capital, and resources [5].

Together with other objectives of the transport system including flexibility, effective personnel and commodities movement, environmental concerns, public health objectives, and economic objectives, enhancing safety is one of those objectives. In this sense, trade-offs are decisions to prioritize one aim at the price of another that are made by politicians and transportation experts. Public agencies continue to face many situations where they must weigh multiple objectives for a location or section of the road network and decide what trade-offs should be made in order to achieve the goal of improving highway safety, even though those working in the field of road safety are constantly looking for new design features and technological advances to promote all goals. The numerous trade-offs must be discussed by transportation experts in the context of the mobility objectives of a particular demographic.

Pipelines, highways, railroads, air routes, sea routes, and river routes are all necessary for the transport chain in logistics and transportation systems, much as constructions, infrastructures, and other output physical assets are required for the manufacturing of products. Similar to other production costs, the cost of roads is passed to the cost of transportation services rather than being lost during manufacturing. The status of the state's transportation infrastructure affects how well the transportation services are provided. It is necessary to take into account the ambiguity of its working circumstances in order to ensure the flexibility of the transportation and logistics system. The vast array of factors influencing the use of technical processes for production, transportation, and logistics may be distilled down to comparable quantitative indicators that directly affect the make-up and structure of the system.

The basics are as follows: Serve the needs of the community via operating. Increase the number of places where people may ride bikes and stroll in safety, boosting passengers' travel experience. Encourage the safe and effective flow of people and products. Organize appetite for travel; give information to help with decisions. Encourage place making especially in the urban, utilize performance metrics that are fair, broaden collaboration, and coordination. The description of each of these principles is followed by instances of how they have been used in various communities both domestically and abroad, although they are not all included and rated in any particular priority order [3].

Regardless of whether they belong to a class of variables, quantitative equivalents of working circumstances may be categorized into three broad groups based on the nature of the influence:

(1) Characteristics of the objectives and how they are organized, such as how tasks are organized for conducting loading and unloading activities, how quickly items are loaded and unloaded, etc.

(2) Manufacturing, transport, and logistics firms' economic efficiency metrics, which depict the costs of certain iterations of their constructed organizational structures while accounting for the costs of their adaptability to shifting operating conditions.
(3) The quantity of loading and unloading, the name of the products being transported, the dynamics of changes in fixed assets, debt, etc. are examples of indicators of the production, transport, and logistics organization's capacity to operate and achieve the intended goals in a variety of external environmental conditions. The operational efficacy of the logistics system is determined by this collection of indicators, which provides a direct characteristic of the system. These elements, however, can serve as quantitative features—or prerequisites for a production and transportation organization—when combined with the indications of the initial group [16, 17].

19.4 Recommendations and Future Scope

The economy depends heavily on the transportation system. Communities benefit from the benefits of transportation in today's world, and as cities expand and change, so does the need for public amenities and services. Transportation systems have grown independently of economic growth since economic development is dependent on the development of transportation networks. As a result, there are now more automobiles in urban areas, which has detrimental effects on both the environment and human health. As a result, public awareness about these effects has increased. The development of computer and location technology may provide a new path toward sustainable, low-carbon transportation [18].

New developments in processing technology could create effective management systems as if IT that could manage the flow of thousands of moving vehicles, and intelligent algorithms like AI could improve the quality of decisions. Geo-sensing technologies could provide a reliable and continuous position of all mobile and stationary objects on our planet. The combination of geosensing and processing technologies gave birth to numerous new technologies and services, including eco-driving, eco-routing, IoT, anonymous cars, signalized junctions, and many others. Given these advances, a different mindset and approach from what has previously been used are necessary.

In order to choose an option for the growth and management of the transport and logistics system that ensures the fulfillment of transport service tasks with the least amount of efficiency variances under any (real) set of circumstances for the execution of objects of transport and logistics connectivity, the proposed approach to modeling of conditions of uncertainty of procedure and success of a firm, organizations, and objects of transport infrastructure must be used. You can avoid spending a lot of money on plans and projects that need to be prematurely rebuilt or adjusted while transport facilities are being built and operated, and transportation services are being provided by developing theoretical regulations in the field of modeling the operating conditions and development of transport and logistics systems.

In order to address the existing congestion issues, the performance of our current facilities must be optimized. Give organizations the tools they need to manage and operate the infrastructure they already have more effectively and efficiently before investing in new technology. Applying techniques that are less costly than ideas for new roads can result in a sizable return on investment. It may concentrate on unanticipated delays, decrease their impact on the system, and restore the majority of the lost capacity, which is one important benefit.

In terms of how many locomotives the system can accommodate, their frequency, etc., the core network offers a fundamental degree of capacity. Connectivity modifications are often a lengthy analysis process. The middleware estimates the consultative role for various origin–destination combinations in terms of the number of departs, free space, etc., taking into account technological considerations. Through tactical and strategic planning choices, alterations may be made in the short to medium term. Both infrastructure and service capacity should ideally be planned to satisfy requirements. Even if this is the case under normal circumstances, system layer disturbances can seriously impair the system's ability to function. The entire freaking impacts of COVID-19 on the rail transportation sector are yet unclear as of mid-2020. In the coming years, operators' and experts' primary attention will be on how to continue the transition toward a robust and sustainable transportation system [19].

Monitoring the growing traffic is a major issue everywhere in the world. With the assistance of cutting-edge technologies, the smart transportation system (STS) offers a solution to these issues. A holistic system uses a variety of sensors, automotive sensing, and multimedia applications to address and mitigate traffic issues. Although it has been in use in industrialized nations for the past twenty years, when it comes to emerging nations like India, Brazil, China, South Africa, and others, it is still a novel idea. It will cause information gaps in the current study, which can be investigated later. The study summarizes key findings drawn from research on various systems and discusses opportunities for improvement going forward.

Blockchain technology has the potential to improve customer affordability, reduce fraud risk, and increase transparency in the financial services sector. more openness. Considering that users are conducting transactions on a public ledger, blockchain technology can increase transparency in the financial sector. To assist explain the idea from a financial and non-financial viewpoint, and to demonstrate financial effect, the following three must-know tools must be used: total ownership costs (TCO), cost–benefit evaluation (CBA), and return on investment expectations (ROI) [20, 21].

Better passenger experience, operational effectiveness, and safety are requirements for a contemporary train transportation system. In order to do this, railway transportation networks are including an increasing number of smart devices, such as environmental sensors, key status monitors, and related actuators. It is anticipated that the railway transportation system of the future will be covered by a vast network of intelligent "things," which can contribute to the improvement of all aspects of the transportation system by effectively and efficiently utilizing emerging ITs to interconnected trains, infrastructures, and people. All these connected smart gadgets create a massive Internet of things (IoT) for the rail transportation system.

References

1. Tahir, M.N., Saud, M.S.: Implementation of a cooperative intelligent transport system utilizing weather and road observation data. In: Autonomous and Connected Heavy Vehicle Technology (2022)
2. Oracle India in supply chain management products, logistics and what is a transportation management. Last accessed 29 July 2022
3. Harrabin, R.: Climate change: set target to cut car use, minister told. BBC. The original on 22 June 2021. Retrieved 23 June 2021
4. Making Transit Work: insight from Western Europe, Canada and the United States (PDF).: Transportation Research Board (2001). The original on 2017-08-08. Retrieved 2008-07-22
5. Ermoshin, N., Romanchikov, S., Denisov, A.: Adaptive approach to economic security management of transport and logistics systems. Transp. Res. Procedia **63**, 195–202. ISSN 2352-1465
6. Abou-Senna, H., Radwan, E., Navarro, A., Abdelwahab, H.: J. Traffic Transp. Eng. **5**(1), 44–45 (2018)
7. Akhtaruzzaman, Md.: Recent trends in smart transportation systems: a review, pp. 73–84 (2016)
8. https://synoptek.com/insights/it-blogs/trends-shaping-logistics-and-transportation-industry/
9. http://www.asean.org/communities/asean-economic-community
10. https://www.winfreight.co.za/the-importance-of-a-transportation-management-system/
11. https://airspeed.ph/blog/benefits-transport-management-system/
12. Forbes-Innovation 10 Critical Aspect to consider before Adopting a New Technology by post written by Expert Panel, Forbes Technology Council
13. https://ops.fhwa.dot.gov/publications/fhwahop12004/c3.htm
14. Rodrigue, J.-P.: Routledge, New York, 456 pp. (2020). ISBN 978-0-367-36463-2
15. Jenelius, E.: Rail Transport Resilience to Demand Shocks and COVID-19 (2020)
16. Litman, T.: Sustainable Transportation and TDM, Online TDM Encyclopedia. Victoria Transport Policy Institute. The original on 2020-05-13. Retrieved 2009-04-07 (2009)
17. Gifford, J.L.: Adaptability and flexibility in urban transportation policy and planning. Technol. Forecast. Soc. Change **45**(2), 111–117 (1994). ISSN 0040-1625
18. Lu, C., Yan, X.: The break-even distance of road and inland waterway freight transportation systems. Marit. Econ. Logist. **17**. https://doi.org/10.1057/mel.2014.14
19. WSP.: Rail and the effects of the COVID-19 pandemic (2020). https://www.wsp.com/en-SE/insights/rail-and-the-effects-of-the-covid-19-pandemic. Accessed 7 July 2020.
20. https://www.thinkhdi.com/library/supportworld/2016/three-must-know-financial-tools-effective-decision-making.aspx
21. https://money.usnews.com/investing/cryptocurrency/articles/how-blockchain-can-transform-the-financial-services-industry

Chapter 20
Comparison of Economic Viability of Electric and Internal Combustion Engine Vehicles Based on Total Cost of Ownership Analysis

Deepak Kumar, Gautam Kalghatgi, and Avinash Kumar Agarwal

Abstract Global climate change and local air quality concerns due to transport activities have led to several governmental interventions to accelerate the transition of internal combustion engine vehicles (ICEVs) powered transport sector to alternative powertrains such as battery electric vehicles (BEVs). In today's world, every county is aiming for sustainable development. There are questions about the sustainability of BEVs which need to be answered. There are three main pillars of sustainability: environment, economy, and social. This study reviews the comparison of BEVs and ICEVs based on the total cost of ownership (TCO), a tool for ensuring economic sustainability. TCO varies from country to country and their policies. This chapter reveals that for a BEV to be TCO-competitive without subsidies/incentives, the initial purchase price of the vehicle needs to be reduced substantially or the average annual distance travelled must be increased severalfold. Technological innovations and economies of scale will reduce the price of a BEV; however, this will take a long time to materialize. From a TCO perspective, a BEV can be cost-competitve only in high mileage use cases, such as taxi fleet operators or ride-hailing companies, and it's not competitive for most private car owners.

Keywords ICEV · BEV · TCO · 2W · 4W · Subsidy

20.1 Introduction

Intergovernmental Panel on Climate Change (IPCC) report suggested that "Unless there are immediate, rapid, and large-scale reductions in greenhouse gas (GHG) emissions, limiting global warming to 1.5 °C will be beyond reach." According

D. Kumar · A. K. Agarwal (✉)
Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology, Kanpur 208016, India
e-mail: akag@iitk.ac.in

G. Kalghatgi
Shanghai Jiao Tong University, Shanghai, China

R. K. Upadhyay et al. (eds.), *Transportation Systems Technology and Integrated Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-99-1517-0_20

to the BP (British Petroleum) report on World Energy, the overall global energy consumption was 557.10 exajoules (EJ) in 2020 [1]. The contribution of oil, natural gas, coal, nuclear energy, hydroelectricity, and renewables in the energy sector was 31.27, 24.7, 27.18, 4.3, 6.84, and 5.7%, respectively [1]. Primary energy consumption was higher in non-organization for Economic Co-operation and Development (non-OECD) countries than in OECD countries; however, on a per capita basis, non-OECD countries consumed one-third lesser energy than OECD countries. Non-OECD countries emitted almost double CO_2 emissions than OECD countries [1]. Nearly 75% of worldwide GHG emissions originate from the energy industry [2]. Approximately one-quarter of all energy-related GHG emissions originate from the transport sector [3]. According to the Ward's, a USA publisher, 1.4 billion motor vehicles were operating worldwide in 2019 [4], and this number is increasing rapidly, especially in non-OECD countries like India and China. According to IPCC, crude oil caters to >95% of the total transport energy demand. This demand was fulfilled by the available oil reserves, which were 244.4 billion tonnes (1732 billion barrels) at the end of 2020. These oil reserves increased by 33% compared to 2000 because of new oil discoveries. The reserve-to-production ratio of oil is 53.5. This means that current known oil reserves can cater for over 50 years from 2020 at the present production and consumption rates. Venezuela, Saudi Arabia, and Canada are the top three countries with the highest proven oil reserves of 17.5, 17.2, and 9.7%, respectively of the global petroleum reserves.

India is the world's third-largest energy consumer after China and the USA. The current energy consumption has doubled since 2000. However, energy usage and emissions are less than half of the world's average per capita. India had over 295.8 million registered vehicles in 2019 [5]. These vehicles were responsible for ~13% of the total energy-related GHG emissions [6]. In India, 92% of vehicles are non-transport vehicles out of total registered vehicles, including two-wheelers (2Ws), cars, jeeps, buses, tractors, and trailers. Amongst all the registered vehicles, 2Ws have the highest share (~75%) [5]. Between 2000 and 2019, the total GHG emitted by Indian transport sector quadrupled, while the energy demand in transport sector grew by ~3.5 times [6]. India's current vehicle ownership rate is substantially below the average rate reported by other countries. Several G20 countries have more than 500 cars per 1000 persons. However, India still had a modest national average of ~37 cars per 1000 persons in 2019 [6]. Even in mega-cities like Delhi, the vehicle ownership rate is ~100 cars per 1000 persons, which is significantly lower than in other comparable megacities globally. Therefore, India has significant vehicle ownership growth prospects since its gross domestic product (GDP) per capita is projected to increase significantly in the next 2–3 decades. Since India is projected to be the growth engine for the world, access to easy, and cheap personalized transportation would unleash new opportunities for its aspiring and young population.

The automotive sector makes a major contribution to the industrial and economic growth of the world, accounting for ~3% of the global GDP [7]. As the number of vehicles increases, there will be challenges associated with the automotive sector. Most vehicles are internal combustion engine vehicles (ICEVs) powered by fossil fuels. Hence, their energy requirement is bound to increase. Since fossil fuel reserves are limited, alternative energy sources will be required in the future. Advanced technology development is necessary to provide superior fuel economy and lower emissions. Studies concluded that the ownership cost of a BEV varies from country to country. In most cases, the cost of owning a BEV is more than owning an ICEV for an average period of ownership. This chapter reviews battery electric vehicles (BEVs) and ICEVs comparative study from the economic sustainability perspective.

20.2 Emission Reduction Technologies

Gasoline and diesel engines power most passenger and heavy-duty commercial vehicles respectively. The reduction in fuel consumption and emission also result in improved IC engine performance. Compression ignition (CI) engines have higher efficiency than spark ignition (SI) engines and suffers from high nitrogen oxides (NO_x) and particulate emissions. Modern CI engines use various technologies to moderate the knocking tendencies and control the exhaust emissions.

Confront with ever-stringent environmental regulations, automakers have adopted various new technologies to increase efficiency and reduce emissions with minimal increase in cost. The transport sector is at a critical juncture where radical technologies are required to meet the growing demand for an affordable and sustainable transport ecosystem. Researchers have developed different low-temperature combustion (LTC) strategies, such as homogenous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), reactivity-controlled compression ignition (RCCI), and gasoline compression ignition (GCI), to address some of these challenges. LTC technologies are designed to use the advantages of both SI and CI engines and simultaneously reduce NO_x and particulates while delivering higher efficiencies. Thermal efficiencies of engines are significantly higher in HCCI mode of combustion. However, the maximum achievable brake mean effective pressure (BMEP) is limited due to higher rates of pressure rise (RoPR) [8–10]. HCCI engines produce an insufficient heat release rate (HRR) at low loads and higher unburned hydrocarbons (HC). Also, their combustion phasing is difficult to control, restricting their use in practical applications. Another novel LTC technology, PCCI, showed tremendous potential to reduce NO_x and particulate emissions without significantly affecting the engine power output and efficiency [11–14]. PCCI combustion uses an early fuel injection and higher exhaust gas recirculation (EGR) rates. However, it can't be used at higher engine loads due to unacceptable knocking. Hence, used only at medium engine loads and employed with other combustion modes in a mode-switching engine.

RCCI uses fuels with two different cetane numbers having different mixture reactivities [15–17]. One is a high-reactivity fuel (HRF), the primary fuel having high cetane number, such as mineral diesel and biodiesel. The secondary fuel is a low reactivity fuel (LRF) with a low cetane number, such as alcohol, gasoline, or compressed natural gas (CNG). LRF is injected into the intake manifold, which mixes with the intake air to form a premixed charge. This premixed charge is then supplied to the combustion chamber, where this charge will be homogenized during the compression stroke. HRF is then directly injected into the combustion chamber, which acts as an ignition trigger for the combustion of the premixed charge. This combustion technology can operate over a wide range of engine loads with ultra-low NO_x, particulate emissions, and high efficiency. However, its high-pressure rise rate can cause noisy engine operation. This technology requires two fuel injection systems, increasing the vehicle's cost and complexity. The gasoline compression ignition (GCI) technology emerged as future LTC technology. Kalghatgi and Johansson (2017) reported that GCI combustion engines could operate in the range of fully homogenous combustion engines, such as HCCI, to conventional diffusion combustion, such as CI engines, at different loads [10]. In the GCI concept, gasoline-like fuels come under the gasoline's auto-ignition quality range are used in CI engines to replace diesel. The fuel used in GCI engines has a long ignition delay, which gives sufficient time for premixing before the combustion initiation. It makes easier to control the particulate and NO_x emissions, reducing the engine complexity and cost without losing efficiency.

Engine technologies are fuelled by fossil fuels, increasing GHG emissions and having fluctuating costs. Therefore, alternative fuels are required, which are environment-friendly, easy to handle, and inexpensive. Major biofuels of interest include biodiesel, ethanol, methanol, and dimethyl ether (DME). Biodiesel can be produced from edible and non-edible oils, straight vegetable oils, waste cooking oils, and animal fat. Alcohols are also emerging as important alternative fuels. Methanol is a simple compound with no sulphur or complex organic compounds and high octane number. They emit low emissions than gasoline and are best suited for SI engines. It can also be used for CI engines but requires a few engine hardware modifications. Apart from their merits, they have challenges, e.g., methanol has half energy content of gasoline.

Hence, vehicles require double fuel tank size for the same range. Methanol is toxic and corrosive to metals. If it spills into water, can create an environmental hazard since it is completely miscible with water. On the other hand, ethanol is a cleaner, less toxic, and less corrosive alcohol than methanol. Bioethanol is produced from grains like corn, maize, and sugarcane. During farming, it requires fertilizers and lots of water. It degrades the soil. Like methanol, ethanol is a high-octane fuel but has ~35% lower energy content than gasoline. DME is also one alternative fuel option with a higher cetane rating and can be used in CI engines. It is a colourless, odourless, and non-toxic hydrocarbon. It can be produced from the syngas generated by feedstocks such as natural gas, coal, municipal solid waste (MSW), and biomass. It has a very low viscosity and may leak through the feed pump and increase the wear of FIE components. It does not contain sulphur and offers soot-less combustion. It is gaseous at normal temperature and pressure (NTP) and liquefies at 5 bar pressure at room temperature. Therefore, modifications are necessary to deploy DME in the existing CI engines.

In addition to engine and fuel technologies, there are other options to reduce emissions from the transport sector, such as BEVs, hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), and fuel-cell electric vehicles (FCEVs). BEVs are powered by a battery, and they do not have a combustion chamber. They do not emit tailpipe emissions, helping improve the urban air quality. However, batteries are quite heavy, increasing the vehicle's overall weight. BEVs use rare earth metals in batteries, increasing the cost. The BEV powertrains are still not fully matured for deployment for many reasons, such as high upfront cost, coal-generated electricity, and limited charging infrastructure. HEVs and PHEVs are other options. The HEV and PHEV use both ICE and electric motor. In the case of HEV, an electric motor assists the IC engine. Regenerative braking converts waste energy into electricity, which charges the battery and recovers some energy. Only electricity is used to operate the vehicle during light load conditions, e.g., during initial acceleration. In the case of a PHEV, the battery is charged by plugging it into an outlet or using a charging station. It can run solely on fuel, electricity, or a combination. Another option is FCEV, operated by electricity generated from hydrogen fuel cells. Here, no emissions are produced; however, it discharges quickly, reducing the vehicle's range [18, 19].

20.3 Current Status of BEVs

Environmental pollution, GHG emissions, and climate change impacts of the transport sector have led to several governmental interventions to accelerate the transition to alternative powertrains such as BEVs [20]. BEVs are not a new technology. They were initially introduced over 100 years ago, at the same time when ICEVs were introduced. This technology is still not matured due to many practical challenges not addressed fully in over 100 years. As of 2022, BEVs account for only 1.5% of the global vehicle population, standing at only 20 million BEVs [21]. There are ~1.3 million commercial BEVs on the road, including buses, delivery vans, and lorries, and over 280 million BEV mopeds, scooters, motorcycles, and 3W [21]. BEV sales are slowly increasing due to improvements and subsidies/benefits offered by various governments. China is the biggest BEV market, followed by Europe and the USA. In 2021, China and Europe contributed to more than 85% of worldwide BEV car sales, followed by the USA (10%), where sales have more than doubled from 2020 to 6,30,000 units [22]. Bloomberg NEF predicted 77 million passenger BEVs will be on the roads worldwide, accounting for ~6% of the total fleet by 2025 [21].

Several non-Annex 1 countries intend to promote BEV uptake, but the risks and benefits have not been adequately assessed under their specific national context. As a participating member of the Electric Vehicle Initiative (EVI) of the Clean Energy Ministerial, India aims for BEVs to account for 30% of new vehicle sales by 2030 under its EV30@30 campaign. Presently, 7.6 lakh BEVs are registered in India [23]. The BEVs contributed ~1.32% of overall vehicle sales in FY21-22. A growth of 133% was observed in BEV sales from FY 2015–20 [23]. According to a NITI Aayog report, the majority of BEVs are three-wheelers (3Ws), contributing ~79%, followed by 2Ws (~17%) and 4Ws (3%) [24]. The number of BEVs sold in India is significantly lower than ICEVs for several reasons, including high initial vehicle cost. The government provides customers with direct and indirect benefits/incentives to ramp up BEV sales. The central and state governments offer incentives for BEV sales in India. The Government of India recently launched phase II of the Faster Adoption and Manufacturing of Hybrid & Electric Vehicles in India (FAME-India) scheme to encourage faster adoption of BEVs and HEVs [25]. Under the phase II of the FAME scheme, the Government of India aims to offer a subsidy of ₹ 15,000/kWh or up to 40% of the vehicle price for each registered 2W BEV and ₹ 10,000/kWh (up to a maximum of 1.5 lakhs) for each 4W BEV registered for commercial purpose only, except buses. To encourage the electrification of public transport, ₹ 20,000/kWh subsidy is provided to the battery electric buses. However, there is no central government subsidy/incentive for privately owned 4W BEVs.

Apart from the central government subsidy/incentives (FAME-II), several state governments in India offer a variety of incentives such as purchase incentives, road tax exemption, and tax benefits. At least 13 Indian states have adopted an EV policy. But, only few states/cities (like Delhi and Mumbai) give direct incentives that subsidize the initial purchase of a BEV, while other states offer road tax exemptions [26–28]. As per the state EV policy of Delhi, a registered 2W BEV owner is entitled to a ₹ 5,000/kWh of battery capacity with a maximum of up to ₹ 30,000 subsidies per vehicle. A 4W BEV owner is entitled to a ₹ 10,000/kWh battery capacity with a maximum of up to ₹ 1,50,000 subsidy per vehicle. However, this subsidy is offered only to the first 1000 electric cars registered in Delhi as direct purchase incentives, and they are also eligible for scrappage incentives [27]. Similarly, as per the Maharashtra government EV policy, a purchase incentive of ₹ 5,000/kWh of battery capacity up to a maximum of ₹ 10,000 subsidies for each 2W BEV and ₹ 1,50,000 subsidy for each 4W BEV is given [28]. Apart from these purchase incentives, tax, scrappage, and early bird incentives are also offered for an initially limited number of vehicles.

BEV registration increased by ~163% in 2021 compared to 2020 due to these incentives [29]. The 2W, 3W, and 4W BEV sales increased by 422, 75, and 230%, respectively. Amongst the Indian states, the top four Indian states with the highest BEV sales in 2021 were Uttar Pradesh, Karnataka, Tamil Nadu, and Delhi. In Uttar Pradesh, Karnataka, Tamil Nadu, Maharashtra, and Delhi, BEV sales increased by 113%, 242%, 427%, 318%, and 109%, respectively, in 2021 compared to 2020, though the absolute number of vehicles sold remains very low [29]. Therefore, BEVs are being accepted to some extent, primarily due to the government's incentives offered to the customers. However, it still has many challenges that must be addressed for large-scale adaptation.

20.4 Pillars of Sustainability

In today's world, every country is aiming towards sustainable development. There are three pillars of sustainability: environment, economy, and social, commonly referring to people, planet, and profits [30]. These three sustainability aspects must be critically examined for any technology to be sustainable.

20.4.1 Environmental Sustainability: Life Cycle Assessment

The environment is the main pillar of sustainability. A tool used to measure a product/service's environmental sustainability aspects is known as life cycle assessment (LCA). LCA is becoming popular as a method of environmental sustainability evaluation for well-informed discussions about the effects of various fuels and powertrain combinations in the transport sector. LCA is not a new method. Its first known application dates back to 1969 when Coca-Cola submitted an application to analyse bottled products in a way other than the customary method of evaluating the environmental effects connected to their end use [31]. Since then, life cycle theory has progressed at varying rates in Europe and US fairly independently. Comprehensive LCA enables a more all-encompassing approach by eliminating the burden-shifting between sectors, value chains, and nations. Due to the global push for net-zero emissions, LCA has taken centre stage in helping businesses and governments to create successful mitigation plans with the least negative environmental impact.

This is especially important for the transport industry, given the proliferation of apparently zero-emission vehicles like BEVs and hydrogen fuel cell vehicles. Despite the claim that vehicles emit no GHGs in their exhaust, a large portion of these emissions are created earlier during the manufacturing of vehicles or the production of energy like electricity. In some instances, the advantages of having no tailpipe emissions can be more than outweighed by their high upstream emissions [32, 33]. Therefore, any advancements in fuels and vehicle technology must go beyond the conventional strategy of narrowly focusing solely on tailpipe emissions and consider the broader lifecycle effects of their use.

To deploy mitigation measures as efficiently and effectively as feasible, it is possible to identify major emissions hotspots using a cradle-to-grave assessment technique [34]. For instance, Abdul-Manan et al. (2020) investigated how to make the best use of the world's limited battery capacity to reduce life cycle GHG emissions as much as possible by integrating the batteries into a variety of electrified cars, from a mild hybrid to a full battery electric, with different battery sizes, as shown in Fig. 20.1 [32].

LCA is also used for assessing various health, ecological, and social implications in addition to the impact of climate change. Because of this, it is a great tool for policymakers to help comprehend any potential trade-offs related to any policy intervention. For instance, Hawkins et al. (2012) used LCA to illustrate the trade-offs

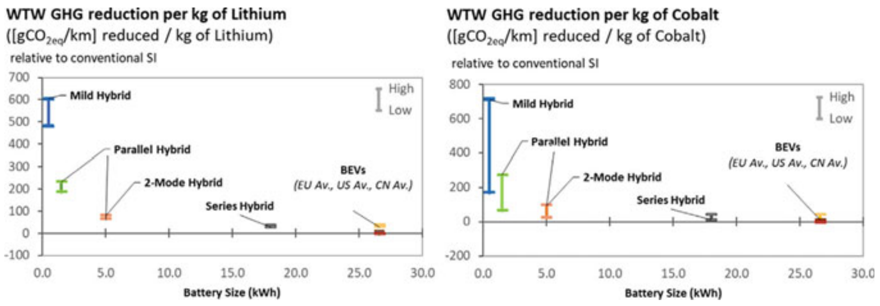
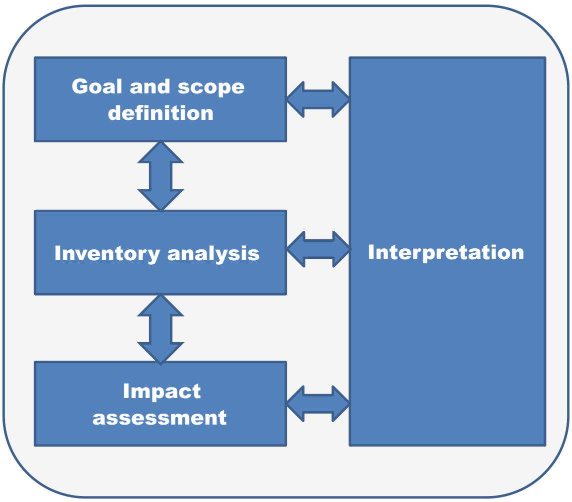


Fig. 20.1 Effectiveness of every kg of lithium (left) and cobalt (right) in reducing the Well-to-Wheel (WTW) GHG emissions [32]

related to BEV in Europe. Its decreased climate change impact is at the expense of noticeably worse detrimental effects such as human toxicity, freshwater ecotoxicity, and metal depletion [35].

The International Standards Organization (ISO) has developed a series of international standards and technical reports under the ISO-14000 series on Environmental Management to provide guidelines for the LCA. Between 1997 and 2000, ISO developed a set of four standards establishing the principles and framework for the LCA (ISO 14040:1997) and the lay down the requirements for different phases of LCA (ISO 14041–14,043). The key accomplishment of these ISO standards was establishing the LCA framework that involves these four phases in an iterative process, namely: (i) goal definition and scoping, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation (Fig. 20.2). Each of these phases is discussed in detail in the following paragraphs.

Fig. 20.2 Framework of LCA [36]



Goal Definition and Scoping: Since it specifies the study's goals and establishes the scope, methodology, and strategy, it is undoubtedly one of the most crucial steps in the LCA. Ultimately, all LCA studies contribute to decision-making, whether it is policymaking, corporate decision-making, or regulatory compliance. Products, processes, and services must be defined at this level. The context of the assessment is established through this approach. The user must establish system boundaries throughout the process, which will be reviewed in the next stages. Analysts must choose the scope of the analysis for system boundaries. Analysts must be transparent about these choices and the thinking behind them. This stage requires the definition of a functional unit, which describes emissions or consumptions per "given quantity of a product, process, or service," for example, let's say a vehicle emits 20 g of CO_2, 3 mg of CH_4, and 0.5 mg of NO_x per 5L gasoline. In this scenario, 5L would be the functional unit. The functional unit in the situation would be 100 km if the emissions were measured per 100 km. Analysts must use the functional unit to compare procedures, goods, or services across several systems. The purpose of the study and the target audiences for which it is being undertaken must be specified by the analysts in this step.

Inventory Analysis: During this stage, analysts identify and quantify all pertinent inputs, such as the amount of water, energy, and materials consumed, as well as outputs, such as emissions into the air, water, and soil. An orderly collection of all relevant information leads to more accurate outcomes. The possible lifecycle stages are shown in Fig. 20.3.

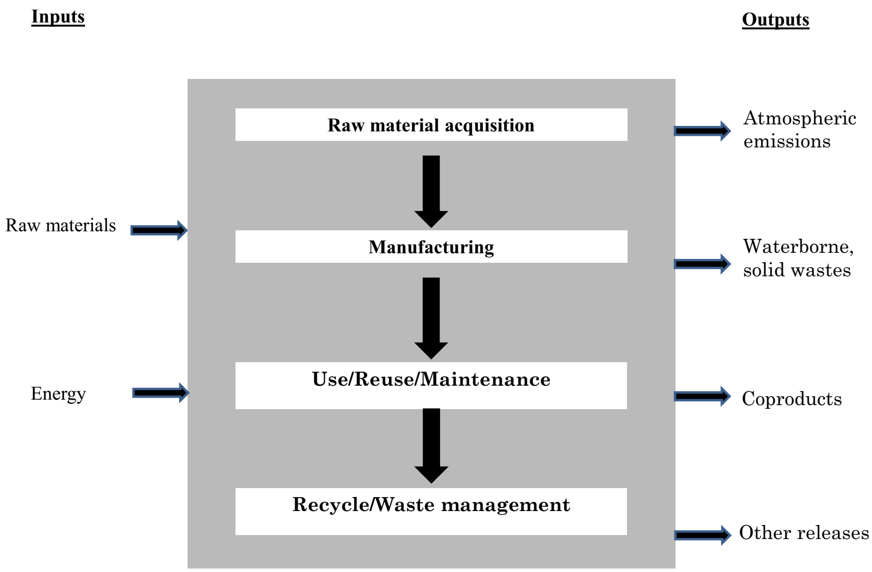


Fig. 20.3 Possible lifecycle stages [36]

Different inputs, outputs, and processes are considered during a life cycle. Many of these pathways result in both the desired products and unwanted "co-products," which need to be considered. Even though the allocation should be avoided wherever possible, according to ISO-14044 for lifecycle evaluation. Some well-known studies have employed "allocation" techniques, in which energy and emissions from a process are distributed amongst the different products in proportion to their mass, energy content, "exergy," or monetary worth. Although the ease of implementation of such allocation methods makes them appealing, sometimes they can have no true physical foundation. The "system expansion and substitution" method, founded on the idea that "any gain from a co-product must depend on what the co-product substitutes, as realistically this is the most likely fate of the co-product itself," is an alternate approach to handling co-products. The co-products are given credit in the substitution method (negative GHG emissions). The credit's worth is based on how much emissions are produced by the product currently on the market and is most likely to be replaced by this by-product.

Impact Assessment: With the aid of the inventory analysis, the user can examine potential environmental and human concerns in this stage resulting from the consumption of water, energy, materials, and environmental emissions. It creates a connection between a process or product and its environmental impact. Equivalents are used to measure a variety of impact categories; for example, climate change is often reported in CO_2 equivalent. This is because each gas has a different global warming potency, even though many gases together contribute to a single impact category, in this case, global warming. For instance, over 100 years, methane has a potential for global warming that is roughly 28 times worse than CO_2, whereas N_2O has a potential for global warming that is about 265 times worse than CO_2, according to the IPCC's 5th Assessment Report (AR5).

Interpretation: In this stage, the user assesses the outcomes of the inventory analysis and impact assessment. Based on the outcome, one can choose an appropriate procedure, service, or good with the least undesirable environmental impact and reasonable trade-offs. Based on inventory analysis and impact assessment, issues are identified through this method. It helps decision-makers comprehend the situation better and suggest the best items or procedures to use. It is the last phase of the LCA. There are different LCA software globally available that simulate and assess the environmental effects, such as Building for Environmental and Economic Sustainability (BEES), Biofuel Energy Systems Simulator (BESS), Chain Management by Life Cycle Assessment (CMLCA), Economic Input Output-Life Cycle Assessment, GaBi, Global emission model for integrated systems (GEMIS), GHGenius, Greenhouse gases, Regulated Emissions, and Energy use in transportation (GREET), System for Integrated Environmental Assessment of Products (SimaPro), Tools for Environmental Management and Analysis (TEAM), UMBERTO, Eco-indicator 99, Ecoinvent, etc.

It is crucial to remember that LCA is a technique for calculating environmental impacts, for which many strategies can be used. Different methodological approaches result in various conclusions; hence, it is crucial to create the approach to fulfil the study's goals carefully. Although the LCA space is a continuum with several scenarios occurring inside the spectrum, LCA may be divided into two main categories: attributional and consequential approaches [37]. An attributional approach often adopts an accounting viewpoint by providing a picture of the energy system at a specific moment. Any changes are frequently considered linearly extrapolated [38]. On the other hand, a consequential method seeks to gauge how an energy system reacts to change. The anticipated effects may not be linear due to possible hidden economic linkages between sectors. As policymakers create regulations that mandate market changes, the significance of the various approaches grow. This applies equally to discussions of how grid decarbonisation affects carbon intensity of electricity and how biofuels use in the transport sector cause changes in land usage.

20.4.2 Economic Sustainability: Total Cost of Ownership

The economy is the second pillar of sustainability. The total cost of ownership (TCO) is a tool that evaluates the overall economic aspect of goods/services. TCO calculates all expenses incurred throughout the useful life of the goods/services. Comprehending the actual cost of obtaining a specific commodity or service from a specific provider serves as both a purchasing technique and a purchasing philosophy. In other words, the TCO is a tool for analysing and predicting the cost of buying, using, and maintaining a product throughout its useful life [38]. Economists have always realized the role of considering factors other than price, such as the transaction costs associated with buying from outside sources. They have mostly considered vertical integration versus purchasing goods/services from the market when analysing transaction costs from a make-or-buy standpoint. This transaction cost analysis also sets the foundation for TCO analysis. Bill Kirwin of the Gartner Group developed TCO (1987) to address the true cost associated with owning and managing an IT infrastructure in a corporation [39]. TCO represents direct and indirect/hidden costs during acquiring a product/service like an iceberg. If someone wants to buy a product, they generally focus on upfront cost or acquisition cost. It could be similar to the tip of an iceberg, but there may be several hidden costs, like the tail of an iceberg, as shown in Fig. 20.4.

As shown, the tail of the iceberg consists of hidden costs such as operational, maintenance, and logistical costs, as the product/service has to operate for a period and requires maintenance after its acquisition. For example, the TCO calculation of vehicles consists of procurement, operation, maintenance, fuel, labour (for a large vehicle), and miscellaneous costs (extra costs during the ownership period), as shown in Fig. 20.5.

There is another logical approach related to the TCO with the transaction sequence of the cost components incurred: Pre-transaction, transaction, and post-transaction [39]. Figure 20.6 shows the cost components of TCO calculations based on the transaction sequence.

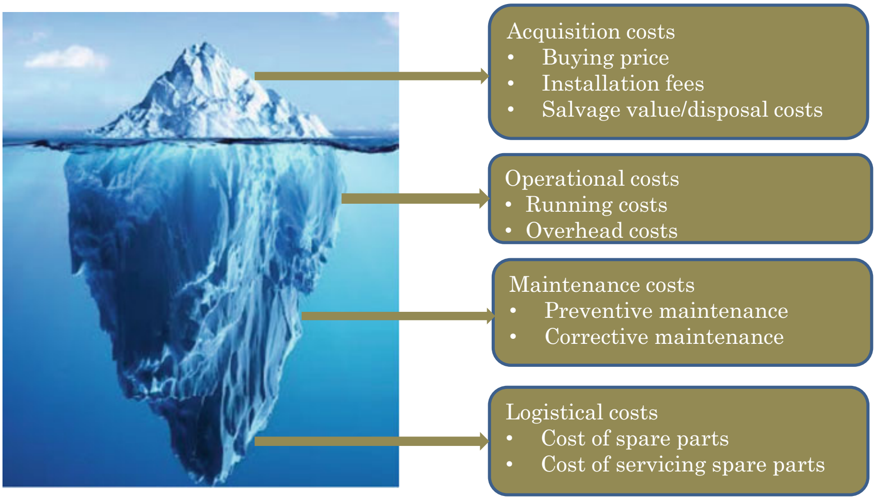


Fig. 20.4 All direct and indirect/hidden costs in the form of an Iceberg

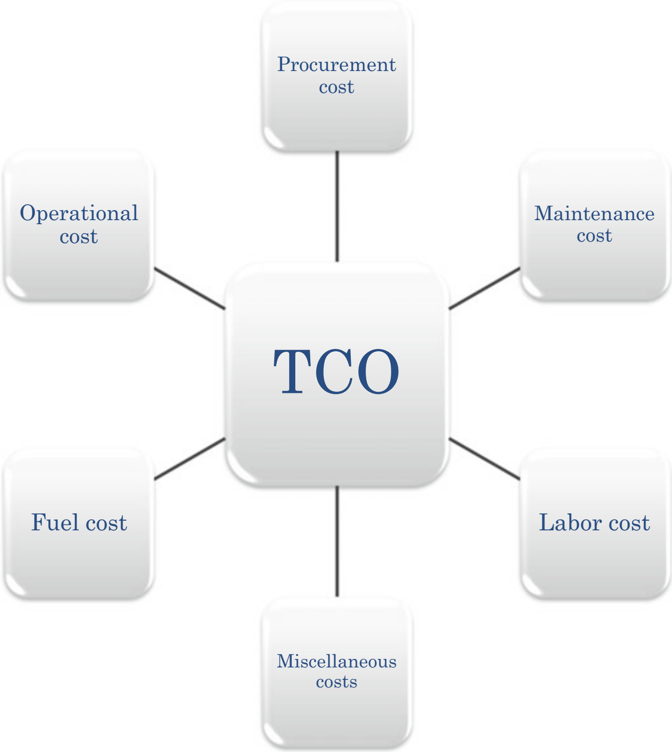


Fig. 20.5 Cost components of a vehicle for the calculation of TCO

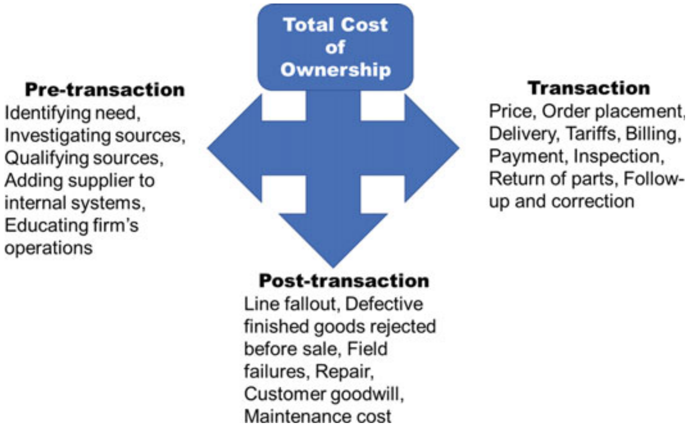


Fig. 20.6 Cost components of TCO based on transaction sequence

Pre-transaction expenses are incurred before an order is placed or the delivery of acquired goods. These costs contain any expenses incurred before the transaction occurs, up until but excluding the time an order is placed, like the costs of looking into potential alternatives, qualifying and training suppliers on the systems and expectations of the company, and adjusting to the systems, styles, and delivery mode of new sources of supply. Transaction costs are more widely recognized than post- and pre-transaction costs because they are the expenses closest to the transaction in terms of place, time, and relationship. Transaction expenses are those incurred throughout the order preparation, placement, tracking, delivery, data matching to the invoice, and bill payment processes. Post-transaction costs occur after the delivery of the product; it may be just after receiving the order or after some years. Post-transaction expenses include the operational cost, repair cost, special maintenance cost, parts replacement cost, etc. In summary, the importance of TCO analysis is as follows:

I. It demonstrates the cost structures of goods/services throughout their lifecycle.
II. Since every step in the TCO process is precisely recognized and recorded, everyone is made aware of the 'concrete' facts.
III. All steps have been recognized and documented, so there is a general awareness of the overall situation, allowing the decision-making based on reliable, fact-based information.
IV. It helps prevent wrong processes that do not satisfy the supplier and customer needs (increasing/decreasing overall cost).
V. It assists in monitoring performance

Apart from benefits, some complexities prevent the wider use of TCO analysis. The main complication is the absence of a standard method of TCO analysis. Another barrier is the unavailability/lack of accounting and costing data. The culture also changes TCO, which is a key factor in the perception of TCO as a philosophy rather than a tool. The substantial and relevant costs to decision-making vary, depending

Fig. 20.7 Framework of TCO calculations

on various criteria, including the purchase's type, size, and significance. It is also one of the reasons that complicate the TCO analysis. First of all, the TCO model is made for the TCO calculations, considering all the costs throughout the lifetime of a product. For example, TCO per km is calculated for a vehicle using the technique shown in Fig. 20.7.

The TCO model consisting of fixed, operational, and variable costs is selected. After putting all these inputs in the TCO model, the output in TCO/km can be calculated.

20.4.3 Social Sustainability

The third pillar of sustainability is social sustainability. The social pillar ensures the social-ethical value of a product/service. In corporate words, the social pillar is connected to the social licence [30]. The community, stakeholders, and employees should support a sustainable business. There are many ways to gain and keep support, e.g., treating the employees fairly and doing their part to improve the community locally and globally. A company must be aware of how its supply chain is being filled on a worldwide social scale. Does the finished product contain any child labour? Does everyone receive a fair wage? Is the workplace secure? There are six dimensions to measure social sustainability: (i) involvement, (ii) cooperation, (iii) equal opportunity, (iv) professional growth, (v) health and safety, and (vi) external partnership amongst employees [40]. Social sustainability is calculated using S-LCA. This approach is also based on the LCA methodology and incorporates all life cycle stages, from creation to consumption to end of life [41]. Its goal is to make social and economic situations better [42].

20.5 TCO of ICEVs and BEVs

TCO is used for the quantification of economic pillar of sustainability. Several studies have quantified the economic sustainability of electric vehicles (BEV, HEV, PHEV) and internal combustion engine vehicles (ICEVs) by calculating the TCO. These studies are discussed region wise in this section.

20.5.1 North American Study

Delucchi and Lipman were the first to report the use of TCO to assess the cost-competitiveness of BEVs against ICEVs in the USA [43]. They developed a comprehensive model to compare the performance, energy consumption, production cost, retail cost, and lifecycle cost of gasoline-powered ICEVs to comparable BEVs. They concluded that for BEVs to be cost-competitive with ICEVs that run on gasoline, batteries must have a lower production cost and a longer life than the best lithium-ion and nickel-metal hydride batteries modeled.

Parker et al. calculated the five-year TCO for four BEV-ICEV car pairs across Los Angeles County, including the Nissan Leaf and Versa Note, the Chevrolet Bolt and Trax, the Volkswagen eGolf, and Golf, and the Tesla Model 3 and Toyota Camry [44]. They also performed sensitivity analysis examining various assumptions, such as yearly vehicle miles travelled (VMT), discount rate, depreciation, fuel expenses, and government subsidies. Figure 20.8 shows the 5-year TCO and breakdown of cost components for each vehicle in the base model.

Except for E-Golf, all BEVs were costlier than comparable ICEVs, as shown in Fig. 20.8. Figure 20.9 shows the 5-year TCO comparison based on sensitivity analysis for variable VMT, discount rates, rebates, subsidies, charging cost, maintenance cost, etc.

Based on the above results, they concluded that depending on the vehicle, five-year TCO changed across Los Angeles County by a ratio of 1.2–1.35. Electricity rate, insurance rate, utility rebate, sales tax, and median VMT were some of the sources of the TCO differences. They realized that heterogeneity is important for comparing electric and gasoline-powered vehicle prices. They found that except for automakers that provide extremely low-priced models (e.g., VW e-Golf), BEVs were not cost-competitive with ICEVs for an average vehicle owner. According to the study, current

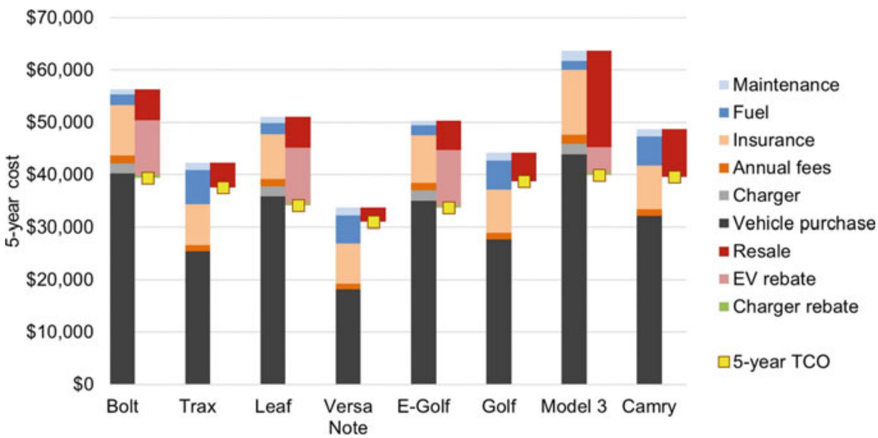


Fig. 20.8 Median cost components for considered vehicles [44]

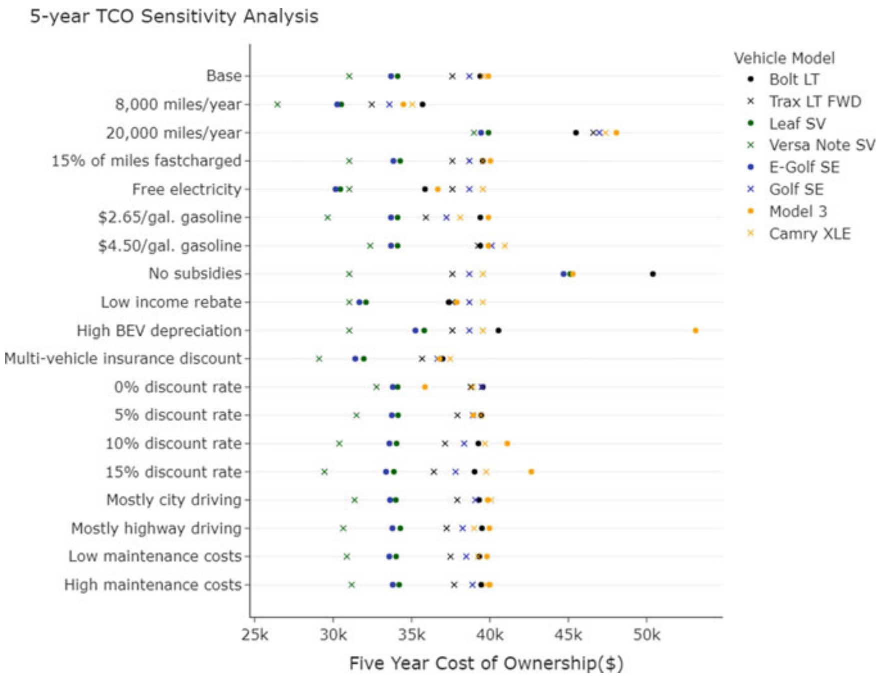


Fig. 20.9 TCO comparison for five years with sensitivity analyses [44]

BEVs still require subsidies to be cost-competitive with ICEVs for most consumers. It also supports that having access to inexpensive electricity is essential for ensuring the affordability of BEVs.

Arthur D. Little tried to gain a deeper understanding of BEVs and their transformative potential by calculating the TCO and environmental impacts of Li-ion-powered BEVs and comparing them to ICEVs [45] in their US-based comprehensive study. Their analysis was for 20 years ownership period. The study considered compact and mid-sized vehicles. They found that the TCO of BEVs was higher than ICEVs for 20 year ownership period, as shown in Fig. 20.10.

The TCO of compact and mid-sized BEVs was 44 and 60% more than ICEVs, respectively, as shown in Fig. 20.10. Liu et al. compared ICEVs and BEVs in the US market with the help of a TCO study [46]. They compared BEVs and ICEVs based on their curb weight. They concluded that BEVs could not achieve cost parity but might achieve in the future. They indicated that without the cost of home charger installation and no cost of alternative transportation, BEVs will take 6.6 and 7.7 years to achieve cost parity for 1000 and 2500 kg curb weight ICEVs, respectively. This period will increase to 11.2 and 14.1 years for 1000 and 2500 kg curb-weight vehicles, respectively, when the cost of home charger installation and alternative transportation are added. The main barrier to cost parity for the buyers is BEV's current higher purchasing price than an equivalent ICEV. Al-Alawi and Bradley developed a

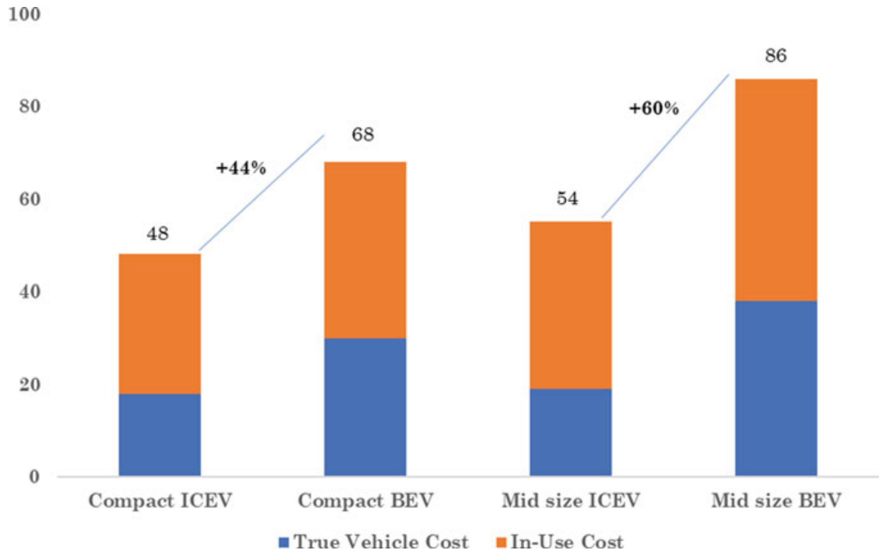


Fig. 20.10 TCO for a 2015 ICEV versus Equivalent BEV (In'000 US$) over a 20-Year Lifetime

thorough ownership cost model so that consumers can accurately evaluate the costs associated with purchasing and using combustion vehicles, HEVs, and PHEVs [47].

Similarly, Hutchinson et al. calculated the TCO of hybrid vehicles [48]. They collected and analysed data on the designs of 44 hybrid automobiles available in the US market. Breetz and Salon examined the TCO of electric, hybrid, and conventional vehicles across 14 US cities for five years from 2011 to 2015 [49]. The study was based on two main questions: (i) When compared to HEVs or conventional ICEVs, do drivers in major US cities save money by switching to BEVs? and (ii) How much did government subsidies affect the cost-competitiveness of BEVs? They considered three vehicles: Toyota Corolla (ICEV), Toyota Prius (HEV), and Nissan Leaf (BEV). They used information relevant to each city, including gas prices, insurance premiums, upkeep and repair expenses, residual value, taxes, fees, and subsidies. Additionally, they conducted a detailed sensitivity assessment to determine how depreciation rate, discount rate, fuel price, ownership period, and distances travelled might affect BEV's cost-competitiveness in the absence of federal and state subsidies. Figure 20.11 shows the 5-year TCO and breakdown of cost components for each vehicle across 14 US cities.

The study reported that high capital cost, related sales tax, and higher depreciation rate of BEVs, state and federal subsidies were required to compete on price with the HEVs. However, even with a high incentive of $10,000, the BEVs still could not compete in price with the ICEV unless it was coupled with highly cheap electricity. Lajevardi et al. calculated the life cycle GHG emissions, TCO, and abatement costs for 16 heavy-duty truck (HDT) drivetrains, including those fuelled by hydrogen, natural gas, and electricity, in British Columbia, Canada [50]. The TCO

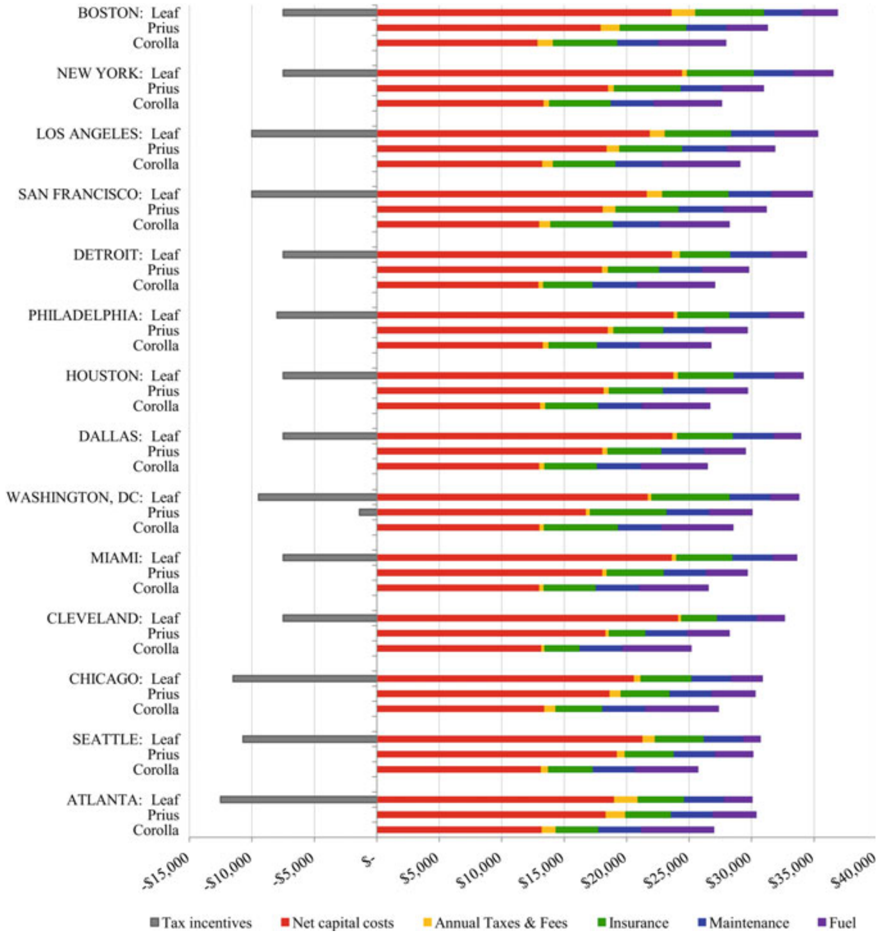


Fig. 20.11 TCO for three cars in 14 US cities for five years [49]

per unit distance, which included infrastructure cost, capital cost, energy cost, and maintenance costs, was assessed in this study. A similar hybrid diesel vehicle was found to be the least expensive powertrain for both short- and long-haul cycles. It was determined that a similar hybrid diesel vehicle was the most cost-effective choice for both short-haul and long-haul operations.

20.5.2 European Study

Thiel et al. assessed the life cycle of CO_2 emissions and TCO, including CO_2 abatement costs of several types of standard European automobiles [51]. These automobiles included a gasoline vehicle, a diesel vehicle, a gasoline hybrid, a diesel hybrid, a plug-in hybrid, and a battery electric vehicle. The study suggested BEVs as a better option from an environmental perspective, but BEVs and PHEVs were not good options from an economic perspective. This problem may remain till 2030 and beyond. Wu et al. created a probabilistic simulation model that was comprehensive enough to encompass most national markets and offered an in-depth analysis [52]. The study was done in Germany, and all data was taken from the German market. According to this research, the relative cost-effectiveness of BEVs strongly depends on the vehicle class and the consumer's annual driving distance. They found that conventional vehicles were likely to continue to be the most economical option for short distances. For medium distances, electric vehicles of small sizes and for long distances, electric vehicles of all sizes can be cost-effective. They also discussed three main policy implications of EVs: customer education, charging infrastructure, and technological (R&D) support for batteries. Letmathe and Suares examined the German market by developing and improving consumer-oriented TCO models [53]. It then compared the cost-effectiveness of BEVs and ICEVs, considering the battery's resale value for second use and second life, to demonstrate the model's viability. Compared to ICEVs in the same vehicle class, they assessed the ten most often registered BEVs and HEVs. Results showed that compared to ICEVs in all scenarios, only a limited number of BEVs and HEVs were economically viable without subsidies. Overall, they concluded that subsidies help BEVs to remain competitive, but they do not result in a lower TCO across various vehicle categories and tested yearly mileages.

Kim et al. conducted a comprehensive techno-economic study of the public transportation system in a small-to-medium-sized city and its environment [54]. A TCO model based on historical data and market pricing projections was used to compare the ownership cost of public battery-electric and hydrogen fuel-cell buses in a Germany-based study. The TCO results for electric buses demonstrated a significant cost reduction (~23.5%) by 2030 compared to diesel buses. Hydrogen buses would still have a 15.4% higher TCO than diesel buses by 2030. The bus with pantograph charging would be the least expensive in 2030, followed by the bus with depot charging, the diesel bus, and the hydrogen bus. The pantograph (opportunity) charging technique assumes that several buses use a terminal and that there is a "hotspot," whereas many bus lines converge. The TCO and breakdown of electric, hydrogen, and diesel buses in 2020 and 2030, respectively, are shown in Fig. 20.12.

Figure 20.12 shows that the hydrogen bus will not be able to achieve cost parity in 2020 and 2030. The study asked a questionnaire to the Offenburg citizens about the acceptance of hydrogen buses. The results of the questionnaire are shown in Fig. 20.13.

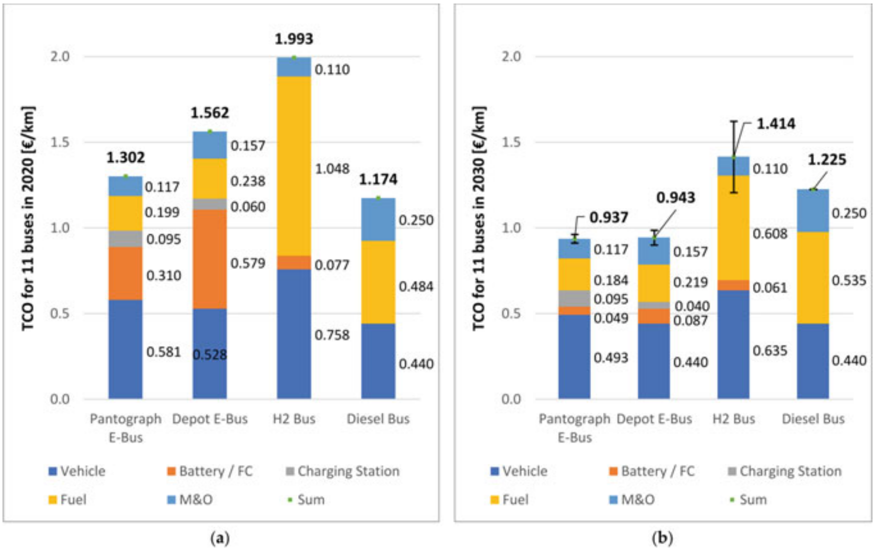


Fig. 20.12 TCO for 11 buses considered: **a** in 2020; **b** in 2030 with the sensitivity analysis of battery prices for e-buses and hydrogen cost for fuel cell buses in 2030 [54]

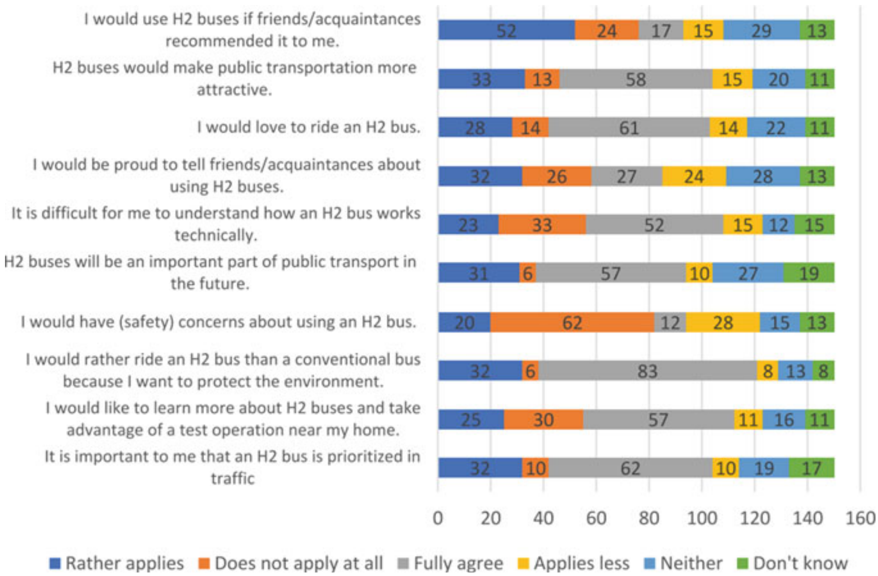


Fig. 20.13 Questionnaire results of the acceptance of hydrogen buses by Offenburg citizens [54]

Scorrano et al. developed a TCO model that estimated the Italian auto market and clarified the role played by the unique qualities of BEVs [55]. They examine the TCO for 36 popular automobile models ranging from small-to-medium cars across four powertrains: petrol, diesel, HEVs, and BEVs. They conducted an analysis based on three factors that affect the TCO: percentage of trips made in cities, accessibility to private parking, and annual distance travelled (ADT). They found that the ADT greatly influenced BEVs competitiveness. Still, it is also significantly influenced by the ability to charge at home at lower costs and, to a lesser extent, by the share of urban journeys. They discovered that purchasing a cheaper BEV rather than an HEV made them better off financially in the absence of government subsidies; however, this was not the case when it came to the purchase of diesel or gasoline vehicles unless a high ADT is taken into consideration (more than 23,000 and 29,000 km, respectively). This study also confirmed that purchasing subsidies are necessary to make BEVs competitive. Similarly, Danielis et al. assessed the present and future of BEVs in Italy using a probabilistic TCO model that incorporated stochastic and non-stochastic variables, vehicle usage, and contextual assumptions [56]. According to Danielis et al., BEVs are currently more expensive than traditional ICEVs in Italy. However, they can compete on price with HEVs for longer yearly trips. The study suggested that the BEV market will expand in future due to various policies like incentives given to BEVs, increase in fuel (gasoline/diesel) prices, and reduction in battery prices. Fevang et al. used linked organizational microdata from the entire population of private automobile owners to describe the anatomy of BEV ownership in Norway, a nation with the most significant BEV customer base [57]. The information on passenger cars included technical details like vehicle's company, weight, size, age, energy carrier, per km energy consumption, engine power, vehicle price, distance travelled, and owner characteristics. The data on passenger cars cover all types of vehicles. The study has shown how the BEV fleet has grown across regions, income brackets, educational attainment, occupation, and other family traits and how it interacts with ICEV ownership. Their findings demonstrated that socioeconomic factors are reliable indicators of the car portfolio. The ownership of BEVs is increasing while income and education are rising. Early BEV owners differed from other automobile owners, but as time passed, BEV owners began to resemble other car owner communities. The study revealed that BEV buyers are less inclined to trade in their old automobiles than other car buyers; however, this disparity has gradually decreased. López-Ibarra et al. proposed a hierarchical energy management strategy design technique for the plug-in hybrid electric buses at the fleet-level TCO management [58]. The suggested strategy is based on a hierarchical decision-making structure with three levels of management. A fuzzy logic-based energy management strategy (EMS) is built into the inner components to control the online operation. To simplify the EMS design, the fuzzy-logic design has been automated offline at the top level of online operation. The offline data exploitation and decision-making, which aims to create a dynamic programming optimization design, is a component of the outer section. Compared to a charge-sustaining charge-depleting strategy, the acquired results in terms of TCO at the fleet level demonstrated a significant improvement of 7.65%. In terms of a technological element, an increase in fuel economy by

6.26–21.61% was made compared to a charge-depleting charge-sustaining strategy. If the buses' energy management measures had not been updated, the fleet's TCO would have improved by 5.51%. Langshaw et al. assessed the economic and environmental benefits of using liquefied natural gas (LNG) to replace diesel in the UK's heavy-duty goods vehicles (HGVs) [59]. To compare the TCO for LNG HGVs to diesel HGVs, they defined a Monte Carlo technique, using probability distributions to reflect the uncertainty surrounding important stochastic variables. Their study found that LNG vehicles were 18% less energy efficient, increasing the WTW GHG emissions by 7%. But LNG vehicles have the potential to reduce emissions by 13% more than diesel vehicles, if the efficiency of LNG vehicles improved. The economic analysis based on the TCO study found that benefits depend on the refueling network. If LNG is refueled at publicly available stations, it decreased the TCO by 7% and achieved cost parity compared to diesel vehicles. But if refueling was done at privately-owned infrastructure, it increased the overall cost and did not achieve cost parity. Munshi et al. calculated TCO of heavy-duty trucks and compared diesel, H_2-fuel cell trucks, and H_2-powered high-pressure direct injection (H_2-HPDI) trucks [60]. Figure 20.14 shows the TCO of different powertrains during five years of the ownership period.

Figure 20.14 shows that a diesel-powered truck is the best option of the three powertrains considered. However, there is a chance of a reduction in TCO for other powertrains due to future technological advancements. Velzen et al. combined cost and technology selection literature to provide fresh insight into an electric power-train's TCO [61]. This European study provided a comprehensive TCO forecasting methodology using a combination of interviews and literature evaluation for BEVs. They establish a conceptual framework comprising 34 elements that directly or indirectly affected the TCO of BEVs, as shown in Fig. 20.15.

The black boxes in Fig. 20.15 indirectly impact the TCO, in contrast to the red boxes, which directly impact the TCO. Their major conclusion was a list of 34

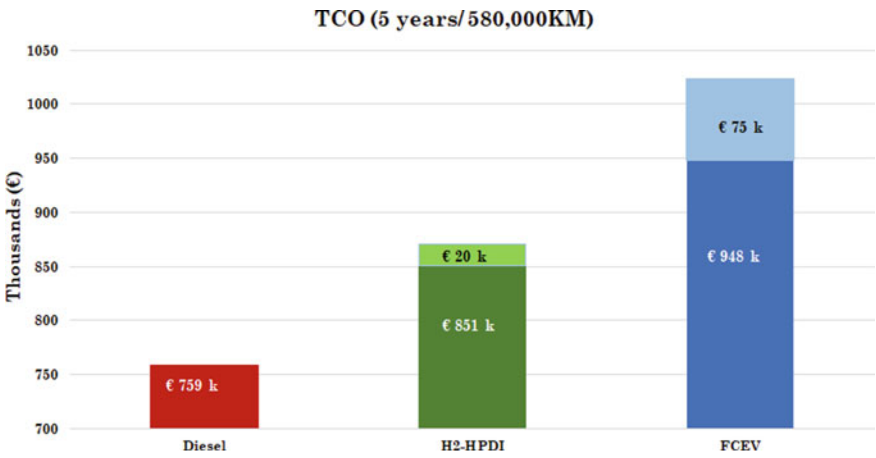


Fig. 20.14 TCO of vehicles considered in the study

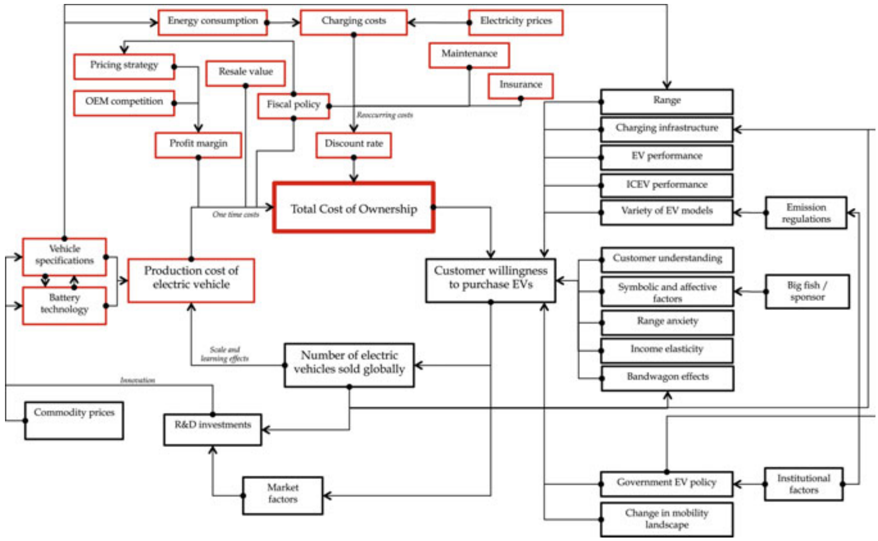


Fig. 20.15 Conceptual framework of factors influencing directly or indirectly the future TCO of BEVs [61]

variables combined from the literature on the cost model and technology selection, which may impact the TCO of BEVs. Ajanovic and Haas examined the TCO, current costs, and future possibilities for BEVs vis-a-vis ICEVs for the European market [62]. Future possibilities were examined while considering fuel CO_2 taxes, technology advancements for BEVs, and numerous other policy framework requirements, such as incentives for purchasing BEVs. They concluded that BEVs did not achieve cost parity, as shown in Fig. 20.16.

The study suggested introducing fuel and car registration taxes based on CO_2 emission and giving subsidies or rebates on purchasing BEVs to improve their TCO. Topal and Nakir performed a TCO-based economic analysis of CNG, diesel, and electric-powered buses for public transportation in Istanbul [63]. TCO was calculated for ten-year ownership period. The breakdown of TCO in operating and purchase costs is shown in Fig. 20.17.

Figure 20.17 shows that the purchase price of a BEV bus was more than double that of the CNG bus, but the operating cost was very low due to cheap electricity. They performed a sensitivity analysis, and one of the sensitivities in TCO, based on daily distance travelled, is shown in Fig. 20.18.

Figure 20.18 shows that the BEV bus was a better option for a very high distance travelled because TCO decreased more in cases of high distances travelled than CNG and diesel-powered buses.

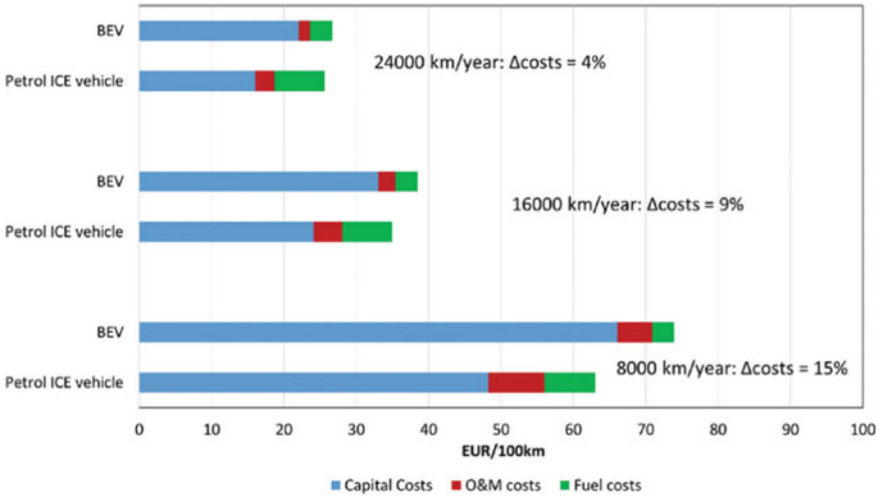


Fig. 20.16 TCO of petrol ICEVs and BEVs in the European countries for different driving ranges, 2018 (Car power: 80 kW) [62]

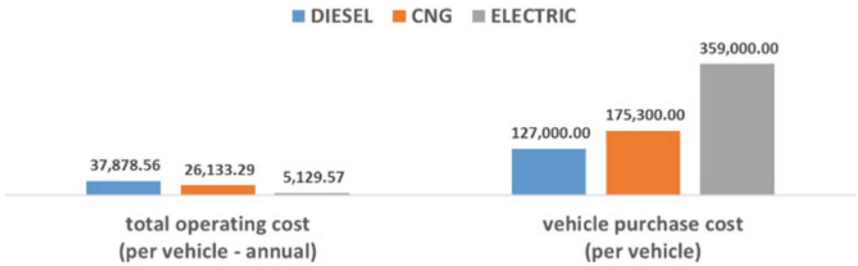


Fig. 20.17 Comparison of TCO based on operation and purchase costs (Euro) [63]

20.5.3 Asian Study

Ouyang et al. assessed the TCO of BEVs, PHEVs, and ICEVs in China using a consumer-oriented model for an ownership period of 5 and 10 years in the post-subsidy era [64]. They considered Chinese consumer characteristics such as consumer usage habits and non-monetary costs. They also considered alternative transportation costs due to dissatisfaction with BEVs. They found that some classes of battery-powered SUVs and sedans reached cost parity with ICEVs by 2025 for the five-year ownership period. Still, the remaining vehicles did not achieve cost parity even by 2030. The TCO gap between BEVs and ICEVs would reduce eventually. When battery replacement costs were considered, the time it took for medium and large vehicles to achieve parity was slightly longer. Lee et al. conducted an economic analysis based on the TCO of hydrogen-powered fuel cell electric vehicles (FCEVs)

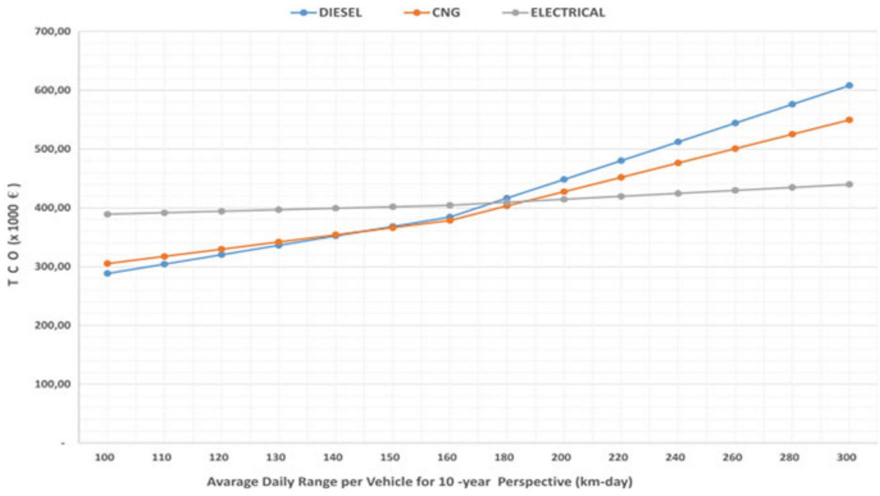


Fig. 20.18 TCO of a bus based on vehicle run (km/day) [63]

in Korea [65]. A regression curve was drawn to determine a correlation between the TCO and Korea's FCEV market share. They also considered the learning rate for the future TCO. They found that, currently, FCEVs have a very high upfront cost; hence, they require incentives from the government. They predicted their market share would increase in 2040 with the increasing learning rate. They also discussed the roadmap for H_2 filling infrastructure in Korea.

20.5.4 South American Study

Falcão et al. compared two different powertrain minibuses of the same company with similar specifications in Brazil. One was diesel-powered, and the other was a battery-powered electric minibus [66].

Their study compared both powertrains based on performance, environmental impact, and economics. The TCO was calculated for 15-year ownership period, as shown in Fig. 20.19. In addition to the expenses of maintaining its batteries, the upfront cost of an electric vehicle contributed significantly to the TCO. It led to 2.5 times higher TCO for a battery electric vehicle than diesel one.

20.5.5 African Study

Ayetor et al. conducted a case study to compare the TCO of four plug-in electric vehicles (PEV) in Ghana over a 20-year ownership period to a comparable ICEV

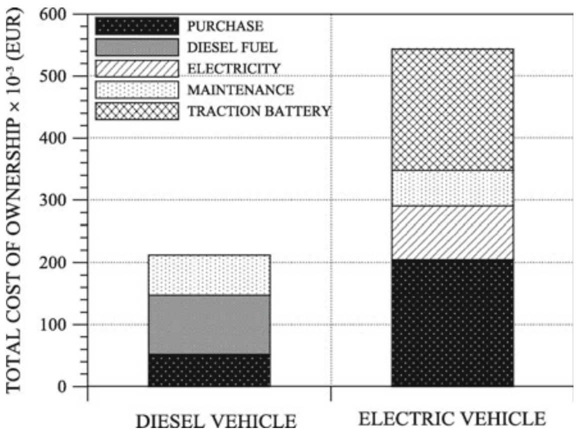


Fig. 20.19 TCO of diesel and electric-powered minibus for a 15-year ownership period [66]

[67]. They considered Toyota Camry XLE (ICEV), Toyota Prius Prime (PHEV), Tesla Model 3 (BEV), Nissan Leaf (BEV), and Hyundai Ionic (BEV) in this study. The manufacturer's suggested retail price (MSRP), fuel, tax, charging, maintenance, social cost, and resale value, including depreciation, were all included in the TCO model.

The impact of variables on the TCO was investigated via sensitivity analyses. They reported a 30% higher TCO of an ICEV than PEV. To make PEVs cost-competitive, their study recommended maintaining a price difference between the cost of fuel per gallon and the cost of electricity per kilowatt of $4. The TCO of considered vehicles is shown in Fig. 20.20. It shows that the electric vehicles (battery and plug-in hybrid) were cost-effective upon longer use. The study also examined the life cycle emission components of volatile organic compounds (VOC), particulate matter (PM) with a diametre of 2.5 microns ($PM_{2.5}$), PM_{10}, oxides of sulphur (SO_x), and nitrogen oxides (NO_x) from PEVs and ICEVs. The emissions of BEVs and PEVs were equal to ICEVs if the share of renewable energy in the energy mix started to fall below 20%.

20.5.6 Inter-country Study

The BEV charging emissions would be more than those of the ICEVs if the share of renewable energy in the energy mix was 15% and below. The emissions of the BEVs would decrease by 16% if the proportion of renewable energy were raised from 40 to 50%. Palmer et al. undertook an inter-country TCO study. They presented a thorough TCO assessment for the HEVs, PHEVs, BEVs, and conventional vehicles in the USA (California and Texas), UK, and Japan from 1997 to 2015 [68]. Their study used a panel regression model to analyse the relationship between the market share and TCO. TCO of all considered vehicles from different regions is shown in

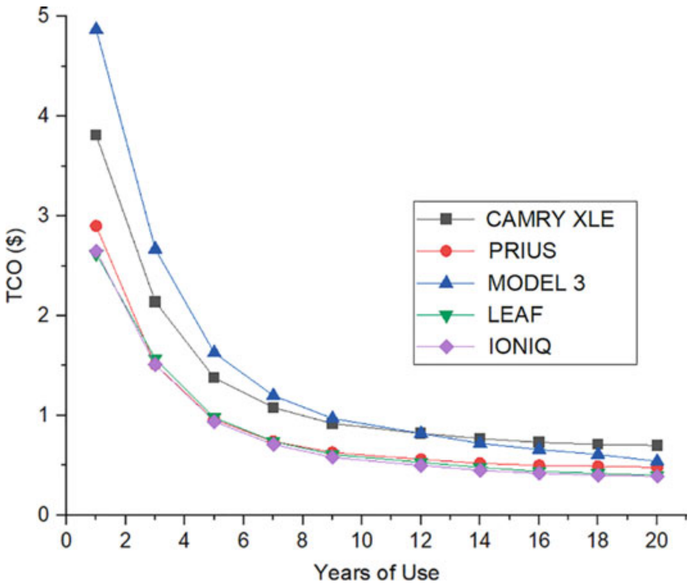


Fig. 20.20 TCO of vehicles considered by years of usage [67]

Fig. 20.21. It indicated that TCO varied from country to country and their policies. The TCO of BEVs was least in each region due to heavy government subsidies, but in the case of PHEVs, the TCO was higher in most regions compared to petrol vehicles due to the absence of government subsidies.

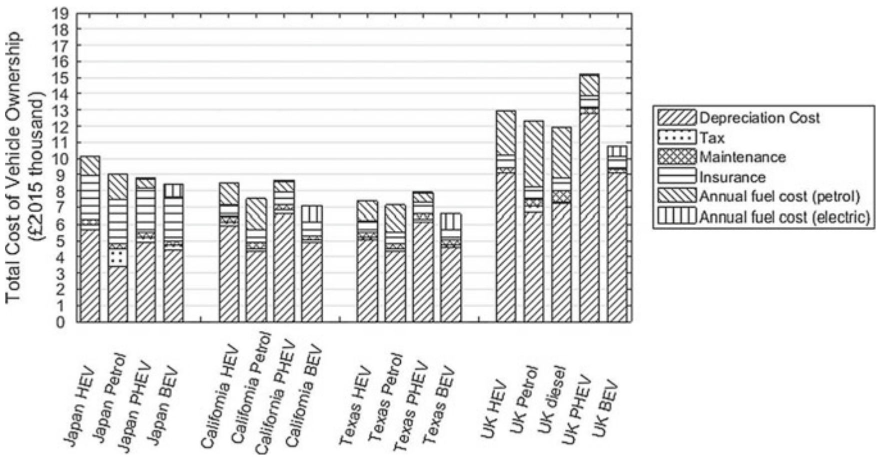


Fig. 20.21 TCO component breakdown for 2015 [68]

20.6 Indian Scenario for TCO of ICEVs Versus BEVs

While there is a growing number of TCO studies for various transport technologies in the literature, very few cover the TCO of BEVs in India. Bhosale et al. developed an extensive TCO model for the Indian scenario [69]. Both financed and purchased vehicle TCOs were assessed in the study, conducting a full examination of which choice and value achieve economic compatibility. They compared 4W BEVs and ICEVs only. Their study used solar power to charge the BEVs. The main objective of their study was to amplify and display the economic analysis linked with BEVs during their lifetime based on actual expenses instead of virtual estimates. They also performed a sensitivity analysis with variable battery prices, interest rates, and annual distance travelled. This study used a pairing vehicle strategy that paired BEVs and ICEVs based on the same or almost identical specifications, such as the Manufacturer, Model, Segment (Hatchback, Sedan, or SUV), and Kerb weight. They only considered the SUV segment of vehicles. They compared Tata Nexon Electric (SUV) to Tata Nexon (Diesel/Petrol) and Hyundai Kona Electric (SUV) to Hyundai Creta (Diesel/Petrol) as the BEV and ICEV pairs in their study. They considered different rates of interest for financed purchases. For the base case analysis, the interest rate was assumed to be 9.75%, the annual distance travelled was assumed to be 15,000 km, and the total travelled distance was assumed to be 2,25,000 km over 15 years. For sensitivity analysis, higher annual distance travelled (20,000 km), incentives, reduced battery prices, and reduced interest rates of 6% for EV + PV integration were considered. An average electricity cost of ₹ 8.5/kWh was considered. A 3-kW rooftop solar array was projected to generate 1450 kWh/year/kW (Global Solar Atlas), with a panel deterioration rate of 0.70%/year. They also considered the rooftop solar panel installation cost at ₹ 70,000/kW. This study showed that BEVs were not cost-competitive to ICEVs in India under current conditions [69]. For Hyundai pairs, BEV was 32 and 24% costlier than comparable ICEVs in financed (FTCO) and purchased (PTCO) buying options, respectively, whereas, for Tata Nexon pairs, BEV was 8.3% (FTCO) and 2.4% (PCTO) costlier than paired ICEV. The main reason for higher TCO for BEVs was higher initial purchase cost and finance interest costs collectively, which were responsible for 75% of overall TCO for Hyundai BEVs and 68% for Tata Nexon BEVs. Battery replacement cost accounted for ~10% of overall TCO in both pairs. But the fuel cost of BEVs was lower than ICEVs. For ICEVs, fuel cost accounted for 38% of the overall TCO. BEV's low fuel cost advantage was compromised due to its higher initial purchase price, finance cost, and battery pack replacement expenses. The study also criticized current government incentive policies and suggested increasing the incentives to promote BEVs economic competitiveness in India. According to this study, the EV + PV partnership was well suited for the Indian setting since it allowed customers to avoid high-cost storage batteries, enabled charging time flexibility, and reduced solar array size, lowering the TCO. The study recommended government funding to the solar industry with no interest and reinstating the cancelled solar panel installation incentives to promote the EV + PV alliance.

Murugan and Marisamynathan tried to identify the hurdles based on expert and customer views [70]. The fuzzy Decision-Making Trial and Evaluation of Laboratory (DEMATEL) approach was used to identify potential challenges based on expert opinion data. Their study used the Relative Importance Index (RII) method to prioritize barriers based on customer viewpoints. Their study identified the following most significant barriers to the electrification of the transport sector in India:

- Higher initial purchase price of BEVs.
- Many electric vehicle manufacturers are relatively new in the business.
- Lower mileage after full battery charge.
- Battery technology is immature and unreliable.
- Competitive vehicle design is less adaptive.
- Insufficient numbers of local technicians are available for repairs and maintenance.
- A limited number of public charging stations are available.
- An increased time spent waiting at the charging station when several vehicles are in the queue.
- Concerns about safety during charging.
- Lack of charging facilities while travelling long distances.
- Lack of understanding about subsidy policies, which include a vehicle purchase subsidy and other BEV incentives offered by the governments.

Kumar and Chakrabarty compared both Li-ion and lead-acid battery-powered 2W-BEVs to petrol-powered 2W-ICEVs, Li-ion-powered 3W-BEVs to CNG, petrol, and diesel-powered 3W-ICEVs, Li-ion-powered small and mid-sized cars to CNG, petrol and diesel-powered cars and Li-ion-powered electric bus to CNG, petrol, and diesel-powered bus, based on TCO [71]. They used the same TCO given by Wu et al. [52]. They reported that for 2Ws, lead-acid-powered BEVs cost less than petrol-powered ICEVs, but Li-ion-powered BEVs cost more than petrol-powered ICEVs on a per km basis. In the case of 3Ws, BEVs were the most cost-competitive, followed by CNG, petrol, and diesel-powered ICEVs. CNG-powered ICEVs were the most economical for small- and mid-sized cars compared to BEVs, petrol, and diesel-powered ICEVs. Similarly, TCO/km for low-cost diesel-powered buses was less than for electric and CNG-powered buses. They also reported that BEVs were cost-competitive in cases with higher utilization (distance travelled) and could achieve cost parity after incentives to further lower the upfront purchase cost of the vehicle. They also discussed major concerns for slow adoption rate of BEVs in India were lack of charging infrastructure, long charging time, and high upfront costs of BEVs. However, their study did not examine how state and central government incentives might affect the TCO of BEVs.

The Council on Energy, Environment, and Water (CEEW) have performed various calculations assuming a 30% penetration of BEVs in India's vehicle market in 2030 [72]. According to CEEW, the TCO of battery-powered 2W, 3W, cars, and buses would decrease by 20, 18, 19, and 8%, respectively, by 2030 if the sale of battery-powered 2Ws, 3Ws, cars, and buses contributes 35, 35, 13, and 30% of overall vehicle sale, respectively, in their category by 2030.

One report examined the development and achievements of low-carbon road transportation (LCRT) and electric mobility in India as supported by policy, programs, and regulatory interventions [24]. In the report, they calculated TCO and compared BEVs (Tata Tigor and Tata Nexon) to petrol (Ford Ecosport), diesel (Ford Ecosport), and CNG-powered (Maruti Suzuki Ertiga Vxi) ICEVs. They selected vehicles based on their power rating. The study reported that the TCO of BEVs such as Tata Nexon was quite high compared to conventional ICEVs. According to their calculation, the TCO of CNG vehicles was the least, and the TCO of BEVs was the highest among the vehicles considered. It inferred that BEVs were not cost-competitive to conventional vehicles.

Patil et al. analysed the TCO of 2Ws and compared the BEVs to ICEVs in the Indian context [73]. The TCO was computed for ten-year ownership period using 2021 as the base year. They concluded that 2Ws BEVs were cost-competitive with ICEVs, however, only with the help of existing incentive plans of the government.

Shrimali calculated the TCO of BEVs for 2W, 3W, and 4W used in personal and commercial usage [73]. The study discovered that BEVs typically required no government subsidies and were cost-competitive. The authors suggested different subsidy plans for BEV 4Ws used in personal and commercial applications. The study had two significant drawbacks, despite providing information on the impact of BEV subsidies. First, despite the analysis's coverage of various vehicle segments, it concentrated on just one pair of vehicles from each segment. It raises the concern whether such a broad generalisation can be made given an extremely small sample size. Second, the study used fixed values for each input variable, restricting the analysis to a particular situation and omitting potential variations related to the enormous and diverse Indian subcontinent. Additionally, like many others, the authors neglected to consider how actual fuel and electricity consumption would affect the TCOs of ICEVs and BEVs, respectively. Several studies revealed that real-world driving could increase electricity/fuel consumption by up to 40% [74–79], which is generally neglected by most TCO studies.

20.7 Summary

BEVs are assumed to be more efficient powertrains than ICEVs. BEVs can be viable in urban areas having ambient air quality concerns. However, BEVs are currently limited in terms of their economy of usage compared to ICEVs, i.e. their cost per km usage is significantly higher than comparable ICEVs. This chapter discusses several TCO studies comparing BEVs with ICEVs in various parts of the world in various vehicle segments. Based on these studies, it emerges that the initial purchasing cost of BEVs is significantly higher than ICEVs. To make BEVs cost-competitive, governments need to give huge subsidies/benefits to BEV owners. However, it is unfair to support one powertrain with billions of dollars of subsidies while degrading the other by imposing additional taxes, inspite of having served humanity for over a hundred years. BEVs can be cost-competitive to ICEVs in some regions with the help of subsidies. However, it also increases the economic burden on their governments and forces them to subsidize rich people at the expense of the poor. With the high initial purchasing cost of BEVs, operational costs remain low due to the availability of cheap electricity.

On the other hand, the higher price of petrol and diesel, due to very high taxes, further increases the operational costs of the ICEVs. For longer distances, cheap electricity prices reduce the impact of the high capital cost of BEVs on the TCO, whereas higher fuel price increases the TCO of ICEVs. Therefore, from a TCO perspective, BEVs can achieve cost parity by reducing the initial purchasing price of BEVs by offering government subsidies or by increasing their travel distances severalfold than the average distance, for example, by the taxi fleet operators (e.g. Ola and Uber), product delivery operations (e.g. Flipkart and Amazon). For policymakers to make well-informed decisions about selecting appropriate technologies (BEVs vs ICEVs) for the transport sector and for the public to accept these technologies, there is a need to increase awareness via comprehensive LCA studies to ensure environmental and comprehensive TCO studies to ensure economic sustainability. This is crucial, especially for developing nations like India, poised to become the world's economic growth engine in the next decade, to make a well-informed choice of technologies in the transport sector and the consequences of wrong choices.

References

1. Full report—statistical review of world energy 2021. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf. Accessed 4 June 2022
2. IEA. World Energy Outlook 2021—revised version October 2021. Int. Energy Agency 2021
3. Transport | UNEP—UN Environment Programme. https://www.unep.org/explore-topics/energy/what-we-do/transport. Accessed 3 June 2022
4. DriveTribe n.d. https://drivetribe.com/p/how-many-cars-are-there-in-the-dqbpAzrATLOOSgDfRrgkjQ?iid=B8Prt7paR3G7Rf82CnLLTA (accessed June 3, 2022).
5. MORTH report. https://morth.nic.in/sites/default/files/RTYB-2017-18-2018-19.pdf. Accessed 10 June 2022
6. India Energy Outlook 2021—Analysis—IEA. https://www.iea.org/reports/india-energy-outlook-2021. Accessed 8 March 2022
7. Top 5 Challenges & trends for automotive industry in 2020–TechSci Research. https://www.techsciresearch.com/blog/top-5-challenges-trends-for-automotive-industry-in-2020/136.html. Accessed 10 June 2022
8. Hwang, W., Dec, J.E., Sjöberg, M.: Fuel stratification for low-load HCCI combustion: performance & fuel-PLIF measurements. SAE Tech. Pap. (2007)
9. Aroonsrisopon, T., Werner, P., Waldman, J.O., Sohm, V., Foster, D.E., Morikawa, T., et al.: Expanding the HCCI operation with the charge stratification. SAE Tech. Pap. (2004)
10. Kalghatgi, G., Johansson, B.: Gasoline compression ignition approach to efficient, clean and affordable future engines. Proceed. Inst. Mech. Eng. Part D: J. Automob. Eng. **232**(1), 118–138 (2018). https://doi.org/10.1177/0954407017694275
11. Singh, A.P., Agarwal, A.K.: Performance and emission characteristics of conventional diesel combustion/partially premixed charge compression ignition combustion mode switching of biodiesel-fueled engine. Int. J. Engine Res. **22**(2), 540–553 (2021). https://doi.org/10.1177/1468087419860311

12. Jain, A., Singh, A.P., Agarwal, A.K.: Effect of fuel injection parameters on combustion stability and emissions of a mineral diesel fueled partially premixed charge compression ignition (PCCI) engine. Appl. Energy **190**, 658–669 (2017). https://doi.org/10.1016/J.APENERGY.2016.12.164
13. Jain, A., Singh, A.P., Agarwal, A.K.: Effect of split fuel injection and EGR on NOx and PM emission reduction in a low-temperature combustion (LTC) mode diesel engine. Energy **122**, 249–264 (2017). https://doi.org/10.1016/J.ENERGY.2017.01.050
14. Singh, A.P., Jain, A., Agarwal, A.K.: Fuel-injection strategy for PCCI engine fueled by mineral diesel and biodiesel blends. Energy Fuels **31**, 8594–8607 (2017). https://doi.org/10.1021/ACS.ENERGYFUELS.6B03393
15. Kokjohn, S.L., Hanson, R.M., Splitter, D.A., Reitz, R.D.: Fuel reactivity controlled compression ignition (RCCI): a pathway to controlled high-efficiency clean combustion. Int. J. Engine Res. **12**(3), 209–226 (2011). https://doi.org/10.1177/1468087411401548
16. Kokjohn, S., Hanson, R., Splitter, D., Kaddatz, J., Reitz, R.: Fuel reactivity controlled compression ignition (RCCI) combustion in light- and heavy-duty engines. SAE Int. J. Engines **4**, 360–374 (2011). https://doi.org/10.4271/2011-01-0357
17. Singh, A.P., Sharma, N., Kumar, V., Agarwal, A.K.: Experimental investigations of mineral diesel/methanol-fueled reactivity controlled compression ignition engine operated at variable engine loads and premixed ratios. Int. J. Engine Res. **22**(7), 2375–2389 (2020). https://doi.org/10.1177/1468087420923451
18. BEV, PHEV, HEV, FCEV: The key differences between electric car options | OpenRoad Auto Group. https://openroadautogroup.com/blog/bev-phev-hev-fcev-key-differences-between-electric-car-options. Accessed 11 June 2022
19. E-Mobility | Bureau of Energy Efficiency. https://beeindia.gov.in/content/e-mobility. Accessed 11 June 2022
20. Kester, J., Sovacool, B.K., Noel, L., Zarazua de Rubens, G.: Between hope, hype, and hell: electric mobility and the interplay of fear and desire in sustainability transitions. Environ. Innov. Soc. Trans. **35**, 88–102 (2020). https://doi.org/10.1016/J.EIST.2020.02.004
21. EVO 2022. https://bnef.turtl.co/story/evo-2022/page/2/1?teaser=yes. Accessed 12 June 2022
22. Global EV Outlook 2022—Analysis—IEA. https://www.iea.org/reports/global-ev-outlook-2022. Accessed 12 June 2022
23. e-AMRIT. https://e-amrit.niti.gov.in/home. Accessed 17 June 2022
24. Status quo analysis of various segments of electric mobility and low carbon passenger road transport in India. https://www.niti.gov.in/sites/default/files/2021-04/FullReport_Status_quo_analysis_of_various_segments_of_electric_mobility-compressed.pdf. Accessed 12 June 2022
25. Policy document: National Automotive Board (NAB). https://fame2.heavyindustries.gov.in/content/english/11_1_PolicyDocument.aspx. Accessed 29 January 2022
26. EV policies and subsidies of 13 states of India | state EV policies—E-Vehicleinfo n.d. https://e-vehicleinfo.com/ev-policies-and-subsidies-of-13-states-of-india/. Accessed 29 January 2022
27. Delhi EV policy n.d. https://transport.delhi.gov.in/sites/default/files/All-PDF/Delhi_Electric_Vehicles_Policy_2020.pdf. Accessed 29 January 2022
28. Maharashtra EV policy 2021. https://maitri.mahaonline.gov.in/PDF/EV%20Policy%20GR%202021.pdf. Accessed 29 January 2022
29. Electric Vehicles: EV sales up 163% in 2021, UP registers highest sales, followed by Karnataka and Tamil Nadu | India Business News—Times of India. https://timesofindia.indiatimes.com/business/india-business/ev-sales-up-163-in-2021-up-registers-highest-sales-followed-by-karnataka-and-tamil-nadu/articleshow/90282217.cms. Accessed 17 June 2022
30. 3 Pillars of corporate sustainability explained: https://www.investopedia.com/articles/investing/100515/three-pillars-corporate-sustainability.asp. Accessed 19 June 2022
31. Hunt, R.G., Franklin, W.E: LCA—how it came about. Int. J. Life Cycle Assess. **1**:4–7. https://doi.org/10.1007/BF02978624
32. Abdul-Manan, A.F.N., Won, H.W., Li, Y., Sarathy, S.M., Xie, X., Amer, A.A.: Bridging the gap in a resource and climate-constrained world with advanced gasoline compression-ignition hybrids. Appl Energy **267**, 114936 (2020). https://doi.org/10.1016/J.APENERGY.2020.114936

33. Abdul-Manan, A.F.N.: Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making. Energy Policy **87**, 1–7 (2015). https://doi.org/10.1016/J.ENPOL.2015.08.029
34. Bessou, C., Chase, L.D.C., Henson, I.E., Abdul-Manan, A.F.N., Canals, M.I., L, Agus F, et al.: Pilot application of PalmGHG, the roundtable on sustainable palm oil greenhouse gas calculator for oil palm products. J. Clean Prod. **2014**(73), 136–145 (2014). https://doi.org/10.1016/J.JCLEPRO.2013.12.008
35. Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H.: Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. **17**, 53–64 (2013). https://doi.org/10.1111/J.1530-9290.2012.00532.X
36. Kumar, D., Abdul-Manan, A.F.N., Kalghatgi, G., Agarwal, A.K., Review of life cycle analysis studies of less processed fuel for gasoline compression ignition engines **2022**, 245–273 (2022). https://doi.org/10.1007/978-981-16-8735-8_9
37. Abdul-Manan, A.F.N.: On the appropriate use of lifecycle thinking for evidence-based sustainable transport policy. Environment **60**, 18–25 (2018). https://doi.org/10.1080/00139157.2018.1472508
38. Ellram, L.M.: Total cost of ownership. Handb. Ind. Beschaffungsmanage. **2002**, 659–671 (2002). https://doi.org/10.1007/978-3-663-01582-6_34
39. (1) Total Cost Of Ownership | Iuliia Timofeeva—Academia.edu. https://www.academia.edu/25629804/Total_Cost_Of_Ownership. Accessed 18 June 2022
40. Staniškienė, E.: Stankevičiūtė Ž (2018) Social sustainability measurement framework: The case of employee perspective in a CSR-committed organisation. J. Clean. Prod. **188**, 708–719 (2018). https://doi.org/10.1016/J.JCLEPRO.2018.03.269
41. Six, L., Velghe, F., Verstichel, S., De Meester, S.: Sustainability considerations on the valorization of organic waste. Biotransform. Agric. Waste By-Prod. Food, Feed Fibre, Fuel Econ. **2016**, 287–307 (2016). https://doi.org/10.1016/B978-0-12-803622-8.00011-2
42. Benoît, C., Norris, G.A., Valdivia, S., Ciroth, A., Moberg, A., Bos, U., et al.: The guidelines for social life cycle assessment of products: just in time! Int. J. Life Cycle Assess. **15**, 156–163 (2010). https://doi.org/10.1007/S11367-009-0147-8
43. Delucchi, M.A., Lipman, T.E.: An analysis of the retail and lifecycle cost of battery-powered electric vehicles. Transp. Res. Part D Transp. Environ. **6**, 371–404 (2001). https://doi.org/10.1016/S1361-9209(00)00031-6
44. Parker, N., Breetz, H.L., Salon, D., Conway, M.W., Williams, J., Patterson, M.: Who saves money buying electric vehicles? heterogeneity in total cost of ownership. Transp. Res. Part D Transp. Environ. **96**, 102893 (2021). https://doi.org/10.1016/J.TRD.2021.102893
45. BEVs vs ICEVs: A United States-Based Comprehensive Assessment 2016. https://www.adlittle.de/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL_November_292016.pdf. Accessed 12 June 2022
46. Liu, Z., Song, J., Kubal, J., Susarla, N., Knehr, K.W., Islam, E., et al.: Comparing total cost of ownership of battery electric vehicles and internal combustion engine vehicles. Energy Policy **158**, 112564 (2021). https://doi.org/10.1016/J.ENPOL.2021.112564
47. Al-Alawi, B.M., Bradley, T.H.: Total cost of ownership, payback, and consumer preference modelling of plug-in hybrid electric vehicles. Appl. Energy **103**, 488–506 (2012). https://doi.org/10.1016/J.APENERGY.2012.10.009
48. Hutchinson, T., Burgess, S., Herrmann, G.: Current hybrid-electric powertrain architectures: applying empirical design data to life cycle assessment and whole-life cost analysis. Appl. Energy **119**, 314–329 (2014). https://doi.org/10.1016/J.APENERGY.2014.01.009
49. Breetz, H.L., Salon, D.: Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities. Energy Policy **120**, 238–249 (2018). https://doi.org/10.1016/J.ENPOL.2018.05.038
50. Mojtaba, S., Axsen, J., Crawford, C.: Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: simulations of freight routes in British Columbia. Transp. Res. Part D Transp. Environ. **76**, 19–55 (2019). https://doi.org/10.1016/J.TRD.2019.08.031

51. Thiel, C., Perujo, A., Mercier, A.: Cost and CO2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy **38**, 7142–7151 (2010). https://doi.org/10.1016/J.ENPOL.2010.07.034
52. Wu, G., Inderbitzin, A., Bening, C.: Total cost of ownership of electric vehicles compared to conventional vehicles: a probabilistic analysis and projection across market segments. Energy Policy **80**, 196–214 (2015). https://doi.org/10.1016/J.ENPOL.2015.02.004
53. Letmathe, P., Suares, M.: A consumer-oriented total cost of ownership model for different vehicle types in Germany. Transp. Res. Part D. Transp. Environ. **57**, 314–335 (2017). https://doi.org/10.1016/J.TRD.2017.09.007
54. Kim, H., Hartmann, N., Zeller, M., Luise, R., Soylu, T.: Comparative TCO analysis of battery electric and hydrogen fuel cell buses for public transport system in small to midsize cities (2021). https://doi.org/10.3390/en14144384
55. Scorrano, M., Danielis, R., Giansoldati, M.: Dissecting the total cost of ownership of fully electric cars in Italy: the impact of annual distance travelled, home charging and urban driving. Res. Transp. Econ. **80**, 100799 (2020). https://doi.org/10.1016/J.RETREC.2019.100799
56. Danielis, R., Giansoldati, M., Rotaris, L.: A probabilistic total cost of ownership model to evaluate the current and future prospects of electric cars uptake in Italy. Energy Policy **119**, 268–281 (2018). https://doi.org/10.1016/J.ENPOL.2018.04.024
57. Fevang, E., Figenbaum, E., Fridstrøm, L., Halse, A.H., Hauge, K.E., Johansen, B.G., et al.: (2021) Who goes electric? The anatomy of electric car ownership in Norway. Transp. Res. Part D Transp. Environ. **92**, 102727 (2021). https://doi.org/10.1016/J.TRD.2021.102727
58. López-Ibarra, J.A., Gaztañaga, H., Saez-de-Ibarra, A., Camblong, H.: Plug-in hybrid electric buses total cost of ownership optimization at fleet level based on battery aging. Appl. Energy **280**, 115887 (2020). https://doi.org/10.1016/J.APENERGY.2020.115887
59. Langshaw, L., Ainalis, D., Acha, S., Shah, N., Stettler, M.E.J.: Environmental and economic analysis of liquefied natural gas (LNG) for heavy goods vehicles in the UK: a Well-to-Wheel and total cost of ownership evaluation. Energy Policy 137:111161 (2020). https://doi.org/10.1016/J.ENPOL.2019.111161
60. Munshi, S., Garner, G., Theissl, H., Hofer, F., Raser, B.: Total cost of ownership (TCO) analysis for heavy-duty hydrogen fueled powertrains. https://wfsinc.com/file_library/files/wpt-wfsinc/20201225_Westport_AVL_Whitepaper_Hydrogen_HPDI_final.pdf. West port AVL report. Accessed 12 June 2022
61. Velzen van, A., Annema, J.A., van de Kaa, G., van Wee, B.: Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles. Energy Policy **129**, 1034–1046 (2019)
62. Ajanovic, A., Haas, R.: On the economics and the future prospects of battery electric vehicles. Green Gases Sci. Technol. **10**, 1151–1164 (2020). https://doi.org/10.1002/GHG.1985
63. Topal, O., Nakir, I.: Total cost of ownership based economic analysis of diesel CNG and electric bus concepts for the public transport in Istanbul city (2018). https://doi.org/10.3390/en11092369
64. Ouyang, D., Zhou, S., Ou, X.: The total cost of electric vehicle ownership: a consumer-oriented study of China's post-subsidy era. Energy Policy **149**, 112023 (2021). https://doi.org/10.1016/J.ENPOL.2020.112023
65. Lee, H., Kim, A., Lee, A., Lee, B., Lim, H.: Optimized H2 fueling station arrangement model based on total cost of ownership (TCO) of fuel cell electric vehicle (FCEV). Int. J. Hydrogen Energy **46**, 34116–34127 (2021). https://doi.org/10.1016/J.IJHYDENE.2021.08.012
66. Falcão, E.A.M., Teixeira, A.C.R., Sodré, J.R.: Analysis of CO_2 emissions and techno-economic feasibility of an electric commercial vehicle. Appl. Energy **193**, 297–307 (2017). https://doi.org/10.1016/J.APENERGY.2017.02.050
67. Ayetor, G.K., Opoku, R., Sekyere, C.K.K., Agyei-Agyeman, A., Deyegbe, G.R.: The cost of a transition to electric vehicles in Africa: a case study of Ghana. Case Stud. Transp. Policy (2021). https://doi.org/10.1016/J.CSTP.2021.12.018
68. Palmer, K., Tate, J.E., Wadud, Z., Nellthorp, J.: Total cost of ownership and market share for hybrid and electric vehicles in the UK. US and Jpn. Appl. Energy **209**, 108–119 (2018). https://doi.org/10.1016/J.APENERGY.2017.10.089

69. Bhosale, A.P., Sharma, S., Mastud SA (2018) Characterizing the economic competitiveness of battery electric vehicles in India. Asian Transp. Stud. **8**, 100069 (2022). https://doi.org/10.1016/J.EASTSJ.2022.100069
70. Murugan, M., Marisamynathan, S.: Analysis of barriers to adopt electric vehicles in India using fuzzy DEMATEL and relative importance index approaches. Case Stud. Transp. Policy (2022)
71. Kumar, P., Chakrabarty, S.: Total cost of ownership analysis of the impact of vehicle usage on the economic viability of electric vehicles in India. Transp. Res. Rec. **2674**(11), 563–572 (2020). https://doi.org/10.1177/0361198120947089
72. How electric vehicle transition can impact India's economy in 2030? https://www.ceew.in/sites/default/files/CEEW-India's-EV-Transition-Post-COVID-19-22Dec20.pdf. Accessed 12 March 2022
73. Patil, M., Majumdar, B.B., Sahu, P.K.: A comparative evaluation of the total cost of ownership between electric two-wheelers and motorized two-wheelers from an Indian perspective. Transp. Res. Rec. **2676**(5), 526–550 (2022). https://doi.org/10.1177/03611981221077087
74. Shrimali, G.: Getting to India's electric vehicle targets cost-effectively: to subsidize or not, and how? Energy Policy **2021**(156), 112384 (2021). https://doi.org/10.1016/J.ENPOL.2021.112384
75. Fontaras, G., Zacharof, N.G., Ciuffo, B.: Fuel consumption and CO_2 emissions from passenger cars in Europe—laboratory versus real-world emissions. Prog Energy Combust. Sci. **60**, 97–131 (2017). https://doi.org/10.1016/J.PECS.2016.12.004
76. Küng, L., Bütler, T., Georges, G., Boulouchos, K.: How much energy does a car need on the road? Appl. Energy **256**, 113948 (2019). https://doi.org/10.1016/J.APENERGY.2019.113948
77. Ntziachristos, L., Mellios, G., Tsokolis, D., Keller, M., Hausberger, S., Ligterink, N.E., et al.: (2014) In-use vs type-approval fuel consumption of current passenger cars in Europe. Energy Policy **67**, 403–411 (2014). https://doi.org/10.1016/J.ENPOL.2013.12.013
78. Pavlovic, J., Marotta, A., Ciuffo, B.: CO_2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedures. Appl. Energy **177**, 661–670 (2016). https://doi.org/10.1016/J.APENERGY.2016.05.110
79. Fontaras, G., Dilara, P.: The evolution of European passenger car characteristics 2000–2010 and its effects on real-world CO_2 emissions and CO_2 reduction policy. Energy Policy **49**, 719–730 (2012). https://doi.org/10.1016/J.ENPOL.2012.07.021