Greening of Industry Networks Studies

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Green Logistics and Transportation

A Sustainable Supply Chain Perspective

Springer

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Contents

Part I Green Logistics Network

Part II Green Land Transportation

Part III Green Air and Water Transportation

Conclusion

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Chapter 1
The Role of Green Logistics and Transportation in Sustainable Supply Chains

Behnam Fahimnia, Michael G.H. Bell, David A. Hensher and Joseph Sarkis

Abstract This chapter introduces general issues and initiates the discussion on the role of green logistics and transportation in sustainability of supply chains. General overview issues relevant to greening the supply chain, logistics network and freight/ public transportation are presented. The potential practical and research concerns that arise are the major elements of these initial issues. Given that this is the introductory chapter of the book, some reasoning and support for the need of such a book is further delineated. Introducing the chapters of the book and their interrelationships provide a broad overview of the topics covered.

Keywords Sustainable supply chain · Green logistics · Green freight transportation · Green passenger public transport

1.1 Green Logistics and Freight Transport

The emergent field of sustainable supply chain management has been rapidly growing for at least twenty years and is well into its third decade of investigation. The relative importance of strategic supply chain management and environmental management practices can be traced to the early periods of the environmental management movement from the late 1960s. However, it has not been until the last decade that significantly more research attention has been garnered with clusters of research in green and sustainable supply chain design and management (Fahimnia et al. 2015a).

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The importance of sustainable supply chain management, both from a practitioner and from a research perspective, has never been more emphasized. Recent practical evidence is provided from the latest United Nations Global Compact sustainability survey emphasizing that managing the sustainability of supply chains is one of four key issues for diffusing corporate sustainability (Borges and Garcia Herreros 2011). Not only are environmental sustainability (greening) issues a concern, but emergent issues related to social sustainability have been gaining in importance (Seuring and Müller 2008; Sarkis et al. 2010).

A consensus definition for sustainable supply chains does not exist. In fact, a review paper focusing just on definitions for green and sustainable supply chains found a total of 22 definitions for green and 12 definitions for sustainable supply chain management (Ahi and Searcy 2013). The problem is partly due to what defines a supply chain and where the boundaries are drawn (Sarkis 2012). Whether terms such as logistics, reverse logistics, purchasing, and procurement would be considered synonyms for supply chain management has been another source of confusion. We bound the focus of this book to logistics and transportation operations within a supply chain, leaving procurement and manufacturing operations out of the scope of this book.

In general terms, logistics and freight transportation is that part of the supply chain that concerns the movement and storage of material and products along the supply chain. Given that today's supply chains operate globally and just-in-time (JIT) practices require rapid movement of materials and products, logistics and transport management and growth has become an economic imperative. Growth in global goods movement means growth in the share of trucking compared to other modes of in-country freight transportation (Kamakaté and Schipper 2009). These flows and the processes that manage them cause both undue social and environmental burdens. For example, freight transportation accounts for the largest share of the freight-related emissions (Piecyk and McKinnon 2010). This might be due predominantly to increasing trends in JIT practices (characterized by small lot size orders and quick changeovers) which encourage small and frequent deliveries and less than truckload shipments (Fahimnia et al. 2015b).

Greening of logistics and freight transportation operations involve the incorporation of environmental measures when designing logistics and distribution networks, whilst managing the underpinning transportation and warehousing operations. At the strategic design level, the green logistics objectives may include the evaluation and selection of sustainable logistics providers and transport fleets as well as determining the related distribution strategies. At the tactical and operational levels, the primary concerns usually include green routing, consolidation of delivery schedules, and efficient inventory management. Sustainability analyses and investigations at the strategic, tactical and operational planning levels must be completed with respect to the consequent influences on other logistics characteristics such as capacity to survive and adapt in the face of unforeseen disruptions. Achieving sustainability will require the development of resilient logistics networks whose sustainability remains unaffected or less affected in disruptive events such as natural and man-made disasters.

In the context of freight transportation, the debate on road versus rail continues unabated. In general, rail wins out for bulk freight, typically captured at the source, such as a mine, and delivered to a final land destination, such as a shipping port. For non-bulk commodities the advantages of trucking can be significant. Trucks can ensure door-to-door distribution in a typical complex origin-destination situation where rail heads are often too far away and even if close entail double and often triple handling, exposing goods to additional damage and loss through pilfering. Freight distribution through trucking is only one component of the full supply chain, even though it is often deemed to be the most inefficient part of the chain, due in part to traffic congestion both on the road and at terminals. In the case of the latter situation, waiting times can be excessive adding to costs and loss of productivity.

A greening freight strategy should be encapsulated within the broader domain of the supply chain and logistics tasks. Logistics performance measures are the best indicators of the success of a freight strategy and identifying performance capabilities for business success are central to a meaningful green freight strategy. Such business success measures include transport dependability, customer service, low logistics costs, delivery flexibility, and delivery speed. Transportation capabilities as interpreted through transport policy traditionally embrace the 4C's of capacity, congestion, condition and connectivity. The mechanisms necessary to build these 4C's may include infrastructure development, management and maintenance of infrastructure, inter-modal connectors and market reform, for example through economic deregulation, safety and training regulation.

Physical interpretations include transport networks as a right of way, hubs, ports, access connectors, transfer points and permissible operations. Transport users take the 4C's as inputs into facilitating the fifth 'C' of logistical capabilities such as mode availability, distribution coverage, carrying capacity, delivery speed, dependability, flexibility, customer responsiveness, expedited delivery and inter-modal transfer and E-commerce. Other matters to consider as interpretations of the 5C's might include building codes, dock and off-loading facilities and freight elevators, incentives to retrofit docks and manage the final link in the supply chain —the drop off to the end customer, improvements in road maintenance, provision of accurate signage, use of intelligent transport systems to actively manage parking in commercial zones, and monitoring freight deliveries to prevent theft and vandalism. All of these considerations should take into account the environmental implications.

1.2 Green Passenger Public Transport

Apart from freight transportation that relates to managing the movement of materials and products, another critical aspect of sustainable supply chains is concerned with moving people, an organizational resource critical to all supply chains. Greening and sustainability of transport systems, private and public, is necessary to achieve the goals of sustainable supply chains. The popular consensus is that passenger public transport is greener than the car. Within passenger public transport, rail is seen as more environmentally friendly than the bus. This latter position is in large measure associated with the key energy source for each mode, respectively electricity and diesel. However the relationship between the source of energy and its resultant emissions (as contributions to local air pollution and enhanced greenhouse gas emissions) is not well understood. There is a significant lack of awareness about the resource base from which electricity is produced in some countries (for example, from coal-fired power stations in Australia) as well as the improvements in processing that delivers clean diesel. Supporters of alternative fuels such as compressed natural gas (CNG) and hybrid technologies (mixtures of diesel and electricity) as alternatives to clean diesel focus on the future supply of fossil-fuels; however, the arguments in support of such alternative fuels are often confounded with environmental merits related to local air pollution and enhanced greenhouse gas emissions.

Table 1.1 illustrates the emission efficiency of bus over rail per passenger kilometer in Australia, which may surprise many readers. It is calculated from energy inputs in all stages of the supply chain that delivers the transport technology as well as the fuel source in addition to the end use of transport.

To highlight the risk of presuming the environmental advantage of rail, consider the following evidence as presented in Puchalsky (2005). Bus rapid transit (BRT) is an evolving public transport mode consisting of rubber-tyred vehicles running on dedicated rights-of way for all or part of a transit route (see Hensher et al. 2013). The vehicles are typically diesel powered, although some are dual diesel and electric. BRT has emerged as a low-cost contender against light rail transit (LRT) in many situations and even heavy rail. The relative merits of both modes are often debated generically and for specific applications (see Hensher et al. 2015; O'Toole

Table 1.1 Enhanced greenhouse gas emissions (direct and indirect sources) for rail and bus passenger activity in Australia

Year ending June 30	CO_2-e per rail Pkm per Gg	CO_2-e per bus Pkm per Gg	Percent change (%)
2001	0.137	0.094	−31.03
2002	0.132	0.093	−29.15
2003	0.136	0.094	−30.62
2004	0.134	0.094	−29.59
2005	0.140	0.095	−32.22
2006	0.132	0.094	−28.86
2007	0.124	0.094	−24.59
2008	0.114	0.094	−18.22
2009	0.119	0.094	−20.71
2010	0.117	0.094	−19.13
2011	0.113	0.095	−15.84
2012	0.111	0.095	−14.77
2013	0.105	0.094	−10.58

Data provided by Dr David Cosgrove of the Australian Bureau of Infrastructure, Transport and Regional Economics

2008). One area of comparison is energy use and emissions. Electric rail vehicles emit no propulsion system pollution at their point of operation. They are responsible for fuel cycle emissions from electricity-generating plants, which tend to be located on the urban periphery, and other upstream processes. Diesel buses, however, have typically been perceived as producing strongly negative pollution-related externalities directly into the high density areas that they serve. Diesel buses are also responsible for other emissions due to refining and other processes in the fuel cycle. In the area of energy consumption, rail, with its low-friction steel-on-steel support and guidance technology, has been assumed to be superior to rubber-tyred buses. Because of these factors, electric LRT and other rail passenger modes have been considered superior to diesel BRT and other bus modes in terms of emissions. Diesel technology has improved dramatically in recent years because of high-pressure injection systems, advanced after treatment systems, and other measures. Compressed natural gas (CNG) combustion systems for heavy-duty vehicles have also continued to improve and have been advocated for decreasing oxides of nitrogen (NOx) emissions in particular. Advances have also occurred in the generation of electricity. The changing technology landscape requires the periodic re-examination of old paradigms.

The case for investment in public transport is indisputable to not only offer a real alternative to the car but to support the broader objectives of integrated transport and land use planning that can deliver efficient and effective accessibility that also aligns with notions of wellbeing, social inclusion and environmental sustainability (see Stopher and Stanley 2014). All of these features are interlinked with greening of the passenger supply chain. Within the set of public transport options, governments have mainly focused on supporting a mix of road and rail-based modes; and depending on the historical evolution of a specific geographical context, the extent to which one mode has dominated the other is clearly visible. Within an urban setting, for example, it is generally understood that cities which evolved in the automobile era are very much the product of roads that service urban sprawl, where bus services have been the offered public mode. Nineteenth and Twentieth century cities in the USA and Australia are some of the best examples. Even though rail has been an alternative in many of these cities, its popularity has been limited by the appeal of the accessibility advantage of the car, despite the growing levels of congestion and lack of parking.

We are now witnessing a greater commitment to improving public transport; however the emphasis on modal priority varies significantly between locations. Drivers of modal preferences include emotional ideology (see Hensher 1999, 2007), citizen and political preferences, and especially the ability to show visible commitment to new investment in public transport infrastructure. On balance, the revival of rail in many western societies (and a number of Asian countries) is very noticeable; in contrast we see growing support for bus-based systems in developing economies, especially in Latin America. There are always exceptions to this trend; for example the busway system in Brisbane that was supported in its early days by a charismatic politician who saw virtue in dedicated roads for buses at a cost lower than the equivalent level of service offered by rail.

The issues pertaining to greening freight and public transportation will affect the supply chain and its organization, but innovations in these areas can affect public and private activities as well. Technological innovations, behavioral concerns, economic outcomes, and social issues all arise from activities related to logistics and transportation greening. Given this very initial background, much of which is dealt with in greater detail later in the book, we now discuss the book itself and some of its contributions.

1.3 Contributions of This Book

According to the latest report of the U.S. Environmental Protection Agency (2014), the transportation industry represents 28 % of the total greenhouse gas emissions in the U.S. The industrial emissions from this sector are only second to the electricity and energy industry. Transportation also appropriates significant resources and can cause local, regional, and global environmental burdens. Investigation of the environmental burdens and sustainability issues associated with transportation continues to be an important requirement. In this book, current trending environmental and greening concerns facing transportation and logistics industries will be investigated. The primary focus of this book is on (1) reviewing green logistics and transportation studies, (2) presenting some of the available tools and techniques that can be used for green design, planning and management of logistics networks and transport operations, and (3) providing directions for future work in these areas.

Research works on logistics and transportation issues and concerns date back to the early years of automobile transportation. This would include the issues of scarcity of resources, environmental damage along the supply chain, and the greenhouse gas emissions. Design of vehicles, raw material sourcing, developing transportation infrastructure, and use of vehicles and facilities are all life cycle and supply chain sources of environmental burden from transportation design, planning, and usage. The significance of these environmental burdens can be local, such as smog and air pollution; regional such as acid rain and biodiversity concerns; or global such as global warming and climate change.

The linkages between transportation, supply chain management and logistics is self-evident. Managing each concern will affect the other dimensions. Integrative evaluation of these topics to balance economic with environmental performance, and sometimes general social performance issues, is not simple due to the complex multidimensional nature of each topic. This book will focus more on the environmental dimensions, but broader social sustainability dimensions may be included in various portions of the book. As noted, the environmental burdens of transportation and logistics operations may affect air, water, and land as well as flora and fauna. The concerns for management may also include operations and strategic complexities such as abiding by existing laws and regulations in reactive ways or proactively competitive pursuits such as design of green products, building green markets, and strategic financial investments. The variety of corporate greening issues encompasses operational, strategic, technological, organizational, and behavioral concerns. These concerns also permeate the transportation and logistics field and industry. All dimensions of these greening issues cannot be covered in one book, but many will be investigated here.

In addition to the managerial complexities associated with transportation and logistics strategies, there may be differences across various transportation and logistics functions and sub-industries. For example, while many concerns overlap and commonalities exist, there are clearly differences in environmental burdens caused from air transport and logistics when compared to maritime transport and logistics. A single paper or chapter cannot address all these issues, but a book can integrate these concerns and delve deeper into some of the more important topics.

Given these various complexities, this book helps identify and further the state of the art in greening transportation and logistics with a supply chain focus. There will be concerns and linkages across policy, corporate strategy and operations, inter-organizational relationships and practices. Linking research with practice will also be important as various techniques and research methodologies are utilized in this book. Case study information, conceptual theoretical modeling approaches, practical applications, and broad based studies are all part of this book. These methods are needed to help make sense and address the complex greening issues. It also allows readers access to differing approaches to address similar problems, with advantages and disadvantages clearly identified.

The authors of these works come from throughout the world and seek to provide insights from their regional and global perspectives. Each has contributed in a variety of ways to transportation, logistics, greening (sustainability), and supply chain research. They also come from a variety of backgrounds which include policy, technical, engineering, and management backgrounds. It takes these and other backgrounds to arrive at solutions and insights to some of the world's most critical issues related to environment and society.

1.4 The Book Contents

We now overview each chapter of the book and discuss the flow and interrelationships amongst the topics. Each chapter can be viewed as a standalone topic, but can also be integrated with other readings in the book. There are many ways to structure this book and related topics. We decided on three major sections to help group common themes amongst the chapters. The three sections are greening logistics network, green land transportation, and green air and water transportation. Each section contains 3 or 4 chapters. An overview of each chapter is provided below.

After this introductory chapter, the second chapter is titled "Behavioral influences on the environmental impact of collection/delivery points" authored by Andrew Collins. This chapter argues that the design of distribution networks is dynamic. For example, a shift in markets from brick-and-mortar stores to electronic commerce has caused organizations to rethink their logistics operations and designs. The environmental implications of such designs and e-logistics in general has been a concern for most of the past decade (Sarkis et al. 2004). Conventional delivery mechanisms and designs may not be as efficient. Collins provides insight into how the collection/delivery point (CDP) is a valuable alternative. In this design, parcels are delivered to a CDP of the customers' choosing, which is either a locker, or an existing business. The parcel is then picked up at the customers' convenience. Environmentally, this approach can greatly reduce failed deliveries and allows for consolidation of delivery schedules. Offsetting these advantages are the customers' movements required to make the pickups, where a full environmental assessment would also consider these pickup movements. The environmental footprint of thus final mile delivery can be studied from a variety of perspectives (Edwards et al. 2010), in this chapter the focus is on the behavioral perspective. Discrete choice models are utilized to help model expectations and behavioral choices. The approach uses a stated choice survey, to investigate what is influencing the choice of these market offerings. The final mile alternatives investigated will extend beyond a pickup-conventional delivery dichotomy, to include alternative ways in which the pickups might be integrated in existing travel. Probabilistic choice over a number of market offerings and the environmental footprint is evaluated in this chapter.

Whereas in Chap. 2 the disruption that influences new designs is based on new business models, in Chap. 3, dynamic logistic network design is influenced by critical events. Chapter 3, by Armin Jabbarzadeh and Behnam Fahimnia and titled "Dynamic supply chain greening analysis" argues that organizations need to consider disruptions of various types including natural disasters (e.g. floods, earthquakes) and man-made disasters (e.g. strikes, terrorist attacks) when designing green logistics networks. This is referred to as designing a "resiliently green" logistics network where dynamic sustainability analysis is required to examine how sustainability performance of a logistics network is influenced in the face of disruptions. Designing resilient networks in an environmentally sustainable way is a highly intricate process. Resilience has been evaluated with tradeoffs associated with economic and business factors, but environmental sustainability has not seen as much investigation. Using mathematical programming and optimization approaches, this chapter investigates the economic and environmental tradeoffs of resilient logistics network design in different circumstances.

In Chap. 4 the logistics design shifts from an organizational to a public logistics design. As with Chaps. 7 and 8, the focus in Chap. 4 is on urban transportation. Chapter 2, with its last-mile, focus also fits within this scope as much of the CDP deliveries also focus on an urban setting. In Chap. 4, Eiichi Taniguchi, considers this greening and urban logistics design in a chapter titled "City logistics for sustainable and liveable cities". Similar to most decisions and designs made throughout this book, economic, environment and quality of life dimensions are considered with a focus on stakeholder and technological issues for urban freight transport design. Joint delivery systems with urban consolidation centers, truck bans on road network, and the use of intelligent transport systems for a guidance to greener truck routes, are all policy considerations available to planners that will be overviewed in Chap. 4. Given the complexity of these relationships, multi-agent simulation models, are part of the multiple toolsets evidenced by other chapters. Behavior, similar to Chap. 3, plays an important role. In this case, behaviors of shippers, carriers, administrators, and residents are investigated. Case study examples show how these multi-stakeholders serve as agents to arrive at better solutions for urban transportation planning.

In the next two sections of the book, we advance the discourse from concerns associated with general logistics network issues to more specific delivery modes. Section 1.2 focuses on land delivery and transportation modes.

Chapter 5 by Chunguang Bai, Behnam Fahminia and Joseph Sarkis returns to decisions associated with private organizations in their work titled “Green transport fleet appraisal”. Their argument is that private organizations should identify and incorporate sustainable transportation metrics for the evaluation and selection of transportation fleets. Once again, given the complexities of product and decision criteria, complications arise. An integrative multiple criteria decision modeling approach with fuzzy sets, VIKOR, and rough set techniques, along with various transportation fleet selection criteria is introduced in this chapter. Using the literature they set a foundation of what metrics to consider and how these are integrated into the methodology. The technique can be useful with other decision modeling efforts in this book, as long as discrete criteria and alternatives are considered.

When managing transportation costs, there are many managerial decisions and factors that come into play. In any logistics network study, tactical and operational decisions will almost certainly involve inventory and capacity concerns. Hooman Maleky, Chap. 6, “The inventory pollution-routing problem under uncertainty”, similar to other chapters on private corporate decision tradeoffs, seeks to balance the environmental and economic dimensions in an inventory routing problem. Supply chain vertical collaboration is the core issue within this transportation modeling effort. Specifically, vendor-managed inventory (VMI) as the collaborative and integrative industrial practice is investigated. A combinatorial optimization model is introduced for an inventory routing problem, where inventory and routing decisions are made simultaneously. Solutions for simultaneous reduction of costs and emissions are investigated. Thus, operational philosophies, such as JIT, Lean, and VMI can all influence transportation and environmental costs faced by organizations. This chapter exemplifies this relationship.

Innovations in design, processes, and decision models have been evident in the first few chapters of this book. In Chap. 7, the focus shifts slightly to technological innovations, with the target of urban freight systems. Russell G. Thompson’s chapter, titled “Vehicle related innovations for improving the environmental performance of urban freight systems”, introduces various innovation initiatives for urban freight transport. Urban freight vehicles produce a variety of emissions including sulphur oxide, particulate matter and nitrogen oxide, in addition to carbon emissions. A number technological and policy innovations are reviewed. Initiatives such as alternative fuels, low emission zones, high productivity freight vehicles, multi-modal freight networks and alternative modes are overviewed. Implications are clearly drawn, and can be utilized with the various models and techniques presented in other chapters.

Remaining in the urban transport environment, Chap. 8 shifts to public passenger transport. Chinh Ho and David Hensher's chapter is titled "Greening demand chains in urban passenger transport: emission savings from complex trip chains". The complexity involved in this situation focuses on the significant amount to passenger trip activity that involves multiple modes, destinations and trip purposes. These trip complexities arguably have important implications on how travel demand is represented in transport planning modeling. Understanding the impacts that greater complexity in trip chains has on greening the demand chain is the goal of this chapter. This study represents one of few, if any, greening of passenger demand chains associated with the changing complexity of trip chains. Econometric modeling using the city of Sydney, Australia is used in this investigation. Transportation behavior, similar to Chaps. 3 and 4, is found to play a significant role in energy consumption and emissions.

Section 1.3 of this book will include chapters that focus on water (maritime) and air transport. In this situation, the focus has shifted from mostly a local and regional perspective, to incorporate global considerations.

Chapter 9 begins this section by setting the stage for green port and maritime logistics with a review of the literature. Hoda Davarzani, Behnam Fahimnia, Michael Bell, and Joseph Sarkis author this chapter titled "A review of the literature of green ports and maritime logistics". This is one of the few chapters that seek to provide insights into the broader literature to help identify patterns and directions for future research. A network analysis tool is used to focus on a review of environmental sustainability of ports and maritime logistics. Insights from a topological analysis are completed to identify key research clusters. Graphical mapping of these research clusters and their interconnections are also utilized. In addition to the provided insights and future research directions, the chapter introduces an analytical modeling approach with a form of meta-analysis that can be used for future literature reviews. Chapter 10 will seek to address some of these identified research directions.

In Chap. 10, titled "Economic and environmental tradeoffs in water transportation," by Thalis Zis, Panagiotis Angeloudis and Michael Bell, the tradeoff analysis focuses on the topic of slow steaming. Slow steaming across the whole journey is compared with localized slow steaming near the calling port for various case studies including different ship sizes, trip distances, sailing speeds and fuel policies. The approach investigating these case studies is an activity based methodology for estimating fuel consumption and emissions savings during lower sailing speed operation for machinery on-board. The economic and environmental tradeoffs from various stakeholders are identified and discussed. The chapter includes guidelines to port authorities and shipping companies, two of the major stakeholders in this study. The perspectives of various stakeholders are similar in tone to those of Chap. 4, although these are more direct ones. Multiple perspectives on winners and losers in some of these tradeoffs can be evaluated in almost each decision or model within this book.

The last chapter of this section, Chap. 11, takes us to the air. The economic-environmental link is very much at the center of this chapter. Chikage Miyoshi and Rico Merket author "The economic and CO_2 emissions performance in aviation: an empirical analysis of major European airlines". The economic argument for the survival of the airline industry is made evident and fuel utilization is core to aiding them survive. This chapter compares the carbon efficiency of 14 major European airlines for the period 1986–2007 and examines the relationship between carbon efficiency and fuel price, distance flown and load factors.

1.5 Conclusion

Thank you for utilizing this book and we hope that the forthcoming chapters can help you to further understand some of the major issues in transportation, logistics and supply chain sustainability. Whether as researchers or practitioners, we believe there is much to be learned and much to be shared. Overall, the sustainability of our society is dependent on many dimensions presented in this book and thus we hope you find all the topics worthy of your time and help you address your concerns. Let us also hope that these chapters provide motivation to further research in the critically important and interdisciplinary area of sustainable logistics and supply chain management.

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Part I
Green Logistics Network

Chapter 2
Behavioural Influences on the Environmental Impact of Collection/Delivery Points

Andrew T. Collins

Abstract For more than a decade, business-to-consumer parcel deliveries have been growing rapidly. Despite this, the 'last mile' of the supply chain, which involves the final physical transfer of goods to the customer, is particularly problematic for many customers, as delivery times are often unpredictable and/or not convenient. An increasingly prevalent alternative to conventional delivery is the collection/delivery point (CDP), where parcels are delivered to a CDP of the customers' choosing, and picked up at a more convenient time. From an environmental perspective, CDPs can reduce failed deliveries and allow consolidation of the delivery schedules. However, a full environmental assessment should also consider the customers' movements required to make the pickups. In this chapter, competing delivery and pickup offerings are framed in terms of the utility that each provide to the customer. A random parameter error components logit model is estimated, using stated choice survey data, to uncover what is influencing the choice of these market offerings. The last mile alternatives investigated extend beyond a pickup-conventional delivery dichotomy, to include alternative CDP locations, pickup access modes, and ways in which the pickups might be integrated into existing travel. We find that changing the price, quality and location of the CDP and delivery offerings can disproportionately influence more environmentally friendly means of picking up from CDPs, such as walking, cycling, and integrating the pickup into an existing car trip. This provides the groundwork for a more complete, behaviourally informed quantification of the last mile parcel delivery and pickup environmental footprint.

Keywords Parcel delivery · Last mile · Collection/delivery point · Environmental impact · Mode choice · Trip chains · Time windows · Online shopping

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2.1 Introduction

For more than a decade, business-to-consumer parcel deliveries have been growing rapidly, driven to a large extent by a corresponding growth in e-commerce. However, the ‘last mile’ of the supply chain, which involves the final physical transfer of goods to the customer, is particularly problematic for many customers. Failed deliveries are common, notwithstanding some market moves to extend delivery hours and narrow delivery time windows. An alternative to conventional delivery that has become increasingly prevalent is the collection/delivery point (CDP). Parcels are delivered to a CDP of the customers’ choosing, which is either a locker, or an existing business. The parcel is then picked up at the customers’ convenience. CDPs have been adopted in a number of countries, including Germany (e.g., DHL Packstation), the United Kingdom (e.g., CollectPlus) and The Netherlands[1] (e.g., Kiala). The uptake has been more recent in Australia, where the government owned postal service Australia Post has introduced both parcel lockers, and a parcel pickup option from existing post offices. The leading competitor to their service, ParcelPoint, offers pickup from existing businesses.[2]

Of interest is what is driving the uptake of CDPs, and what will lead consumers to choose CDPs over conventional delivery, given that the two are often in competition. Last mile parcel delivery can be viewed as a customer oriented service with a strong behavioural component. Different delivery and pickup alternatives provide different amounts of utility, and the consumer chooses an alternative so as to maximise their utility, subject to various constraints that are imposed on them, such as when they can accept a delivery, and what modes they have available to travel to a CDP. A CDP has various sources of utility and disutility, including those based on location (distance from the customer, parking availability, etc.), quality (opening hours, days before returned to sender, etc.), and cost. Conventional delivery also provides a mix of product features and price. Decisions must be made by CDP providers as to what sort of CDP network to assemble, with decisions made on each of these utility bearing product features.

The decisions that CDP providers make regarding their network will also have an impact on the environmental footprint of the last mile. Contributions to this footprint will come from the delivery of parcels either to the end customer as with conventional delivery, or to the CDP locations under the CDP model. From the environmental perspective of the carrier, the CDP approach greatly reduces failed deliveries, and allows consolidation of the delivery schedules to only include CDP locations. At the holistic level, offsetting these advantages are the customers’ movements required to make the pickups, where a full environmental assessment of the end-to-end supply chain would also consider these pickup movements. This is complicated by the possibility of incorporating car pickup trips into existing trip

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[1] See Weltevreden (2008) for analysis of the uptake of CDPs in The Netherlands.

[2] As this book went to press, Australia Post had approximately 180 parcel lockers and 3500 collection points across Australia, while ParcelPoint had over 1300 locations.

chains, where this could greatly reduce or even eliminate the environmental impact of the pickup. This has been recognised in the context of store shopping (Mokhtarian 2004), and applies also to pickup from a CDP (McLeod et al. 2006). Further, where a shopping trip is made by walking, cycling or public transport, the environmental footprint is either eliminated or greatly reduced (Keskinen et al. 2001). Again, this logic extends to pickup from a CDP. Therefore, an assessment of the extended environmental impact of CDPs should consider the mode choice of the customer making the pickup, as well as their trip chaining behaviour. Again these are behavioural influences, and the location, quality and price of the CDPs, as well as the quality and price of any competing delivery service, will have an impact on choice of delivery or CDP, mode choice, and trip chaining choice, all of which have environmental consequences.

Several existing studies have considered the environmental impact of last mile parcel delivery. McLeod et al. (2006) considered CDPs as an alternative to redelivery after a failed delivery attempt, rather than an independent last mile alternative available to the consumer. They calculated the total delivery and pickup distance travelled under alternative scenarios, varying factors such as the delivery failure rate and CDP network configuration. However, by not considering CDP use as an explicit choice on the part of the consumer, with conventional delivery as a competing alternative, their simulations do not capture the market dynamics of CDP offerings in many parts of the world. McLeod and Cherrett (2009) extended this approach by determining a variety of emission impacts, including carbon dioxide and particulates.

The last mile footprint investigated herein will only consider parcel delivery. A more complete modelling effort might also include conventional shopping as another choice alternative, along with the associated environmental footprint stemming from shopping trips. Various studies have considered the choice of store shopping verses e-shopping with conventional delivery. Rotem-Mindali and Salomon (2007, 2009) did so with revealed preference data, while Hsiao (2009) did so with stated preference data. However, this chapter will instead focus on the nuance of alternative delivery options conditional on already making a purchase that requires parcel delivery.

The chapter will investigate the environmental footprint of the last mile of parcel delivery from a behavioural perspective. Competing delivery and pickup offerings will be framed in terms of the utility that each provide. A discrete choice model will be estimated, using stated choice survey data, to investigate what is influencing the choice of these market offerings. The last mile alternatives investigated will extend beyond a CDP-conventional delivery dichotomy, to include various ways in which pickups from CDPs might be integrated into existing travel patterns. The environmental footprint will be evaluated in terms of the propensity of customers to choose environmentally friendly alternatives. A final assessment in terms of VKT or emissions will not be provided, but the methodology herein provides a framework in which such simulations could incorporate the behaviour of the customer, thus quantifying the total environmental footprint given the probabilistic choice over a number of market offerings.

2.2 Data

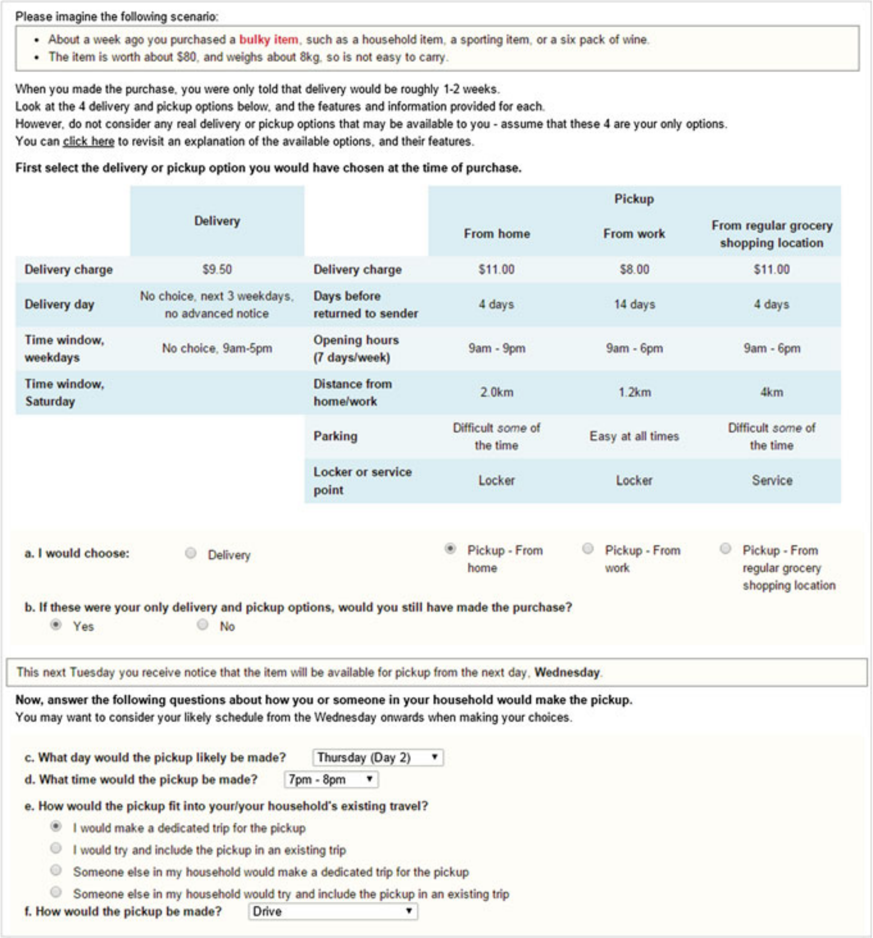
This chapter utilises data collected from a survey that was run in Sydney, Australia in June 2014. The survey was conducted online, with respondents recruited through an online research panel. To be eligible for the survey, respondents had to be 18, live in the Sydney metropolitan area, and have had at least one parcel delivered for non-work purposes in the most recent 12 months. After some respondents were omitted due to concerns about excessively fast survey completion, a sample of 504 respondents remained. A good coverage was achieved in terms of geographic spread over the Sydney region, and the sample was broadly representative in terms of gender and age. The survey contained questions on household composition, the frequency with which someone in the household is at home through the day, regular and online shopping patterns, work status and hours, car availability, work and regular grocery shopping location, and socio-demographic characteristics.

Stated choice methods work by presenting decision makers with a set of hypothetical alternatives, and asking them to make a choice between them (Louviere et al. 2000). Multiple such choice tasks are typically presented to every decision maker. The choice tasks form a key part of this survey, as they facilitate choice between alternative hypothetical delivery and CDP offerings, and allow systematic influences on this choice to be modelled (the model applied will be introduced in Sect. 2.3). An example choice task is presented in Fig. 2.1.

First, the scenario surrounding the choice task was framed. Each of the six choice tasks presented to the respondents involved the recent purchase of a particular good that needed to be either delivered or picked up from a CDP. Three broad types of goods were presented with two choice tasks apiece, where they differed by weight and value: a bulky item worth about $80 AUD, a book worth about $45, and a non-bulky electronic item worth about $500.

Four elemental alternatives were presented: delivery, pickup from home, pickup from work, and pickup from the respondents' regular grocery shopping location. If neither they nor their partner worked, the work alternative was omitted. The respondents were asked to only consider the three or four alternatives presented, and not consider any real market offerings available to them. Three distinct CDP locations were potentially presented because it is likely that each of these would be integrated into daily travel patterns in different ways, and thus the behavioural response to changes in CDP location, quality and price may differ accordingly.

Of the further questions asked of the respondents within each choice task, two are of particular interest in this study. They were only asked in choice tasks in which one of the pickup alternatives was selected. First, whether they or someone in their household would make a dedicated pickup trip, or whether they would try and include it in an existing trip, and second, the mode of transport they would use for the pickup: car, walk, bike or public transport. It is reasonable to expect that such decisions will not always be the same, as circumstances and constraints in the household will vary day to day and week to week. Thus, part of the scenario formation in this study was for the survey software to pick a random day over the next



Please imagine the following scenario:

- About a week ago you purchased a bulky item, such as a household item, a sporting item, or a six pack of wine.
- The item is worth about $80, and weighs about 8kg, so is not easy to carry.

When you made the purchase, you were only told that delivery would be roughly 1-2 weeks.
Look at the 4 delivery and pickup options below, and the features and information provided for each.
However, do not consider any real delivery or pickup options that may be available to you - assume that these 4 are your only options.
You can click here to revisit an explanation of the available options, and their features.

First select the delivery or pickup option you would have chosen at the time of purchase.

			Pickup		
	Delivery		From home	From work	From regular grocery shopping location
Delivery charge	$9.50	**Delivery charge**	$11.00	$8.00	$11.00
Delivery day	No choice, next 3 weekdays, no advanced notice	**Days before returned to sender**	4 days	14 days	4 days
Time window, weekdays	No choice, 9am-5pm	**Opening hours (7 days/week)**	9am - 9pm	9am - 6pm	9am - 6pm
Time window, Saturday		**Distance from home/work**	2.0km	1.2km	4km
		Parking	Difficult *some* of the time	Easy at all times	Difficult *some* of the time
		Locker or service point	Locker	Locker	Service

a. I would choose: ○ Delivery ● Pickup - From home ○ Pickup - From work ○ Pickup - From regular grocery shopping location

b. If these were your only delivery and pickup options, would you still have made the purchase?
● Yes ○ No

This next Tuesday you receive notice that the item will be available for pickup from the next day, **Wednesday**.

Now, answer the following questions about how you or someone in your household would make the pickup.
You may want to consider your likely schedule from the Wednesday onwards when making your choices.

c. What day would the pickup likely be made? Thursday (Day 2) ▾
d. What time would the pickup be made? 7pm - 8pm ▾
e. How would the pickup fit into your/your household's existing travel?
● I would make a dedicated trip for the pickup
○ I would try and include the pickup in an existing trip
○ Someone else in my household would make a dedicated trip for the pickup
○ Someone else in my household would try and include the pickup in an existing trip
f. How would the pickup be made? Drive ▾

Fig. 2.1 Example choice task

week from which the parcel becomes available for delivery or pickup. The respondent can thus answer these supplementary questions subject to whatever constraints they may have in the days subsequent. Thus, whilst the choice alternatives remain purely hypothetical, the personal constraints that may very well influence the choice of delivery or CDP remain real and consideration of these was encouraged.

Each of the alternatives were described by various attributes, where each can assume a number of possible levels or states. The attributes and their levels are listed in Table 2.1. The range of possible delivery charges depended on whether the scenario was for the delivery of a book (lower range), or bulky items or an electronic item (higher range). The distances of the CDPs were shorter from work than from home. Constraints were imposed on the delivery quality attributes, so that the 'no advanced notice' and 'morning notice of delivery' attribute levels for delivery

Table 2.1 Attribute levels in choice tasks

Attribute	Delivery	CDP	Attribute levels
Delivery charge	X	X	\$4.00 AUD, \$5.00, \$6.00, \$7.00 (books)
			\$8.00, \$9.50, \$11.00, \$12.50 (bulky or electronic items)
Delivery day	X		No choice, next 3 weekdays, no advanced notice
			No choice, next 3 weekdays, morning notice of delivery that day
			Choice of 1 of the next 5 weekdays
			Choice of 1 of the next 5 weekdays, or Saturday
Time window, weekdays	X		No choice, 9 am–5 pm
			Choice of a 4 h window (9 am–1 pm or 1 pm–5 pm)
			Choice of a 2 h window (8 am–10 am, … , 4 pm–6 pm)
			Choice of a 2 h window (8 am–10 am, … , 6 pm–8 pm)
			Choice of a 2 h window (6 am–8 am, … , 4 pm–6 pm)
			Choice of a 2 h window (6 am–8 am, … , 6 pm–8 pm)
Time window, Saturday	X		Blank
			Choice of a 2 h window (10 am-noon, …, 2 pm–4 pm)
Days before returned to sender		X	2, 4, 7, 14 days
Opening hours (7 days/week)		X	9 am–6 pm, 9 am–9 pm, 7 am–6 pm, 7 am–9 pm, 24 h
Distance from home/work		X	0.5, 1.0, 1.5, 2.0 km (home)
			0.3, 0.6, 0.9, 1.2 km (work)
Parking		X	Easy at all times, difficult some of the time, difficult most of the time
Locker or service point		X	Locker, service

day only coexisted with the ‘no choice’ level for the time window. The option of Saturday delivery was only possible with two hour time windows. Narrow time windows were deemed an important delivery feature to include in the choice tasks, as they are recognised as being valued by the customer, but also impose a significant cost burden on the carrier (Cullinane 2009). Further, narrower windows will lead to a worse environmental impact. The experimental design, which determines the specific combinations of attribute levels to present in each choice task, was generated with the Ngene software package, as an efficient design with optimisation on the *d*-error of the design (Rose and Bliemer 2009).

2.3 Methodology

This chapter will utilise a random parameter error components logit (RPECL) model. For a more detailed exposition of this model, the reader is referred to Train (2009). The objective is to estimate a model that can explain the choices between a set of J discrete alternatives, for a sample of N decision makers. Each decision maker n will derive some utility U_{nj} from each alternative j, where

$$U_{nj} = \alpha' x_{nj} + \beta'_n y_{nj} + \mu'_n z_{nj} + \varepsilon_{nj}.$$

In this generalised utility function, x_{nj}, y_{nj} and z_{nj} are vectors of observed variables related to the alternative j and decision maker n, α is a vector of fixed coefficients representing the tastes of the sample as a whole, β_n is a vector of coefficients representing the tastes of decision maker n, μ_n is a vector of random terms with zero mean, and ε_{nj} is an independently and identically distributed (IID) extreme value error term representing unobserved influences on choice.

The two vectors that vary over the decision makers, β_n and μ_n, do so with densities $f(\beta)$ and $f(\mu)$ respectively. The shape of $f(\beta)$ gives an indication of the nature of the preference heterogeneity across the decision makers, and forms the 'random parameter' component of the model. The assumed shape of density $f(\beta)$ is determined by the analyst, and controlled by one or more structural parameters to be estimated. Density $f(\mu)$ represents the 'error components' (ECs). It is typically specified as a normal distribution, and relaxes the IID restriction of ε_{nj}. By introducing the normal disturbances into subsets of alternatives, the unobserved component of utility can be correlated across alternatives. This can result in potentially more realistic substitution patterns between the alternatives, such that as the probability of one alternative changes due to a change in some systematic influence on utility, the percentage change in probability of the remaining alternatives need not be identical. Instead, some alternatives may draw disproportionately.

It is necessary to integrate over the three densities, $f(\beta)$ and $f(\mu)$ and ε_{nj}. Integration can be performed analytically for ε_{nj}. The choice probability for alternative i conditional on any given values of β and μ can be expressed as

$$L_{ni}(\beta_n, \mu_n) = \frac{e^{\alpha' x_{ni} + \beta'_n y_{ni} + \mu'_n z_{ni}}}{\sum_j e^{\alpha' x_{nj} + \beta'_n y_{nj} + \mu'_n z_{nj}}}.$$

Integration of $f(\beta)$ and $f(\mu)$ is typically performed with simulation, resulting in a choice probability of

$$P_{ni} = \iint \left(\frac{e^{\alpha' x_{ni} + \beta' y_{ni} + \mu' z_{ni}}}{\sum_j e^{\alpha' x_{nj} + \beta' y_{nj} + \mu' z_{nj}}} \right) f(\beta, \mu) d\beta d\mu.$$

We employ Halton draws to boost the efficiency of the simulation, and have selected 500 draws.

Stated choice datasets typically contain multiple observations per respondent. The panel nature of these data can be accommodated in the RPECL model. Consider a sequence of alternatives being observed across T choice tasks, $\{i_1, \ldots, i_T\}$. The probability of this sequence being observed is

$$L_{n\{i_1,\ldots,i_T\}}(\beta_n,\mu_n)=\prod_{t=1}^{T}\frac{e^{\alpha' x_{ni_t t}+\beta_n' y_{ni_t t}+\mu_n' z_{ni_t t}}}{\sum_j e^{\alpha' x_{njt}+\beta_n' y_{njt}+\mu_n' z_{njt}}},$$

and after integration of $f(\beta)$ and $f(\mu)$, the final choice probability becomes

$$P_{n\{i_1,\ldots,i_T\}}=\iint\left(\prod_{t=1}^{T}\frac{e^{\alpha' x_{ni_t t}+\beta' y_{ni_t t}+\mu' z_{ni_t t}}}{\sum_j e^{\alpha' x_{njt}+\beta' y_{njt}+\mu' z_{njt}}}\right)f(\beta,\mu)d\beta d\mu.$$

A simulated log-likelihood (SLL) function can be expressed as

$$SLL=\sum_{n=1}^{N}d_{n\{i_1,\ldots,i_T\}}\ln P_{n\{i_1,\ldots,i_T\}},$$

where $d_{n\{i_1,\ldots,i_T\}}$ is an indicator variable, set to one if respondent n choses the sequence of alternatives $\{i_1,\ldots,i_T\}$. The model can be estimated by maximising this SLL.

Several points need to be made regarding the specification of the utility functions in the models to be estimated. Not all of the attributes of the choice alternatives entered into x_{nj} and y_{nj} will directly correspond to the attributes and levels specified in Table 2.1. Some will be recoded to get the most meaningful outputs and model fit. Population density (a characteristic of the decision maker and their household) will also be employed, as will the type of good specified in the scenarios used to frame the choice tasks (e.g. bulky goods). Other decision maker and household characteristics were not tested, however entering these variables either as main effects or interactions with choice task attributes would allow market segments to be identified, and the analysis could be disaggregated to these segments.

In terms of model outputs, of interest is what is systematically influencing utility and hence choice. Willingness to pay (WTP) measures could be calculated but will not be a focus of this chapter. Elasticities can be calculated to determine the percentage change in choice of an alternative, in response to a percentage change in a particular attribute. However, given the often categorical nature of the attributes and their levels, a more useful approach is to calculate choice shares for each alternative for various scenarios, and compare the changes in these shares. A caveat must be issued since with the stated choice data employed herein, it is not possible to calibrate the model constants. While the exact market shares should be treated with caution, the relative changes in shares of the alternatives are useful, especially where they have environmental implications. The error components in the model play a particularly useful role in accommodating complex substitution patterns across the alternatives.

The proposed methodology cannot quantify the final VKT for carriers and customers under different scenarios. Such an approach, extended to include the behavioural realism proposed in this chapter, will be discussed in Sect. 2.5. However, the scenarios will give indicative shifts between various last mile choices by the customer, where each will have varying levels of environmental impact.

2.4 Results

2.4.1 Model Specification and Results

The RPECL model is reported in Table 2.2. The table lists each parameter estimated, and its associated *t*-ratio, together with markers indicating under which of the 10 alternatives those parameters enter into the utility expressions of the choice model. The reported model constitutes a highly significant improvement in model fit over both a constants only model, and the MNL model that omits the random parameters and error components.

Recall that each choice task presented a scenario which involved the delivery of a particular type of parcel. It is found that there is a tendency to choose the three other pickup mode (walk, cycle, public transport) alternatives less when the scenario involves a bulky parcel. This parameter was specified with a constrained triangular distribution, and thus there is heterogeneity in terms of how much the bulky parcel matters. This finding is plausible, as a bulky item is likely to be difficult or inconvenient to carry, and the extent of this inconvenience is likely to vary across individuals. The finding suggests that the type of product might influence the environmental impact over the last mile.

The cost of the delivery was also specified as a constrained triangular random parameter. As expected, the parameter is negative and highly significant. The magnitude of the coefficient is not so meaningful in itself. A more intuitive way to interpret it is by considering how much respondents are prepared to trade off other delivery and pickup features, by calculating WTP measures. This will not be the focus of this chapter, but we will report them for the various delivery quality features.

The key utility generating features of the delivery alternative centre on provision of advanced notice of a delivery date, the ability to choose a delivery time window, and the width of the window. These features were dummy coded, with two hour windows forming the base level. Coefficients for no notice of delivery, advanced notice, and four hour windows of −1.278, −0.924 and −0.67, respectively, suggest that any deterioration in quality from the two hour windows will lower the probability of choosing delivery. The addition of a late delivery option (6 pm–8 pm) will increase the probability of choosing delivery. This will be investigated in one of the scenarios in Sect. 2.5. These coefficients can also be expressed as the mean WTP to transition from each of the product features to two hour windows. In the same order as above, these WTP values are $1.46, $1.06, and $0.77. A further $0.56 could be extracted by offering late delivery. So for example, the average customer would be prepared to pay $0.77 + $0.56 = $1.33 to narrow the time windows from four hours to two hours and have a late delivery option. These values can be compared to the increased cost of delivery, for example that incurred by imposing narrow time windows on the vehicle routing, to see if these delivery features are commercially viable.

As well as a preference for a late time window, there is evidence that shopping opening hours beyond 6 pm is likely to increase the share of driving trips to a

Table 2.2 Model results

	Param.	*t*-ratio	Alternative membership									
			Delivery	Home car ded.	Home car exist.	Home other	Work car ded.	Work car exist.	Work other	Shop car ded.	Shop car exist.	Shop other
Cost[a]	−0.875	−23.23	X	X	X	X	X	X	X	X	X	X
Bulky parcel scenario[a]	−1.573	−8.74				X			X			X
No notice of delivery[b]	−1.278	−6.10	X									
Advanced delivery notice[b]	−0.924	−4.44	X									
4 h time windows[b]	−0.670	−2.98	X									
Late delivery (6−8 pm)	0.487	3.42	X									
Open late (after 6 pm)	0.260	1.57								X	X	
Days before return to sender	0.031	2.00									X	
Parking difficult mostly/sometimes	−0.619	−3.83		X	X							
Parking difficult mostly	−0.769	−2.38					X	X				
Parking difficult sometimes	−0.397	−1.52					X	X				
Parking difficult mostly	−1.022	−2.88								X	X	
Distance (km)	−0.482	−3.15				X						
Distance (km)	−1.242	−4.24							X			
Distance (km)	−0.195	−5.95										X
Population density[c]	0.155	3.18				X						
Population density[c]	0.165	3.41							X			
Population density[c]	−0.089	−1.27									X	
Population density[c]	0.245	5.01										X

(continued)

Table 2.2 (continued)

	Param.	*t*-ratio	Alternative membership									
			Delivery	Home car ded.	Home car exist.	Home other	Work car ded.	Work car exist.	Work other	Shop car ded.	Shop car exist.	Shop other
ASC[d] 1	−4.072	−15.13		X								
ASC 2	−3.544	−15.23			X							
ASC 3	−2.903	−9.72				X						
ASC 4	−5.189	−15.91					X					
ASC 5	−4.378	−14.70						X				
ASC 6	−3.011	−8.45							X			
ASC 7	−4.587	−16.12								X		
ASC 8	−3.584	−10.25									X	
ASC 9	−4.180	−13.20										X
Error component 1	2.287	14.75		X	X	X	X	X	X	X	X	X
Error component 2	0.751	3.59		X	X	X						
Error component 3	1.369	7.76					X	X	X			
Error component 4	1.594	10.13								X	X	X
Error component 5	2.076	11.17		X	X		X	X		X	X	
Error component 6	2.079	10.98		X			X			X		
Model fit												
LL		−3726.87										
LL (MNL)		−4432.03										
Pseudo r-squared		0.464										
AIC/N		2.491										
Number of parameters		34										
Number of respondents		504										

[a]Constrained triangular random parameter. [b]Base level of 2 h time windows. [c]1000 people/km^2. [d]Alternative specific constant

shopping centre CDP, although the statistical significance of this relationship is marginal. The impact was not detected on other modes of transport to the shopping location, suggesting that extended opening hours may disproportionately favour less environmentally friendly modes when a parcel pickup is made. The days before the parcel is returned to sender (RTS) was only found to have a significant influence for pickup from a shopping location in an existing trip, with more days making this alternative more attractive. This is quite plausible, as people may wish to fit the pickup into their regular shopping trip, and short RTS periods, especially those under seven days, are likely to prevent such a pickup. Thus, longer RTS periods at shopping locations should have an environmental benefit, particularly since there is likely to be no extra VKT from an existing trip to a shopping location (and unlike existing trips from home and work, where the pickup may be integrated into a trip chain, with some degree of detour from the existing route).

Parking influences are evident for all CDP alternatives with car access. From home, there is no estimable distinction between difficult parking some of the time and most of the time. Such a distinction can be made for CDP pickup from work, although the significance of difficult parking some of the time is marginal. For shopping, there is only significance for difficult parking most of the time, suggesting that if parking is difficult only some of the time, and difficult parking matters to them, they might choose a shopping time in which there is adequate parking. Clearly, an increase in car trips has negative environmental impacts. One scenario will test the impact of a change in parking.

The distance of the CDP from home or work was only significant for the other modes. This may have been due to the range of distances employed in the stated choice tasks (0.3–2 km), which may have been too short to have any impact on driving. Distance appears to have a much greater impact on utility for pickup from work. However, the alternative specific parameters must be interpreted in the context of those alternatives, and the impact of the distance is best tested in the simulations. In terms of the propensity to utilise other modes for pickup, over and above the measurable impact of distance, population density also has an influence. The greater the population density at the home, work or shopping location, the more likely the individual is to take other modes. There are numerous possible reasons for this, including a higher quality of public transport supply and walking and bicycling infrastructure, habit formation as other trip attractions are also more likely to be within walking and cycling range, and home and work self-selection whereby those with a higher propensity to use these other modes will locate themselves where these modes are more prevalent or easier, i.e. in regions with higher population density. Higher population density is also associated with a lower share of existing shopping trip pickup, although the influence has low statistical significance.

The constants must be interpreted carefully, since they are in part a consequence of the stated choice approach. Nonetheless, they do imply that delivery is a dominant alternative. More interesting are the error components, which allow for greater rates of substitution between various subsets of the alternatives. Six ECs are found to be significant. One encompasses all pickup alternatives, implying that respondents are prone to choosing between delivery and pickup, and if they choose the latter, they will switch disproportionately between the various locations, modes and levels of existing trip integration. One EC is specified for each of home, work and shopping pickup, where each includes the three possible access modes (car dedicated, car existing, and other). These imply a tendency to choose one of the three pickup locations, with a greater tendency to switch mode or trip chaining behaviour to retain this location choice. The fifth EC spans all pickup alternatives that have car access, and implies some tendency to switch between locations, with some varying amount of unobserved (dis)utility associated with the car mode. The sixth EC is similar to the fifth, but only includes dedicated car trip alternatives. This reveals variation in the propensity to trip chain, with environmental consequences over and beyond the tendency to use a car.

2.4.2 Scenarios

In these scenarios, we wish to test the impact that changes in the location, quality and price of the delivery and CDP alternatives have on the choice shares of each of the alternatives. Since the focus is on the environmental impact, particular attention is paid to the increases and decreases of shares of the more environmentally friendly alternatives. For each scenario, the before and after choice shares are reported for all alternatives, as well as the shares aggregated over CDP location of dedicated car trips, existing car trips, and other modes. For all of the shares reported, the percentage shift from the before scenario is also reported.

Consider first some alternative scenarios wherein the level of control of the delivery process by the recipient is increased (see Table 2.3 and Fig. 2.2). The delivery choice share increases dramatically, from a base of 42.55 % for no notice of pending delivery, to 46.44 % if advanced notice is provided, to 49.23 % if four hour windows are offered, with a large jump to 56.57 % with two hour windows, and finally to 61.76 % if the two hour windows include a 6 pm–8 pm option. This most attractive option represents a 45 % increase in delivery market share over the least attractive option. In terms of the corresponding decreases in shares of other alternatives, there is a disproportionate decrease in the more environmentally friendly modes. For example, with no notice replaced by two hour time windows with the 6 pm–8 pm option, total dedicated car pickup trips across locations decrease by 27.48 %, existing car trips by 32.27 %, and other modes by 39.45 %. No conclusions are drawn here about the environmental performance of the delivery option, for example by comparing the routing performance when the demand points are final customers to when they are CDPs, however some conclusions can be drawn about the customer-side environmental impact.

The provision of narrow time windows will have a detrimental impact on the efficiency of vehicle routing. A second set of scenarios were run in which the price of the delivery service increased in line with the narrowing of time windows and extending of delivery hours (see Table 2.3, second part). Price increases specified are $0.50 for four hour windows, $1 for two hour windows, and $1.25 for two hour

Table 2.3 Delivery scenarios

Alternative(s)	No notice	Advanced notice		4 h windows		2 h windows		2 h windows w. 6 pm–8 pm option	
	Share	Share	Change	Share	Change	Share	Change	Share	Change
Delivery	42.55	46.44	9.12	49.23	15.69	56.57	32.94	61.76	45.12
Home car dedicated	7.14	6.75	−5.52	6.46	−9.55	5.68	−20.48	5.11	−28.51
Home car existing	6.48	6.05	−6.73	5.73	−11.59	4.90	−24.44	4.31	−33.55
Home other	8.84	8.05	−8.96	7.49	−15.25	6.08	−31.20	5.14	−41.90
Work car dedicated	2.78	2.65	−4.68	2.55	−8.17	2.28	−17.82	2.08	−25.05
Work car existing	3.22	3.03	−5.75	2.89	−9.98	2.53	−21.37	2.26	−29.67
Work other	6.64	6.15	−7.38	5.80	−12.68	4.88	−26.50	4.24	−36.17
Shopping car dedicated	7.31	6.92	−5.28	6.64	−9.15	5.87	−19.66	5.31	−27.39
Shopping car existing	9.83	9.20	−6.46	8.74	−11.12	7.52	−23.47	6.66	−32.28
Shopping other	5.21	4.77	−8.32	4.47	−14.21	3.68	−29.25	3.15	−39.49
All car dedicated	17.23	16.32	−5.28	15.65	−9.16	13.84	−19.70	12.50	−27.48
All car existing	19.53	18.27	−6.43	17.36	−11.09	14.95	−23.44	13.23	−32.27
All other	20.69	18.97	−8.29	17.76	−14.16	14.65	−29.20	12.53	−39.45
Alternative(s)				4 h windows, delivery cost +$0.50		2 h windows, delivery cost +$1.00		2 h windows w. 6 pm–8 pm option, delivery cost +$1.25	
				Share	Change	Share	Change	Share	Change
Delivery				44.54	4.67	47.21	10.93	50.18	17.92
Home car dedicated				6.94	−2.87	6.66	−6.79	6.34	−11.17
Home car existing				6.26	−3.46	5.96	−8.11	5.62	−13.30
Home other				8.44	−4.57	7.91	−10.53	7.33	−17.07
Work car dedicated				2.71	−2.38	2.62	−5.72	2.51	−9.50

(continued)

Table 2.3 (continued)

Alternative(s)	No notice	Advanced notice		4 h windows		2 h windows		2 h windows w. 6 pm–8 pm option	
	Share	Share	Change	Share	Change	Share	Change	Share	Change
Work car existing				3.12	−2.92	2.99	−6.91	2.85	−11.42
Work other				6.39	−3.82	6.05	−8.91	5.68	−14.50
Shopping car dedicated				7.12	−2.67	6.84	−6.37	6.54	−10.59
Shopping car existing				9.51	−3.28	9.07	−7.73	8.58	−12.76
Shopping other				4.99	−4.21	4.70	−9.80	4.37	−16.02
All car dedicated				16.76	−2.70	16.12	−6.44	15.39	−10.66
All car existing				18.89	−3.28	18.02	−7.72	17.04	−12.72
All other				19.81	−4.24	18.65	−9.83	17.38	−15.98

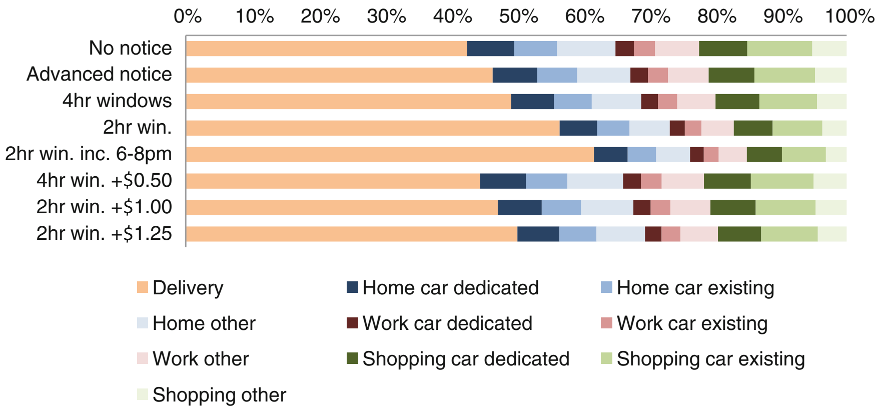


Fig. 2.2 Delivery scenarios

windows with the late delivery option. Delivery choice shares still increased, but to a lesser extent. Once again, these increases drew disproportionately from the more environmentally friendly modes.

Next, in Table 2.4, various changes are made to the home and work based pickup alternatives. The baseline scenario is based on the choice shares in the data. First, the distance to the CDPs was reduced by 25 %. The key increases in share come in home and work CDP pickups with the other modes, with 8.56 and 12.13 % increases over the baseline, respectively. Delivery decreased by just over one percent. The net increase in other modes is 6.9 %, with the percentage decrease for car dedicated and existing roughly equal.

Table 2.4 Home and work pickup scenarios

Alternative(s)	Baseline	25 % shorter distance		Good parking	
	Share	Share	Change	Share	Change
Delivery	55.31	54.72	−1.07	54.03	−2.32
Home car dedicated	5.76	5.67	−1.42	6.85	19.01
Home car existing	4.97	4.86	−2.15	6.08	22.25
Home other	6.15	6.68	8.56	5.77	−6.27
Work car dedicated	2.35	2.30	−2.38	2.67	13.26
Work car existing	2.62	2.53	−3.51	3.05	16.22
Work other	5.09	5.71	12.13	4.80	−5.85
Shopping car dedicated	6.07	6.03	−0.66	5.63	−7.28
Shopping car existing	7.78	7.71	−0.96	7.34	−5.67
Shopping other	3.89	3.79	−2.60	3.80	−2.31
All car dedicated	14.18	14.00	−1.26	15.14	6.80
All car existing	15.37	15.10	−1.78	16.46	7.09
All other	15.14	16.18	6.90	14.36	−5.11

Table 2.5 Introduction of shopping pickup scenario

Alternative(s)	Baseline	Introduce shopping CDPs	
	Share	Share	Change
Delivery	63.95	55.31	−13.50
Home car dedicated	8.27	5.76	−30.42
Home car existing	6.98	4.97	−28.78
Home other	7.81	6.15	−21.26
Work car dedicated	3.27	2.35	−28.11
Work car existing	3.54	2.62	−26.02
Work other	6.17	5.09	−17.49
Shopping car dedicated	0.00	6.07	–
Shopping car existing	0.00	7.78	–
Shopping other	0.00	3.89	–
All car dedicated	11.54	14.18	22.81
All car existing	10.52	15.37	46.12
All other	13.99	15.14	8.22

In the next scenario, parking was changed to be easy all of the time, for the home and work alternatives (see Table 2.4). Predictably, car usage increased for these two alternatives. In aggregate, delivery decreased by 2.32 % and other modes to CDP locations by 5.11 %, while dedicated car trips increased by 6.8 %, and existing car trips by 7.09 %.

In the study area of Sydney, a large majority of existing CDPs are not located at conventional grocery shopping destinations, meaning that for many, picking up a parcel at their regular shopping location is not an option. Part of the appeal of these locations is that customers can pick up the parcel either during a regular shopping visit, or opportunistically do some shopping when picking up the parcel. Further, if a car is typically used for shopping, heavy parcels may not be so much of a burden. In this next scenario, presented in Table 2.5 and Fig. 2.3, the shopping CDP alternatives are omitted in the baseline scenario, and then subsequently introduced. The largest absolute change comes to the delivery alternative, from 63.95 to 55.31 %, a 13.5 % decrease. Aggregated across CDP locations, dedicated car trips

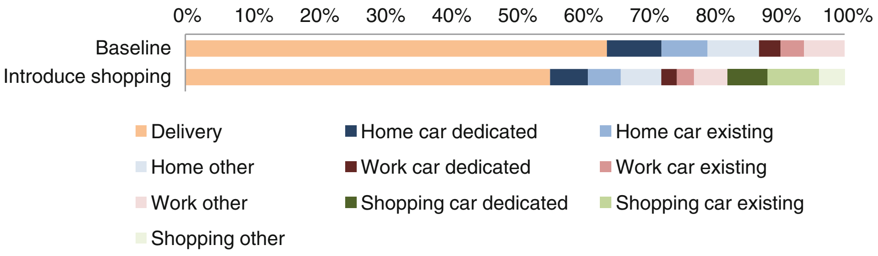


Fig. 2.3 Introduction of shopping pickup scenario

Table 2.6 Varying days before return to sender at shopping pickup scenarios

Alternative(s)	RTS 2 days	RTS 4 days		RTS 7 days		RTS 14 days	
	Share	Share	Change	Share	Change	Share	Change
Delivery	55.62	55.51	−0.19	55.35	−0.48	54.93	−1.24
Home car dedicated	5.79	5.78	−0.28	5.75	−0.69	5.69	−1.74
Home car existing	5.04	5.01	−0.61	4.96	−1.57	4.85	−3.91
Home other	6.19	6.17	−0.23	6.15	−0.61	6.09	−1.57
Work car dedicated	2.37	2.36	−0.21	2.35	−0.59	2.33	−1.52
Work car existing	2.66	2.64	−0.56	2.62	−1.39	2.57	−3.46
Work other	5.12	5.11	−0.21	5.09	−0.55	5.05	−1.37
Shopping car dedicated	6.24	6.18	−0.95	6.09	−2.39	5.87	−5.93
Shopping car existing	7.00	7.29	4.07	7.73	10.40	8.84	26.26
Shopping other	3.98	3.95	−0.75	3.90	−1.91	3.79	−4.78
All car dedicated	14.40	14.32	−0.56	14.19	−1.41	13.89	−3.52
All car existing	14.70	14.94	1.63	15.31	4.16	16.25	10.54
All other	15.29	15.23	−0.36	15.14	−0.93	14.93	−2.34

increase by 2.63 % in absolute terms, from a 11.54 to 14.18 % share. The increase for existing car trips is greater, at 4.85 % in absolute terms to a new total of 15.37 %, while the share for other modes increases from 13.99 to 15.14 %. Overall, the introduction of CDPs at shopping destinations leads to a disproportionate increase in more environmentally friendly access modes.

Finally, in Table 2.6, four scenarios were run, where the days before the parcel is returned to sender progressively increased. Reflecting the utility expression specified for the choice model, only the shopping alternative with an existing car trip benefits from this increase. Its share increases from 7.00 % to 7.29, 7.73 and 8.84 % for days before RTS of two, four, seven and 14 respectively. These increases are relatively small, but not trivial in the context of annual parcel flows. No particular pattern is discerned in the decreases of the shares of the other alternatives, except for a slightly larger percentage decrease for the non-shopping alternatives that incorporate existing trips.

2.5 Discussion and Conclusions

This chapter has investigated the environmental impacts of parcel delivery over the last mile, in which CDPs and conventional delivery compete against each other. The modelling employed has focused on the behavioural response of the consumer to the products offered, and the associated total environmental footprint. An online survey was used to collect stated choice data, on which a RPECL model was estimated. The environmental impact has been examined through a set of scenarios, with changes in shares of more and less environmentally friendly alternatives calculated.

Some caveats regarding the methodology are in order. The choice tasks as specified provide a degree of abstraction from the reality of the individual decision maker. Explicit home and work CDP locations are not specified—only a distance from home or work is provided. The advantage of this is that such an abstract representation avoids the potential for large unobserved effects associated with specific and problematic CDP locations. However, it does make the dedicated verses existing car trip less meaningful. The grocery shopping location, however, was framed as their regular shopping location, so the dedicated/existing decision is arguably more meaningful for this alternative. Further, the choice tasks were also framed around the next week or two, and they were asked to consider their schedule over that time. It was also made clear that someone else in the household could make the pickup or receive the parcel, furthering the realism of the choice task.

The proposed methodology cannot alone quantify the final VKT or emissions for carriers and customers under different scenarios. A larger modelling effort would consider a real network of CDPs, and the actual locations of customers. Routing plans could be generated for parcel deliveries to customers and CDPs (see, for example, McLeod et al. 2006). Travel to pick up the parcels from the CDPs would also be modelled.[3] This would allow the choice shares reported in this paper to be converted to aggregate VKT and emissions under a range of scenarios, in a way that accommodates behavioural responses to the location, quality and price of the CDP and delivery offerings. This will remain an avenue for future research.

Various changes to CDPs were investigated through the scenarios, and will be discussed further here. A CDP network with higher density would imply a shorter distance for many customers. It was found that this would lead primarily to a shift to walk, cycle and public transport modes, although the absolute shift is relatively small. A large increase in CDP uptake can be gained from locating them at shopping centres, if they were not previously located there. Here, from an environmental perspective, the largest percentage increase will come in existing car trips, however dedicated driving trips increase also. More broadly, this finding suggests that CDP locations that integrate into existing trip destinations will lead to a large increase in CDP usage, with much but not all of this travel integrating into existing trips. Distribution efficiencies are likely to be particularly strong for CDPs at shopping locations, given the well established distribution into these locations, often with large vehicles. Sufficiently long number of days before the parcel is returned to sender can also stimulate integration into existing trips.

An increase in the prevalence of CDPs may trigger a competitive response from conventional delivery, where narrow time windows is an obvious tool to increase market share and/or yields. This chapter has shown that narrow windows lead to a clear and dramatic increase in delivery choice share. Further, this increase draws disproportionately from the more environmentally friendly CDP access modes. However, before being able to draw definitive conclusions about the environmental

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[3] The integration of pickups into existing travel patterns would be the most challenging component of this model.

impact, the net impact would need to be calculated. Environmental benefits would accrue from the reduction in dedicated car trips to the CDP, and to a lesser extent from the reduction in VKT from existing trips that integrated the pickup, but required extra VKT to do so. Even with advanced notice of delivery and choice of time windows, missed deliveries can still occur. Nonetheless, the narrowing of the window should reduce the prevalence of missed deliveries, and the associated VKT either from a redelivery, or a subsequent customer pickup from a warehouse or even a CDP. Environmental costs would stem from a less efficient delivery schedule associated with narrow windows. The net change would require further research.

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Chapter 3
Dynamic Supply Chain Greening Analysis

Armin Jabbarzadeh and Behnam Fahimnia

Abstract Greening of supply chain operations is best to be addressed at the network design phase where strategic facility location, technology and transport mode decisions are made. This has been an important area of research focus for almost a decade now. Given the increasing frequency and intensity of disruptive events facing today's organizations, the greening analyses of supply chains need to take into consideration how the economic and environmental performance of the supply chain can be affected in the face of unanticipated disruptions. Thus, static greening analysis is simplistic and achieving a truly green supply chain requires a dynamic analysis to develop robust supply chains whose sustainability performance remains unaffected or only lightly affected by disruptions of various types. This chapter presents a framework and optimization model for dynamic sustainability analysis. A numerical example is presented to illustrate the application of the approach in performing tradeoff analysis in business-as-usual and disruption circumstances.

Keywords Supply chain network design · Dynamic greening analysis · Sustainability · Green · Supply chain resilience · Disruption risk

3.1 Static Supply Chain Greening Analysis

Many organizations today are lauded for being carbon-neutral, zero-waste, and energy efficient. Greening initiatives and innovations have predominantly focused on the reduction of emissions, wastes and energy consumption; not only because it is better for the planet, but to "future-proof" the organizations. The two primary challenges in this context are (1) identifying economic and environmental metrics based upon which the performance of the supply chain can be assessed,

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and (2) exploring the tradeoff solutions that can balance the economic and environmental sustainability of the supply chain. We here review some of the related modeling efforts in these areas.

Supply chain cost and carbon emissions have been the most popular economic and environmental metrics amongst both researchers and practitioners (Fahimnia et al. 2014a; Zakeri et al. 2015). There are a few studies that do not fall in this category. For example Fahimnia et al. (2014b) and Nagurney and Nagurney (2010) use emissions, waste and energy as environmental metrics. More comprehensive environmental criteria can also be drawn from the established environmental impact assessment methods such as Eco-indicator 99 (Goedkoop et al. 2009), IMPACT 2002+ (Jolliet et al. 2003), CML 2001 (Guinèe et al. 2001) and ReCiPe 2008 (Goedkoop et al. 2009). Environmental impact assessment methods use a set of criteria such as energy sources, water usage, carbon emissions, hazardous/chemical material usage, land use, and environmental technology and innovation investments to assess the environmental performance of the supply chain at every stage in the product life cycle. The information is translated into a set of socio-environmental impact categories and a score is assigned to each impact category. The scores are then aggregated to produce a single score that represents the sustainability performance of the supply chain [see for example the works of Boukherroub et al. (2015); Pinto-Varela et al. (2011); Pishvaee and Razmi (2012)].

Most modeling efforts in this context arrive at multi-objective optimization models that aim to simultaneously address economic and environmental goals (Fahimnia et al. 2015). In multi-objective problems, there is no unique solution that can satisfy all objectives. In most cases, an objective function is improved at the cost of compromising at-least one other objective. In these situations, a multi-objective solution approach is used to find a tradeoff solution or a set of tradeoff solutions. Numerous approaches have been developed and implemented to solve multi-objective programming models. Weighted sum methods, goal programming, “ε-constraint” method, multi-objective evolutionary algorithms, and fuzzy programming approaches are amongst the most popular.

Weighted sum methods aim to convert multiple objectives into a single objective equivalent by assigning a weight to each objective function corresponding to its importance (Arntzen et al. 1995). A weight will turn into a normalisation constant if objective values have different units/dimensions. In goal programing, instead of minimizing or maximizing the objective function(s), their deviations from goals or aspiration levels are minimized (Aouni and Kettani 2001). A weighted goal programming approach assigns weighting coefficients (or normalisation constants in case of different dimensions) to the deviation values to generate a unified objective function. The so-called “ε-constraint” method prioritizes one objective function and transforms the remaining objective functions to constraints (Sabri and Beamon 2000). Multi-objective evolutionary algorithms generate a set of non-dominated solutions to the problem and attempt to improve the solutions in several iterations seeking for a better tradeoff among objectives (Altiparmak et al. 2006). One primary issue with these methods is determining the weights of objective functions. Fuzzy programming approaches can be used to imprecisely express the relative importance of each goal (Aköz and Petrovic 2007; Chen and Tsai 2001; Narasimhan 1980; Tiwari et al. 1987). Applications of fuzzy goal programming has been studied in aggregate production planning (Jamalnia and Soukhakian 2009; Wang and Liang 2004), supplier evaluation and selection (Amid et al. 2006; Chen et al. 2006; Kumar et al. 2004), supply chain network design (Özceylan and Paksoy 2012; Selim and Ozkarahan 2008) and supply chain planning (Liang 2007; Selim et al. 2008; Torabi and Hassini 2008).

3.2 Dynamic Supply Chain Greening Analysis

Accelerating climate change and global warming increase the likelihood that disruptive events from natural disasters will continue to occur. History also records a continuous stream of anthropogenic catastrophes that can affect supply chain operations at various levels. To remedy these extensive problems, organizations need to build resilience into their supply chains. Resilience is defined as the capacity for a supply chain to survive and continue operating in the face of unanticipated disruptions. Looking for best practices to manage supply chain imbalance in disruptions can become a formidable challenge.

In this environment, achieving sustainability will necessitate the development of resilient supply chains whose sustainability performance remains unaffected or lightly affected in disruption situations. A focus on supply chain greening without considering the dynamic nature of the operating environment means trying to operate in an environmentally sustainable fashion in one specific state of the system with no effort to manage supply chain sustainability imbalance when changes occur in the state of the system (e.g. when the supply chain is affected by a disruptive event). In other words, in an increasingly volatile world, a steady-state sustainability analysis is simplistic. In this environment, a realistic supply chain greening analysis in this environment requires moving beyond a static supply chain analysis towards a dynamic evaluation where supply chain greening can be examined in multiple states of the system. Section 3.3 of this chapter presents a framework and optimization model that can be used for dynamic supply chain greening analysis.

In the context of supply chain resilience, different approaches and solution techniques have been developed and applied to address system resilience issues. Expected value approaches have been amongst the most popular to measure and account for supply chain resilience. The approach helps in making sound decisions on investment and prioritizing resilience building options by assigning weights to future events and calculating the expected value of different disruption scenarios (Snyder and Daskin 2005). A standard expected value approach can be extended to address independent likelihood for disruption occurrence (Aryanezhad et al. 2010; Chen et al. 2011), unequal disruption probabilities (Berman et al. 2007; Cui et al. 2010; Li et al. 2013; Li and Ouyang 2010; Lim et al. 2010; O'Hanley et al. 2013), and dependent disruption probabilities (Jabbarzadeh et al. 2012; Shen et al. 2011). Other approaches include, but are not limited to, scenario-based models that incorporate the risk preferences of a decision maker (Baghalian et al. 2013) and those approaches that aim to minimize the relative regret of the decision maker under a set of disruption scenarios (Peng et al. 2011).

3.3 A Mathematical Model for Dynamic Supply Chain Greening Analysis

We now present an optimization model that can be used to evaluate the design of a green supply chain, using cost and carbon emissions as economic and environmental performance metrics, under a set of disruption scenarios. Let us consider a supply chain comprised of a set of factories, distribution centers (DCs) and end-users. Fixed and variable production costs and emissions performance of each factory is determined based on the location and capacity of the factory, manufacturing technology adopted, and sustainability initiatives undertaken. Multiple transport modes are available for the shipment of products between factories, DCs and end-users. Shipment costs and emissions data are available for every transport mode. DCs may have different fixed and variable holding costs depending on the location, size, material handling system adopted, and environmental initiatives undertaken.

Factories and DCs are subject to major disruptions. A set of disruption scenarios need to be developed to represent situations where one or more facilities are affected by disruption(s). The objective is to minimize the overall supply chain costs in both business-as-usual and disruption situations; whilst ensuring that the environmental performance of the network is kept within a desired range. Another way to look at this analysis is to seek for the desired greening degree at which an acceptable economic performance can be attained for the supply chain in both business-as-usual and disruption situations.

The following set of indices, parameters and decision variables are used for mathematical modeling of this problem.

Indices

I	Set of candidate locations for factories, indexed by i
J	Set of candidate locations for DCs, indexed by j
K	Set of end-users, indexed by k
L	Set of capacity levels of a factory, indexed by l
T	Set of product types, indexed by t
M	Set of transport modes for the shipment of products from factories to DCs, indexed by m
N	Set of production technologies, indexed by n
O	Set of capacity levels of a DC, indexed by o

R	Set of transport modes for the shipment of products from DCs to end-users, indexed by r
S	Set of disruption scenarios, indexed by s

Parameters

a_i^s	Equal to 1 if factory i is disrupted in scenario s; 0, otherwise
b_j^s	Equal to 1 if DC j is disrupted in scenario s; 0, otherwise
d_{kt}	Forecasted demand for product t in end-user k (units)
f_{iln}	Fixed cost of establishing a factory with capacity level l and technology n at location i ($)
f'_{jo}	Fixed cost of establishing a DC with capacity level o at location j ($)
g_{int}	Variable cost of manufacturing a unit of product t in factory i using technology n ($/unit)
h_{nt}	Processing time to produce a unit of product t using technology n (hour)
c_{iln}	Production capacity of a factory with capacity level l and technology n at location i (hour)
v_{ijmt}	Unit cost of transportation for the shipment of product t from factory i to DC j through transport mode m
v'_{jkrt}	Unit cost of transportation for the shipment of product t from DC j to end-user k through transport mode r
u_{kt}	Unit cost of lost sales for product t at end-user k ($/unit)
h'_t	Volume of a unit of product t (m^3)
c'_{jo}	Storage capacity of a DC with capacity level o at location j (m^3)
e_{int}	Estimated carbon emissions to produce product t using technology n in factory i (ton)
e'_{ijmt}	Estimated carbon emissions for the shipment of product t from factory i to DC j through transport mode m (ton)
e''_{jkrt}	Estimated carbon emissions for the shipment of product t from DC j to end-user k through transport mode r (ton)
ε	Emissions cap: maximum allowed carbon emissions for the supply chain (ton)
w	Resilience weight: the contribution of the disruption cost function
p_s	Probability of disruption scenario s to occur

Decision variables

X_{iln}	A binary variable, equal to 1 if a factory with capacity level l and technology n is established at location i; 0, otherwise
X'_{jo}	A binary variable, equal to 1 if a DC with capacity level o is established at location j; 0, otherwise

Q_{int}^{s} Quantity of product t produced in factory i using technology n under scenario s

U_{kt}^{s} Quantity of lost sales for product t at end-user k under scenario s

Y_{ijmt}^{s} Quantity of product t shipped from factory i to DC j through transport mode m under scenario s

Z_{jkrt}^{s} Quantity of product t shipped from DC j to end-user k through transport mode r under scenario s

Using the above parameters and decision variables, we can now formulate the cost parameters the summation of which will form the objective functions.

Cost of establishing factories:

$$\mathrm{MC_s} = \sum_{i \in I} \sum_{l \in L} \sum_{n \in N} f_{iln} X_{iln} \tag{3.1}$$

Cost of establishing DCs:

$$\mathrm{DC_s} = \sum_{j \in J} \sum_{o \in O} f'_{jo} X'_{jo} \tag{3.2}$$

Shipment costs:

$$\mathrm{SC_s} = \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \sum_{t \in T} v_{ijmt} Y_{ijmt}^{s} + \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} v'_{jkrt} Z_{jkrt}^{s} \tag{3.3}$$

Production costs:

$$\mathrm{PC_s} = \sum_{i \in I} \sum_{n \in N} \sum_{t \in T} g_{int} Q_{int}^{s} \tag{3.4}$$

Cost of lost sales:

$$\mathrm{LC_s} = \sum_{k \in K} \sum_{t \in T} u_{kt} U_{kt}^{s} \tag{3.5}$$

The problem is formulated as a bi-objective mixed-integer linear programming model. Objective function 1, formulated in Eq. 3.6, represents the supply chain cost in business-as-usual situation. Scenario 1 (s = 1) denotes the “business-as-usual” scenario when no disruption occurs.

Objective function 1:

$$G_1 = (MC_1 + DC_1 + SC_1 + PC_1 + LC_1) \tag{3.6}$$

Objective function 2 (Eq. 3.7) represents the expected supply chain cost in disruption situations.

Objective function 2:

$$G_2 = \frac{\sum_{s \in S-\{1\}} P_s (MC_s + DC_s + SC_s + PC_s + LC_s)}{\sum_{s \in S-\{1\}} P_s} \tag{3.7}$$

The two objectives can be aggregated to form a tradeoff objective function as shown in Eq. 3.8, where w denotes the resilience weight ($0 \le w \le 1$), the relative importance of supply chain performance in disruptions.

Tradeoff objective function:

$$(1-w)G_1 + wG_2 \tag{3.8}$$

The goal of the proposed model is to minimize the value of the tradeoff objective function subject to the following constraints:

$$\sum_{l \in L} \sum_{n \in N} X_{iln} \le 1 \quad \forall i \in I \tag{3.9}$$

$$\sum_{o \in O} X'_{jo} \le 1 \quad \forall j \in J \tag{3.10}$$

$$\sum_{n \in N} Q^s_{int} = \sum_{j \in J} \sum_{m \in M} Y^s_{ijmt} \quad \forall i \in I, \forall t \in T, \forall s \in S \tag{3.11}$$

$$\sum_{i \in I} \sum_{m \in M} Y^s_{ijmt} = \sum_{k \in K} \sum_{r \in R} Z^s_{jkrt} \quad \forall j \in J, \forall t \in T, \forall s \in S \tag{3.12}$$

$$\sum_{j \in J} \sum_{r \in R} Z^s_{jkrt} = d_{kt} - U^s_{kt} \quad \forall k \in K, \forall t \in T, \forall s \in S \tag{3.13}$$

$$\sum_{t \in T} h_{nt} Q^s_{int} \le \left(1 - a^s_i\right) \sum_{l \in L} c_{iln} X_{iln} \quad \forall i \in I, \forall n \in N, \forall s \in S \tag{3.14}$$

$$\sum_{i \in I} \sum_{m \in M} \sum_{t \in T} h'_t Y^s_{ijmt} \le \left(1 - b^s_j\right) \sum_{o \in O} c'_{jo} X'_{jo} \quad \forall j \in J, \forall s \in S \tag{3.15}$$

$$\begin{aligned} &\sum_{i \in I} \sum_{n \in N} \sum_{t \in T} e_{int} Q^s_{int} + \sum_{i \in I} \sum_{j \in J} \sum_{m \in M} \sum_{t \in T} e'_{ijmt} Y^s_{ijmt} \\ &+ \sum_{j \in J} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} e''_{jkrt} Z^s_{jkrt} \le \varepsilon \quad \forall s \in S \end{aligned} \tag{3.16}$$

$$X_{iln} \in \{0, 1\} \quad \forall i \in I, \forall l \in L, \forall n \in N \tag{3.17}$$

$$X'_{jo} \in \{0, 1\} \quad \forall j \in J, \forall o \in O \tag{3.18}$$

$$Q^s_{int} \geq 0 \quad \forall i \in I, \forall n \in N, \forall s \in S, \forall t \in T \tag{3.19}$$

$$U^s_{kt} \geq 0 \quad \forall k \in K, \forall s \in S, \forall t \in T \tag{3.20}$$

$$Y^s_{ijmt} \geq 0 \quad \forall i \in I, \forall j \in J, \forall m \in M, \forall s \in S, \forall t \in T \tag{3.21}$$

$$Z^s_{jkrt} \geq 0 \quad \forall j \in J, \forall k \in K, \forall r \in R, \forall s \in S, \forall t \in T \tag{3.22}$$

Constraints (3.9) and (3.10) ensure that only one facility can be established in candidate locations for factories and DCs, respectively. Constraints (3.11), (3.12) and (3.13) represent the flow balance constraints in factories, DCs and end-users, respectively. Constraints (3.14) and (3.15) enforce the capacity limitation of factories and DCs at different disruption scenarios. Constraint (3.16) expresses the carbon emission constraint. Constraints (3.17)–(3.22) define the domains of the decisions variables.

Using the proposed model in this section, one can examine the performance of a green supply chain under a set of hypothetical disruption scenarios. These test experiments and performance evaluations can assist in making more informed decisions on investment for design or reconfiguration of a green supply chain that can maintain its economic and environmental performance when facing real disruptions. Section 3.4 illustrates the application of the proposed model in a hypothetical case example.

3.4 An Illustrative Example

Consider a manufacturing supply chain with four production factories and three DCs supplying five product types to five customer zones. The company is considering a supply chain reconfiguration which may involve shutting down or re-sizing one or more of the factories and DCs. The primary objective for the supply chain reconfiguration is to improve the environmental sustainability of the network. The goal is to become at-least 20 % greener using overall supply chain emissions generation as the environmental performance metric. A manufacturing plant can be built in three sizes: large, medium, and small. The availability of production technologies may vary from one factory to another, but, in general, production technologies are graded between 1 and 5, with 5 being the greenest and usually the most expensive to adopt. The location and size of a plant, the type of the production technology, the labor and management wages, and the associated overhead costs determine the fixed and variable production costs and emissions rates of each factory. DCs can be leased in three sizes: large, medium and small. The fixed and variable storage costs at each DC are determined based on the location and size of a

DC, the material handling technology, the labor wages, and the associated overhead costs.

The mixed-integer linear model presented in Sect. 3.3 can be solved using standard linear solvers such as CPLEX and GAMS. A set of disruption scenarios needs to be developed representing possible facility disruption situations. Scenario 1 ($s = 1$) represents a business-as-usual situation when no facility is disrupted. Other scenarios may include situations when different combination of factories and warehouses are affected by disruptions. With four plants and three DCs there will be a total of 28 scenarios considering all possible disruption combinations, excluding a business-as-usual scenario.

For a concerned greening degree, in this case 20 % emissions reduction which appears in constraint 16, the proposed model can be solved for different resilience weights (w). The results are shown in Table 3.1. When $w = 0$, disruption scenarios are overlooked and the model is solved for objective function 1 only. In this situation, the business-as-usual cost is the lowest, but the supply chain cost can rise dramatically to more than double its business-as-usual costs in the face of disruptions. Setting the resilience weight equal to zero implies a *static supply chain greening analysis* which results in a green supply chain that is unprepared to tackle disruptions.

The larger the resilience weight is, the greater the disruption consideration would be in supply chain design decisions. In this case, at $w = 0.2$ (i.e. 20 % is the contribution of objective function 2, the disruption cost function), the supply chain cost in the business-as-usual situation would increase by \$169,660 (rising from \$3,850,412 to \$4,020,072), whilst the supply chain can save an average of \$897,379 in disruptions (\$7,935,957 − \$7,038,578). The potential savings increase as resilience weight gets larger, but these savings are yielded at increased business-as-usual costs. This is where the management needs to seek for a tradeoff solution (seeking an optimal value for w) depending on the decision makers' risk attitude, budget availability (for increased supply chain cost in business-as-usual situation), and the knowledge of risk situations.

Table 3.1 Supply chain costs and location decisions at different resilience weights

Resilience weight	Cost in business-as-usual (\$)	Expected cost in disruptions (\$)	Factories				DCs		
			i1	i2	i3	i4	j1	j2	j3
$w = 1$	4,609,460	5,057,268	L 2	L 4	L 5	M 4	L	L	L
$w = 0.8$	4,482,864	5,567,674	L 3	L 5	L 5	M 3	L	L	L
$w = 0.6$	4,300,372	6,011,936	M 2	S 5	M 5	M 3	M	M	M
$w = 0.4$	4,152,904	6,474,855	S 3	S 4	S 5	S 3	S	M	M
$w = 0.2$	4,020,072	7,038,578	S 3	S 3	S 4	S 1	S	M	M
$w = 0$	3,850,412	7,935,957	S 5		M 1	S 1	S	M	M

Factory and DC sized: *L* Large, *M* Medium, *S* Small size
Production technology grades: 1–5 with 5 being the greenest

Table 3.1 also shows the configuration of the supply chain network at different resilience weights. What is obvious from these results is that larger factories and DCs and greener production technologies are required at larger resilience weights to maintain the same greening level. The extra capacity of factories and DCs would enhance the supply chain flexibility and enable switching production between facilities and storage between DCs when disruptions occur. This observation also explains why business-as-usual costs increase towards larger w values.

What we have shown in this section is a simplified dynamic supply chain greening analysis. A more thorough analysis may also require a greening adjustment exercise which requires the development of a number of greening scenarios corresponding to the desired emissions caps/targets. The model will then need to be solved for different ε and w values. We name this a "nested scenario development" approach where disruption scenarios operate within greening scenarios. Such an approach can help perform a greening adjustment exercise for designing a supply chain that is both green and resilient to unforeseeable disruptions.

3.5 Conclusions

Theoretically, from a global perspective, while sustainability aims to put the world back into balance, resilience looks for ways to manage an imbalanced world (Zolli and Healy 2012). At the organizational level, both sustainability and resilience initiatives and strategies are required for companies to survive and maintain competitive advantage. Achieving sustainability will necessitate the development of resilient supply chains whose sustainability performance remains unaffected or merely lightly affected in disruption situations. Thus, a thorough supply chain sustainability analysis requires moving beyond a static supply chain analysis by performing a dynamic evaluation where supply chain sustainability can be examined in multiple states of the system. This chapter presented a framework and optimization model that can be used for dynamic supply chain greening analysis (focusing on economic and environmental sustainability aspects). The application of the proposed model and approach was illustrated using a hypothetical case example.

Our modeling effort and discussion in this chapter can set the stage for future research in the area of dynamic sustainability analysis. Future research can focus on (1) the inclusion of additional sustainability performance metrics, (2) the incorporation of innovative robustness approaches to measure and enhance supply chain resilience, (3) developing and applying novel multi-objective optimization methods that can help explore tradeoff solutions within a reasonable time tolerance, (4) completing dynamic sustainability analysis at the tactical and operational levels which may require the development of innovative solution methods that can handle significantly larger number of variables and constraints, (5) the use of real data for broader acceptance of the developed models by industry practitioners.

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Chapter 4
City Logistics for Sustainable and Liveable Cities

Eiichi Taniguchi

Abstract There are many complicated and challenging urban freight transport problems which result in high logistics costs, negative environmental impacts, unsafe traffic conditions, and high energy consumption. The behaviour of the multiple stakeholders involved in urban freight transport needs to take into account for creating efficient and environmentally friendly and safe urban freight transport systems. City logistics has been proposed to achieve the goals of mobility, sustainability, and liveability by balancing the smart growth of economy and cleaner, safer and quieter environment. This chapter addresses the definition of city logistics, the driving forces of technical innovations and behaviour change of stakeholders, the governance of public sectors for providing a better framework for city logistics. The modelling techniques highlight how to describe problems and evaluate policy measures for decision support. Future perspectives relating to co-modality, home health care, and disasters are also given.

Keywords Urban freight transport · Environment · ITS · Public private partnerships · Models

4.1 Introduction

Urban freight transport issues are essential elements for sustainable and liveable cities. Recently more attention has been paid to urban freight transport, since there is increasing concern about the global and local environmental problems including air pollution, noise and vibration as well as safety and security issues. Balancing economic development with environmental preservation and safety is vital to achieve better living conditions in cities. In most cases trucks are used for delivering

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and collecting goods in urban areas and they are not welcome by residents in local communities due to the negative environmental impacts, traffic accidents, and visual intrusion. In addition to these issues, the development of e-commerce requires more efficient and environmentally friendly urban distribution systems, as consumers would like to receive commodities quickly and at the designated times periods at their home.

The urban distribution of goods is the last part of supply chains, but it is hard to deliver goods to customers within designated time windows by pickup-delivery trucks on congested urban road networks. Smaller amount of goods are delivered more frequently in modern logistics systems to meet the demands of customers for quick response from shippers. Based on the survey of freight flows throughout Japan by the Ministry of Land, Infrastructure, Transport and Tourism, the weight of freight flows which were less than 100 kg increased to 75.1 % in 2010, whereas it was 55.6 % in 1990 and 63.6 % in 2000.

4.2 What Is City Logistics?

To solve these complicated and challenging issues relating to urban freight transport, the idea of city logistics has been proposed (Taniguchi et al. 2001b; Taniguchi and Thompson 2014). City logistics is defined as, "*the process for totally optimising the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of a market economy*" (Taniguchi et al. 2001b). The central idea of city logistics is the concept of total optimisation instead of partial optimisation of logistics and transport activities considering various aspects of environment, congestion, safety and energy consumption. Therefore, we need to take into account the social issues as well as commercial issues. Basically there is a difference between commercial logistics and city logistics. Namely, the commercial logistics can be operated only by private firms of shippers and freight carriers, whereas in city logistics, administrators from the public sector of and residents also participate. This means that public-private partnerships (Browne et al. 2004) between shippers, freight carriers, administrators and residents are required (Fig. 4.1). However, each of these entities have different objectives. For example, shippers hope to send their products to receivers within designated time windows with higher reliability and lower costs. Freight carriers aim to maximise their profits by minimising costs to meet with the demands of shippers. Administrators in any level of national, regional, and municipality, try to vitalise the economy and improve the environment in urban areas. Residents want quieter, safer and cleaner environment in their communities. Figure 4.1 includes one more entity of city logistics, Non-Profit Organisations (NPO), which can coordinate the conflicts among the stakeholders. This type of organisation is needed in reality for better communication and making decision of

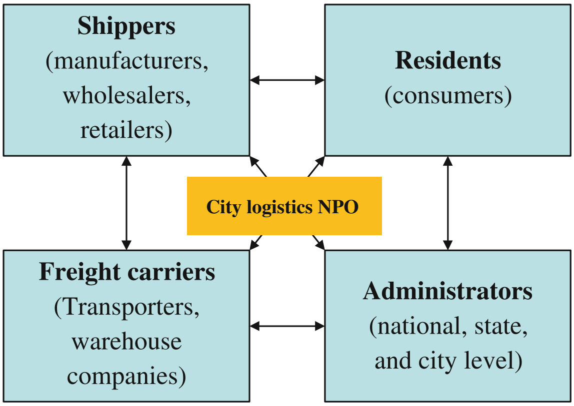

Fig. 4.1 Stakeholders for city logistics

executing city logistics initiatives. Support by advanced information systems is critical for collecting data and sharing data among stakeholders who are involved in city logistics. This definition assumes the market economy that allows the collaboration of public sectors and private firms in terms of planning, implementing and evaluating urban freight policy measures.

The targets of city logistics are "mobility," "sustainability," and "liveability". These three pillars show the multi-objectives of city logistics and the achievement of these objectives ensures the efficient and environmentally friendly urban freight transport systems. The bracings indicate multiple evaluation criteria such as "global competitiveness," "efficiency," "environmental friendliness," "congestion alleviation," "security," "safety," "energy conservation," and "labour force." Therefore, city logistics can be visualized as multi-objective optimisation with multi-criteria (Fig. 4.2). Recently "resilience" has become an urgent and important issue. There is a need to consider risks associated with disasters after we experienced catastrophic disasters by the tsunami after Northern Sumatra earthquake in Indian sea region in 2004 as well as Tohoku earthquake and cascading tsunami in Japan, in 2011, Hurricane Catharina in Mexican bay area, USA in 2005, Sichuan earthquake in China in 2008 and bush fires in Melbourne, Australia in 2009. As well, we had chemical attack using sarin on the subways in Tokyo in 1995, September 11 terrorism in New York in 2001, blast attack in London in 2005 and piracy attack off the Somalia coast in 2009. The humanitarian logistics is required for providing relief supplies of water, food, and daily commodities to people in difficulty. The research area of humanitarian logistics is important for supporting a healthy, safe and secure life (Zeimpekis et al. 2013; Taniguchi et al. 2014a).

The Information and Communication Technology (ICT) and Intelligent Transport Systems (ITS) plays an important role for achieving the goals of city logistics. As city logistics deals with multi-objective optimisation, providing dynamic traffic information using ICT and ITS allows the costs of urban distribution to be reduced and it results in the reduction of CO_2, NOx and SPM emissions

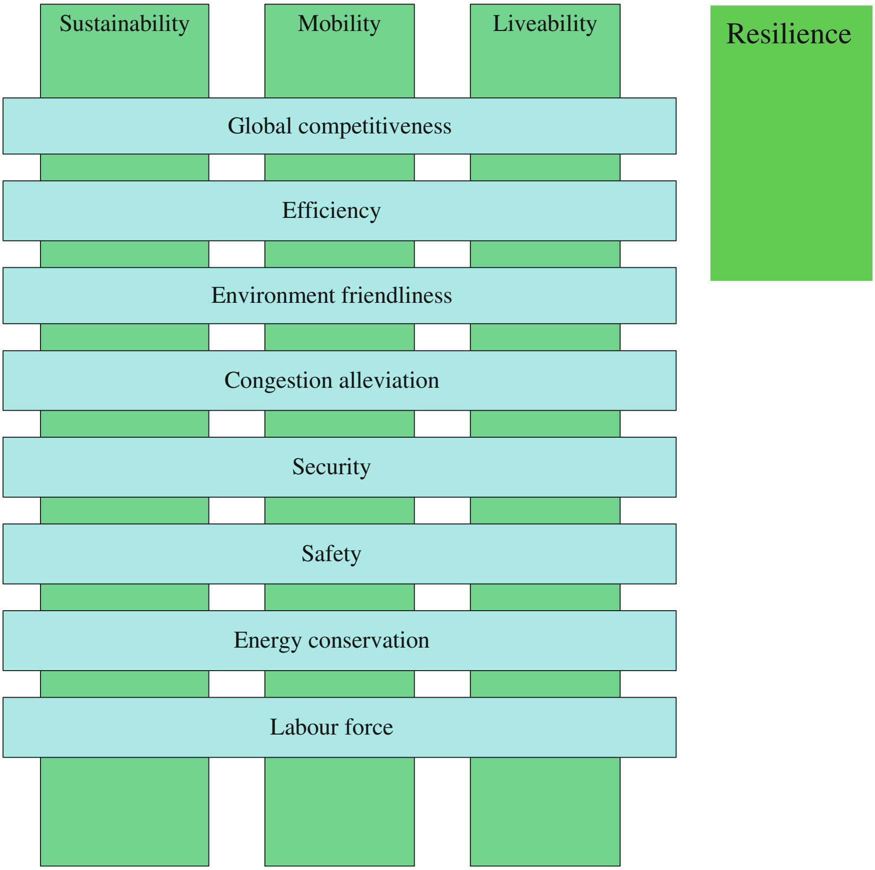

Fig. 4.2 Targets and evaluation criteria of city logistics

caused by truck operations (Taniguchi and Shimamoto 2004). The functions of ICT and ITS for city logistics are categorised as follows:

(a) Collecting data
(b) Storing and sharing data
(c) Communicating with other stakeholders

Precise data of truck movements can be collected using Global Positioning Systems (GPS). It is possible to use the data of these vehicle movements for optimising vehicle routing and scheduling problems, in particular using historical data of vehicle movements for some periods allow to treat probabilistic vehicle routing and scheduling problems for reliability analyses (Ando and Taniguchi 2006). The historical data of travel times on road network is very important for reducing the average costs of vehicle operations in the long term. On-line communication between shippers, receivers and freight carriers are beneficial for decreasing costs as well as negative environmental impacts based on data sharing and exchange, especially using joint delivery systems with urban consolidation centres (van Duin et al. 2007).

The change in behaviour of shippers and freight carriers is essential elements for promoting city logistics. Recently a number of firms are moving towards greener transport and logistics systems. Typically public private partnerships (PPP) for sustainable urban freight transport systems have been established to discuss the problems relating to urban freight and find appropriate solutions (Browne et al. 2004). During the discussion and exchange of perspectives among stakeholders in PPP, collaboration between public and private sectors can be achieved.

The history of city logistics is relatively short in research and practice. In 1970s some researchers performed research on urban freight issues focusing on the estimation of goods movements in urban areas (Hutchinson 1974; Ogden 1977, 1978; Roberts and Kullman 1979). Early in the 1990s German researchers started to study city logistics (Ruske 1994; Kohler 1997) but the term city logistics simply meant the joint delivery systems in German context. Japanese and Dutch researchers also initiated research on city logistics in 1990s (Taniguchi et al. 1995; van Duin 1997; Taniguchi et al. 1998). They decided to organise the International Conference which is dedicated to City Logistics. The first International Conference on City Logistics was held in Cairns, Australia in 1999 (Taniguchi and Thompson 1999). Since then, conferences have been organised every two years by Institute for City Logistics (http://www.citylogistics.org) at various cities in the world. Reviewing the advances of research and practical planning has been presented at each conference (Taniguchi et al. 1999, 2001a, 2004, 2006, 2008, 2010, 2012, 2014b; Visser et al. 1999, 2001; Browne et al. 2004; Nemoto et al. 2006; Browne et al. 2008, 2010, 2012; Visser et al. 2014). The OECD (Organisation for Economic Cooperation and Development) set up a working group for discussing urban goods transport from economic, environmental, and social points of view. In 2003, this international working group published a report (OECD 2003). The report was the first attempt to draw attention to urban freight issues. Until that time there had been almost no cities that considered urban freight issues in their urban planning, the report tried to encourage urban planners and other professionals to be aware the importance of urban freight issues for the sustainable development. After the report was issued, a number of research and practical projects on city logistics were initiated including BESTUFS I, II (http://www.bestufs.net/), Citylog (http://www.city-log.eu/), and SUGAR (http://www.sugarlogistics.eu/). In the educational area, some textbooks have been published (Taniguchi and Thompson 2003; McKinnon et al. 2010; Macharis and Melo 2011; Gonzalez-Feliu et al. 2013; Tavasszy and De Jong 2014; Taniguchi et al. 2014a; Taniguchi and Thompson 2014c). These books have provided an introduction and disseminated broad knowledge on city logistics.

4.3 Governance

For achieving the goals of “mobility,” “sustainability,” and “liveability,” appropriate governance of the public sector is required. The World Road Association (WRA), Technical Committee B4 published, “public sector governance on urban freight transport management” (WRA 2012). The governance of public sector plays an important role for promoting city logistics initiatives, since there are multiple stakeholders who are involved in city logistics and adaptive management is needed to successfully implement city logistics policy measures. WRA guidance applies the “Plan” “Do” “Check” and “Act” (PDCA) cycle for urban freight transport management. The “Plan” part includes the design and assessment stages. The “Do” part includes implementation stage and the “Check” and “Act” parts represent the evaluation and feedback stages.

Firstly, the design stage starts with problem identification that finds the cause of problems, sets appropriate goals and desirable freight vehicle movements and reaches the combination of approaches and measures. The infrastructure, regulatory, logistical, co-operative, technology, and behavioural approaches are typically given in urban freight transport management. Also typical policy measures are listed: (a) Traffic management (traffic flow management, parking management, time management, vehicle management), (b) Better transport method (joint delivery, intermodal transport), (c) Harmony with urban structure (land use planning), and (d) Others (improve vehicle movement using ICT and ITS, public private partnerships). Secondly the assessment stage requires a pilot project for identifying the side effects of policy measures. It is important to know the side effects in advance, since predicting the response of freight carriers and shippers to policy measures by public authority is difficult. This stage gives specific traffic data and opinions from participants of city logistics initiatives. Then the implementation and evaluation stages follow. In the implementation stage, we can check if the programme is feasible and practical and then the carefully-planned measures can be put into action. The evaluation and feedback is equally essential to guarantee the success of policy measures. The main objectives of evaluation is to check that actions are implemented as planned, to analyse the effects of actions undertaken, to determine whether objectives have been met, and to react and develop solutions where objectives have not been met or new problems have been raised. Evaluation must be done considering various points of view using key performance indicators or criteria considering quality of life, economic development, accessibility, and transport efficiency.

4.4 Modelling City Logistics

Modelling city logistics is required for estimating freight demand in urban areas and evaluating the effects of policy measures. The systems approach can be applied in city logistics (Taniguchi et al. 2001b; Taniguchi and Thompson 2002) and three types of models are used in the systems approach: (a) Demand models, (b) Supply models, and (c) Impact models.

Demand models are models used to estimate the generation and attraction of goods or vehicles in urban areas. A number of multi-stage demand models have been proposed relating to urban goods movements (Taniguchi et al. 2001b; Comi et al. 2012; De Jong et al. 2013; Holguin-Veras et al. 2014). Multi-stage demand models address the generation, distribution, mode choice and assignment of vehicles within road network. Nuzzolo et al. (2014) discussed the demand modelling requirements for city logistics planning including shopping mobility and goods restocking. Gonzalez-Feliu et al. (2013) proposed models for the integration of passenger traffic for shopping and freight vehicle traffic. As the shopping behaviour is associated with the recent e-commerce development, the integration of passenger shopping traffic and freight vehicle traffic for delivering goods has become an important issue.

To duplicate vehicle movements in urban areas, Vehicle Routing and scheduling Problems with Time Windows (VRPTW) models are often used in modelling city logistics. VRPTW models (Solomon 1987; Braysy and Gendreau 2005; Qureshi et al. 2009; Bhusri et al. 2014) can represent a trip chain of freight vehicles which start from a depot to visit customers for delivering and picking up goods considering time windows set by customers. VRPTW models with dynamic and stochastic travel times (Taniguchi and Shimamoto 2004; Potvin et al. 2006; Ehmke et al. 2014) are needed to take into account congested traffic conditions in urban areas. These models can be applied in practical problems of urban freight transport using real travel times data which are provided by ITS. Qureshi et al. (2014) used an exact solution approach of VRP with soft time windows for assessing the truck ban policy on the road network. Two echelon vehicle routing and scheduling problems have been used to understand the efficiency of two stage delivery systems in urban areas which are observed in real operation of courier services (Crainic et al. 2009; Hemmelmayr et al. 2012).

Supply models are essential for describing the level of service of road networks and cost structure of using road networks depending on the traffic conditions. These models can provide the reduction of costs by road network improvement in normal cases and also the increase of costs by the disruption of road networks after disasters.

Impact models are central in modelling city logistics. It is vital to know the social, economic, financial, environmental, energy impacts of implementing policy measures in urban areas. Therefore, impact models are required to describe the behaviour of shippers and freight carriers to respond any policy measures implemented by municipalities. Multi-agent simulation models are often used for this purpose (Tamagawa et al. 2010; van Duin et al. 2007, 2012; Teo et al. 2012, 2014; Anand et al. 2014). Multi-agent models can represent stakeholders including shippers, freight carriers, residents, administrators and in addition, other agents such as urban consolidation centre operators or urban motorway operators. These models allow city logistics policy measures to be evaluated in a dynamic manner with the updated travel times on road networks given by traffic simulation. Reinforcement learning including Q-learning (Teo et al. 2012) techniques can be used for modelling the decision making of agents that can adapt to a dynamic environment.

Although multi-agent modelling is promising for evaluating the effects of policy measures, validation of these models need to be carefully done based on precise data sets on realistic road networks. If public private partnerships are set up, multi-agent models are suitable for providing the basic information on the effects of implementing policy measures in advance and re-thinking of the policy measures after implementing them and monitoring their impacts. The process represents the evaluation and feedback in PDCA cycle described in the previous section.

4.5 Future Perspectives

Innovative solutions for city logistics are becoming a reality. The idea of co-modality has been introduced, which involves the efficient use of different modes individually and in combination with each other that results in optimal and sustainable utilisation of resources (Commission of the European Community 2006). In urban goods distribution, this can involve usage of inland waterways (van Duin et al. 2014), railways and trams (Taniguchi and Nemoto 2008; Diziain et al. 2014). Automated goods distribution systems in underground tubes (Taniguchi et al. 2000) were investigated but have not yet been realised due to the lack of profitability of the dedicated underground freight transport systems. The combination of passenger traffic and freight transport may be achieved using the peer-to-peer on-demand home delivery systems of grocery (e.g. Instacart) using mobile phone and matching systems with customers and volunteer carriers who go shopping and deliver commodities using their cars or on foot to customers. Recently unmanned drones (multi-copter) are getting attention for delivering goods in congested areas. This is a promising technology. However, regulations associated with the licencing and areas allowable for drones to operate in are currently being developed in many cities.

Health care issues have become more important in the aging society. Home health care (HHC) problems in particular are urgent issues due to the limitation of beds at hospitals and the increase of patients at home. As HHC problems are similar to vehicle routing and scheduling problems of goods distribution in structure where doctors, nurses and home carers visit patients at home for giving medical and health care, modified VRPTW models with additional consideration of benefits of patients are often applied (Blais et al. 2003; Bertels and Fahle 2006; Liu et al. 2013; Eveborn et al. 2006; Benzarti et al. 2013; Trautsamwieser et al. 2011). The application of ICT and ITS should also be effective in the area of HHC, since the work scheduling of health care teams need to be rationalised to reduce costs and ensure the satisfaction of patients at home.

After disasters urban freight transport is vital to help providing people in affected area by hazards including earthquake, flood, landslides, and bushfires with relief supplies and accelerate the recovery of infrastructure, industry, and life of citizens. The distribution of relief supplies is studied as humanitarian logistics (Holguin-Veras et al. 2012; Taniguchi and Thompson 2013; Das and Hanaoka 2014; Liberatore et al. 2014). Humanitarian logistics takes into account the suffering of affected people by disasters, whereas city logistics mainly considers the environment and safety. Although these areas are quite different, both humanitarian and city logistics incorporate the social costs which are composed of the external costs as well as the internal costs of logistics.

4.6 Conclusion

City logistics is essential for creating sustainable and liveable cities by providing efficient, environmentally friendly and safe urban freight transport systems. Technological innovation of ICT and ITS as well as collaboration among stakeholders who are involved in urban freight transport can promote the movements toward achieving the goals of city logistics. Public private partnerships are key elements for the success of urban freight management. Modelling techniques including demand forecasting models, VRPTW models, and multi-agent models can help to identify the problems associated with urban freight and evaluate the city logistics policy measures. In the future, an integrated urban logistics platform may provide a better framework for organising public private partnerships of stakeholders and successfully manage the commercial and social issues in urban freight transport systems based on city logistics.

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Part II
Green Land Transportation

Chapter 5
Green Transport Fleet Appraisal

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Abstract One effective approach to improve the environmental burdens of logistics and transport operations is to ensure that evaluation and selection of transportation vehicles for organizations incorporate green attributes. The availability of different types of vehicles with varying performance characteristics as well as the breadth of environmental performance metrics have made the transport fleet decision making more complex and dynamic. This chapter presents a multi-criteria decision-making (MCDM) approach, integrating Rough Set theory and VIKOR method, for sustainable transportation vehicles selection. First, the related sustainability attributes are identified from the existing literature to be added to the conventional performance-based and economic vehicle evaluation criteria. The MCDM approach is then used for ranking and selecting the sustainable transportation vehicles. A numerical example is finally presented to illustrate the application of the proposed approach.

Keywords Sustainable transportation fleet · Green · Environmental sustainability · Transportation vehicle · Rough set theory · VIKOR

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5.1 Introduction

Demand for logistics and transportation services has increased rapidly along with the global economic growth and strengthen supply chain cooperation. Transportation vehicles have consequently become one of the major fossil-fuel consumers and source of air pollution emissions (Takeshita 2012; Yan and Crookes 2010). In response to regulatory and competitive pressures, the evaluation and selection of more sustainable transportation vehicles have gained increasing attention by organizations in various industries (Bae et al. 2011). Many transportation and logistics providers have started adopting alternative-fuel vehicles. For example, UPS and FedEx are experimenting with all-electric vehicles with a range of over 50 miles (King 2013). In addition to the logistics industry, companies in the retail industry (e.g. Wal-Mart), telecommunications and utilities industry (e.g. AT&T and Verizon), beverage industry (e.g. Coca-Cola and Pepsi), and even forestry and banking industries have planned for sustainable transportation fleet strategies (Bae et al. 2011).

Most sustainable transportation vehicles rely on alternative fuel sources such as electricity, solar, wind, bio-fuels, and compressed natural gas (Capasso and Veneri 2014; Rose et al. 2013; Mabit and Fosgerau 2011; Arsie et al. 2010). Depending on the type of alternative fuels, every transportation vehicle type (e.g. full electric vehicles, hydrogen/fuel cell vehicles, and internal combustion/electric hybrids) has its operational, environmental, and economic strengths and weaknesses. Therefore, organizations need to evaluate the transport fleet requirements given their internal economic goals and sustainability strategies. Although there has been some effort to identify the attributes of alternative-fuel vehicles selection (Hsu et al. 2014; Awasthi et al. 2011; Tzeng et al. 2005), a holistic framework does not exist. The adoption of alternative-fuel vehicles requires a holistic consideration of economic, environmental and social dimensions when making important purchasing decisions (Byrne and Polonsky 2001). Yet, research on modeling transport fleet management has been rather limited and studies focusing on managing sustainable vehicle appraisal are virtually non-existent. In this chapter, we introduce a multi-criteria decision-making (MCDM) model, integrating Rough Set theory and the VIKOR method, for green transport fleet appraisal.

In the next section, we start the chapter by providing some background information on sustainability-based corporate transport fleet evaluation and selection. The hybrid MCDM model is then introduced. An illustrative example is provided to build comprehension of the multi-methodology technique. Insights, implications, limitations and future research directions are discussed in the concluding section.

5.2 Literature on Sustainability-Based Transportation Vehicle Fleet Selection

Conventional transportation vehicle selection practices have ignored the systematic inclusion of sustainability attributes (Bai et al. 2012). The literature on sustainable transportation vehicle fleet management is rather limited. To develop a framework for sustainable evaluation and selection of vehicle types, we review some of the major sustainability attributes used in the literature including sustainable transportation systems, transportation modes, and alternative-fuel vehicle characteristics (Do et al. 2014; Bai and Sarkis 2013, 2014; Litman 2013; Bae et al. 2011; Awasthi et al. 2011; Yan and Crookes 2010; Gehin et al. 2008; Zhao and Melaina 2006; Litman and Burwell 2006; Litman 2005; Byrne and Polonsky 2001; Deakin 2001). We classify the identified attributes in eight categories including vehicle characteristics, policies and regulations, pollution emissions, resources consumption, infrastructure, recycling scrap, employees, and scalability. A total of 51 attributes and measures are considered under these categories. Table 5.1 summarizes the results and the related literature support for each attribute.

Table 5.1 Attributes for sustainable vehicle evaluation and selection

Category	Attributes	Related literature
Vehicle characteristics	Vehicle price	Zhao and Melaina (2006)
	Maintenance costs	Zhao and Melaina (2006)
	Running costs	Awasthi et al. (2011)
	Travelling speed range	Litman and Burwell (2006)
	Driving range (e.g. high-speed roads, hills)	Litman and Burwell (2006)
	Traffic safety	Litman (2005)
	Quality of service (e.g. breakdown rate)	Litman (2013)
	Loading capacity	Litman (2013)
	Requirements for goods specifications (e.g. size, shape)	Litman (2013)
	Information technology (e.g. routing or scheduling systems)	Deakin (2001)
	Technical innovation for improved efficiency	Litman and Burwell (2006)
Policies and regulations	Compliance with energy-base government regulations	Byrne and Polonsky (2001)
	Compliance with emission-based government requirements	Byrne and Polonsky (2001)
	The use of hazardous substances (RoHS)	Gehin et al. (2008)
	The use of volatile organic compounds (VOCs)	Do et al. (2014)
	Tax relief benefits	Byrne and Polonsky (2001)
	Fuel subsidies	Byrne and Polonsky (2001)

(continued)

Table 5.1 (continued)

Category	Attributes	Related literature
	Governments subsidies or incentives	Zhao and Melaina (2006)
Pollution emissions	CO_2 emissions rate	Awasthi et al. (2011)
	GHG emissions rate	Awasthi et al. (2011)
	Noise pollution rate	Awasthi et al. (2011)
	Solid or water waste generation	Litman and Burwell (2006)
	Other air pollutants (e.g. NOx, VOCs, CO, particulates, toxics)	Awasthi et al. (2011)
Resources	Unit fuel cost	Byrne and Polonsky (2001)
	Sufficient fuel supply	Byrne and Polonsky (2001)
	Alternative fuels	Byrne and Polonsky (2001)
	Energy saving	Awasthi et al. (2011)
	Fossil fuel usage rate	Awasthi et al. (2011)
	Renewable energy use	Awasthi et al. (2011)
	Fuel efficiency	Litman and Burwell (2006)
	Clean technologies	Zhao and Melaina (2006)
	Fuel safety	Awasthi et al. (2011)
Infrastructure	Market availability of the vehicle	Byrne and Polonsky (2001)
	Availability of fuels	Byrne and Polonsky (2001)
	Availability of fuel delivery outlets	Byrne and Polonsky (2001)
	Availability of maintenance services	Byrne and Polonsky (2001)
	Financing and lending policies	Zhao and Melaina (2006)
	Transportation easements (e.g. lower transportation tolls)	Byrne and Polonsky (2001)
Recycling	Vehicle compliance with ELV (end-of-life vehicle)	Gehin et al. (2008)
	Vehicle compliance with WEEE	Gehin et al. (2008)
	Waste from end-of-life vehicle or used tires	Gehin et al. (2008)
	Recycling costs	Gehin et al. (2008)
	Recyclability rate	Gehin et al. 2008
	Dismantling and reuse possibility	Gehin et al. (2008)
	Recycled materials usage	Gehin et al. (2008)
Employees	Health and safety	Litman and Burwell (2006)
	Comfort of use (e.g. comfortable seats, accessories)	Tzeng et al. (2005)
	Personnel training	Russo and Comi (2010)
	Availability of technical support staff	Russo and Comi (2010)
Scalability	The impact of weather changes on vehicle operations	Abkowitz (2002)
	The impact of road conditions on vehicle operations	Litman and Burwell (2006)
	Vehicle operation in disasters	Abkowitz (2002)

A range of approaches have been adopted for sustainability evaluation of transportation vehicles. Some of these approaches include life cycle analysis (LCA) (Wang et al. 2013; Nanaki and Koroneos 2012), cost-benefit analysis (CBA) (Damart and Roy 2009), cost-effectiveness analysis (CEA) (Wood 2003), environmental impact assessment (EIA) (Fischer 2002), optimization and mathematical programming models (Mula et al. 2010; Shah et al. 2012), system dynamics models (Wang et al. 2008), assessment indicator models (Phillis and Andriantiantsaholiniaina 2001), game theoretic models (Bae et al. 2011) and multi-criteria decision analysis (MCDA) methods (Awasthi et al. 2011).

A number of combined approaches have been recently developed to overcome the weaknesses of individual approaches. For example, Yedla and Shrestha (2003) rank alternative transport options by means of analytic hierarchy process (AHP) using weighted arithmetic mean method (WAMM) for group aggregation. Tzeng et al. (2005) apply TOPSIS and VIKOR to find the best compromise alternative-fuel bus with the relative weights of evaluation criteria determined by AHP.

Despite the importance of greening corporate fleets, none of the above methods have been used for sustainability evaluation of transportation vehicles. We introduce in this chapter a methodology that can be used to evaluate the sustainability performance of vehicles using the attributes defined in Sect. 2.1. This approach involves the integration of Rough Set theory and the VIKOR method to evaluate the importance of sustainability attributes of vehicles.

5.3 A Hybrid MCDM Approach

This section presents the foundational elements for the hybrid MCDM approach and introduces the background on the various mathematical developments and notations. The two major elements of the proposed approach include Rough Set theory and the VIKOR method.

5.3.1 Rough Set Theory

Rough set theory (Pawlak 1982), is an analytical approach for managing vagueness and ambiguity. The method classifies objects into similarity classes (clusters) containing objects that are indiscernible with respect to previous occurrences and knowledge. These similarity classes are then employed to determine various patterns within the data. Rough set theory has been utilized for sustainable supply chain and operations management applications (Bai and Sarkis 2010a, b, 2014). Some particulars of Rough Set theory, for later integration, are now introduced with notation and definitions.

Definition 5.1 Let $S = (U, R)$ be an approximation space, where U is a non-empty finite universe and R is an equivalence relation on U. An approximation space $S = (U, R)$ can be regarded as a knowledge base about U.

The equivalence relation R can be defined that two objects are equivalent if and only if they have the same value on every attribute based on a set of attributes (Pawlak 1991). The equivalence class, which are called elemental information granules in the approximation space, contain an object $x(x \in U)$ defined as $[x]_R = \{\ y|y \in U, xRy\}$.

Definition 5.2 Given any equivalence relation R and any subset $X \in U$, we can define a lower approximation of X in U and an upper approximation of X in U by the following expressions:

$$\underline{R}X = \{x \in U | [x]_R \subseteq X\} \tag{5.1}$$

and

$$\bar{R}X = \{x \in U | [x]_R \cap X \neq \phi\} \tag{5.2}$$

Approximation vagueness is usually defined by precise values of lower and upper approximations. Lower approximations $POS_R(X) = \underline{R}X$ describe the object domain that definitely belongs to the subset of interest. Upper approximations describe objects which may possibly belong to the subset of interest. The difference between the upper and the lower approximations constitutes a boundary region $BND_R(X) = \bar{R}X - \underline{R}X$ for the vague set. Hence, Rough Set theory expresses vagueness by employing a boundary region of a set. If the boundary region of a set is empty, $BND_R(X) = 0$, the set is crisp; otherwise, the set is rough (inexact).

5.3.2 VIKOR Method

The VIKOR method was developed for multi-criteria optimization and compromise solutions of complex systems (Opricovic and Tzeng 2002, 2004). It is a discrete alternative multiple criteria ranking and selection approach based on a particular measure of proximity to an ideal solution. VIKOR focuses on ranking of solutions in the presence of conflicting criteria helping decision-makers select the "best" compromise solution (Opricovic and Tzeng 2007).

The multi-criteria measure for compromise ranking is developed from the Lp-metric used as an aggregating function in a compromise programming method (Yu 1973). Let i = 1, 2, …, m and $F_1, F_2, \ldots, F_m$ denote the m alternatives facing a decision-maker. Let j = 1, 2, …, n, with n being the number of criteria. Then the performance score for alternative F_i with respect to the jth criterion is denoted by f_{ij}.

Let w_j be the weight on the jth criterion which expresses the relative importance of that criterion. Development of the VIKOR method starts with the following form of the Lp-metric:

$$L_{p,i} = \{\sum_{j=1}^{n} [w_j(\left|f_j^+ - f_{ij}\right|)/(\left|f_j^+ - f_j^-\right|)]^p\}^{1/p}, \quad 1 \le p \le \infty;\ i = 1,\ldots,m \tag{5.3}$$

where f_j^+ represents the highest performance score with respect to the jth criterion among all alternatives. Likewise, f_j^- represents the lowest performance score with respect to the jth criterion. $L_{1,i}$ (as S_i) and $L_{\infty,i}$ (as Q_i) are used to formulate ranking measures.

$$S_i = L_{p=1,i} = \sum_{j=1}^{n} [w_j(\left|f_j^+ - f_{ij}\right|)/(\left|f_j^+ - f_j^-\right|)] \tag{5.4}$$

$$Q_i = L_{p=\infty,i} = \max_j [w_j(\left|f_j^+ - f_{ij}\right|)/(\left|f_j^+ - f_j^-\right|)] \tag{5.5}$$

VIKOR ranks the alternatives by sorting the values of S_i, Q_i and R_i, for $i = 1, 2, \ldots, m$, in decreasing order.

$$R_i = v(S_i - S^+)/(S^- - S^+) + (1 - v)(Q_i - Q^+)/(Q^- - Q^+) \tag{5.6}$$

where $S^+ = \min_i S_i, S^- = \max_i S_i, Q^+ = \min_i Q_i, Q^- = \max_i Q_i$ and v is introduced as a weight on the strategy of maximum group utility (average gap in scale normalization), whereas $1-v$ is the weight of the individual regret (maximal gap in special criterion for priority improvement).

Opricovic and Tzeng (2004) propose a compromise solution, for a transportation vehicle in this case, (A(1)), which is ranked by the measure R (minimum) when the following two conditions are satisfied:

C1. Acceptable advantage:

$$R(A(2)) - R(A(1)) \ge 1/(m - 1), \tag{5.7}$$

where $A(2)$ is the alternative positioned second in the ranking list by R and m is the number of alternatives.

C2. Acceptable stability in decision making:

The alternative $A(1)$ must also be the best ranked by S and/or Q. This compromise solution is stable within a decision making process, which could be the strategy of maximum group utility (when v > 0.5 is needed), or “by consensus” v ≈ 0.5, or “with veto” ($v < 0.5$). Here, v is the weight of the decision making strategy of maximum group utility.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed consisting of:

- Alternatives $A(1)$ and $A(2)$ if only the condition C2 is not satisfied, or
- Alternatives $A(1)$, $A(2)$, …, $A(\mathrm{M})$ if the condition C1 is not satisfied; $A(\mathrm{M})$ is determined by the relation $R(A(M)) - R(A(1)) < 1/m$ for maximum M (the positions of these alternatives are “in closeness”).

5.4 Application of the Hybrid MCDM Approach: An Illustrative Example

We now illustrate the application of the proposed hybrid methodology for evaluation and selection of sustainable transportation vehicles using example, hypothetical data.

Step 1: *Construct the Original Decision System*

To start evaluating and ranking transportation vehicles based on various sustainability metrics, a decision table is constructed for the potential alternatives (see Table 5.2). For the sake of this example, a total of six potential vehicle alternatives, $U = \{F_{\mathrm{i}}, \mathrm{i} = 1, 2, \ldots, 6\}$ is considered. The performance of each vehicle alternative is weighted against 18 attributes $C = \{c_j, j = 1, 2, 3, \ldots, 11\}$. The attributes outlined in Table 5.1 were used as the starting point and were further refined to reflect the current transport vehicle fleet selection practice.

Step 2: *Determine the performance of each vehicles against the sustainability attributes*

The performance of each vehicle is then evaluated against the identified attributes. Some of this data is related to crisp values (such as the vehicle price), and others are scaled in linguistic perceptual scores such as very poor, medium/average, good and very good. The hypothetical data is shown in Table 5.2.

Step 3: *Normalize the Information Decision System*

For consistency in evaluations, a normalization procedure is introduced such that sustainability attributes and all the later calculations, such as distance measures, use similar scales. Note that some of these raw values are in crisp (regular) form and some are based on qualitative judgments. This normalization will adjust all the sustainability attribute values for each alternative (f_{ij}) to be $0 \leq f_{ij} \leq 1$.

Table 5.2 Information system table: the performance of each vehicle

Vehicles type	Vehicle characteristics			Pollution emissions		Policies and regulations		Resources		Infrastructure	
	Vehicle price	Travelling speed range	Safety features	CO_2 emissions rate	Noise pollution rate	Compliance with government regulations	Governments subsidies/ incentives	Alternative fuel	Energy consumption rate	Availability of fuels	Availability of maintenance services
Vehicle 01	$84,000	70	VG	VG	VG	VG	$2000	VP	VG	VG	MG
Vehicle 02	$74,000	70	G	MG	VG	VG	$0	VP	G	VG	VG
Vehicle 03	$70,000	70	MG	M	G	VG	$0	VP	G	VG	M
Vehicle 04	$68,000	70	M	M	G	VG	$0	VP	MG	VG	M
Vehicle 05	$65,000	70	M	MP	G	VG	$0	VP	M	VG	M
Vehicle 06	$52,000	70	P	VP	MG	G	$0	VP	P	VG	M

Step 3.1: *Transform linguistic values into crisp numbers*

All values are transformed into a number crisp f. For the linguistic or qualitative form, we introduce a crisp numerical scale table that would correspond to the qualitative values given by the decision makers. Seven linguistic variables, namely "very good", "good", "medium good", "medium", "medium poor", "poor" and "very poor", are used to assess the level of the performance criteria. This seven-level scale is shown in Table 5.3. The qualitative variables and natural language variables are transformed into crisp numbers.

Safety is an example of a qualitatively valued attribute, for which the transformation to a crisp number for vehicle 01 is given as: $F_{01\mathrm{Safety}} = \mathrm{VG} = 1$.

Step 3.2: *Normalize the numeric variables by membership function*

All the crisp values are now normalized. To address this issue a membership function, expressions (5.8) and (5.9) are introduced. Normalization of the incremental (beneficial) value is completed using the membership function in expression (5.8).

$$U(f_{ij}) = \begin{cases} 0 & if\, f_{ij} \le Lower, \\ v_{ij} & if\, Lower \le f_{ij} \le Upper, \\ & where\, v_{ij} = \frac{f_{ij} - Lower}{Upper - Lower} \\ 1 & if\, f_{ij} \ge Upper, \end{cases} \tag{5.8}$$

where f_{ij} is the specific evaluation value, *Lower* is the minimum historical value, and *Upper* is the maximum historical value for a factor.

The negative (decreasing) membership value of the crisp number is determined using the membership function in expression (5.9):

$$U(f_{ij}) = \begin{cases} 1 & if\, f_{ij} \le Lower, \\ v_{ij} & if\, Lower \le f_{ij} \le Upper, \\ & where\, v_{ij} = \frac{Upper - f_{ij}}{Upper - Lower} \\ 0 & if\, f_{ij} \ge Upper, \end{cases} \tag{5.9}$$

For vehicle price attribute (decreasing is better) of vehicle 01 which was exemplified in step 3.1, the normalization using expressions (5.9) is as follows:

Table 5.3 The linguistic variables and their corresponding crisp numbers

Linguistic variables	Crisp numbers
Very poor (VP)	0
Poor (P)	0.2
Medium poor (MP)	0.4
Medium(M)	0.5
Medium good (MG)	0.6
Good (G)	0.8
Very good (VG)	1

$$F_{01\text{Price}} = v_{11} = \frac{|f_1^{\max} - f_{11}|}{|f_1^{\max} - f_1^{\min}|} = \frac{|84,000 - 84,000|}{|84,000 - 52,000|} = 0;$$

Thus, the normalized value of crisp number for vehicle price attribute of vehicle 01 would be $F_{01\text{Price}} = 0$. We arrive at a normalized matrix v_{ij} from the original matrix f_{ij} with expressions identified in this step 3.2. The normalization process alters all normalized decision attributes to have increasing values representing better sustainability attributes. The resulting normalized values are shown in Table 5.4.

Step 4: *Determine information content of each attribute*

In the following steps we focus on the use of Rough Set theory to determine the importance (weight) of each attribute. The goal is to determine the various 'conditional attribute elementary sets' (X) for each vehicle. First, expression (5.10) is used to determine the level of information content across the conditional attributes (c) (Liang et al. 2006).

$$\mathrm{I}(c) = 1 - \frac{1}{|U|^2} \sum_{i=1}^{|U|} |X_i^c| \tag{5.10}$$

where I(c) is the information content[1] for each conditional attribute, in the case of this study, it is each of the sustainability attributes. $|U|$ is the cardinality of the universe of vehicles. $|X_i^c|$ is the number of vehicles with similar attributes levels across the conditional attribute c for vehicle i. It is also defined as the number of members within the conditional attribute c for vehicle i.

Given lower approximation $\underline{R}X$ of a Rough Set from Definition 5.2, a lower approximation of X for attribute c can be determined using expression (5.11):

$$X_i^c = \{x_j \in U | d_c(x_i, x_j) \leq \delta\}, \tag{5.11}$$

where δ is the inclusion threshold value and $0 \leq \delta \leq 0.5$. In this case study, $\delta = 0.1$. That is, two vehicles i and j are members of the same set only if $d_c(x_i, x_j) \leq \delta$ for $c \in C$, where $d_c(x_i, x_j)$ denotes the distance measure of two transportation vehicle i and j for the value of attribute $c \in C$.

Take for example, the distance measure $d_{\text{Price}}(x_{03}, x_{04}) = 0.06$ between transportation vehicle 3 and 4 is less than 0.1. The distance measure $d_{\text{Price}}(x_{04}, x_{05}) = 0.09$ between vehicles 4 and 5 is also less than 0.1. Overall, $|X_{04}^{\text{Price}}| = 3$. Table 5.5 shows the listing of vehicle price attribute elementary set types and respective $|X_i^{\text{Price}}|$ values for each vehicle within that set. The various 'conditional attribute elementary set types' (X_i^c) for the vehicles are determined for the vehicle set when they have similar attributes levels across the conditional attribute c for a vehicle i.

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[1] This term has also been defined as information entropy of a system (Liang and Shi 2004).

Table 5.4 Normalized values of all sustainability attributes

Vehicles type	Vehicle characteristics			Pollution emissions		Policies and regulations		Resources		Infrastructure	
	Vehicle price	Travelling speed range	Safety features	CO_2 emissions rate	Noise pollution rate	Compliance with government regulations	Governments subsidies/ incentives	Alternative fuel	Energy consumption rate	Availability of fuels	Availability of maintenance services
Vehicle 01	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	0.00	0.20
Vehicle 02	0.31	0.00	0.75	0.60	1.00	1.00	0.00	0.00	0.75	0.00	1.00
Vehicle 03	0.44	0.00	0.50	0.50	0.50	1.00	0.00	0.00	0.75	0.00	0.00
Vehicle 04	0.50	0.00	0.38	0.50	0.50	1.00	0.00	0.00	0.50	0.00	0.00
Vehicle 05	0.59	0.00	0.38	0.40	0.50	1.00	0.00	0.00	0.38	0.00	0.00
Vehicle 06	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ideal vehicle	1.00		1.00	1.00	1.00	1.00	1.00		1.00		1.00

Table 5.5 Elementary sets for vehicle price attribute

Elementary set type	Members in elementary set type	Number in set ($\lvert X_i^{\text{Price}} \rvert$)
TYPE1	Vehicle 01	1
TYPE2	Vehicle 02	1
TYPE3	Vehicle 03 Vehicle 04	2
TYPE4	Vehicle 03 Vehicle 04 Vehicle 05	3
TYPE5	Vehicle 04 Vehicle 05	2
TYPE6	Vehicle 05	1

Using expression (5.8) and data in Table 5.5, the information content for the vehicle price attributes will be:

$$\mathrm{I(vehicle\ price)} = 1 - \left(\frac{1}{|6|^2}(1 + 1 + \cdots + 1)\right) = 1 - \frac{10}{36} = 0.72.$$

An analogous approach is used to calculate the information content for the remaining vehicle attributes. The results are shown in Table 5.6. The information content will be valuable input to help identify the relative importance weight of each attribute, which is described in step 5.

Step 5: *Determine the importance (weight) of each attribute*

Expression (5.12) is a normalization equation used to identify the information significance (weight) of each attribute.

$$w(c_j) = \frac{\mathrm{I}(c_j)}{\sum_{j=1}^{n} \mathrm{I}(c_j)} \tag{5.12}$$

where aggregated weight values meet the condition $\sum_{j=1}^{n} w_j = 1$.

Table 5.6 Information Content and Importance for each sustainability attribute

Category	Attributes	Information content	Weight
Vehicle characteristics	Vehicle price	0.72	0.160
	Travelling speed range	0	0.000
	Safety features	0.78	0.173
Pollution emissions	CO_2 emissions rate	0.56	0.124
	Noise pollution rate	0.61	0.135
Policies and regulations	Compliance with government regulations	0.28	0.062
	Governments subsidies/incentives	0.28	0.062
Resources	Alternative fuel	0	0.000
	Energy consumption rate	0.78	0.173
Infrastructure	Availability of fuels	0	0.000
	Availability of maintenance services	0.5	0.111

The cumulative information content of all attributes is equal to $\sum_{j=1}^{n} \mathrm{I}(c_j) = 4.51$. The information content for vehicle price attributes is 0.72. Then the normalized weight for vehicle price attribute is $w(\text{vehicle price}) = \frac{0.72}{4.51} = 0.16$. The calculated weights of all attributes are shown in Table 5.6. For some attributes, the weight is equal to zero. According to the original Rough Set approach these attributes do not provide useful information in distinguishing the sustainability performance of different vehicles, they are excluded from subsequent analyses.

Step 6: *Determine the ideal vehicle/solution*

The most 'ideal' vehicle F^* is defined by selecting the maximum value for the attributes using expression (5.13).

$$F^+ = \{v_1^+, \ldots, v_n^+\} = \{(\max_i v_{ij})\} \tag{5.13}$$

Using expressions (5.13), we arrive at: $F^* = \{1, 1, 1, 1, 1, 1, 1, 1\}$.

Step 7: *Calculate the group utility S_i and the maximal regret Q_i*

The values of S_i and Q_i are calculated based on the expression (5.4) and (5.5). For the vehicle price attribute of vehicle 01, the distance measure is calculated as $w_{\text{Price}} d(v_{01\text{Price}}, v^*_{\text{Price}}) = 0.160^*(|0 - 1|) = 0.160$. The results for other attributes are 0, 0, 0, 0, 0, 0, and 0.087 respectively. The value of S_i for vehicle 01 is the sum of the above values, which will be equal to 0.248. The value of Q_i for vehicle 01 is the max of above values, i.e. 0.160.

Step 8: *Compute the index values (R_i)*

R_i is a compromise solution for a vehicle which is the highest ranked when considering the maximum group utility and the individual regret jointly. We set parameter v equal to 0.5 implying that the weights on the strategy of maximum group utility would be equal the weight of the individual regret. Then, we get $S^+ = \min_i S_i = 0.248, S^- = \max_i S_i = 0.840, Q^+ = \min_i Q_i = 0.110$, and $Q^- = \max_i Q_i = 0.173$. The value of R_1 for vehicle 01 would be $R_i = v(S_i - S^+)/(S^- - S^+) + (1 - v)(Q_i - Q^+)/(Q^- - Q^+) = 0.5^*(0.248 - 0.248)/(0.840 - 0.248) + 0.5^*(0.160 - 0.110)/(0.1720.110) = 0.395$. The values of S_i, Q_i, and R_i for other vehicles are shown in Table 5.7.

The compromise solutions for vehicles, which are ranked as better by the measure R_i, where smaller values are better, must satisfy the C1 and C2 conditions. For the acceptable advantage condition (C1), we have $R_3 - R_2 = 0.190 \geq 0.167$ where $R_2 = 0.050$ and $R_5 = 0.240$ and $\frac{1}{m} = \frac{1}{6} = 0.167$ shown in the Table 5.7. For the acceptable stability in decision making condition (C2), vehicles F_2 is the compromise solution.

Table 5.7 The index values for each vehicle type

Vehicle type	S_i	Ranking	Q_i	Ranking	R_i	Ranking
Vehicle 01	0.248	1	0.160	5	0.395	5
Vehicle 02	0.308	2	0.110	1	0.050	1
Vehicle 03	0.522	3	0.111	2	0.240	2
Vehicle 04	0.577	4	0.111	2	0.286	3
Vehicle 05	0.596	5	0.111	2	0.302	4
Vehicle 06	0.840	6	0.173	6	1.000	6

Step 9: *Compute the dominance probability*

VIKOR can rank the transportation vehicles, but it cannot determine the dominance probability value for each vehicle when compared to other vehicles. We introduce this important extension to the method at this time. The VIKOR methodology is enhanced since the initial data is based on decision makers' subjective judgment, the ranking result contains some probability degrees. The dominance probability degree is now determined by establishing a dominance matrix. First Definition 5.3 is introduced to help us construct the dominance matrix.

Definition 5.3 Let $x = \{x_1, x_2, \ldots, x_n\}$ and $y = \{y_1, y_2, \ldots, y_n\}$ be a transportation vehicle decision sequence consisting of the various attributes. Then the dominance probability degree of two alternative vehicles based on the VIKOR theory is obtained from expression (5.14).

$$P(x \succ y) = \begin{cases} 1 & S_x \geq S_y, Q_x \geq Q_y \\ \frac{1}{2} + \frac{1/n(S_x - S_y) + Q_x - Q_y}{1/n|S_x - S_y| + |Q_x - Q_y|} & other \\ 0 & S_x \leq S_y, Q_x \leq Q_y \end{cases} \tag{5.14}$$

where the expression "$p(x \succ y)$" represents the probability that transportation vehicle x is better than transportation vehicle y. S_x and S_y represent the maximum group utility in VIKOR for transportation vehicles x and y, respectively [see expression (5.4)]. Q_x and Q_y represent the greatest individual regret in VIKOR for transportation vehicles x and y, respectively [see expression (5.5)]. According to the dominance probability degree, the dominance probability matrix is developed using expression (5.15):

$$P_{n \times n} = p(x_j \geq x_k)_{n \times n} \tag{5.15}$$

Then the probability measure that vehicle 01 is better than vehicle 02 is $p(F_{02} \succ F_{01}) = \frac{1/6(0.248-0.308)+(0.160-0.110)}{1/6(0.308-0.248)+(0.160-0.110)} = 58.9\,\%$. The complete dominance matrix is show in Table 5.8.

Thus, with a score of 0.050 for the relative closeness, vehicle 02 is the most preferred transportation vehicle among all vehicles in the original set. Vehicle 02

Table 5.8 The dominance probability matrix

Vehicles	Vehicle 01 (%)	Vehicle 02 (%)	Vehicle 03 (%)	Vehicle 04 (%)	Vehicle 05 (%)	Vehicle 06 (%)
Vehicle 01	50.0	58.9	100.0	100.0	100.0	100.0
Vehicle 02	41.1	50.0	100.0	100.0	100.0	100.0
Vehicle 03	0.0	0.0	50.0	100.0	100.0	100.0
Vehicle 04	0.0	0.0	0.0	50.0	100.0	100.0
Vehicle 05	0.0	0.0	0.0	0.0	50.0	100.0
Vehicle 06	0.0	0.0	0.0	0.0	0.0	50.0

has a 41.1 % probability that it is better than the fifth preferred alternative, vehicle 01. The relative closeness rank with the index values (R_i) of vehicles are:

$$F_{02} \underset{100\%}{\succ} F_{03} \underset{100\%}{\succ} F_{04} \underset{100\%}{\succ} F_{05} \underset{0\%}{\succ} F_{01} \underset{100\%}{\succ} F_{06}$$

where the expression "$F_{02} \underset{100\%}{\succ} F_{03}$" represents the 100 % probability that transportation vehicle 02 is better than transportation vehicle 03. $F_{02} \succ F_{03}$ means that vehicle 02 is better than vehicle 03 according the relative closeness rank; 100 % means that vehicle 02 is 100 % likely to be better than vehicle 03 (a probability degree).

A general rank for vehicles with the index values (R_i) from the VIKOR method now exist. Also pairwise comparisons with a probability value (degree) exist. The probability degree can be used evaluate the quality of the VIKOR method rank. From the dominance probability matrix, vehicle 02 has a 41.1 % percent probability of being better than vehicle types 01. But from Table 5.7, vehicle 01 is ranked lower, using the R_i value, than vehicles 02. Additionally, we can also adjust ranks by considering dominance probability degrees for vehicles with more than 50 % dominance. In this situation, vehicle 01 is ranked first.

$$F_{01} \underset{100\%}{\succ} F_{02} \underset{100\%}{\succ} F_{03} \underset{100\%}{\succ} F_{04} \underset{100\%}{\succ} F_{05} \underset{100\%}{\succ} F_{06}$$

The reason for different results produced by the VIKOR distance measure and the dominance probability degree is that the distance measure calculates the relationship with the ideal vehicle, while the dominance probability degree measures the relationship between two vehicles in a pairwise comparison.

5.5 Conclusions

Given the critical significance of the environmental burdens of transportation activities, the need for the development of decision support tools for evaluation and selection of environmentally conscious transportation fleets is evident. This chapter introduced a novel 9-step methodology based on the integration of Rough Set theory and the VIKOR method. These two approaches allow for consideration of intangibility and ambiguity from expert judgment amongst the attributes and help reduce the number of most pertinent factors and attributes to consider. To help provide an analysis of the reliability of the VIKOR ranking results a new dominance probability degree (valuation) approach was introduced.

Although the methodology can prove valuable for evaluation of the environmental sustainability of transportation fleets by organizations, certain limitations do exist. One of the primary limitations of the modeling effort in this chapter is that we have introduced a conceptual illustrative example, rather than a real world application. There are nuances in the development and application of the methodology that can be determined through a real world application. Practical questions pertaining to the validity and accuracy of these decisions would need to be investigated.

This chapter provided a powerful tool for researchers and practitioners for complex multi-criteria transportation vehicle fleet decision making, whether it is for sustainability or business purposes.

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Chapter 6
The Inventory Pollution-Routing Problem Under Uncertainty

Hooman Malekly

Abstract Carbon emissions from supply chain operations are extensively contributing to the global warming. Sustainable supply chain management literature has seen more emphasis on greening of production operations and designing of greener supply networks, considering transportation emissions as “necessary evil”. This chapter aims to investigate the economic and environmental consequences of transport routing decisions in a supply chain with vertical collaboration, for instance through Vendor Managed Inventory. An optimization model and solution method is presented for an Inventory Pollution-Routing Problem (IPRP) in which inventory and transportation costs and emissions as well as demand uncertainty concerns are explicitly incorporated. The proposed model can be used to explore possible tradeoffs between emissions costs and operational costs for green inventory routing decision making. A set of computational tests are designed for performance benchmark of the proposed model and solution method.

Keywords Inventory routing · Fuel consumption · Emissions pollution · Uncertainty · Optimization model

6.1 Introduction

Reducing and mitigating carbon emissions, the culprit of global warming and climate change, is an increasingly important concern for both industry practitioners and governments (IPCC 2007). In the UK, the government has targeted to reduce carbon emissions by 60 % from 1990 levels by 2050 (Carbon Trust 2006). The UN, the EU, and many countries have enacted legislations or designed/implemented mechanisms, such as carbon tax, carbon offset, clean development, and cap and

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trade, to curb the total amount of carbon emissions. In response to such mandates and to address the related stakeholder concerns, companies worldwide have undertaken initiatives to reduce their carbon footprints.

However, these initiatives have largely focused on investment in new technology, developing energy-efficient equipment and facilities, and finding cleaner energy sources. While such efforts are valuable, they tend to ignore a potentially more significant sources of emissions derived. It is therefore necessary to address the problem of carbon emissions reduction from a supply chain and logistics perspective. Carbon Trust (2006) in the UK suggests that companies use a supply chain perspective to look for new ways of reducing carbon emissions. For example, it is shown that supply chain emissions reduction program may be less costly to achieve the same emissions reduction goals obtained by cleaner technologies (Benjaafar et al. 2013).

Recent literature reviews have identified a growing need for developing quantitative models, empirical research, and decision support tools for green production, operations, logistics and supply chain management (Fahimnia et al. 2015b). At the forefront of this call for future research is greening of transportation and distribution sub-system, one of the major contributors to Greenhouse Gas (GHG) emissions. According to the corporate GHG emissions report published by OECD, transportation is responsible for almost 14 % of total CO_2 emissions, since these emissions are directly proportional to the amount of fuel consumed by vehicles (OECD 2012). Only road-based transportation takes approximately 80 % of the transportation-related emissions. Within the EU, about 28 % of emissions are due to transportation with about 71 % of which is caused by road transport. This introduces the transportation sector as second biggest polluter after energy industries and the only sector that was not able to reduce its emissions compared to recent years (EU 2012). Unlike these, transportation activities are not currently subject to strict environmental regulations with respect to GHG emissions, although it is highly advisable to consider environmental metrics in distribution decision makings (Fahimnia et al. 2015a).

One possibility to reduce emissions from transportation activities is to improve transport efficiency which can be measured through a vehicle's average load factor and the amount of empty trips. The improvement of these two measures is very attractive for companies, since both economic and environmental performance can be enhanced at the same time (Edwards and McKinnon 2010).

In this regard, vehicle emissions (CO, HC and NO_x) directly relate to the rate of fuel consumption (FC) (Barth et al. 2005). Routing vehicles for efficient distribution of goods so as to minimize the total FC can be a green logistics initiative. The selection of routes to be travelled by a vehicle is a tactical decision which can easily be implemented for a given network. From a broader perspective, reducing the FC serves the twin goals of improved emissions performance and reduced resource depletion.

Sbihi and Eglese (2007) discussed the impact of logistics activities on the society and presented a review of the combinatorial optimization problems in green logistics (reverse logistics, waste management, and vehicle routing and scheduling).

Dekker et al. (2012) described the role of operations research in integrating the environmental aspects with logistical practices. They presented a review of the available methods and possible developments in green logistics. Jensen (1995) analyzed the relationship between travel speeds and emissions on different types of roads. Models to estimate the energy and FC by a vehicle based on operating parameters (such as speed, load and acceleration) and on vehicle parameters are available (Akçelik and Besley 2003; Barth et al. 2005). A comparison of FC models using real-time measurements under different conditions is available in the works of Silva et al. (2006), Demir et al. (2011) and Koç et al. (2014).

There is a considerable amount of ongoing research on the methods to reduce CO_2 emissions. However, observations show that, in many situations, when one factor is improved in a logistics system, the costs of other factors increase accordingly (Savelsbergh and Song 2007). Having inventory management on one side, where the routing aspects of the transportation is not properly treated, and routing on the other, with a number of predefined orders to serve, a natural extension to both problems is to study a combined problem where the key components of both inventory management and routing problems are explicitly incorporated. The integration of the two well-studied problems of inventory management and the Vehicle Routing Problem (VRP) arrives at the so-called Inventory Routing Problem (IRP).

In the inventory side of IRP, it is practical to combine groups of products in a single replenishment order to yield substantial cost savings due to the sharing of fixed replenishment costs. It therefore makes a great deal with resupplying policy of customers over a short or long-term planning period. The literature is quite limited on the ecological aspects of this important research topic with carbon emissions used as the predominant environmental measure.

Benjaafar et al. (2013) incorporated carbon emissions constraints on single and multi-stage lot-sizing models with a cost minimization objective. Four regulatory policy settings are considered, based respectively on a strict carbon cap, a tax on the amount of emissions, the cap-and-trade system and the possibility to invest in carbon offsets to mitigate carbon caps. Insights are derived from an extensive numerical study. In a paper proposing a research agenda for designing environmentally responsible inventory systems, Bonney and Jaber (2011) briefly presented an illustrative model that includes vehicle emissions cost into the economic order quantity (EOQ) model. The authors referred to this model as an "environmental EOQ". Emissions associated with the storage of products are not taken into account. The order quantity is thus larger than the classical EOQ. Hua et al. (2011) extended the EOQ model to take carbon emissions into account under the cap-and-trade system. Analytical and numerical results are presented and managerial insights are derived. Except Venkat (2007) who did not consider the cost, these papers can be classified as a regulation based integration of sustainable development (or its restriction to carbon footprint) into inventory models.

To the best of our knowledge, the number of researches in "green IRP" area are extremely virginal. In this chapter, we extend a new mathematical modeling framework. A new IRP variant, called the Inventory Pollution-Routing Problem (IPRP) that take emissions pollution from vehicle travels into account.

The two more related works in this context are the studies of Treitl et al. (2012) and Mirzapour Al-e-hashem and Rekik (2014). Treitl et al. (2012) focused on the analysis of transport processes and showed the economic and environmental concerns associated with routing decisions in a supply chain with vertical collaboration. An IRP model was presented and further applied to a case study from the petrochemical industry. Another work is Mirzapour Al-e-hashem and Rekik (2014) who addressed an environmental issue for an IRP model with a transshipment option. This was done by considering the interrelationship between the transportation cost and GHG emissions level. Given the significance of research in this area, our modeling effort in this chapter focuses on presenting an integrated model that incorporates the environmental aspects into a traditional economic-oriented IRP, an early attempt for IPRP modeling and analysis. There are several solution approaches to solving IRPs. We contribute by introducing an exact solution method and exploiting a brand-new decomposition algorithm for the simultaneous inventory management and vehicle routing. Computational results of the performance benchmark exercise confirm the efficiency of the algorithm in terms of the quality of solutions obtained.

6.2 Problem Description

The way of introducing the IRP model in this chapter is slightly different. It is considered that there are k vehicles of the same capacity under an EOQ policy delivering some goods from a central warehouse to a set of customer nodes $N = \{1, 2, \ldots, n\}$ in a complete directed graph with arc set A where $A = \{(i,j): i,j \in N, i \neq j\}$ Euclidean distance is an arc set which assumed that the underlying distance matrix is symmetric and satisfies the triangle inequalities. At the beginning of the planning horizon, customer i supplied with a delivery quantity Q_i and this process lasts to the end of the period. Each customer i is characterized by a demand D_i, and may not be satisfied in an infinite time horizon which means shortage assumption is permitted. Considering the differentiations in customers' time periods, the delivery process continues while total demands fulfilled. Similar planning will be projected for the next periods; therefore, restarting each period, there is a routing policy with known delivery quantities. Also it is considered that a limited amount of inventory can be stored at the customer sites as well as the warehouse from which it is delivered; however, transfers between sites are not allowed (Herer et al. 2006). The vehicle working time is made of a set of heterogeneous routes K where each route starts and ends at the warehouse. We assume, without loss of generality, that the routes are served in the order $1, 2, \ldots, k$. The warehouse is denoted by 0; the symbol N^+ is used for $N \cup 0$ and A^+ for $A = \{(i,j): i,j \in N^+, i \neq j\}$. The goal is to determine an inventory policy and routing strategy such that the long-run costs are minimized to serve all customers while satisfying the capacity constraints.

6.3 Mathematical Model

Considering the importance of inventory insight, we first launch the problem formulation by specifying the inventory policy, thereafter, continue with contributing the routing, and finally assembling a variant presentation for the IRP. The prevailing mathematical expression tries to capture economic of lot sizing in material purchasing. To make more information available for cost, we model the cost issue linked to logistics and warehousing activities as part of the design objectives rather than as constraints, considering the single product replenishment problem based on the traditional EOQ model and applying a direct accounting approach, and assuming that the product demand is deterministic, the product price is exogenous and the customers decide only the order size. The full average cost of replenishment, we assumed, is expressed by the sum of four terms: holding cost (c_{1i}), shortage cost (c_{2i}), setup cost (c_{3i}), and purchasing cost (c_{4i}) that appropriately calculated for customer i.

More specifically, our policy taken, closely resembles to the class of Fixed Partition policies introduced by Bramel and Simchi-Levi (1997) for an IRP in which a single item is distributed among retailers. Although such policies are generally not optimal, they are important from a practical standpoint, as they are easy to implement. In particular, they allow for efficient integration of several business functions. Chan et al. (1998) and Chan and Simchi-Levi (1998) have shown that such policies can be highly effective, by deriving an asymptotic error bound on the obtained solution under different assumptions on the transportation cost structure.

A single vehicle of capacity κ is available. This vehicle is able to perform one route at the beginning of each time period to deliver products from the supplier to a subset of customers. A routing cost $c_{ij}d_{ij}$ is associated with arc (i, j). Whereas many distribution systems make use of several vehicles, most research in the field of inventory-routing still considers only one vehicle, and there are indeed practical applications in which a single vehicle is used at a given echelon of the supply chain, such as in the case study described by Mercer and Tao (1996).

6.3.1 Inventory Definition

Let the amount of stock for ith customer be R_i at time $t = 0$ (see Fig. 6.1). In the interval $(0, T_i(= t_{1i} + t_{2i}))$, the inventory level gradually decreases to meet demands. By this process the inventory level reaches zero level at time t_{1i} and then shortages S_i are allowed to occur in the interval (t_{1i}, T_i). The cycle then repeats itself.

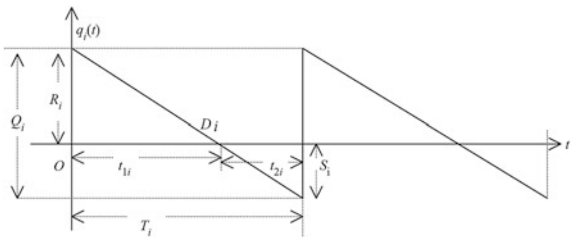


Fig. 6.1 Inventory level of *i*th customer

The differential equation for the instantaneous inventory $q_i(t)$ at time t in $(0, T_i)$ is given by

$$\frac{\partial q_i(t)}{\partial t} = \begin{cases} -D_i, & 0 \le t \le t_{1i} \\ -D_i, & t_{1i} \le t \le T_i \end{cases}$$

with the initial conditions $q_i(0) = R_i (= Q_i - S_i), q_i(T_i) = -S_i, q_i(t_{1i}) = 0$.

For each period a fixed amount of shortage is allowed and there is a penalty cost c_{2i} per items of unsatisfied demand per unit time. From the above differential equation,

$$q_i(t) = \begin{cases} R_i - D_i t, & 0 \le t \le t_{1i} \\ D_i(t_{1i} - t), & t_{1i} \le t \le T_i \end{cases}$$

So, $R_i = D_i\, t_{1i}$, $S_i = D_i\, t_{2i}$, $Q_i = D_i\, t_{3i}$.

Consequently, the holding cost is $c_{1i} \int_0^{t_{1i}} q_i(t)dt = (c_{1i}(Q_i - S_i)^2/2Q_i)T_i$, shortage cost is $c_{2i} \int_{t_{1i}}^{T_i} (-q_i(t))dt = (c_{2i}S_i^2/2Q_i)T_i$ and purchasing cost is $c_{4i}\ Q_i$. Therefore, the total cost is $c_{4i}Q_i + c_{3i} + c_{1i}((Q_i - S_i)^2/2Q_i)T_i + c_{2i}(S_i^2/2Q_i)T_i$. And the total average cost for *i*th customer will be $c_{4i}D_i + c_{3i}(D_i/Q_i) + c_{1i}((Q_i - S_i)^2/2Q_i) + c_{2i}(S_i^2/2Q_i)$.

6.3.2 Model for IRP

In the IRP, the total cost to be minimized is mainly the sum of inventory cost at the supplier and of routing cost for the supplier's vehicle:

$$\text{Min} \quad \sum_{i \in N} \left\{ c_{4i}D_i + c_{3i}{}^{D_i}\!/_{Q_i} + c_{1i}\frac{(Q_i - S_i)^2}{2Q_i} + c_{2i}\frac{S_i^2}{2Q_i} \right\} + \sum_{(i,j) \in \Lambda^+} \sum_{r \in K} c_{ij}d_{ij}x_{ijr} \tag{6.1}$$

where x_{ijr} is equal to 1 if and only if customer j immediately follows customer i on the route r of supplier's vehicle. The objective function (6.1) includes both inventory costs of each customer and as is standard in vehicle routing, travel costs are distance-dependent in which $c_{ij}d_{ij}$ denotes the cost of travelling on arc (i, j).

The constraints are as follows.

6.3.2.1 Routing Constraints

These constraints guarantee that a feasible route is designed to visit all customers served:

(a) A single vehicle is available: Constraints (6.2) require that only one vehicle can leave from retailer i once. Constraints (6.3) denote that only one vehicle can arrive at retailer j once:

$$\sum_{j \in N^+} \sum_{r \in K} x_{ijr} = 1, \quad \forall i \tag{6.2}$$

$$\sum_{i \in N} \sum_{r \in K} x_{ijr} = 1, \quad \forall j \tag{6.3}$$

(b) Flow conservation constraints: these constraints impose that the number of arcs entering and leaving a vertex should be the same, in other words, for each retailer ℓ, the entering vehicle must eventually leave this node:

$$\sum_{i \in N} x_{i\ell r} = \sum_{j \in N} x_{\ell jr}, \quad \forall \ell \in N, r \tag{6.4}$$

(c) Constraints (6.5) designate that each vehicle can leave the warehouse once at most:

$$\sum_{j \in N} x_{0jr} \leq 1, \quad \forall r \tag{6.5}$$

(d) Constraints (6.6) are the vehicle capacity constraints that links two terms of inventory and distribution systems of the model:

$$\sum_{i \in N} \sum_{j \in N} Q_j x_{ijr} \leq \kappa, \quad \forall r \tag{6.6}$$

(e) Sub-tour elimination constraints:

$$\boldsymbol{q}_j \geq \boldsymbol{q}_i - Q_i + D_i(1 - x_{ijr}), \quad \forall i, j, r \tag{6.7}$$

in which it keeps track of the load $\mathbf{q}_i$ on the vehicles and guarantees if customer i is the immediate predecessor of customer j on a route, then the load on the vehicle before visiting customer j must be less than or equal to the load just before visiting customer i minus the amount delivered, which is represented by the variable Q_i. Because the load on each vehicle is monotonically decreasing as customers are visited. Constraints (6.7) also provide the added benefit of eliminating sub-tours. Note that it is considered that D_i is large enough.

6.3.2.2 Integrality and Non-negativity Constraints

$$x_{ijr} \in \{0, 1\}, \quad \forall (i, j) \in \Lambda^+, r \tag{6.8}$$

$$0 \leq \mathrm{q}_i \leq \kappa, \quad \forall i \tag{6.9}$$

$$0 \leq S_i \leq \bar{S}, \quad \forall i \tag{6.10}$$

$$Q_i \geq 0. \quad \forall i \tag{6.11}$$

Constraints (6.8) designate x_{ijr} as a $0 - 1$ integer variables. After all deliveries are made, the fleet returns to the warehouse empty so $\mathbf{q}_0$ can be set to 0. To conclude the formulation, variables are defined in Constraints (6.9)–(6.11).

6.4 Uncertain Modeling

In the real world, after designing a network of facilities, the respective costs, demands, distances, times and other relevant data may change due to uncertain circumstances happening when working in a dynamic and chaotic business environment. For example, in IRPs, with variability in the demand may result in huge and non-measureable costs, such as lost-opportunity and lost-sale costs due to causing unsatisfied customers. Typically, there are two types of modeling techniques for addressing uncertain data, namely, stochastic programming and fuzzy programming.

Therefore, one important consideration is in line with combined inventory management and routing so that there are technical uncertainties due to transportation conditions and equipment, as well as environmental, economical or market uncertainties. In many businesses the market conditions have changed dramatically over the last years with new market opportunities arising continuously. As a result, the demand for products becomes highly uncertain in some business areas. Moreover, most companies are not aware of the possibilities of introducing uncertain elements in the planning. Neither they are familiar nor confident with uncertain planning systems. For recent reviews on the IRP, one can refer to Coelho and Laporte (2013, 2014) and Coelho et al. (2014).

In this regard, demand is widely accepted to be dynamic and stochastic in real life inventory routing problems. Studies on uncertain IRPs also assume full knowledge of the demand data, which may be unavailable or difficult to obtain. There is clearly a need to consider the IRP with demand data in a tractable way, where no information for the probability distribution function (PDF) of demand is required. Nevertheless, in many practical situations, due to lack of historical data for some parameters such as demand, it is hard or even impossible to fit a PDF. In these cases, it is more reasonable to adopt a suitable possibility distribution for each demand based upon the available (but often insufficient) objective data as well as subjective opinions of DMs, or a fully subjective (preference-based) fuzzy set for each judgmental data based upon expert's subjective knowledge, experience and professional feelings. Though, in both cases, fuzzy programming approaches should be used to cope with such vague uncertainties (Panda et al. 2014). Herein, these variants of IRPs are called IRPs with "hybrid uncertainty" since we are dealing with a mixture of uncertain data (i.e., fuzzy and random data) in our problem. To the best of our knowledge, in IRPs no attempt have been formally made where fuzziness and randomness coexist. Hence, the second objective of this study is to, indeed, deliberating IPRP under uncertainty.

In the following the aim is to extend the formulation into an IRP under hybrid uncertain demand which is also common problem in practice. Doing so, we first refer the readers to Appendix to find the type of uncertainty scheme brought here and its deterministic counterpart formulation.

$$\begin{aligned}\text{Min}\ &\left\{\sum_{i\in N} c_{4i}\tilde{\underline{D}}_i + c_{3i}\left(\tilde{\underline{D}}_i/Q_i\right) + c_{1i}\left((Q_i - S_i)^2/2Q_i\right) + c_{2i}\left(S_i^2/2Q_i\right)\right\}\\ &+ \sum_{(i,j)\in\Lambda^+}\sum_{r\in K} c_{ij}d_{ij}x_{ijr}\end{aligned} \tag{6.12}$$

st.

$$\boldsymbol{q}_j \geq \boldsymbol{q}_i - Q_i + \tilde{\underline{D}}_i(1 - x_{ijr}), \quad \forall i, j, r \tag{6.13}$$

(6.2)–(6.6) and (6.8)–(6.11).

Considering the imperfect nature of the demands, the model is converted into its deterministic version. Then by definition of $\tilde{\underline{D}}_i = (D_{1i}, D_{2i}, D_{3i})(+)'\left(\mu_i, \sigma_i^2\right), \forall i$, and following the mathematical theory of hybrid numbers described in Appendix the objective function (6.12) and constraints (6.13) extend to:

$$\begin{aligned}&\text{Min } TC = E\tilde{T}C(+)'(0, VTC)\\&\text{st.}\end{aligned} \tag{6.14}$$

$$E\big(\boldsymbol{q}_j - \boldsymbol{q}_i + Q_i - \underline{\tilde{D}}_i(1 - x_{ijr})\big) \geq 0, \quad \forall i, j, r \tag{6.15}$$

$$V\big(\boldsymbol{q}_j - \boldsymbol{q}_i + Q_i - \underline{\tilde{D}}_i(1 - x_{ijr})\big) \geq 0, \quad \forall i, j, r \tag{6.16}$$

(6.2)–(6.6) and (6.8)–(6.11),
where $E(\cdot)$ and $V(\cdot)$ are mean and variance operators, respectively. On the other hand, $E\tilde{T}C = (ETC_1, ETC_2, ETC_3)$ with $ETC_m = \sum_{i\in N}\{c_{4i}(D_{mi} + \mu_i) + c_{3i}((D_{mi} + \mu_i)/Q_i) + c_{1i}((Q_i - S_i)^2/2Q_i) + c_{2i}((S_i)^2/2Q_i)\}$, $\forall m \in \{1, 2, 3\}$. So the approximated value of $E\tilde{T}C$ is $E\hat{T}C = {}^1\!/\!_4(ETC_1 + 2ETC_2 + ETC_3) = \sum_{i\in N} \{c_{4i}(\hat{D}_i + \mu_i) + c_{3i}((\hat{D}_i + \mu_i)/Q_i) + c_{1i}((Q_i - S_i)^2/2Q_i) + c_{2i}((S_i)^2/2Q_i)\}$ if $\hat{D}_i = {}^1\!/\!_4(D_{1i} + D_{2i} + D_{3i} + D_{4i})$.

Hence, Constraints (6.12) and (6.13) is reduced to a "*bi-objective mixed integer nonlinear program*" as follow:

$$\begin{aligned}&\text{Min } \{AETC, VTC\}\\&\text{st.}\end{aligned} \tag{6.17}$$

$$\boldsymbol{q}_j \geq \boldsymbol{q}_i - Q_i + \hat{D}_i(1 - x_{ijr}), \quad \forall i, j, r \tag{6.18}$$

$$\sigma_i^2(1 - x_{ijr})^2 \geq 0, \quad \forall i, j, r \tag{6.19}$$

(6.2)–(6.6) and (6.8)–(6.11),
where $AETC = E\hat{T}C + \sum_{(i,j)\in\Lambda^+}\sum_{r\in K} c_{ij}d_{ij}x_{ijr}$, and $VTC = \sum_{i\in N}\{c_{4i}^2\sigma_i^2 + c_{3i}^2(\sigma_i^2/Q_i^2)\}$. As seen, from (6.8), Constraints (6.19) is evident, so it will be omitted from the rest of our computations.

6.5 Integrating Ecological Issues

The way of considering ecological issues in routing problem is rather interesting. We present fundamental ideas to enrich VRPs by green aspects in the following. Several ecologically oriented extensions of the VRP have been introduced which aim at minimizing the fuel consumption or the amount of CO_2 emission. In any of these problems, the evaluation of transportation plans relies on an estimation of the quantity of fuel consumed for request fulfillment. There exists a variety of methods for estimating fuel consumption and emissions of road transportation in dependence of a bunch of parameters. Most of the estimation methods are based on analytical emissions models. The methods found in the literature differ in the assumed basic principles and with respect to the parameters they take into account for estimation. A comparison of several vehicle emission models for road freight transportation can be found in Demir et al. (2011). In addition to comparing different methods for estimating fuel consumption and pollution, Demir et al. (2011) analyze the discrepancies between the results yielded by the models on the one hand and the results of measurements of on-road consumptions of real vehicles on the other hand. For other relevant references and a state-of-the-art coverage on green road freight transportation, the reader is referred to the survey of Lin et al. (2014) and Demir et al. (2014). In this chapter, we follow the idea of chose by Bektaş and Laporte (2011).

6.5.1 Model to Estimate Fuel Consumption

The comprehensive modal emission model developed by Barth et al. (2005), Barth and Boriboonsomsin (2009) for diesel engines gives a good estimate of the vehicular emissions (Bektaş and Laporte 2011; Demir et al. 2011); it considers the speed, load carried and other vehicle parameters. They relate the tail-pipe emissions e directly to the fuel use rate F as $e = \text{ϭ}_1 F + \text{ϭ}_2$ (Bektaş and Laporte 2011) where ϭ_1 and ϭ_2 are GHG emissions index parameters.

The expression for the instantaneous fuel consumption or fuel use rate F mL/s for a diesel engine with displacement φ L is given as follows Barth and Boriboonsomsin (2009) and Barth et al. (2005):

$$F \approx \psi \left(Es\varphi + \frac{P}{\eta} \right) \tag{6.20}$$

where $\psi = (1/0.85) \cdot (1/43.2) \cdot (1 + b_1(s - s_0)^2), E = E_0(1 + c(s - s_0))$ is the engine friction factor, and s the engine speed (revolutions/s), P the total engine power requirement (watt), η the efficiency of diesel engine, E_0 the engine friction factor when the vehicle is idle, $s_0 \approx 30\ (3/\phi)^{½}$, $c \approx 0.00125$ and $b_1 \approx 10^{-4}$ are constant coefficients, 43.2 kJ/g the lower heating value of diesel and 0.85 kg/L the density of diesel. The engine power requirement P for a vehicle with drive-train efficiency ϑ is expressed as

$$P = \frac{P_{tract}}{\vartheta} + P_{acc} \tag{6.21}$$

P_{acc} accounts for the power required by the vehicle air conditioner and other accessories.

The tractive power required P_{tract} (watt) by the vehicle to carry a weight M (including the load to be carried) can be determined from the following expression (Barth and Boriboonsomsin 2009; Bektaş and Laporte 2011):

$$P_{tract} = M\big(a + g\ \sin\theta + g\ C^{roll}\cos\ \theta\big)v + 0.5A\,\rho C_d\,v^3 \tag{6.22}$$

where v m/s is the velocity of the vehicle, θ the road angle (degree), A (m^2) the frontal surface area of the vehicle, ρ (kg/m^3) the air density, a (m/s^2) the acceleration of the vehicle, g (m/s^2) the acceleration due to gravity, C^{roll} the coefficient of rolling resistance and C_{d} the coefficient of aerodynamic drag.

The expression for the fuel use rate (F) provides the estimate of the fuel consumption (**FC**) by a vehicle on travelling a route.

6.5.2 Factors Affecting Fuel Consumption

If the velocity v and other parameters of a vehicle remain constant, the **FC** by a vehicle travelling and distance d can be estimated from the fuel use rate F as follows:

$$\mathbf{FC} \approx F\left(\frac{d}{v}\right) \tag{6.23}$$

The **FC** by a vehicle in a trip is proportional to the distance travelled and the load carried. The **FC** on an arc depends on the load carried and varies according to the sequence of nodes to be visited. The **FC** by an empty truck depends on its curb weight (Barth and Boriboonsomsin 2009; Barth et al. 2005; Bektaş and Laporte 2011). For the sake of uniformity of scale, we also take the load to be carried in units of weight (kg in this study).

The product of η and ϑ is inversely proportional to the **FC**. Thus, choosing a vehicle with higher values of engine and drive-train efficiencies will result in better fuel economy. The **FC** is fairly low for moderate speeds (35–45 km/h) and high for very low and very high speeds. Variations in driving speeds contribute significantly to the **FC** and emissions than driving at a steady speed (Tong et al. 2000). A driver who maintains a constant speed and drives within a moderate speed range will help to reduce the consumption of fuel. In general, the average speed of travel in an arc is assumed (Bektaş and Laporte 2011; Suzuki 2011) for modeling purposes. The most likely average speed with which a vehicle can travel can be predicted using historical and real-time data (Rice and Van Zwet 2004).

The parameters θ and C^{roll}, which are entirely dependent on the nature of the road, are very sensitive and play a dominant role in the **FC** by the vehicle. C_{d} depends on climatic conditions and is a measure of the drag force exerted on the vehicle due to air resistance. Apart from these parameters, the velocity of travel also depends on the nature of the road and other road conditions. Hence, alternative routes have to be considered for distribution planning to determine the velocity and the road to be travelled in order to reduce the fuel consumption. Table 6.1 offers a description of all the parameters.

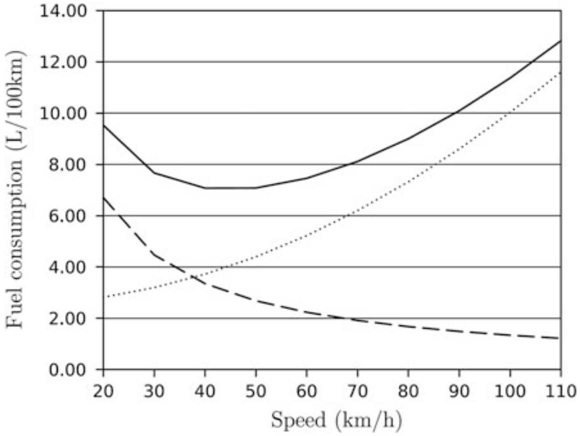
Table 6.1 Parameters used in the computational experiments

Notation	Description	Typical values
E	Engine friction factor (kg/revolution/L)	0.2
s	Engine speed (revolution/s)	33
φ	Engine displacement (L)	5
g	Gravitational constant (m/s^2)	9.81
C_d	Coefficient of aerodynamic drag	0.7
ρ	Air density (kg/m^3)	1.2041
A	Frontal surface area (m^2)	3.912
C^{roll}	Coefficient of rolling resistance	0.01
ϑ	Vehicle drive-train efficiency	0.4
η	Efficiency of diesel engines	0.9
b_1	Heating value of a typical diesel fuel (kJ/g)	44
ψ	Conversion factor (g/s to L/s)	737
$\underline{v}$	Lower speed limit (km/h)	20
$\bar{v}$	Upper speed limit (km/h)	85

6.5.3 Nature of Alternative Routes

A variety of alternative routes can exist between a pair of nodes and each route is taken as a distinct arc connecting the two nodes. If each lane of a highway is considered as an alternative route, the length is the same but the velocity is different. Another possibility is the existence of multiple routes with different lengths and different average velocities. The availability of multiple routes between two nodes can be observed in countries which rely heavily on road transport for freight movement. The average velocity along each route can be determined based on the condition of the road, past data etc. The nature of the routes is illustrated in Fig. 6.2.

Fig. 6.2 Fuel consumption as a function of speed, as estimated by function (6.23)



It shows a U-shape curve between **FC** and speed, which is consistent with the behavior of functions suggested by other authors (e.g., Demir et al. 2011), confirming that low speeds (as in the case of traffic congestion) lead to very high fuel use rate.

6.5.4 Fuel Emissions Factors

Let

$$\alpha_{ij} = a + g\ \sin\theta_{ij} + g\,C_{ij}^{roll}\cos\theta_{ij} \tag{6.24}$$

$$\beta = 0.5\,A\,\rho\,C_d \tag{6.25}$$

Using (6.26), the fuel use rate given in (6.27) can be written as follows:

$$P_{tract} = \alpha_{ij}\,w\,v_{ijr} + \alpha_{ij}\,\boldsymbol{q}_i\,v_{ijr} + \beta\,v_{ijr}^3 \tag{6.26}$$

$$F_{ijr} \approx \psi_{ij}\left(E_{ij}s_{ij}\phi + \frac{1}{\vartheta\eta}(\alpha_{ij}\,w\,v_{ijr} + \alpha_{ij}\,\boldsymbol{q}_i\,v_{ijr} + \beta\,v_{ijr}^3) + \frac{P_{acc}}{\eta}\right) \tag{6.27}$$

Assuming that the velocity and other parameters of a vehicle remain constant on a route, the fuel consumed $\mathbf{FC}_{ijr}$ mL by a vehicle travelling from node i to node j along route r can be estimated from the fuel use rate F_{ijr} as follow:

$$\mathbf{FC}_{ijr} \approx F_{ijr}\left(\frac{d_{ij}}{v_{ijr}}\right) \tag{6.28}$$

where d_{ij}/v_{ijr} is the time taken to travel the route.

As perceived from above, the ecologically speaking purpose concerns with consumption of fuel, is based on parameters relating to vehicles, load, speed, distances and road conditions. Substituting (6.27) in (6.28) and rearranging the terms and considering that economic benefits strongly influence decision-making in most businesses. However, unlike same-topic-papers, the "speed" is considered as a decision variable and establish its relevant necessary constraint. Given this, we refer to this problem as "Pollution-Routing Problem" (PRP).

6.5.5 Model Formulation for IPRP

The proposed "*mixed integer nonlinear program*" is very difficult to solve. Thus we decompose the decision variables $\{Q_i, S_i, x_{ijr}, \mathbf{q}_i, v_{ijr}\}$ into two groups: $\{Q_i, S_i\}$ and

$\{x_{ijr}, \mathbf{q}_i, v_{ijr}\}$. The first group is associated with the inventory problem and the second group is subject to the routing problem.

With the concept of decomposition, Constraints (6.12) and (6.13) schematically, rearranged with the following bi-level structure:

Upper level:

$$\begin{cases} \underset{\{Q_i,S_i\}\in\Omega_1}{\text{Min}} & Z_1 = E\hat{T}C + Z_{PRP} \\ \underset{\{Q_i,S_i\}\in\Omega_1}{\text{Min}} & Z_2 = \sum\limits_{i\in N}\left(c_{4i}^2\sigma_i^2 + c_{3i}^2\frac{\sigma_i^2}{Q_i^2}\right) \end{cases} \tag{6.29}$$

where Ω_1 is the feasible region represented by non-negative Constraints (6.19) and (6.20) in which Z_{PRP} is the VRP's objective function including green issue. Accordingly, the Z_{PRP} is calculated as follows:

Lower level:

$$\begin{cases} \underset{\{x_{ijr},\boldsymbol{q}_i,v_{ijr}\}\in\Omega_2}{\text{Min}} \quad Z_{PRP} = \left(\begin{array}{l} \sum\limits_{(i,j)\in\Lambda^+}\sum\limits_{r\in K}\psi_{ij}d_{ij}\left(E_{ij}s_{ij}\phi + \dfrac{\alpha_{ij}w}{\vartheta\eta}\right)C_{fuel}x_{ijr} \\ + \sum\limits_{(i,j)\in\Lambda^+}\sum\limits_{r\in K}\psi_{ij}d_{ij}\left(\alpha_{ijr}/\vartheta\eta\right)C_{fuel}\,\boldsymbol{q}_i \\ + \sum\limits_{(i,j)\in\Lambda^+}\sum\limits_{r\in K}\psi_{ij}d_{ij}(\beta/\vartheta\eta)\,C_{fuel}\,v_{ijr}^2x_{ijr} \end{array} \right) \\ \text{st.} \\ \underline{v}_{ijr}x_{ijr} \le v_{ijr} \le \bar{v}_{ijr}x_{ijr}, \quad \forall i,j,r \end{cases} \tag{6.30}$$

where Ω_2 represents Constraints (6.2)–(6.6), (6.8) and (6.18) with $\{Q_i, S_i\}$ given. As seen, Constraints (6.6) incurs a nonlinear solution set for problem (6.30). By the decomposition technique that has been carried out here, Z_1 and Z_2 solve Q_i and perform Ω_2 to transform into a linear feasible region for problem (6.30).

In the lower level, the objective function is derived from (6.28) and contains three components. The first two, measure the cost comprised by the load carried on the vehicle (including curb weight). Finally, the last component measures the cost implied by variations in speed. All of these three components translate directly into total cost of **FC** and GHG emissions calculated by the unit cost C_{fuel} multiplied by the total amount of fuel consumed over each link $(i, j) \in \Lambda^+$.

Constraint $\underline{v}_{ijr}x_{ijr} \le v_{ijr} \le \bar{v}_{ijr}x_{ijr}, \ \forall i,j,r$ links the green strategy and routing plan, aiming at *Greening the Routes*. In other words, the adjunct constraint guarantee that if arc (i, j) is traversed on route r, service at node j will be started under limit of lower and upper bounds of vehicle speed; otherwise no value kept for constraint satisfaction if arc (i, j) is not traversed.

If a given $\{Q_i, S_i\}$ causes problem (6.30) to be in feasible, simply let Z_{PRP} equal infinity. Note that, since by definition, x_{ijr} could be either 0 or 1, once it takes 0, then automatically v_{ijr} becomes 0, and when it takes 1, then v_{ijr} will be permitted to designate a value among $\underline{v}_{ijr}$ and $\bar{v}_{ijr}$, thus x_{ijr} could be easily dropped from the last term of the objective function (6.30), and relaxed to $\sum_{(i,j)\in\Lambda^+}\sum_{r\in K}\psi_{ij}d_{ij}(\cdot)C_{fule}v_{ijr}^2$.

The Constraints (6.12) and (6.13) is now converted into a "*bi-level bi-objective mixed integer nonlinear program*" problems (6.29) and (6.30) with convex solution region.

6.6 Solution Approach

Problem (6.29) itself can be solved using either a sensitivity-analysis based or a direct search algorithm. The former uses sensitivity analysis to obtain the derivative information of the reaction function (either explicitly or implicitly) while the latter employs only functional evaluations. Since the interdependence between delivery quantity and shortage variables $\{Q_i, S_i\}$ and vehicle routes $\{x_{ijr}, \mathbf{q}_i, v_{ijr}\}$ are too complicated and the derivative information is not available in this problem, we adopted a direct search algorithm to solve the problem. One of the most widely used direct search methods for solving nonlinear unconstrained optimization problems is the Nelder–Mead simplex algorithm (see Nelder and Mead 1965).

In the next two subsections, the Nelder–Mead method with boundary constraints is adopted to solve the upper level inventory problem (6.29) and a plenary exact heuristic algorithm is proposed to solve the lower level the PRP (6.30).

6.6.1 Solving the Multiobjective Inventory Problem

A "simplex" is a geometrical figure consisting, in n-dimensions, of $(n + 1)$ points $y^0; \ldots; y^n$ (Nelder and Mead 1965)[1]. If any point of a simplex is taken as the origin, the n other points define vector directions that span the n-dimension vector space.

If we randomly draw as initial starting point y^0, then we generate the other n points y^i according to the relation $y^i = y^0 + \lambda y^0 I_i$, where the I_i are n unit vectors, and λ is a turbulence factor which is which is typically equal to one (but may be adapted to the problem characteristics).

Through a sequence of elementary geometric transformations (reflection, contraction, expansion and multi-contraction; internal/external), the initial simplex y^0 moves, expands or contracts. To select the appropriate transformation, the method only uses the values of the function to be optimized at the vertices of the simplex considered. After each transformation, the current worst vertex is replaced by a

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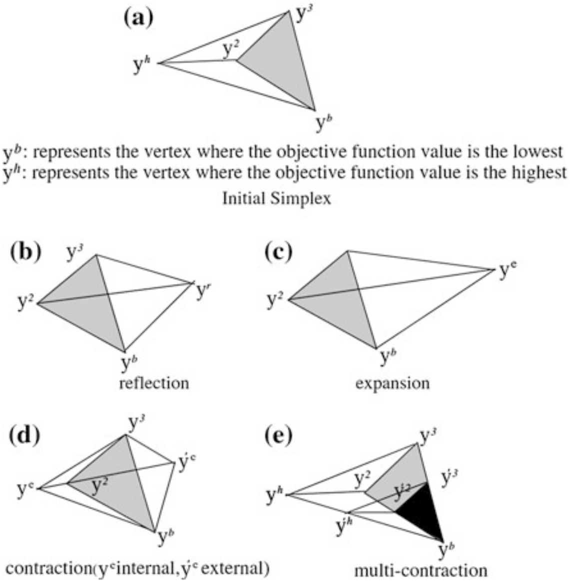
[1] Since this section we exploit "y" as an axillary variable.

Fig. 6.3 Available moves in the Nelder–Mead simplex method, in the case of 3 variables



better one. Trial moves shown on Fig. 6.3 are generated according to the following basic operations (where $\hat{y}$ called center of gravity and defined by $\hat{y} = (\Sigma_i y_i)/n$, and $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$ are constants):

reflection: $y^r = \hat{y} + \boldsymbol{\alpha}(\hat{y} - y^n)$
expansion: $y^e = \hat{y} + \boldsymbol{\beta}(y^r - \hat{y})$
internal contraction: $y^c = \hat{y} + \boldsymbol{\gamma}(y^n - \hat{y})$
external contraction: $\dot{y}^c = \hat{y} + \boldsymbol{\gamma}(y^r - \hat{y})$

At the beginning of the algorithm, one moves only the point of the simplex, where the objective function is worst (this point is called “high”), and one generates another point image of the worst point. This operation is the reflection. If the reflected point is better than all other points, the method expands the simplex in this direction; otherwise, if it is at least better than the worst one, the algorithm performs again the reflection with the new worst point. The contraction step is performed when the worst point is at least as good as the reflected point, in such a way that the simplex adapts itself to the function landscape and finally surrounds the optimum. If the worst point is better than the contracted point, the multi-contraction is performed. For each rejected contraction step, we replace all y^i of the simplex by ½(y^i + y^1) (y^1 is the vertex of the simplex where the objective function is “low”); thus we obtain the multi-contraction (internal/external) of the simplex, and the process restarts.

The stopping criterion is a measure of how far the simplex was moved from one iteration h to the following one (h + 1). The algorithm stops when:

$$\frac{1}{n}\sum_{i=1}^{n}\left\|y_i^h - y_i^{h+1}\right\|^2 < \varepsilon, \tag{6.31}$$

where y^{h+1} is the vertex replacing y^h at the iteration $(h + 1)$, and ε is a given “small” positive real number.

Because the Nelder–Mead method (NM) is originally applied to an unconstrained problem, an adjustment is necessary that projects its coordinates on the bounds if the new point is out of the domain. However, since the inventory part of the problem is of multiobjective form, it also needs a preparation step before the adjustment.

We start the preparation with a topic of normalized normal constraint method (NNCM; Messac et al. 2003). This method normalizes the design space and introduces new constraints. Considering the new constraints, optimization of only one of the objectives returns a non-dominated solution. When several of these single-objective optimization problems are solved, several non-dominated solutions are obtained. The difference between this method and varying user preferences in a non-generating method is that here the set of constraints are introduced to spread the final solutions uniformly in the criterion space. NNCM is an algorithm for generating a set of evenly spaced solutions on a pareto-frontier (Messac et al. 2003). This method yields pareto-optimal solutions, and its performance is independent of the scale of the objective functions. NNCM method and some related definitions are presented in this section.

Definition 1 (utopia point) Considering a multiobjective optimization problem, a point $F^{o} \in \omega$ in the criterion space (ω) is called a utopia point if and only if:

$$f_i^o = \min\{f_i(y)|y \in \zeta\}, \quad \forall i \tag{6.32}$$

where $\zeta \subset \mathrm{R}^n$ is the feasible region in the design space. Because of contradicting objectives, the utopia point is unattainable.

Definition 2 (anchor point) A non-dominated point $F^{o} \in \omega$ is an anchor point if and only if it is pareto-optimal and at least for one i, $f_i^{**} = \min_y\{f_i(y)|y \in \zeta\}$.

The first step in NNCM is to normalize the design space. For this purpose, the utopia and the anchor points are required. These points are found by optimizing only one of the objectives at a time. After finding these points, the criterion space is normalized using the following transformation.

$$\bar{f}_i = \frac{f_i - f_i^o}{f_i^{\max} - f_i^o} \tag{6.33}$$

$$f_i^{\max} = \max\{f_i(y); y \notin Y^*\} \tag{6.34}$$

where Y^* is All pareto-optimal points in the design space.

The normalization process locates the utopia point at the origin and the anchor points at the unit coordinates. Figure 6.4a shows the original criterion space and the pareto-frontier of a generic bi-objective problem. Figure 6.4b represents the pareto-frontier of the same problem after normalization. The next step is to form the utopia hyperplane, which is a hyperplane with vertices located at the anchor points. For a bi-objective problem, the utopia hyperplane is a line as shown in Fig. 6.4c. Next, a grid of evenly distributed points on the utopia hyperplane is generated. The number of points in this grid is defined by the user. Figure 6.4c shows, for example, a grid of six points on the utopia line. If these points are projected onto the pareto-frontier, several pareto-optimum solutions are obtained. To find the pareto-optimum solution corresponding to each point in this grid, a single-objective optimization problem must be solved. This problem entails minimizing one of the normalized objectives with an additional inequality constraint. For example, the pareto-optimum solution corresponding to point P in Fig. 6.4c can be found by minimizing $\bar{f}_2$ while the feasible region is cut by the line passing through this point and perpendicular to the utopia line. The feasible region of this single-objective optimization problem is shown in Fig. 6.4c. The solution of this problem, $\bar{f}^*$, is a pareto-optimum solution for the original multiobjective problem. Other pareto-optimal points can be found by repeating the same procedure for other points on the utopia line.

If the objective functions have local optima, it is possible to have some dominated solutions among the final solutions. Model (6.29) has local optima; therefore, dominated solutions are expected.

In order to find each pareto-optimum solution, NNCM requires solving a single-objective optimization problem. Since this algorithm is proposed for solving model (6.29), in which the gradients of the objectives are not available; a direct optimization method is required. On the other hand, considering the time consuming analysis of the model, an evolutionary algorithm may not be a good choice due to the low rate of convergence. Hence, integrating with Nelder–Mead simplex algorithm would be an appropriate choice we implement here. We now proceed to formally state the Algorithm 1, as follows:

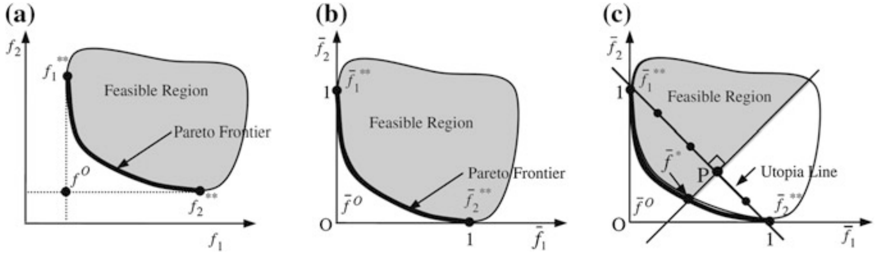


Fig. 6.4 **a** A typical bi-criterion space, **b** normalized criterion space, **c** a normal constraint introduced by NNCM and the feasible region of the resulted single-objective problem (min $\bar{f}_2$)

Algorithm 1 NM

1 Initialization

- 1.1 Find an initial solution $\{Q_i, S_i\}$ (designated as y^0) of (6.29) as follows, and solve corresponding VRP (6.30) considering NNCM. The initial delivery quantity Q_i is usually set as the mean value of the demand quantity with the initial shortage value (S_i) of zero. Calculate the value of objective function (6.29).
- 1.2 Determine other vertices y^1, …, y^n of the initial simplex by disturbing y^0 as follows: $y^i = y^0 + \boldsymbol{\lambda} y^0 I_i$, $\forall i$ where $\boldsymbol{\lambda}$ is a turbulence factor and I_i is a unit base vector. Project its coordinates on the bounds, if y^i is out of the domain. Solve the corresponding VRP (6.30) and calculate the value of objective function (6.29), respectively.

2 Identify the vertices with the highest function value as y^u, the vertices with the lowest function value as y^l, the vertices with the second lowest function value as $\hat{y}$, the center of gravity of the simplex (without y^l), and the corresponding objective function values as $Z(y^u)$, $Z(y^l)$, $Z(\hat{y})$; where Z is the combined objective functions Z_1, Z_2 calculated by NNCM.

3 Apply a reflection with respect to y^l: $y^r = \hat{y} + \boldsymbol{\alpha}(\hat{y} - y^l)$ and project its coordinates on the bounds, if y^r is out of the domain.

4 Update the simplex. We distinguish between three cases:

- (a) If $Z(y^r) > Z(y^u)$, it means that the reflection created a better solution. We attempt to get an even better point through expansion of y^r: $y^e = \hat{y} + \boldsymbol{\beta}(y^r - \hat{y})$. Project its coordinates on the bounds, if necessary. Replace y^l with y^e if $Z(y^e) > Z(y^r)$; otherwise, replace y^l with y^r.
- (b) If $Z(y^r) \geq Z(\hat{y})$, replace y^l with y^r.
- (c) If $Z(y^r) \leq Z(y^l)$, it was probably wrong to do the reflection along that direction. An internal contraction from y^l in direction $\hat{y} - y^l$ will be applied:

$y^c = \hat{y} + \boldsymbol{\gamma}\left(y^l - \hat{y}\right)$, project its coordinates on the bounds, if necessary. Else, if $Z(y^l) < Z(y^r) < Z(\hat{y})$, the selected direction may be right. However, since all vertices except y^l are better than y^r, it can be concluded to go closer to the simplex again. An external contraction from y^r will be applied:

$y'^{c} = \hat{y} + \gamma(y^r - \hat{y})$, project its coordinates on the bounds, if necessary.

After the internal or external contraction, if $Z(y^c) > Z(y^l)$ (or if $Z(y'^{c}) > Z(y^l)$), replace y^l with y^c (or y'^{c}). Otherwise, a total contraction is performed since all attempts to get improvement failed; $y^i = y^u + \boldsymbol{\gamma}\,(y^i - y^u)$ $\forall i \neq u$

5 Check convergence. If the distance between y^u and any other vertices is smaller than a certain tolerance, then stop; y^u and its corresponding

vehicle route is the best solution. Otherwise, go to 2. Another choice of stopping criterion which is more applicable, according to (6.31), is the difference of $Z(y^u) - Z(y^l)$ less than a preset tolerance.

6.6.2 Solving the PRP

6.6.2.1 The Proposed Method

When addressing convex MINLPs, two of the classical methods available in the literature are Generalized Benders Decomposition (GBD) (Geoffrion 1972) and the Outer-Approximation (OA) algorithm (Duran and Grossmann 1986; Fletcher and Leyfer 1994). Both methods are iterative coordination techniques that cycle between the solutions of a relaxed master problem (RMP) and of a sub-problem (SP). While the former, a mixed integer program (MIP), provides lower bounds for the optimal solution, the latter, a linear problem (LP), allows the generation of violated cuts that enrich the RMP at each iteration.

As proved by Duran and Grossman (1986), the lower bounds obtained by the OA method are greater or equal to the ones attained by the GBD, implying, hence, in less iterations for convergence. However, these bounds are provided at the cost of an RMP with a number of variables and constraints larger than the RMP of the GBD. Consequently, the largest instance size that the OA technique is able to tackle, is smaller than the largest of the GBD.

Nevertheless, on MINLPs, whenever a model can be reformulated by separating the nonlinear from the large-scale part via the addition of a family of variables, a hybrid strategy can be efficiently used.

Moreover, the reformulation suggests two possibilities: on one hand, the solution of the entire problem can be done by means of GBD, by projecting out all the non-complicating variables—the large-scale system and the additional variables. On the other hand, the solution can be achieved by means of an RMP that has the complicating and the additional variables—similar to the OA's RMP.

The latter separation represents a great advantage since it allows the parallel solution of the SPs of the OA and BD methods, and hence the addition of both cuts to the RMP. Further, assuming that the required number of additional variables is much smaller than the number of variables of the large-scale system, using the RMP having the complicating and the additional variables may reduce the computational effort when compared to the standard application of OA or GBD. This enhancement is due to the combined effect of having improved lower bounds and a reduced solution overhead of the RMP.

Therefore, despite the chosen sequence of presentation of this article, it is indifferent to think on solving the OA's RMP by BD or on tackling the RMP of the

BD by OA, when the MINLP can be reformulated by separating the nonlinear from the large-scale part via the addition of a family of variables.

The OA method is a simple but effective technique based on a cutting plane approach for solving MINLP (Duran and Grossmann 1986; Fletcher and Leyfer 1994). A general survey of the technique can be found at Grossmann and Kravanja (1995). The method is a coordination technique between an MP and a SP, as aforementioned.

In order to understand the development of the OA technique for the VRP, a general overview of the method is required. Given an MINLP in its most basic algebraic representation, where x and y are the sets of continuous and discrete variables, respectively, $f\colon \mathrm{R}^{n\times q} \to \mathrm{R}$ and $g\colon \mathrm{R}^{n\times q} \to \mathrm{R}^{m}$ are two continuously differentiable functions, and $\boldsymbol{X}$ and $\boldsymbol{Y}$ are polyhedral sets:

$$(\mathrm{ONP})\begin{cases} \mathrm{Min}\, f(x,y) \\ \mathrm{st.} \\ g_j(x,y) \le 0, \quad \forall j \\ y \in \boldsymbol{Y}, \quad y \in \mathrm{Z}^q \\ x \in \boldsymbol{X}. \end{cases}$$

It is possible to reduce this problem to a pure nonlinear program (ONP) by choosing a fixed vector $y = y^h$, $y^h \in \boldsymbol{Y}$, for some iteration h, yielding the following nonlinear NSP:

$$(\mathrm{NSP})\begin{cases} \mathrm{Min}\, f(x,y^h) \\ \mathrm{st.} \\ g_j(x,y^h) \le 0, \quad \forall j \\ x \in \boldsymbol{X}. \end{cases}$$

When solved, the above NSP permits to infer the gradient of the functions $f(x, y)$ and $g_j(x, y)$, $\forall j$ at (x^h, y^h). If no further feasibility constraints are required, then a straightforward manipulation enables the ONP to be equivalent to an MIP:

$$(\mathrm{OLP})\begin{cases} \mathrm{Min} \;\; \xi \\ \mathrm{st.} \\ f(x^h,y^h) + \nabla f(x^h,y^h)^T \begin{pmatrix} x - x^h \\ y - y^h \end{pmatrix} \le \xi, \quad \forall h \\ g(x^h,y^h) + \nabla g(x^h,y^h)^T \begin{pmatrix} x - x^h \\ y - y^h \end{pmatrix} \le 0, \quad \forall h \\ y \in \boldsymbol{Y}, \quad y \in \mathrm{Z}^q \\ x \in \boldsymbol{X} \\ \xi \ge 0. \end{cases}$$

Problem OLP is known as the OA's MP. The two first constraints are responsible for performing the OA of the objective function and the feasible region, respectively. When functions $g(x, y)$ are proper convex and a constraint qualification holds for every solution of NSP, then the second constraints are necessary and sufficient to outer approximate the feasible region.

In the case of model (6.30), the objective function is separable on the linear and nonlinear terms. Then, before applying OA, we should prove that the continuous relaxation of the objective function is convex in order to assure optimality and applicability of the OA approach. Lemma establishes this property.

Lemma *The objective function of model (6.30) is convex.*

Proof By linearity, it suffices to show that the nonlinear term is convex. Let us first expand the function then for all v_{ijr} we have:

$$f_{ijr}(v_{ijr}) = \psi_{ij} d_{ij} (\beta / \vartheta \eta) C_{fuel} v_{ijr}^2$$

If $f(v)$ has a second derivative in $[\underline{v}, \bar{v}]$, then a necessary and sufficient condition for it to be convex on is that the second derivative $\partial^2 f(v) / \partial v^2 \geq 0$ for all v in $[\underline{v}, \bar{v}]$.

$$\begin{aligned} \frac{\partial f_{ijr}(v_{ijr})}{\partial v_{ijr}} &= 2\psi_{ij} d_{ij} (\beta / \vartheta \eta) C_{fuel} v_{ijr} \\ \Rightarrow \frac{\partial^2 f_{ijr}(v_{ijr})}{\partial v_{ijr}^2} &= 2\psi_{ij} d_{ij} (\beta / \vartheta \eta) C_{fuel} \geq 0. \end{aligned}$$

This establishes the convexity of this function, completing the proof. □

Given values for the integer decision variables, the OA's SP finds the optimal value for the continuous variables, providing a feasible point in order to approximate the nonlinear objective function (6.30). In OA algorithm, the SP is typically the algorithmic bottleneck because it requires solving an NLP at each iteration.

We can build the OA's MP provided that the optimal values for variables $\hat{x}^h$, $\hat{\mathbf{q}}_i$ and $\hat{v}^h$ at every iteration h is available. The following proposition shows how the linear approximations of the objective function (6.30) is calculated.

Proposition *If $\hat{v}^h$ is an optimal solution for the nonlinear of the OA's SP algorithm at iteration h, there exists a valid linear OA cut for the objective function (6.30).*

Proof From Lemma, $f(v)$ is convex. Given a feasible assignment point of $\hat{v}^h$ at iteration h for ONP, by convexity of $f(v)$ we again set

$$f_{ijr}(v_{ijr}) = \psi_{ij} d_{ij} (\beta / \vartheta \eta)\, C_{fuel} v_{ijr}^2,$$

then, the linear approximation provides

$$\psi_{ij} d_{ij} (\beta/\vartheta\eta)\, C_{fuel} \left((\hat{v}^h_{ijr})^2 + 2\,\hat{v}_{ijr} (v_{ijr} - \hat{v}^h_{ijr}) \right) \le \xi_{ijr}, \quad \forall h, i, j, r. \tag{6.35}$$

and the proof is complete. □

Hence applying the OA algorithm only requires the replacement of ξ_{ijr}, $\forall i, j, r$ on the objective function and the addition of the first constraints of OLP in the form (6.36). The equivalent formulation of the OA's MP can then be given as[2]:

$$\begin{aligned} \underset{\{x_{ijr}, \boldsymbol{q}_i, v_{ijr}\} \in \Omega_2}{\text{Min}} \quad & \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \psi_{ij} d_{ij} \left(E_{ij} s_{ij} \phi + \frac{\alpha_{ijr}\, w}{\vartheta\eta} \right) C_{fuel} x_{ijr} \\ & + \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \psi_{ij} d_{ij} (\alpha_{ij}/\vartheta\eta)\, C_{fuel} \boldsymbol{q}_i \\ & + \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \xi_{ijr} \\ \text{st.} \quad & \end{aligned} \tag{6.36}$$

constraints of (6.30), (6.35)

$$\xi_{ijr} \ge 0, \quad \forall i, j, r \tag{6.37}$$

The OLP's second constraints are not present in formulation (6.36)–(6.37), because all of the constraints are linear, thus making unnecessary to perform an OA of the feasible region.

A sketch of the implemented algorithm is detailed in Algorithm 2, where ε', UB^* and LB^* are the stopping criteria, the objective function value of the current solution, and the objective function optimal value of the OA's MP, respectively.

Algorithm 2 NM-OA

```
0  Initialize with the given values from Algorithm 1
1  Set UB ← +∞, LB ← −∞, $h = 1$, $\boldsymbol{h} = 1$
2  If (UB − LB) < $\varepsilon'$, then stop. Terminate a near-optimal solution has been
   obtained
3  Solve the OA's MP (6.36)–(6.37), obtaining LB$^*$ and the optimal values
   for the variables $x^h$
4  Add an OA cut to the OA's MP using (6.35)
5  Increase $\boldsymbol{h}$
6  If $\boldsymbol{h} > \boldsymbol{C}$ then go to 3
```

---

[2] For practical reasons it is assumed that in a vehicle trip, some of parameters remain constant on a given arc. For instance, we consider that vehicle travel at invariant lower and upper speeds of $\underline{v} = \underline{v}_{ij}$ or $\overline{v} = \overline{v}_{ij}$ (km/h) on arc (i, j) with road angle $\theta = \theta_{ij}$ carrying a total load, or considering $a = a_{ij}$ and subsequently α to be fixed, among others.

```
7  Solve the OA's MP (6.36)–(6.37), obtaining $LB^*$ and the optimal values for the variables $x^h$
8  Add an OA cut to the OA's MP using (6.35)
9  $UB^* = \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \psi_{ij} d_{ij}(\circ)\, C_{fuel} x^h_{ijr} + \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \psi_{ij} d_{ij}(\circ)\, C_{fuel} q_i + \sum_{(i,j)\in\Lambda^+} \sum_{r\in K} \psi_{ij} d_{ij}(\beta/\vartheta\eta)\, C_{fuel} \left(\hat{v}^h_{ijr}\right)^2$
10 If $UB^* < UB^{h-1}$ then set $UB^h = UB^*$
11 Increase $h$ and go to 2
```

At lines 3 and 7 of Algorithm 2, the OA's MP is solved after relaxing and imposing the integrality constraints (6.8), respectively. In lines 3 through 6, OA cut is added to the OA's MP while a given number of cycles C is not reached. The solution time of the OA's MP (line 7) is usually much higher than the SP because of the integrality constraints. A common strategy to short it is to reduce the number of MPs solved by embedding the generation of the OA cut in a standard B&C framework.

6.7 Computational Results

The proposed models have been tested on a large set of instances. Since no instances are available in the literature for our specific problem formulation, we have combined two datasets of benchmark instances introduced by Aghezzaf et al. (2006) and Bektaş and Laporte (2011) for the IPRP. Each instance set is of a different nature, characterized by the average number of vehicles (minimum number required based on load), and load. All instances are available for downloading from www.apollo.management.soton.ac.uk/prplib.htm.

Hereby, we explain the design of these experiments. Experiments were run with data generated as realistically as possible. Three classes of problems with cities were generated, where each class includes 10 instances and nodes represent United Kingdom cities. All experiments were performed with a single vehicle having a curb weight of three tonnes (implying it could carry goods weighing approximately the same amount). It is considered that the single-vehicle case in the analyses since any savings obtained with one vehicle translate into similar savings for several vehicles. Analyses were carried out for cases where customer demands are initially generated randomly according to a discrete uniform distribution on the interval [130, 150].

All experiments were conducted on a server with 2.13 GHz and 3 GB RAM. We used CPLEX with its default settings as the optimizer to solve the lower level integer linear programming model and the solver was allowed to run its B&C in a parallel mode (up to four threads) to enhance the solution process. A common time-limit of 2 h was imposed on the solution time of all instances.

To assess the quality of NM-OA algorithm, we have compared our algorithm with the LP-Metric standard B&B method. In Tables 6.2 and 6.3, we present the computational results on the instances with 75 and 100 nodes, respectively. Ten separate runs were performed for each instance as done by B&B, the best of which is reported. For each instance, a boldface entry indicates a new best-known solution.

As seen the first column displays the instances. The other columns show the total cost (TC) in £, percentage deterioration in solution quality (Dev.) with respect to the B&B method, and the optimal speed in km/h (Speed). The rows named Avg., Min (%) and Max (%) show the average results, as well as minimum and maximum percentage deviations across all benchmark instances, respectively.

Table 6.2 Computational results on the 75-node PRP instances

Instance	B&B		NM-OA		
	TC	Speed	TC	Dev.	Speed
UK75-1	1213	51.5	**1225**	−0.98	54.4
UK75-2	1180	51.6	**1161**	1.64	54.7
UK75-3	1105	53.5	**1093**	1.10	55.3
UK75-4	1118	52.5	**1098**	1.82	55.1
UK75-5	1055	52.7	**1045**	0.96	54.9
UK75-6	1226	52.2	**1203**	1.91	54.8
UK75-7	1072	51.7	**1057**	1.42	54.5
UK75-8	1119	53.5	**1105**	1.27	55.7
UK75-9	1027	52.6	**1004**	2.29	55.0
UK75-10	1089	53.3	**1075**	1.30	55.6
UK75-11	1222	51.8	**1213**	0.74	54.1
UK75-12	1065	53.4	**1042**	2.21	55.6
UK75-13	1167	51.5	**1144**	2.01	53.5
UK75-14	1277	51.5	**1253**	1.92	54.3
UK75-15	1328	51.9	**1323**	0.38	53.9
UK75-16	1017	54.3	**999**	1.80	56.0
UK75-17	1297	52.6	**1269**	2.21	54.2
UK75-18	1118	51.5	**1101**	1.54	54.2
UK75-19	1057	51.5	**1036**	2.03	54.2
UK75-20	1275	53.4	**1262**	1.03	55.2
Ave.	1151	52.4	1135	1.43	54.8
Min (%)				−0.98	
Max (%)				2.21	

Table 6.3 Computational results on the 100-node PRP instances

Instance	B&B		NM-OA		
	TC	Speed	TC	Dev.	Speed
UK100-1	2124	62.1	**2079**	2.10	64.2
UK100-2	2001	67.0	**1965**	1.76	65.8
UK100-3	2030	56.7	**2008**	1.06	60.4
UK100-4	1946	56.9	**1918**	1.45	59.5
UK100-5	2195	65.4	**2164**	1.41	66.8
UK100-6	1895	57.5	**1871**	1.26	61.5
UK100-7	2034	65.7	**1986**	2.34	67.9
UK100-8	2129	57.2	**2100**	1.35	59.2
UK100-9	1906	59.2	**1836**	3.71	61.7
UK100-10	2212	58.3	**2179**	1.51	59.8
UK100-11	1953	64.1	**1921**	1.66	66.3
UK100-12	2117	61.9	**2116**	0.03	62.8
UK100-13	2153	57.4	**2106**	2.17	59.4
UK100-14	2023	57.5	**2006**	0.83	60.3
UK100-15	2123	59.0	**2079**	2.04	61.4
UK100-16	2088	57.6	**2036**	2.50	59.7
UK100-17	2230	56.8	**2177**	2.37	59.0
UK100-18	2017	63.2	**2016**	0.05	64.0
UK100-19	1857	66.2	**1816**	2.23	67.5
UK100-20	2163	58.9	**2126**	1.68	61.3
Ave.	2060	60.4	2025	1.68	62.4
Min (%)				0.03	
Max (%)				2.37	

The results clearly show that NM-OA outperforms B&B on all instances in terms of solution quality. The average cost reduction is 1.43 % for 75-node instances, for which the minimum and maximum improvements are 0.98 and 2.21 %, respectively. For 100-node instances, the corresponding values are 1.68 % (average), 0.03 % (minimum) and 2.37 % (maximum). On average, the B&B is faster on the 75-node instances, however, this difference is less substantial on the 100-node instances.

In order to quantify the added value of changing speeds, we have experimented with three other versions of the model in which the speed on all arcs is fixed at 70, 85 or 100 km/h. Table 6.4 presents the results of these experiments. The results suggest that while optimizing speeds with NM-OA yields the best results, using a fixed speed of 100 km/h deteriorates the solution quality by only 1.12 % on average. On the other hand, using a fixed speed of 70 km/h deteriorates the solution value by an average value of 14.01 %.

Table 6.4 The effect of the speed

Instance	70 km/h		85 km/h		100 km/h		NM-OA
	TC	Dev.	TC	Dev.	TC	Dev.	TC
UK100-1	1230	15.52	1119	7.11	1044	0.48	1039
UK100-2	1167	13.00	1056	3.91	1031	1.56	1015
UK100-3	1079	13.59	994	6.27	949	1.75	932
UK100-4	1139	11.86	1040	3.46	1008	0.32	1004
UK100-5	1100	14.23	1019	7.44	952	0.88	944
UK100-6	1211	13.29	1112	5.52	1053	0.23	1050
UK100-7	1090	15.12	1006	7.98	947	2.27	925
UK100-8	1140	16.12	1034	7.47	1000	4.30	957
UK100-9	1072	15.72	975	7.43	912	0.95	903
UK100-10	1151	13.03	1068	6.22	1012	1.08	1001
UK100-11	1210	13.45	1103	5.07	1054	0.69	1047
UK100-12	1036	13.86	954	6.53	893	0.10	892
UK100-13	1167	13.19	1066	4.99	1029	1.59	1013
UK100-14	1236	13.85	1124	5.30	1081	1.54	1064
UK100-15	1264	13.26	1169	6.24	1105	0.80	1096
UK100-16	1079	13.20	992	5.58	939	0.28	936
UK100-17	1267	15.58	1145	6.62	1075	0.57	1069
UK100-18	1104	15.31	1004	6.89	955	2.12	935
UK100-19	1085	13.68	997	6.04	945	0.84	937
UK100-20	1235	13.40	1133	5.61	1071	0.07	1070
Ave.	1153	14.01	1056	6.08	1003	1.12	991
Min (%)		11.86		3.46		0.07	
Max (%)		16.12		7.98		4.30	

6.8 Concluding Remarks

This chapter studied a variant IRP model, Inventory Pollution-Routing Problem (IPRP), in an environment with uncertain demand characteristic. An optimization model was presented in which a cost-minimization objective function was formulated as a mixed-integer nonlinear programming problem. An appropriate solution algorithm was developed. The algorithm can be utilized as a useful tool for optimizing both linear and nonlinear Vehicle Routing Problem (VRP) functions. The effectiveness of the algorithm was investigated through a set of computational tests comparing its performance with that of the LP-Metric standard B&B approach in terms of the solution quality.

We observed in this chapter that considering economic and environmental performance measures in isolation can result in varying solutions. There are however tradeoff solutions where environmental performance can be significantly improved at a minimal logistics cost increase. The development and application of

IPRP models in which carbon emissions are implicitly or explicitly incorporated will be of increasing importance in the future, especially as tighter environmental regulations with respect to excessive transport emissions come into force. The availability of decision tools and optimization models, like what we presented in this chapter, can help companies and their supply chains more effectively tackle current and future regulatory mandates, enhance their competitive positioning, and take further steps towards the development of greener supply chains.

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Appendix

Fuzzy Number

The theory of fuzzy sets introduced by Zadeh (1965) was developed to describe vagueness and ambiguity in the real world system. Zadeh defined a fuzzy set $\tilde{a}$ in a universe of discourse $\boldsymbol{X}$ as a class of objects with a continuum of grades of memberships. Such a set is characterized by a membership function $\mu_{\tilde{a}}(x)$ which associates with each point x in $\boldsymbol{X}$ a real number in the interval [0,1]. $\mu_{\tilde{a}}(x)$ represents the grade of membership of x in $\tilde{a}$. A fuzzy set $\tilde{a}$ in the universe of discourse R (set of real numbers) is called a fuzzy number if it satisfies the following conditions:

(i) $\tilde{a}$ is normal i.e. there exists at least one $x \in \mathrm{R}$ such that $\mu_{\tilde{a}}(x) = 1$.
(ii) $\tilde{a}$ is convex.
(iii) the membership function $\mu_{\tilde{a}}(x), x \in \mathrm{R}$ is at least piecewise continuous.

Triangular Fuzzy Number

Triangular fuzzy number (*TFN*) $(\tilde{a})$ is the fuzzy number with the membership function $\mu_{\tilde{a}}(x)$, a continuous mapping: $\mu_{\tilde{a}}(x) : \mathrm{R} \rightarrow [0,1]$, where

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & \{-\infty < x < a_1\} \\ \frac{x-a_1}{a_2-a_1} & a_1 \leq x < a_2 \\ \frac{a_3-x}{a_3-a_2} & a_2 \leq x \leq a_3 \\ 0 & a_3 < x < \infty. \end{cases} \tag{6.38}$$

α-Cut of a Fuzzy Number

An α-cut of a fuzzy number $\tilde{a}$ is defined as a crisp set

$$a_\alpha = \{x \colon \mu_{\tilde{a}}(x) \geq \alpha, \quad x \in \mathrm{R}\} \quad \text{where}\, \eta\ [0, 1].$$

Approximate Value of Triangular Fuzzy Number (TFN)

According to Kaufmann and Gupta (1991), the approximated value of TFN $\tilde{a} \equiv (a_1, a_2, a_3)$ is given by $\hat{a} = 1/4(a_1 + 2a_2 + a_3)$.

Algebraic Operation of Fuzzy Numbers

Addition

Let $\tilde{a} \equiv (a_1, a_2, a_3)$ and $\underline{\tilde{b}} \equiv (b_1, b_2, b_3)$ be two triangular fuzzy numbers. Using max-min convolution on fuzzy numbers $\tilde{a}$ and $\tilde{b}$ the membership function of the resulting fuzzy number $\tilde{a}\,(+)\,\tilde{b}$ can be obtained as $\vee_{z=x+y}\left(\mu_{\tilde{a}}(x) \wedge \mu_{\tilde{b}}(y)\right)$, $\forall_{x,y,z} \in$ R where the symbols '$\wedge$' and '$\vee$' are used for minimum and maximum, respectively. In short we can write $\tilde{a}\,(+)\,\tilde{b} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3)$.

Scalar multiplication For any real constant t,

$$t\tilde{a} = \begin{cases} (ta_1, ta_2, ta_3) & t \geq 0 \\ (ta_3, ta_2, ta_1) & t < 0. \end{cases}$$

Fuzzy Possibility Techniques

Let $\tilde{a}$ and $\tilde{b}$ be two fuzzy quantities with membership functions $\mu_{\tilde{a}}(x)$ and $\mu_{\tilde{b}}(y)$, respectively. Then according to Dubois and Prade (1980), Liu and Iwamura (1998a, b) $pos\left(\tilde{a} * \tilde{b}\right) = \sup\left\{\min\left(\mu_{\tilde{a}}(x), \mu_{\tilde{b}}(y)\right) \colon x, y \in \mathrm{R},\ x * y\right\}$, where the abbreviation '*pos*' represents possibility and * is any of the relations <, >, =, ≤, ≥.

If $\tilde{a}$ and $\tilde{b}$ are two fuzzy numbers defined on R and $\tilde{u} = f(\tilde{a}, \tilde{b})$ where $f \colon \mathrm{R} \times \mathrm{R} \rightarrow \mathrm{R}$ is a binary operation then the membership function $\mu_{\tilde{u}}$ of $\tilde{u}$ is defined as $\mu_{\tilde{u}}(u) = \sup\{\min(\mu_{\tilde{a}}(x), \mu_{\tilde{b}}(y)) \colon x, y \in \mathrm{R}$ and $u = f(x,y)$, $\forall u \in \mathrm{R}\}$.

Random Variable

Let $\underline{L}\,(=(m,\sigma^2))$ be a continuous random variable with probability density function (PDF) $f_{\underline{L}}(l)$ whose mean and variance are m and σ^2, respectively. Similarly, let $\underline{L'}\,(=(m',\sigma'^2))$ be another random variable with pdf $f_{\underline{L'}}(l')$. If $\underline{L}$ and $\underline{L'}$ are two independent random variables, then we have the following algebraic operations:

Addition:

$$\underline{L}_1[+]\underline{L}_2 = (m_1,\sigma_1^2)[+]\,(m_2,\sigma_2^2) = \,(m_1+m_2,\sigma_1^2+\sigma_2^2).$$

Here, according to sum-product convolution $\underline{\boldsymbol{L}}(=\underline{L}+\underline{L'})$ is a random variable with the same type of pdf $f_{\_\boldsymbol{L}}(\boldsymbol{l}) = (\int_{\mathrm{R}} f(\boldsymbol{l}-l')f'(l')dl'$ with mean $\boldsymbol{m}'^2(=m^2+m')$ and variance $\boldsymbol{\sigma}'^2(=\sigma^2+\sigma'^2)$.

Scalar multiplication:

$t\underline{L} = (tm, t^2\sigma^2)$. Here tL and L have the same type of PDF.

Hybrid Number (Kaufmann and Gupta 1991)

Assume $\tilde{A}(=(\tilde{A},\underline{L}))$ is a hybrid number. Here the couple $(\tilde{A},\underline{L})$ represents the addition to a fuzzy number with a random variable without altering the characteristic of each one and without decreasing the amount of available information where $\tilde{A}$ is a fuzzy number and $\underline{L}$ is the random variable with density function $f_{\underline{L}}(l)$.

Let $\underline{\tilde{A}}(=(\tilde{A},\underline{L}))$ and $\underline{\tilde{A}}'(=(\tilde{A}',\underline{L'}))$ be two hybrid numbers in R where $f_{\underline{L}}(l)$ and $f_{\underline{L'}}(l')$ are the pdfs of L and L', respectively. So a hybrid convolution for addition will be defined as $(\tilde{A},\underline{L})\oplus(\tilde{A}',\underline{L'}) = (\tilde{A}(+)\tilde{A}',\underline{L}[+]\underline{L'}) = (\tilde{\boldsymbol{A}},\underline{\boldsymbol{L}})$, where (+) represents the max-min convolution for addition of fuzzy subsets and [+] represents the sum-product convolution for addition of random variables. We denote the couple $(\tilde{\boldsymbol{A}},\underline{\boldsymbol{L}})$ by the symbol $\tilde{\boldsymbol{A}}(+)'\underline{\boldsymbol{L}}$.

So, $\mu_{\tilde{A}_1(+)\tilde{A}_2}(z) = \vee_{z=x+y}(\mu_{\tilde{A}_1}(x)\wedge\mu_{\tilde{A}_2}(y)), \forall x,y,z\in \mathrm{R}$ and $f(l) = \int_{\mathrm{R}} f_1(l-l_2)f_2(l_2)dl_2$ or $\int_{\mathrm{R}} f_1(l_1)f_2(l-l_1)dl_1$.

Note 1 A fuzzy number is a special case of a hybrid number if $\underline{\tilde{A}} = (\tilde{A},\underline{0})$, where $\underline{0}$ is the trivial random variable with the following probabilities:

$$\begin{aligned} P(l) &= 1, \quad l = 0 \\ &= 0, \quad l \neq 0. \end{aligned}$$

Note 2 A random variable is also a special case of a hybrid number if $\underset{\sim}{L} = (\tilde{0}, \underline{L})$, where $\tilde{0}$ is the trivial fuzzy number with membership function

$$\begin{aligned} \mu_{\tilde{0}}(x) &= 1, \quad x = 0 \\ &= 0, \quad x \neq 0. \end{aligned}$$

Note 3 $\underset{\sim}{0} = (0, 0)$ is the neutral for addition of hybrid numbers.
If $\tilde{u}_1$ is a fuzzy cost, $\underline{u}_2$ is a random cost and u_3 is a fixed cost then the total cost can be expressed as

$$\tilde{u}_1[+]\underline{u}_2[+]u_3 = (\tilde{u}_1, 0)\,[+]\,(0, \underline{u}_2)\,[+]\,(0, u_3) = (\tilde{u}_1, \underline{u}_2(+)'u_3) = (\tilde{u}_1(+)u_3, \underline{u}_2)\,. \tag{6.39}$$

We can consider the fixed number like a sum of two parts $u_3 = u_3' + u_3''$ and write for (6.39)

$$\tilde{u}_1[+]\underline{u}_2[+]u_3 = (\tilde{u}_1[+]u_3', \underline{u}_2[+]u_3''). \tag{6.40}$$

The mathematical expectation of a hybrid number is defined as follows.
A function $\phi(x)$ in R that is nonnegative and monotonically increasing is:

$$\begin{aligned} &\forall x_1, x_2 \in \mathrm{R}: \\ &(x_1 > x_2) \Rightarrow (\varphi(x_2) \geq \varphi(x_1))\,. \end{aligned} \tag{6.41}$$

For a closed interval of R, $[a_\alpha^1, a_\alpha^2]$ we have:

$$[\phi\,(a_\alpha^1), \phi\,(a_\alpha^2)] \subset \mathrm{R} \tag{6.42}$$

and for $l \in \mathrm{R}$:

$$[\phi\,(a_\alpha^1 + l), \phi\,(a_\alpha^2 + l)] \subset \mathrm{R}. \tag{6.43}$$

If l is the value of the random variable L, the lower and upper bounds of (6.43) depend only on l for a given level α. The mathematical expectation for each bound is now computed:

$$E[\phi\,(a_\alpha^1 + l), \phi\,(a_\alpha^2 + l)] = \left[\int_{l_1}^{l_2} \phi(a_\alpha^1 + l) \cdot f(l)dl, \int_{l_1}^{l_2} \phi(a_\alpha^2 + l) \cdot f(l)dl \right]. \tag{6.44}$$

Theorem (Kaufmann and Gupta 1991). The membership function of the mathematical expectation of a hybrid number $(\tilde{A}, \underline{L})$ is the membership of $\tilde{A}$ shifted by the mathematical expectation of $\underline{L}$

Proof Using the intervals of confidence of level α:

$$\begin{aligned} E_\alpha(\tilde{A}[+]\underline{L}) &= \left[\int_{l_1}^{l_2} (a_\alpha^1 + l) \cdot f(l)dl, \int_{l_1}^{l_2} (a_\alpha^2 + l) \cdot f(l)dl\right] \\ &= \left[a_\alpha^1 \cdot \int_{l_1}^{l_2} f(l)dl + \int_{l_1}^{l_2} l \cdot f(l)dl, a_\alpha^2 \cdot \int_{l_1}^{l_2} f(l)dl + \int_{l_1}^{l_2} l \cdot f(l)dl\right] \\ &= \left[a_\alpha^1 + E(l)\,,\, a_\alpha^2 + E(l)\right] \end{aligned} \tag{6.45}$$

Hence, in a hybrid sum, if the random variables satisfy their random expectation, they will have the same effect as ordinary numbers, shifting the sum of fuzzy numbers. □

Using the notation $(\tilde{A}, \underline{L}) = \tilde{A}(+)'\underline{L}$, where $\tilde{A}$ is a triangular fuzzy number, the following example is illustrated.

Example Let $\tilde{A}_1 = (3, 5, 9)(+)'(6, 1.2)$ and $\tilde{A}_2 = (6, 7, 10)(+)'(7, 1.8)$ be two hybrid numbers, then

$$\begin{aligned} \underline{\tilde{A}}_1 \oplus \underline{\tilde{A}}_2 &= [(3, 5, 9)(+)'(6, 1.2)] \oplus [(6, 7, 10)(+)'(7, 1.8)] \\ &= [(9, 11, 15)(+)'(0, 1.2)] \oplus [(13, 14, 17)(+)'(0, 1.8)] \\ &= (22, 25, 32)(+)'(0, 3.0). \end{aligned}$$

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Chapter 7
Vehicle Orientated Initiatives for Improving the Environmental Performance of Urban Freight Systems

Russell G. Thompson

Abstract Freight vehicles contribute a substantial amount to the environmental impacts within cities. There are several emerging engine and alternative fuel technologies that have the potential to reduce the fossil fuel consumption as well as to improve the air quality within urban areas. Larger capacity vehicles allow more freight to be carried with less vehicles and can significantly reduce the amount of freight traffic and emissions. City Logistics schemes provide an opportunity for promoting innovative vehicle technologies. Partnerships between the public and private sectors can lead to solutions that lower the environmental and financial costs for freight transport. This chapter outlines a range of technologies and city logistics schemes that can improve the environmental performance of urban freight systems.

Keywords Alternative fuel vehicles · Performance based standard vehicles · City logistics

7.1 Introduction

Freight vehicles produce a significant amount of emissions that can lead to serious health impacts due to the high level of exposure to populations living and working in urban areas. Goods vehicles contribute between 16 and 50 % of vehicle emissions in urban areas (Dablanc 2007). Recently there has been substantial innovations in alternative fuels, the utilisation of different transport modes and larger capacity trucks as well as a number of City Logistics schemes that can significantly reduce the air quality impacts from freight vehicles operating in cities.

Air quality is influenced by the emissions produced per vehicle kilometre as well as the vehicle kilometres travelled. Emissions per vehicle kilometre depends on characteristics of vehicles such as the mode of transport, type of fuel, vehicle engine

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emission standards and load capacity as well as the operating conditions such as travel speed and the weight of the goods being carried. Vehicle kilometres travelled depends on the nature of the freight networks such as the location of terminals and customers as well as the demand for goods to be transported.

To deal with challenges, a major international study on urban distribution recommended that, “Cleaner, low noise and more energy-efficient vehicles need to be promoted” (OECD 2003: 14). A number of vehicle innovations including environmentally friendly and energy efficient engines and delivery-suited vehicle designs were identified for promotion. City Logistics was also identified in this study as offering opportunities for sustainable urban goods transport. There have been numerous successful implementations of vehicle orientated initiatives aimed at reducing emissions in many European cities (BESTUFS 2007; BESTFACT 2014).

The energy consumption and emissions of freight vehicles should be considered over their life to fully understand the total environmental costs associated with their operations. The components of the life cycle of a vehicle involves the energy, material, process and service inputs being considered through a vehicles design, production, use and end-of-life stages.

Life Cycle Analysis (LCA) has been largely based on a process approach making it difficult to include upstream manufacturing and materials requirements. In addition to the use of a vehicle it is important to consider the end-of-life phases. The supply chains associated with the vehicles manufacturing as well as the disposal of the vehicles also need to be examined. The resources consumed and the environmental discharges for components of a vehicle’s lifecycle, including the fuel cycle (exploration and production, refinery, petroleum marketing and vehicle refuelling), vehicle servicing (parts and fluids, raw material and labour) as well as manufacture, vehicle use, fixed costs and disposal also needs to be considered.

Upstream and downstream processes such as energy production, vehicle production and maintenance as well as infrastructure construction and maintenance should be considered in the environmental assessment of freight vehicles. Energy production effects are those associated with the generation and distribution of fuel before combustion. Vehicle production effects relate to the entire supply chain of vehicles, including all components used in manufacturing as well as ongoing maintenance. Infrastructure effects involve the impacts on the natural and social systems from construction and maintenance of facilities required to operate vehicles.

The complete life cycle (design, production, use and end-of-life) of infrastructure and fuels as well as vehicles have been included in a more comprehensive life cycle analysis of transport modes (Chester and Horvath 2007). Analysis of emissions typically focuses on the tailpipe, ignoring factors such as the resource requirements and the pollution generated from the production of vehicles and their fuels as well as the development of infrastructure. Total energy inputs and greenhouse gas emissions have been estimated to contribute an additional 63 % over vehicle tailpipe operations for on-road vehicles (Chester and Horvath 2009).

The fuel consumption and emissions associated with the use of freight vehicles depends largely on the age and type of the vehicle, its power or energy supply, as well as its driving characteristics. Fuel consumption for petroleum powered internal combustion engines (ICE) is largely dependent on the engine size and the driving cycle. Higher levels of acceleration and braking in urban areas leads to higher fuel consumption compared to that of rural driving.

7.2 Alternative Fuel Vehicles

Alternative Fuel Vehicles (AFVs) provide an opportunity for reducing harmful vehicle emissions that can improve health and reduce greenhouse gases. There are a number of alternative fuels (e.g. CNG, LPG, Biofuels, Hybrid Electric and Electric) and trucks currently available that have the potential to reduce environmental impacts as well as the financial costs of freight transport.

AFVs can produce less pollution for goods delivery. For example, gas-fuelled, using Liquefied Petroleum Gas (LPG) or Compressed Natural Gas (CNG), using biofuels, using hydrogen, where the hydrogen combustion takes place in a typical piston engine compartment, or using fuel cells that produce energy as a result of oxidation of the fuel constantly supplied from outside, using the hybrid drive which is a combination of a traditional engine and an electric motor), can reduce pollution from freight transport.

Although many companies are committed to reducing their emissions as part of their corporate social responsibility agenda, they have limited knowledge and skills to rigorously evaluate the range of AFVs available. Procedures for assessing the financial as well as the environmental costs and benefits of incorporating AFV into specific transport fleets need to be developed.

It is important that case studies are undertaken and disseminated to promote the adoption of AFVs. Experiences need to be accessible to small operators, who comprise a substantial proportion of carriers and often lack the expertise and experience necessary to undertake rigorous evaluation.

The financial competitiveness of alternative fuel freight vehicles against conventional fuels such as diesel and petroleum needs to be assessed. Fleet managers need to consider a range of financial costs, incorporating capital, operating and maintenance as well as the salvage costs within demand, vehicle age and budgetary constraints. Maintenance costs are uncertain with many AFVs and the accessibility of refuelling stations can be a major issue relating to their efficiency.

Electric vans and trucks reduce tailpipe emissions in urban areas but the electricity consumed by the vehicles can add to CO_2 emissions. Although electric vehicles have lower operating costs compared to conventional vehicle they tend to have higher capital costs. The financial evaluation of electric vehicles requires consideration of capital, operating and maintenance costs. Currently there is much uncertainty associated with the depreciation and salvage costs for electric vehicles. Electric trucks will become competitive when the cost savings from the reduced operational cost are sufficient to overcome the significantly higher initial purchase costs. The viability of electric trucks can be increased when the utilisation of vehicles is high.

Electric vehicles can have a number of performance issues such as range, speed and acceleration although recent trails in London and Utreche have been promising. A cooperative system of electric vans was trialled in Osaka (Taniguchi et al. 2000). Vans were able to be booked on the internet for distributing goods and they could be dropped off at a car park near the destination, without the need to return to the origin car park. This system reduced empty running and allowed the recharging infrastructure to be rationalised. Electric vans and tricycles were recently trialled in delivering stationary and office supplies from a small consolidation centre in London, resulting in an estimated 54 % reduction in CO_2eq emissions per parcel delivered (Browne et al. 2012; Leonardi et al. 2012).

7.3 Larger Capacity Vehicles

The Performance Based Standards (PBS) scheme that operates in Australia allows innovative vehicle designs by stipulating what freight vehicles must be able to attain in terms of their safety and infrastructure protection performance compared to prescriptive limits associated with their physical weights and dimensions (OECD 1995; Di Christoforo et al. 2006; NTC 2008). Although the PBS scheme was implemented to increase the productivity, efficiency and safety of road freight vehicles it has led to reduced environmental impacts.

Freight vehicles deliver goods to specific locations in their respective types of networks. In urban areas, quite dense networks with several hundred customers are common. When fleet operations managers incorporate PBS vehicles into their fleets due to the enhanced capability of these vehicles, extra volume and/or extra mass can be transported usually allowing fewer trips, therefore fewer kilometres and fewer trucks to deliver goods. Utilizing PBS vehicles in a network generally leads to a reduction in the total network kilometres and the number of vehicles needed to undertake deliveries. Typically the metrics that reflect the physical productivity of PBS adoption are, total kilometres travelled, total hours of operation and individual fleet vehicle numbers.

A number of PBS vehicle types were identified as having substantial productivity gains in urban freight operations (Hassall and Thompson 2011), including two axle and three axle rigid trucks, Super B Doubles, A Doubles and single semi-trailers (19–20 m). Under PBS rigid trucks can add 1 m to their body length for volumetric operations, as well as 3 axle rigid vehicles extending dimension to under 15 m with a fourth axle. Super B-doubles can replace single articulated trucks in urban areas largely associated with container transport. This is attractive for both the hire and reward and large ancillary operators. They are especially useful for container movements, providing capacity for two, 40 foot shipping containers. Two axle and three axle rigid trucks as well as single semi-trailers operating under PBS are able to operate on general access roads (level 1). However, Super B Doubles and A Doubles are restricted to level 2B roads. Even so, these are becoming common in urban areas in Australia.

Case studies have been used to estimate the productivity gains from operating PBS vehicles in urban areas (Hassall and Thompson 2012). A range of PBS vehicles were identified as being suitable for urban freight operations including Super B-doubles and rigid trucks. Substantial benefits are being achieved by the take-up of PBS vehicles in urban freight networks. This leads to a lowering of several key freight exposure metrics, including kilometres, trips, task travel times and vehicle numbers.

In urban areas, it has been estimated that PBS vehicles can achieve on average, a 19.1 % reduction in vehicle kilometres travelled and a 21 % reduction in the number of vehicles (Hassall and Thompson 2011). These savings are due to the increase in the carrying capacity (both weight and volumetric) of PBS vehicles. This leads to a substantial reduction in fuel consumption and CO_2 emissions. Additional benefits are also achieved from reduced congestion.

7.4 City Logistics Schemes

A number of the City Logistics schemes described in Chap. 4 promote the adoption of more environmentally friendly freight vehicles as well as increasing the efficiency of urban distribution systems. City Logistics schemes typically require partnerships between the public and private sector. This section briefly describes how urban consolidation centres, off hour deliveries and low emission zones can be implemented to reduce the environmental impacts of goods movement in cities.

7.4.1 Urban Consolidation Centres

Urban consolidation centres (UCCs) are logistics facilities that are located in relatively close proximity to the receivers where goods are dropped off, sorted and consolidated for the final stage of delivery (Browne et al. 2005). UCCs often involve joint delivery systems that are undertaken using low emission vehicles.

A joint delivery centre and distribution system using low emission (CNG) vehicles has been operating in the Motomachi Shopping Street in Yokohama, Japan since 2004 (PIARC 2012). The number of trucks entering this area has been reduced from 100 to 29. This scheme has improved the air quality of the roadside environment. Specific parking stations (Eco-Cargo-Areas) have been created for trucks with the final stage of deliveries to shops being performed by hand carts. A recent trial in London involved electric-assisted bikes and electric vans replacing diesel vans for distributing stationary and office supplies in conjunction with an urban consolidation centre (Leonardi et al. 2012).

7.4.2 Off Hour Deliveries

Since traffic congestion has been found to lead to substantial increases in CO_2 emissions for freight vehicles, shifting deliveries to the off hours can lead to a significant reduction in fuel consumption and emissions from freight carriers (Holguín-Veras et al. 2011). To facilitate off-hours deliveries a number of vehicle related technologies for controlling noise can be implemented such as low noise engines, lift platforms and handling equipment such as carts. Noise absorbing coating within vehicles also reduces noise from unloading and loading operations (NSF 2013). Driver education programs can also reduce the noise produced from vehicles whilst performing deliveries. The PIEK certification program was developed to promote technologies for reducing noise levels for night deliveries (SUGAR 2011).

7.4.3 Low Emission Zones

Low emission zones (LEZs) aim to promote the operation of cleaner vehicles, and reduce the number of older, more polluting vehicles operating in central city areas. LEZs are common in Western European cities (SUGAR 2011). Although LEZs can result in improvements in air quality inside designated cordons, it can lead to higher polluting vehicles being transferred to operations in other areas (Ellison et al. 2013). LEZs however can stimulate carriers to renew their fleets and invest in newer cleaner freight vehicles.

7.5 Different Modes

There is a wide range of transport modes other than trucks and vans that are being implemented to reduce the environmental impacts of freight in cities. Rail, trams and barges are becoming popular in some cities. Although these modes typically need to be combined with road freight vehicles and require transhipment, they can relieve congestion and lower emissions from freight transport.

The successful utilisation of rail and waterway systems for urban goods distribution has been largely based on situations where there is normally a high flow of goods and existing facilities can be utilised. Deliveries using alternative modes often result in reduced environmental costs from mode substitution as well as less congestion from larger vehicles using the road for travel and parking. Recently, there has been increased interest in exploiting the environmental benefits associated with rail transport (e.g. cargo trams and using underground rail systems for cargo transport), inland waterway shipping and bicycle transport as alternative forms of delivery.

Multi-modal networks combine rail, tram or barge transport with trucks and vans to reduce the impacts of freight in urban areas. In Zurich, cargo trams are used to transport bulky and e-waste from collection centres to waste disposal centres where the waste is sorted for recycling (SUGAR 2011).

7.5.1 Bicycles

Using bicycles for urban distribution is being rediscovered in many cities and was recently recognised by Time Magazine as one of the 10 big ideas in transportation (Sanburn 2013). There are a number of advantages associated with bike couriers in urban areas including reliability and speed as well as reduced fossil fuel consumption and CO_2 emissions. Electric bikes can be used to increase the range of operations. It has been estimated that 6 t of CO_2 per year could be saved for every van replaced using bike couriers (Maes and Vanelslander 2012).

7.5.2 Rail

There are some recent examples of rail and barge transport being used for freight transport in urban areas. Waste is transported by rail across Tokyo. A daily train service is used to transport goods to a terminal located in central Paris for distribution to Monprix shops. CNG trucks are then used for the final distribution of pallets to stores (SUGAR 2011; Diziain et al. 2014).

7.5.3 Waterways

Waterways are increasingly being used within cities to reduce road freight transport. Some examples include construction materials in Paris as well as waste and petroleum in Tokyo. A combined barge and electric bicycle delivery system has been operating on the Seine River in Paris since 2012 where cargo bikes are loaded on barges and directly transferred to areas of Paris to deliver parcels, clothing and pharmaceutical products.

7.5.4 Co-modality

There is increasing interest in utilising existing passenger transport systems for urban freight. This can reduce the environmental impacts associated with urban distribution. Sharing passenger vehicles for freight transport is becoming more common.

Co-modality involves the use of alternative modes for increasing the efficiency and sustainability of transport systems (Commission of the European Community 2006). Recently public transport systems have been considered for urban freight transport. Integrating passenger and freight transport systems is becoming more feasible due to developments in information and communication technologies (ICT), such as smart phones and global position systems (GPS).

A combination of passenger and freight transport can be realized using buses or taxies for carrying goods as well as passengers. Passenger transport companies can benefit from carrying goods by utilizing space on less crowded vehicles and shippers benefit by having a convenient courier service as an option (Thompson and Taniguchi 2014).

A pilot test was successfully conducted using the subway system to transport parcels to the central area of Sapporo, Japan (Kikuta et al. 2012). Parcels are delivered in Kyoto using conventional trams (Diziain et al. 2014).

Uber frequently runs special offers to deliver certain items within a service area, sometimes themed (e.g. roses on Valentines Day and ice creams in summer). Uber has also moved into offering short-distance cycle and foot courier services in New York City.

7.6 Fleet Operator Recognition Scheme

The Fleet Operator Recognition Scheme (FORS) in London is a project that provides advice to transport operators on safety, fuel use, parking infringement notices as well as vehicle and fleet performance. The FORS is an accreditation scheme aimed at improving freight delivery in London. It facilitates discounted equipment, training and business services for operators. It provides a recognised standard of behaviour that encourages improvements in delivery operations. Currently approximately 39 % of London's regular freight fleet comprising over 1500 companies, operating over 128,000 vehicles are members of this scheme. There is a 35/65 % split between vans and trucks.

The FORS is a funded, voluntary certification scheme aimed at ensuring that fleet operators work lawfully and to best practice by meeting the FORS standard. Accreditation demonstrates to current and prospective customers that operators work to standards above the legal minimum. Access to a range of benefits is provided by the FORS that can provide a competitive advantage. It has three levels which reward excellence: bronze, silver and gold. FORS standards are based upon lawfulness, safety, efficiency, and environmental protection. The standards cover management, vehicles, drivers and operations.

A range of information, tools and training opportunities are provided to assist freight carriers to become safer, greener and more efficient. Tools and advice for reducing fuel consumption and emissions, and to reduce road risks are available. This includes procedures for the evaluation of alternative fuel vehicles, monitoring and benchmarking fuel usage. Advice on how to reduce parking infringement notices by improved understanding of regulations and best parking practice is provided.

Training programs are also offered by the FORS to develop a performance management system, including defining company goals and opportunities for saving money through increasing efficiency. A monitoring system, based on a spreadsheet toolkit, can be used to improve fuel consumption and log incident information. A range of performance management workshops are provided, including efficient fleet management, reducing fuel use and minimising environmental impacts as well as monitoring and measuring road fleet performance.

The FORS also offers a number of computer based driver training resources as well as a range of exclusive offers and discounts on leading safety products that are available to FORS accredited companies. Accreditation allows an operator to display the FORS logo on their vehicle, website, headed paper and any other corporate material they choose.

The City of London Corporation who provide local government services for the financial centre of Britain, after joining the FORS introduced daily vehicle defect check books so that issues could be highlighted and dealt with immediately, along with training documents for drivers on mobile phone use. They were able to reduce their fuel use by a third over the past three years, as a result of better fuel management and using their existing fleet more efficiently and introducing alternative fuel vehicles.

7.7 Delivery Service Plans

Delivery Service Plans (DSPs) are an initiative in London that provides a framework for improving the efficiency of deliveries. Organisations prepare their own DSP using guidelines related to a specific site. DSPs aim to reduce the number of deliveries, improve safety and increase compliance with parking regulations. There are many benefits for receivers, including saving time and money as well as improving the reliability and safety of deliveries. There are also wider benefits from the reduced impact on the environment through less vehicles and congestion. DSPs involve the consideration of all freight and service vehicles visiting a site, including trips for deliveries, services, cleaning and waste removal, catering and vending.

DSPs require a plan to be documented with objectives and action items. This involves describing the current situation by collecting data about existing deliveries. A review of business operations, including procurement processes, supply chain operations and site assessment is also undertaken. Options for more efficiently managing deliveries are then considered. This may entail implementing a delivery booking system, encouraging more deliveries outside of normal working hours, establishing a centralised ordering system or consolidating the number of suppliers. Strategies for cooperatively working with suppliers, other tenants or neighbours are promoted. DSPs also include ideas for supporting carriers to improve the performance of their operations such as encouraging them to join the Freight Operators Recognition Scheme (FORS) as well as using consolidation centres and alternative fuel vehicles.

The Transport for London's Surface Transport Directorates have occupied the Palestra Building, at Blackfriars Road, Southwark London since 2008. So far, by developing a DSP, overall deliveries have been reduced by 20 %, with catering supplies, stationary supply and archive/records deliveries reducing by 40 %. Deliveries made to this site by FORS-registered operators are now 33 %. There has also been a significant increase in materials recycling and reduction in waste generated.

7.8 Conclusions

There are a number of emerging vehicle engine related technologies such as electric vans as well as alternative fuels that can reduce emissions from freight vehicles. Larger capacity trucks can also reduce the amount of freight movements. Bicycles, railways, waterways and public transport systems are also providing opportunities for lowering the environmental impacts of goods movement in cities.

City Logistics schemes such as urban consolidation centres and low emission zones can be a catalyst for promoting alternative fuel vehicles as well as reducing the amount of freight vehicle movements. Night deliveries allow more efficient distribution to be undertaken and reduce congestion during peak periods. Partnerships between public and private sectors are necessary for developing and implementing City Logistics schemes as well as fostering best practice for reducing the environmental impacts from freight transport in cities.

This chapter described initiatives aimed at reducing emissions from urban goods movement. To achieve substantial environmental benefits in the future, it will be important that alternative fuels and different modes be adopted and that these are integrated with schemes that reduce the distance that goods vehicles travel.

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Chapter 8
Greening Demand Chains in Urban Passenger Transport: Emissions Saving from Complex Trip Chains

Chinh Ho and David A. Hensher

Abstract It is well known that a significant amount to passenger trip activity involves multiple modes, destinations and trip purposes. For example, with multi-worker households, we observe a car commuter taking a child to a child care centre en route to work and also dropping their partner off at another location such as a railway station. This example is one of many trip chain configurations that represent the complexity of travel activity, and which have important implications on how we represent travel demand in transport planning models. What is not well understood is the impact that trip chaining has on greening the demand chain. We are unaware of any studies that have investigated the greening of passenger demand chains associated with the complexity of trip chains. This chapter uses the Sydney Household Travel Survey and an econometric model to identify the impact that the changing nature of trip chains has on CO_2 emission. Results suggest that trip chains were stable in Sydney over a period of 15-year from 1997/98 to 2011/12. Emissions saving from chaining multiple activities into a single chain were found to vary between 5 and 19 % depending on whether the mode of travel is car, bus, or train.

Keywords Trip chains · Travel activity · CO_2 emission · Transport modes · Tour complexity · Green travel demand

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8.1 Introduction

Continuing concerns over global warming and pollution have called for prompt action to reduce energy consumption and greenhouse gas (GHG) emissions. In the transport sector, much of the focus has been on the opportunities to reduce car use, notably vehicle kilometres travelled (VKT), as this is the single most relevant driver of resource consumption and environmental degradation. One way of reducing the travel input while still fulfilling individual and household needs is to chain multiple out-of-home activities into a single trip chain. This tactic is well described in the literature as the travelling salesman problem if the objective is to minimise distance travelled. However, the problem of cutting GHG emissions with the trip chaining initiative deals not only with distance travelled but also with mode of travel. The impact of trip chaining on GHG emissions is therefore ambiguous as (spatially) complex trip chains are more likely to be undertaken by car, and the average emission rate of the private car is usually higher than that of public transport.

This chapter explores the impact of trip chaining on CO_2 emission using evidence from the Sydney Household Travel Survey. The central question being addressed is whether different ways of arranging daily activities into trip chains have a significant impact on CO_2 emission by considering the complexity of trip chains and the travel mode used to access activities. We are unaware of any studies that have investigated the greening of passenger demand chains associated with the complexity of trip chains.

This chapter brings together different methods of classifying the complexity of trip chains in the transport literature and proposes a modelling approach to provide insights into the impact of trip chains on CO_2 emission. The research expands on the literature by considering multimodal trip chains in comparison to those involving car only. It also considers the differences in CO_2 emission for alternative arrangements of activities into multiple simple trip chains or a single complex trip chain, given the number of daily activities and their locations.

The chapter is structured as follows. We begin with a brief review of the literature related to trip chaining, including its relationship with travel mode. This is followed by a description of the data and the selection of a method for analysing the influence of trip chaining on CO_2 emission. Estimation and simulation results are then presented, and the chapter concludes with a summary of the key findings and a discussion of the implications for greening passenger demand chains.

8.2 Literature Review

There exist different definitions of a trip chain, with the most popular one, coined by Adler and Ben-Akiva (1979), defined as a series of trips that begin and end at an individual's home. By this definition, a trip chain is equivalent to a home-based tour, and thus these terms are used interchangeably in this chapter. A trip chain can

Table 1 Trip chain typology proposed by Primerano et al. (2008)

Trip chain type	Configuration
Simple chain	H–P–H
Complex to primary activity	H–{S}–P–H
Complex from primary activity	H–P–{S}–H
Complex to and from primary activity	H–{S}–P–{S}–H
Complex at primary activity	H–P–{S}–P–H
Complex to, at, and from primary activity	H–{S}–P–{S}–P–{S}–H

Note H Home, *P* Primary activity, {*S*} one or more secondary activities

be very simple with only one activity accessed by a single mode, but it can also be very complex, involving multiple activities, multiple destinations and multiple modes. To reflect the complexity of trip chains, different trip chain typologies have been proposed in the literature and these can generally be classified into three types. The first typology uses only the number of activities chained into a tour to classify trip chains (e.g., Currie and Delbosc 2011). The second typology also considers the sequence of activities chained into a tour and provides a more detailed coding scheme (Strathman et al. 1994; Golob 1986). The final typology takes into account both the number and the spatial distribution of activities chained into a tour and classifies tours into single purpose at single destination, multiple purposes at single destination, or multiple purposes at multiple destinations (Ho and Mulley 2013a).

An adopted typology needs to consider the purpose of the study and has to be simple and clear to make it useful and manageable (Krizek 2003). Primerano et al. (2008) provided a comprehensive review of trip chain typologies and proposed a classification shown in Table 1. We adopt this tour typology as it is quite flexible to turn this typology into a sophisticated coding by considering the primary travel purpose or a combination of the primary and secondary activities. For example, the simple chain shown in Table 1 can be translated into a simple work chain or a simple non-work chain described in Strathman et al. (1994) and Hensher and Reyes (2000), depending on the travel purpose of the activity being work or non-work.

Trip chaining is an important aspect of travel that has a significant impact on mode choice and distance travelled, which in turn influence GHG emissions. Research on the relationship between the complexity of trip chains and the choice of travel modes has established a causal link from the former to the latter (Krygsman et al. 2007; Ye et al. 2007) and a preference for the private car to public transport for making (spatially) complex trip chains (Hensher and Reyes 2000; Ho and Mulley 2013a; Cicillo and Axhausen 2002). Thus, any reduction in GHG emissions resulting from chaining multiple activities may be offset by the need of using the private car for undertaking complex trip chains. We investigate the relationship between trip chaining and GHG emissions, taking into account the effect of travel mode.

Taking a closer look at the existing literature on changes in trip chaining behaviour, some studies find that trip chains are becoming increasingly complex (McGuckin et al. 2005; Levinson and Kumar 1995), while other studies suggest no change in the complexity of trip chaining over time (Currie and Delbosc 2011). This calls for a deeper investigation of the change in trip chaining behaviour as these different findings may result in part from changes to household structure, vehicle ownership and travel purpose, given that these factors are known to influence tour complexity (Strathman et al. 1994). Understanding the changing nature of trip chains is important for developing policy to reduce GHG emissions and to limit individual reliance on the private car. If trip chains become more complex as people are busier, then car use will increase in the future and greener cars are required to cut GHG emissions. However, if trip chaining behaviour stays stable, promoting public transport ridership can also be counted as a possible way to reduce the impact of travel on the environment. This chapter provides evidence on the change of trip chaining behaviour over a 15-year period from 1997/98 to 2011/12, using the Sydney Household Travel Survey (HTS) data.

8.3 Methodology

8.3.1 *Creating Trip Chaining Dataset from Household Travel Surveys*

The main data for analysis were created from the Sydney HTS which has been described elsewhere (Ho and Mulley 2013a, b). For the purpose of this chapter, we provide a general description of the survey. The Sydney HTS was first conducted in 1997/98 and the latest available wave was 2011/12. To date, the database includes 15 consecutive waves with each wave including a survey of household characteristics, person characteristics, vehicle characteristics, and a 24-h travel diary for each participant. The collected information is organised into four separate tables which can be linked by key variables that are unique to each household, person, vehicle and trip. The trip table was restructured to create a trip chaining dataset where each row (or record) can be viewed as a round-trip journey, beginning and ending at the home. A small number of persons with a travel diary starting or ending outside the home were excluded from the analysis. This trip chaining dataset was used to examine the changing nature of trip chains.

The typology shown in Table 1 was the basis for classifying trip chains. This required the identification of primary and secondary activities and their sequences in trip chains with more than one out-of-home activities. Primary activities were assigned based on a hierarchical basis, with work/work-related business activities being the highest, followed by education, serving passenger (i.e., dropping off, picking up or accompanying someone), shopping, personal business, social and recreation activities. Secondary activities chained into each tour were then identified as activities other than the primary ones. Finally, a set of conditions was applied to classify trip chains into one of the six types shown in Table 1.

As with travel purpose, a trip chain may involve more than one travel mode. By mode, the trip chains were spread across car, bus, train, ferry, walking, cycling, other modes and the combination of these modes with the most popular multimodal tours being car and bus, car and train, and bus and train. By considering multimodal trip chains, this study is different from the existing literature which usually uses the concept of the main travel mode to deal with multimodal trip chains. The differentiation between single modal and multimodal chains is important for examining the effect of mode choice and trip chaining on CO_2 emission.

8.3.2 Approach to Analysing the Effect of Trip Chains on CO_2 Emission

CO_2 emission from each trip chain was calculated based on an average emission rate per passenger km and distance travelled by each of the modes involved in the trip chain. In Sydney, CO_2 emission rates per passenger km were 188 grams for an average car, 120 grams for bus, 105 grams for train and 171 grams for light rail (Demographia 2007). Distance and mode of travel were available in the Sydney HTS for each trip leg in a trip chain. Thus, CO_2 emission from each trip chain was approximated as the summation of emission across all trip legs.

The effect of trip chaining on CO_2 emission was examined using a daily activity arrangement framework. Specifically, given the number and locations of out-of-home activities one has to complete in a day, there are different ways of arranging them into trip chains. People with multiple daily activities can arrange them into one complex chain or multiple simple chains, and the way in which activities are chained will have impact on CO_2 emission, as does the travel mode to access these activities. As is common in the activity based modelling literature, we assume that activity generation and location precede mode choice and trip chaining decisions (Davidson et al. 2007; Bradley and Bowman 2006). The results are discussed in the next section.

8.4 Results

8.4.1 Descriptive Analysis

The changing nature of trip chains was examined by looking at the average number of activities chained into a home-based tour over time, controlling for changes in household structure, car ownership and travel purpose. Figure 8.1 shows the change in the complexity of trip chains in Sydney by household structure over a 15-year period from 1997/98 to 2011/12. Controlling for household structure, the complexity of trip chains appears to be stable over the studied period, with the average

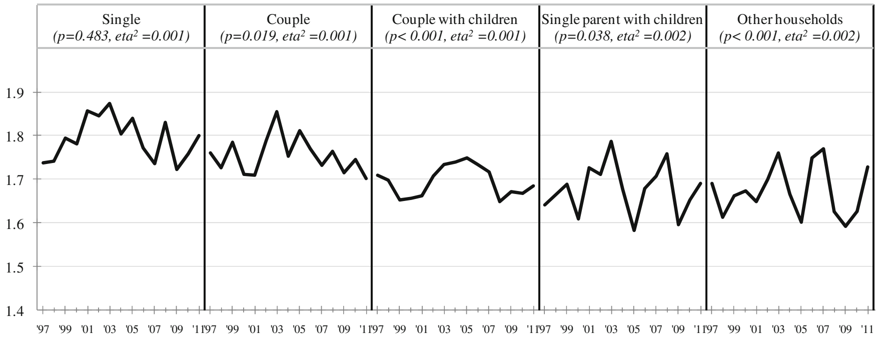


Fig. 8.1 Average number of activities per trip chain by household structure: changing nature over a 15-year period from 1997/98 to 2011/12 in Sydney. *Notes p*-values are for one-way ANOVA tests. *Data source* Sydney HTS 1997/98–2011/12

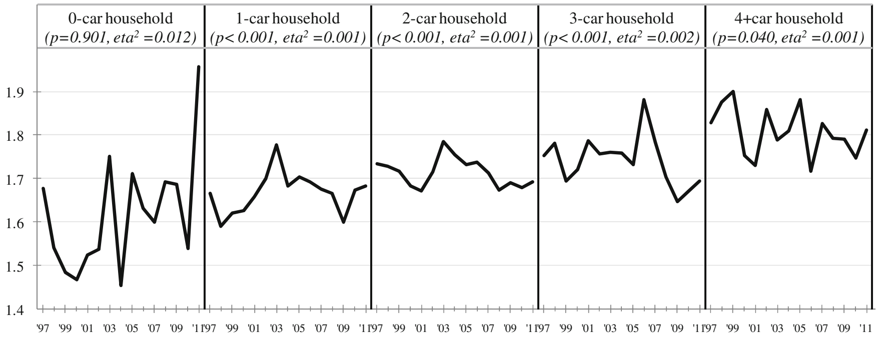


Fig. 8.2 Average number of activities per trip chain by household car ownership: changing nature over a 15-year period from 1997/98 to 2011/12 in Sydney. *Notes p*-values are for one-way ANOVA tests. *Data source* Sydney HTS 1997/98–2011/12

number of activities chained into a tour ranging from 1.58 to 1.87. One-way ANOVA tests conducted for each of the household structures suggest that there are significant differences in the complexity of trip chains across the 15 years but the estimated effect sizes, represented by eta^2, are very small. That is, controlling for changes in household structure, the time element explains less than 0.2 % of the variation in the complexity of trip chains over the 15-year period. An investigation of changes in trip chain complexity by household car ownership and tour main travel purpose, shown in Figs. 8.2 and 8.3, suggests that the complexity of trip chains is also stable over time. This finding is not dissimilar to the findings in Melbourne of Currie and Delbosc (2011), although they did not control for changes in household structure, car ownership and travel purpose.

However, the finding of a stable trip chaining pattern in Australia is in sharp contrast to the results found in the US by McGuckin et al. (2005) who concluded that between 1995 and 2001 trip chains in the home-to-work journey increased by

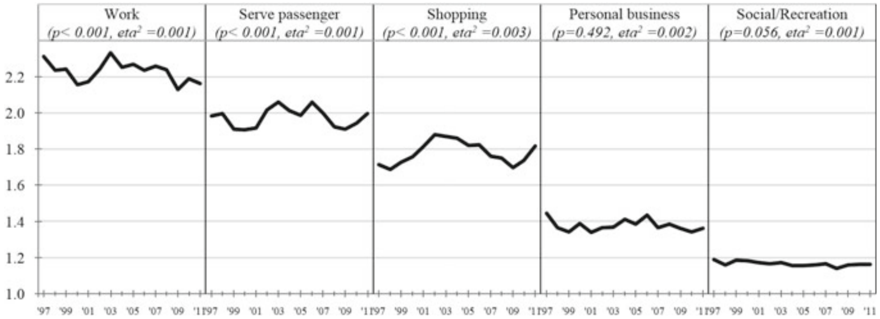


Fig. 8.3 Average number of activities per trip chain by tour main travel purpose: changing nature over a 15-year period from 1997/98 to 2011/12 in Sydney. *Notes p*-values are for one-way ANOVA tests. *Data source* Sydney HTS 1997/98–2011/12

20.74 %. This contrast appears to arise from two sources. The first source relates to the different definitions of a trip chain used across studies. The second reason, which may be more pronounced, relates to the way in which changes in the population have (not) been controlled for. More specifically, McGuckin et al. (2005) adopted a definition that described a trip chain as a sequence of trips with intervening activities (i.e., not change mode) of 30 min or less while our study and Currie and Delbosc (2011) defined a trip chain as a round journey from home to home, including all intervening activities of any duration. Thus, an activity longer than 30 min defines the terminus of a trip chain in the former, but does not do so in the latter. This difference together with an increase in the worker population that was not controlled for by McGuckin et al. (2005) has misled them about a sharp increase in trip chaining amongst US workers between 1995 and 2001. This can be seen clearly from Table 8.1 that was created using data derived from Table 1 in McGuckin et al. (2005) and controlling for the change in the number of workers between 1995 and 2001. While Table 8.1 still supports the conclusions by McGuckin et al. (2005), an increase in the proportion of trip chains associated with work journeys is much less. Also, with the definition of a trip chain that takes all activities of any duration into consideration, it can be said that trip chains amongst US workers were stable between 1995 and 2001.

Figure 8.4 shows the average CO_2 emission per activity by trip chain and selected mode of travel (active chains and other multimodal chains were not shown) in Sydney. More than three quarters (76 %) of the trip chains were undertaken by car (17,450 chains to the total of 23,023 chains). Of the trip chains made by car, 41 % were complex with two or more out-of-home activities. Holding travel mode constant, average CO_2 emission per activity decreases as the complexity of trip chain increases. This result is expected: given the number of activities, the fewer tours are made to chain activities (or the more complex the trip chains) the shorter the total distance travelled due to fewer ‘return home’ trip legs, and thus the lower the CO_2 emission. Figure 8.4 also shows that CO_2 emission is strongly influenced by travel mode, given the trip chain type. Across all trip chain types, average CO_2

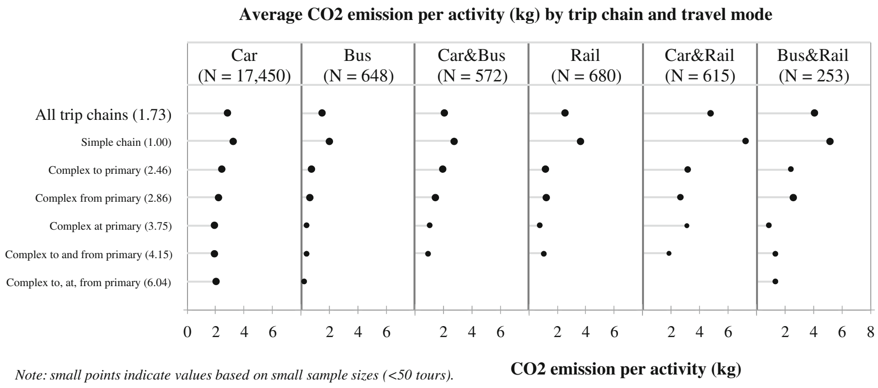
Table 8.1 Proportion of workers who trip chain on work journeys in the US between 1995 and 2001

	1995	2001
Sample size		
Number of weekday workers	68,760,000	68,990,000
Did not chain	31,290,000	31,660,000
Chained work trips	17,276,045	18,842,670
Chain home-to-work trip	5,929,237	7,158,844
Chain work-to-home trip	7,762,956	7,659,436
Chain both	3,583,852	4,024,390
Stopped longer than 30 min	20,193,955	18,487,330
Proportion of workers who chained...		
Work trips (stopped no longer than 30 min)	25 %	27 %
Home-to-work trip	9 %	10 %
Work-to-home trip	11 %	11 %
Both directions	5 %	6 %
Work trips (stopped longer than 30 min)	29 %	27 %
Work trips (stopped any duration)	54 %	54 %

Data source Table 1 in McGuckin et al. (2005)

emission per activity is much higher for multimodal tours involving rail than for single modal tours or car and bus tours. Figure 8.5 shows a breakdown of CO_2 emission per activity by travel mode for multimodal trip chains.

For multimodal chains by car and bus, the contribution to CO_2 emission is split equally between the two modes. This may be explained by a large proportion of trip chains involving bus on an outbound trip and car on an inbound trip or vice versa. Conversely, for multimodal trip chains by car and train or bus and train, the contribution of train legs to CO_2 emission is much larger than that of car legs or bus



Note: small points indicate values based on small sample sizes (<50 tours).

Fig. 8.4 Average CO_2 emission per activity (kg) by trip chain and travel mode. *Note* Values in parentheses after trip chain types are the average number of activities per chain. *Data source* Sydney HTS 2007/08–2010/11

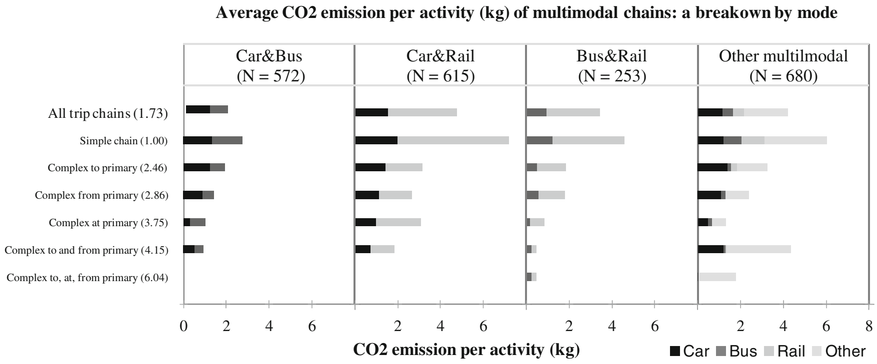


Fig. 8.5 Average CO_2 emission per activity (kg) of multimodal chains: a breakdown by mode. *Data source* Sydney HTS 2007/08–2010/11

legs. As mentioned above, the emission rate of the train mode is lower than that of bus/car mode, and this result reflects the longer distance travelled by train than by car/bus mode for these multimodal tours. This shows the importance of controlling for distance travelled in modelling the influence of trip chaining behaviour on greening travel demand. The modelling results are presented next.

8.4.2 *Modelling Results*

Separate regression models are estimated for people with different numbers of daily activities, given their locations. Table 8.2 shows different ways of arranging daily activities into trip chains and the average CO_2 emission corresponding to each way of arrangement. As shown in Table 8.2, people with one out-of-home activity can only arrange a simple chain to access the activity. They were excluded from modelling analysis as no alternative arrangements to a simple chain are available to evaluate the gain or loss in CO_2 emission resulting from different trip chaining behaviour. People with two daily activities can arrange the activities into two simple chains, or one complex chain to primary activity, or one complex chain from primary activity. Given the number of daily activities undertaken, the average CO_2 emission shown in the last column of Table 8.2 indicates that an arrangement of multiple simple chains does not necessarily produce higher CO_2 emission than one complex trip chain because travel mode and relative distances between activities, and between home and each of the activities also play an important role.

For a person with n daily activities, there are $n*(n + 1)/2$ pair-wise relative distances between home and activities and between one activity to another. For example, for people with 2 daily activities, there are $2*3/2 = 3$ pair-wise distances to be controlled for when examining the influence of trip chaining behaviour on CO_2 emission. These are distances between home and activity 1 (d_{01}), between

Table 8.2 Alternative arrangements of daily activities into trip chains and their CO_2 emission

No. daily activities	Arrangement of activities	N	Average CO_2-e (kg)
1 Activity	1S tour	5,015	3.75
2 Activities	2S tours	1,660	5.27
	1C to primary	1,043	5.45
	1C from primary	822	5.18
3 Activities	3S tours	464	5.93
	1C to primary	348	8.50
	1S + 1C to primary	620	6.31
	1C from primary	577	5.86
	1S + 1C from primary	346	6.13
	1C to and from primary	221	6.20
	1C at primary	139	6.20
4 Activities	4S tours	123	7.77
	1C to primary	197	11.43
	1S + 1C to primary	259	9.76
	2S + 1C to primary	293	7.53
	2C to primary	143	8.41
	1C from primary	419	9.24
	1S + 1C from primary	293	8.33
	2S + 1C from primary	157	7.68
	1C to + 1C from primary	160	9.65
	1C to and from primary	403	9.53
	1S + 1C to and from primary	203	8.02
	1S + 1C at primary	122	7.80
	Other arrangements	429	10.43

Note S simple, *C* Complex. *Data source* Sydney HTS 2007/08–2010/11

home and activity 2 (d_{02}), and between activity 1 and activity 2 (d_{12}). The number of relative distances that have to be considered increases as the number of daily activities increases. A model for 4 daily activities has 4*(4 + 1)/2 = 10 distance variables. The empirical model considers 4 daily activities as a maximum number as the best trade-off between achieving population coverage (78.3 % of the sample) and reducing potential multicollinearity.

Tables 8.3, 8.4 and 8.5 summarise the regression results of CO_2 emission on alternative arrangements of activities into trip chains, distances between home and each activity as well as between one activity to another, and the number of trip chains by mode for people with 2, 3 and 4 daily activities. Alternative arrangements of daily activities were effects coded to compare average CO_2 emission for each arrangement with the grand mean (average across all ways of arranging daily activities into trip chains). The coefficients associated with alternative arrangements of two activities shown in Table 8.3 indicate that, *ceteris paribus*, CO_2 emission per person per day will be 0.332 kg lower than average if the two activities can be

Table 8.3 Model of CO_2 emission for person with 2 daily activities, $R^2 = 0.906$

Variable	Coefficient	t-stat	Sig.	VIF
Constant	0.879	5.97	*	–
2 simple tours (base)[a]	0.789	–	–	–
1 complex to primary (1/0/−1)	−0.332	−5.89	*	1.7
1 complex from primary (1/0/−1)	−0.456	−7.62	*	1.7
Distance between home and activity 1 (km)	0.185	16.10	*	1.4
Distance between home and activity 2 (km)	0.126	8.28	*	1.5
Distance between activities 1 and 2 (km)	0.184	12.58	*	1.5
Number of tours by walking	−1.236	−13.58	*	1.0
Number of tours by bus	−0.812	−6.13	*	1.0
Number of tours by train	−2.102	−10.81	*	1.0
Number of tours by car and bus	−0.533	−5.74	*	1.0
Number of tours by car and train	−1.707	−5.25	*	1.0
Number of tours by bus and train	−1.551	−4.80	*	1.0
Number of other multimodal tours	−0.922	−0.90		1.0

Note * significant at 99 % level

[a] Coefficient is calculated as the negative sum of the coefficients associated with other trip chain types

chained into one complex tour to the primary activity, while it is 0.789 kg higher than average if these two activities are undertaken as two simple tours. The models for 3 and 4 daily activities (Tables 8.4 and 8.5) also suggest that CO_2 emission is highest if activities are chained into multiple simple tours. In addition, the estimation results suggest that given the spatial distribution of daily activities, CO_2 emission can be cut by shifting away from the private car as a single mode. This is shown by the negative coefficients associated with alternative travel modes to the private car across all models. Most distance variables are significantly positive, as expected, except for two variables (d_{13} and d_{24}) that are negative. The counter-intuitive sign of these two variables are due to a high multicollinearity amongst distance variables as indicated in Table 8.5 by Variation Inflation Factor (VIF) values which are larger than a rule-of-thumb value of 5.0. As the distance variables are positively correlated, their coefficient estimates tend to be negatively correlated. This consequence, however, does not influence the effect of trip chaining and mode of travel on CO_2 emission, which is the focus of this chapter.

The estimated models are used to examine the gain or loss in CO_2 emission if multiple activities are chained into a single complex chain in contrast to multiple simple chains. The complex trip chain selected for this simulation is the complex chain from the primary activity due to its prevalence (see Table 8.2) and the smaller time pressure that travellers such as workers experience after undertaking the primary activity as compared to before doing it. The main question of interest is what are the gains in CO_2 emission if people undertaking multiple activities with multiple simple chains now do so with only one complex chain from the primary activity? As the literature suggests that travellers may require the use of a private car for

Table 8.4 Model of CO_2 emission for person with 3 daily activities, $R^2 = 0.930$

Variable	Coefficient	t-stat	Sig.	VIF
Constant	1.015	8.60	***	–
3 simple tours (base)[a]	1.440	–	–	–
1 complex to primary (1/0/−1)	−0.575	−4.61	***	2.1
1 simple + 1 complex to primary (1/0/−1)	0.692	7.37	***	1.7
1 complex from primary (1/0/−1)	−0.751	−8.23	***	1.9
1 simple + 1 complex from primary (1/0/−1)	0.560	4.70	***	2.1
1 complex to and from primary (1/0/−1)	−0.676	−7.03	***	2.4
1 complex at primary (1/0/−1)	−0.690	−7.84	***	3.0
Distance between home and activity 1 (km)	0.191	12.11	***	2.4
Distance between home and activity 2 (km)	0.040	2.31	**	5.6
Distance between home and activity 3 (km)	0.120	8.30	***	2.8
Distance between activities 1 and 2 (km)	0.158	13.45	***	2.9
Distance between activities 1 and 3 (km)	−0.011	−0.98		2.9
Distance between activities 2 and 3 (km)	0.182	11.90	***	1.9
Number of tours by walking	−1.173	−14.29	***	1.1
Number of tours by bus	−1.259	−9.27	***	1.0
Number of tours by train	−2.750	−11.67	***	1.0
Number of tours by car and bus	−0.977	−7.75	***	1.0
Number of tours by car and train	−2.726	−7.83	***	1.1
Number of tours by bus and train	−1.382	−5.65	***	1.0
Number of other multimodal tours	−0.897	−1.96	*	1.0

Note *** significant at 99 % level; ** at 95 %; * at 90 %

[a] Coefficient is calculated as the negative sum of the coefficients associated with other trip chain types

complex trip chains, the simulation assumes that all newly complex chains are to be made by a single mode of car. However, bus and train as single modes are also simulated to provide a range of gains in CO_2 emission. The procedure for estimating the gains/losses in CO_2 includes three steps:

1. The estimated coefficients and the estimation sample data are used to compute CO_2 emission for the base.
2. Changes to trip chaining behaviour and travel mode of individuals with multiple simple tours are simulated by setting the effects coded variables associated with trip chain types to the appropriate values (1, 0 or −1), and their numbers of tours by car to 1 and by other modes to 0 if the complex trip chain is made by car (similarly for the scenarios where the complex chain is made by bus or train).
3. The estimated coefficients and the simulated sample data are used to compute CO_2 emission for the scenario, and the gains/losses in CO_2 emission are calculated as the percentage difference between the scenario and the base.

Table 8.5 Model of CO_2 emission for person with 4 daily activities, $R^2 = 0.911$

Variable	Coefficient	t-stat	Sig.	VIF
Constant	1.571	8.62	***	–
4 simple tours (base)[a]	1.664	–	–	–
1 complex to primary (1/0/−1)	−0.974	−5.23	***	1.8
1 simple + 1 complex to primary (1/0/−1)	0.143	0.79		1.5
2 simple + 1 complex to primary (1/0/−1)	0.843	4.45	***	1.5
2 complex to primary (1/0/−1)	−0.808	−2.55	**	2.2
1 complex from primary (1/0/−1)	−0.769	−4.09	***	1.6
1 simple + 1 complex from primary (1/0/−1)	0.524	2.57	**	1.6
2 simple + 1 complex from primary (1/0/−1)	0.575	3.15	***	1.9
1 complex to + 1 complex from primary (1/0/−1)	0.047	0.21		2.2
1 complex to and from primary (1/0/−1)	−0.816	−4.54	***	1.6
1 simple + 1 complex to and from primary (1/0/−1)	−0.098	−0.72		2.0
1 simple + 1 complex at primary (1/0/−1)	0.384	1.33		2.1
Other arrangements (1/0/−1)	−0.713	−1.68	*	7.7
Distance between home and activity 1 (km)	0.181	7.46	***	1.9
Distance between home and activity 2 (km)	0.010	0.31		8.2
Distance between home and activity 3 (km)	0.014	0.43		11.9
Distance between home and activity 4 (km)	0.102	5.22	***	4.0
Distance between activities 1 and 2 (km)	0.195	6.72	***	5.2
Distance between activities 1 and 3 (km)	−0.088	−2.91	***	10.1
Distance between activities 1 and 4 (km)	0.048	1.94	*	5.0
Distance between activities 2 and 3 (km)	0.237	9.85	***	2.2
Distance between activities 2 and 4 (km)	−0.071	−2.37	**	4.2
Distance between activities 3 and 4 (km)	0.200	8.34	***	3.3
Number of tours by walking	−0.928	−8.86	***	1.1
Number of tours by bus	−1.450	−11.01	***	1.0
Number of tours by train	−1.995	−4.96	***	1.0
Number of tours by car and bus	−0.500	−1.27		1.0
Number of tours by car and train	−1.985	−6.50	***	1.0
Number of tours by bus and train	−0.528	−0.43		1.0
Number of other multimodal tours	−1.352	−2.85	***	1.0

Note *** significant at 99 % level; ** at 95 %; * at 90 %

[a] Coefficient is calculated as the negative sum of the coefficients associated with other trip chain types

The simulation results suggest that if people with multiple simple chains can chain their daily activities into a single complex chain, this would reduce the CO_2 emission by 5.2 % even if the complex chain is made by car. However, the level of CO_2 emission saving from chaining multiple activities is more significant if complex chains from the primary activity are made by bus (13.0 %) or train (19.1 %).

8.5 Conclusions and Discussion

This chapter has explored the changing nature of trip chains over a 15-year period and the emissions saving from complex trip chains using the Sydney HTS. Results reveal that in Sydney the complexity of trip chains in terms of average activities per chain remain stable between 1997/98 and 2011/12. This appears to be contrary to previous evidence which suggests that trip chaining behaviour, especially in the home-to-work direction, has become more popular as people grow time-poor (McGuckin et al. 2005). However, a deeper investigation has suggested that this contrast is a result of the difference in the definition of trip chains adopted by different studies and the failure to account for changes in the population over time in previous studies. Controlling for changes in household structure, car ownership and travel purpose, this chapter found a stable trip chaining behaviour over a long period of 15 years. Consistent with evidence found elsewhere (Currie and Delbosc 2011), this finding suggests a less bleak outlook for public transport and its potential for greening the travel demand chains.

For people with multiple daily activities, there are different alternative arrangements of activities into trip chains and this has a significant impact on CO_2 emission, as does the travel mode to access these activities. This chapter has demonstrated, using both descriptive and modelling evidence, that CO_2 emission can be cut by a substantial amount if activities are chained to fewer complex tours and/or greener travel modes are used. With changes in trip chaining behaviour of people with all activities undertaken separately by multiple simple chains, the simulation suggested a 5–19 % saving of CO_2 emission, depending on the travel mode selected to undertake the complex trip chains.

GHG emissions from urban passenger transport are usually studied through vehicle kilometres travelled (VKT), but this approach cannot be used to examine the potential of greening travel demand by encouraging more trip chains. This is because the VKT approach combines distance travelled by all trip chain types, and thus the information on the ways in which individuals chain their daily activities is lost. A modelling approach at the tour level cannot be used either because this does not allow activities that are chained into different tours to be rearranged into one tour, a critical character for studying the effect of trip chains on CO_2 emission. This chapter has developed a daily activity modelling framework to relate CO_2 emission to different arrangements of daily activities into trip chains, taking into consideration the opportunities of using multiple modes of travel to undertake trip chains. However, this approach also comes with certain limitations, most of which are considered necessary in the estimation of the empirical models used to examine the relationship between trip chains and CO_2 emission. In terms of modelling, we have considered the number of daily activities, their locations, and the travel modes to access them as exogenous variables. While these assumptions are fully consistent with activity-based modelling, this limitation means that the effect on CO_2 emission of changes in daily activities due to changes in land use patterns, which allow people to do the same activity at a different place, cannot be evaluated.

Another limitation relates to the way in which CO_2 emissions are computed as average emission rates of different modes identified in a trip chain. This means that some scenarios such as changes in fuel types and fuel consumption have to be analysed by re-aggregating the daily CO_2 emission from the trip level. These limitations can be overcome with a fully integrated activity based modelling framework that places an activity arrangement model after an activity generation model that generates the number of daily activities undertaken by each person. The mode choice and time of day model would then be applied for each trip chain. Subsequently, other models that form the rest of the activity-based framework (intermediate stop frequency, location, departure and arrival times, and trip mode models) could be applied to each trip chain, and the network assignments and skim matrices can then be performed. Outcomes from the trip mode model and network assignment model would then be aggregated to obtain CO_2 emission for each person per day.

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Part III
Green Air and Water Transportation

Chapter 9
A Review of the Literature of Green Ports and Maritime Logistics

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Abstract Port operations and maritime logistics represent major sources of air pollution. Given the recent greening initiatives and developments in this area and correspondingly a geometric growth in the number of academic publications, this chapter aims to (a) provide some statistics of the key journals, authors and institutions that have contributed to the field, and (b) identify the primary research topics investigated. The proposed literature classification and analysis can help interested researchers and students establish their research agendas in this emerging area of study and investigation.

Keywords Green · Port · Maritime logistics · Environmental sustainability · Literature review · Bibliometric analysis

9.1 Introduction

Emissions from ships and port equipment have long remained out of sight and out of mind, until recently. Concern about the impact of burning high sulphur fuel at sea on adjacent populated areas has led to the introduction of Emission Control Areas (ECAs) where ships are required to switch to low sulphur fuel. Slow

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steaming in the vicinity of coasts and ports, and the use of scrubbers or switching to cleaner fuels like diesel and liquefied natural gas are the alternative greening approaches for maritime transportation (see Chap. 10). Technologies and practices for reducing the environmental footprint of ports may include cold ironing (where ships switch off their generators and plug into landside power supplies), hybrid ferries and hybrid cranes, the electrification of cranes and other equipment, a requirement for slow steaming and/or low sulphur fuel use in the vicinity of ports, vehicle booking systems, and automation (to allow yard operation during the night without lighting). In the context of ship construction, some ships are more environmentally friendly than others by design. Newer ships tend to be more energy efficient than older ones as hull and engine designs improve with time, and engines lose efficiency with age and use.

Given the recent developments in ports and shipping aimed at reducing emissions and improving energy efficiency, it is timely to look at how the corresponding academic research is evolving. This chapter reviews the literature of green ports and maritime logistics to provide some initial statistics of the key journals, authors and institutions contributed to the field, and identify the established research areas/ topics with potential for making additional contributions (i.e. literature classification and data clustering).

The first step is to define the appropriate search terms. This is completed through several trial and error attempts to (1) defining an initial set of keywords and search structure, (2) checking the resulting papers and journals to ensure the appropriate coverage, and updating the keywords accordingly, (3) looking for irrelevant papers and research areas, identifying the ‘exclusion keywords’, and updating the keyword structure accordingly, and (4) looking for irrelevant subject areas to narrow down the search space, updating the keyword structure accordingly. Through this process, a sophisticated keyword structure was designed combining a three-level search structure and a four-level search structure (see Table 9.1).

Using the “title, abstract, keywords” search in Scopus database, we collected and stored articles for the keywords identified in Table 9.1. We limited our search space to English ‘journal’ papers published and excluded conference papers, book series, commercial publications and magazine papers. The initial search attempts resulted in *11,279 articles*. Excluding papers from the irrelevant subject areas reduces the number of papers to *2,180 articles* (also shown in Table 9.1). From 2,180 papers in Table 9.1, some papers appear in both three-level and four-level search results. Also amongst these are short non-refereed papers and those published in commercial magazines which are not regarded as scientific contributions. Further refinement of the search results to eliminate duplications, non-refereed articles, commercial magazine papers, and papers with unknown author names results in *338 journal articles* published between 1975 and 2014.

Table 9.1 The proposed search terms and the initial search results

	Search results (No. of papers before/after removing unrelated subject areas)	
Search keywords	Before	After
(a) *A four-level search structure* Maritime OR port OR harbor OR Harbour OR waterway OR container OR cargo OR bulk Or breakbulk OR deepsea OR shortsea OR sea OR ocean AND Logistics OR supply OR transport OR transportation OR shipping AND Green OR (sustainability environmental) OR (sustainable environmental) OR (sustainability environmentally) OR (sustainable environmentally) OR emission OR ("environmental performance") OR ("environmental management") OR emission OR (carbon footprint) OR pollution AND NOT Fisheries OR fishery OR sediment OR algae OR trout OR salmon OR fisherman OR fishermen OR mussel OR molecular OR herring OR larva OR oyster OR ("sea bass") OR aerosol OR (atmospheric chemistry) OR (atmospheric deposition) OR troposphere OR sewage OR ozone OR microbe OR microbial OR biology OR organism OR animal OR electron OR species OR eutrophication OR odor	10,581	1,711
(b) *A three-level search structure* (port operation) OR (naval architecture) OR (ship design) OR (ship build) OR (ship construction) OR (harbor operation) OR (harbour operation) AND Green OR (sustainability environmental) OR (sustainable environmental) OR (sustainability environmentally) OR (sustainable environmentally) OR emission OR ("environmental performance") OR ("environmental management") OR emission OR (carbon footprint) OR pollution AND NOT Fisheries OR fishery OR sediment OR algae OR trout OR salmon OR fisherman OR fishermen OR mussel OR molecular OR herring OR larva OR oyster OR ("sea bass") OR aerosol OR (atmospheric chemistry) OR (atmospheric deposition) OR troposphere OR sewage OR ozone OR microbe OR microbial OR biology OR organism OR animal OR electron OR species OR eutrophication OR odor	698	469
Sum	11,279	2,180

9.2 Initial Data Statistics

The initial statistics shows that 168 journals have contributed to the publication of 338 papers. It was found that ten journals have published 105 of these identified articles, representing approximately 32 % of all the published papers. Table 9.2 shows the top publishing journals and their number of contributing articles. Sustainability and green operations are the primary focus area for many of the key

Table 9.2 The top publishing journals and the quantity of contributed articles

Journal	No. of articles
Transportation Research Part D: Transport and Environment	29
Maritime Policy and Management	14
Environmental Science and Technology	13
Energy Policy	12
Ocean Engineering	10
Marine Technology	7
Transportation Research Part E: Logistics and Transportation Review	7
Science of the Total Environment	6
Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering	5
Journal of Cleaner Production	4
Total	107

journals identified in Table 9.2. However, journals like *Maritime Policy and Management* and *Transportation Research Part E* appearing amongst the top contributing journals may be a good proof of the significance of this research area within the general context of logistics and supply chain management. Figure 9.1 shows the publishing trend using the quantity of publications in a given year. While still in its early growth and expansion period, the area of green ports and maritime logistics is attracting a geometric growth in the number of academic publications. This significant growth is more noticeable after 2006.

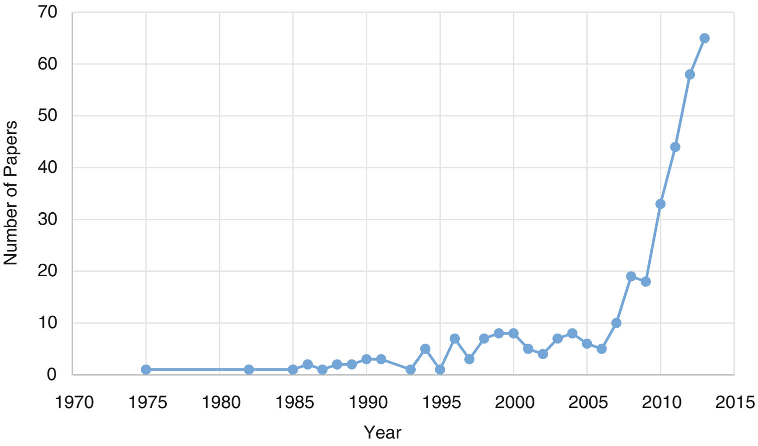

Fig. 9.1 Publication trend in the area of green posts and maritime logistics

9.3 Bibliometric Analysis

We use BibExcel to perform some initial bibliometric and statistical analysis. BibExcel is a tool for analyzing bibliographic data or any data of a textual nature formatted in a similar manner (Persson et al. 2009). BibExcel allows modifying and/or adjusting the input data that can be imported from various databases including Scopus and Web of Science. The data output can be exported to Excel or any program that takes tabbed data records. This high degree of flexibility makes BibExcel a powerful tool, yet relatively difficult to work with especially in performing the initial setups.

BibExcel can be used to analyze the frequency of occurrence of a text in different fields of the bibliographic data. The author field was extracted from the data file and frequency of appearance of all authors was recorded. It was found that only 11 % of 757 contributing authors have contributed to more than one paper, leaving 675 authors appearing in only one paper. Table 9.3 shows the top contributing authors based on the number of published articled. We also completed an analysis to identify the top paired authors (i.e. those appearing on multiple joint papers). Table 9.4 shows the results. Interestingly, seven of the ten top contributing authors (Table 9.3) are also appearing in the list of top contributing paired authors (i.e. Corbett J., Wang C., Kontovas C., Winebrake J., Psaraftis H., Eide M., Lindstad H.).

The affiliations of the authors can also be extracted using BibExcel to provide some statistics on the contributing organizations. The top performing organizations, their geographical locations and the quantity of the contributing papers are shown in Table 9.5. The geographical dispersion of these organizations demonstrates that green ports and maritime logistics has attracted organizations and research centers from around the globe.

A similar analysis is conducted to identify the most frequently used words/phrases in the paper title and the list of keywords. The top 20 words used in paper titles and the top 20 keywords are outlined in Tables 9.6 and 9.7 respectively. From these tables, we find that many of the most frequently used keywords are those related to greenhouse carbon emissions (e.g. greenhouse gas, emission control, carbon dioxide, carbon emission, carbon monoxide, CO_2 emissions, gas emission,

Table 9.3 The top contributing authors

Author	No. of published articles	Author	No. of published articles
Corbett J.	11	Kontovas C.	4
Wang C.	5	Winebrake J.	4
Psaraftis H.	4	Deniz C.	4
Eide M.	4	Chen G.	3
Lindstad H.	4	Yang Y.	3

Table 9.4 The top contributing paired authors

Author 1	Author 2	Number of joint publications
Corbett J.	Winebrake J.	4
Corbett J.	Wang C.	4
Cheng T.	Lai K.	3
Kontovas C.	Psaraftis H.	3
Eide M.	Longva T.	3
Lai K.	Wong C.	3
Asbjørnslett B.	Lindstad H.	3
Cheng T.	Wong C.	3

Table 9.5 The top performing organizations

Organization	Country	No. of papers
Department of Marine Engineering, Istanbul Technical University	Turkey	4
Centre for Maritime Studies, University of Turku	Finland	3
Department of Shipping and Transportation Management, National Kaohsiung Marine University	Taiwan	3
Federal Institute for Health Protection of Consumers and Veterinary Medicine	Germany	3
Department of Biological and Environmental Sciences, University of Helsinki	Finland	3
Department of Civil and Environmental Engineering, University of California	United States	3
College of Marine and Earth Studies, University of Delaware	United States	3
Department of Logistics and Maritime Studies, Hong Kong Polytechnic University	Hong Kong	3
Graduate School of Logistics, Inha University	South Korea	3

Table 9.6 The top 20 words/phrases used in the list of keywords

Frequency	Keyword phrase	Frequency	Keyword phrase
91	Ships	34	Gas emissions
70	Shipping	30	Marine pollution
65	Greenhouse gas	28	Energy efficiency
58	Emission control	27	Environmental protection
57	Carbon dioxide	27	Maritime transportation
50	Air pollution	27	United States
45	Article	25	Environmental impact
35	Nitrogen oxides	24	Cost-benefit analysis
35	Oil spill	24	Port operation
34	Carbon emission	23	Exhaust emission

Table 9.7 The most frequently used words in paper titles

Frequency	Word	Frequency	Word
102	Emission	27	Energy
51	Ship	26	Green
48	Shipping	24	Vessel
35	Environment	24	Oil
35	Port	23	Transportation
35	System	23	Analysis
35	Marine	22	Design
29	Container	22	CO_2
29	Case	22	Study
28	Maritime	21	Gas

carbon footprint, carbon dioxide emissions, carbon, carbon oxide, CO emissions, and CO_2). Nitrogen oxide, oil spill and sulfur dioxide are the next popular keywords after carbon-related keywords.

9.4 Literature Mapping

A network analysis (including a citation analysis and a co-citation analysis) of the published papers is now completed using Gephi, an open source software package that uses a 3D render engine to develop illustrations of large networks in real-time and assist in speeding up the exploration process (Gephi 2013). Gephi provides easy and broad access to network data and assist in specializing, filtering, navigating, manipulating and clustering of data (Bastian et al. 2009).

Different methods have been used in the past to measure the significance of a paper. The most common method is a citation analysis which aims to determine the '*popularity*' of a paper by counting the number of times a paper is cited by others in a given network (Cronin and Ding 2011). Ding et al. (2009) argue that in addition to '*popularity*' of a paper measured by the number of citations, the '*prestige*' is another important indicator which is the number of times a paper is cited by highly cited papers. In other words, a popular paper (a highly-cited paper) may not necessarily be a prestigious paper although in some cases there might be a strong positive correlation between the two measures. PageRank is therefore used as a measure for both popularity and prestige.

Gephi is able to evaluate the importance of articles based on their PageRank. A total of 80 papers out of 338 cite each other which are used for PageRank analysis. Table 9.8 shows the top ten papers based on a PageRank measure. For these papers, the table also shows the number of citations (both local citation and global citation), the pure 'popularity' measures. Clearly, a higher number of local and global citations cannot guarantee a higher PageRank value (e.g. Corbett and Fischbeck (2000) vs. Corbett et al. (2009), and Tzannatos (2010)).

Table 9.8 Top 10 papers using a PageRank citation measure

Paper	PageRank	Local citation[a]	Global citation[b]
Bailey and Solomon (2004)	0.0348	7	46
Corbett and Fischbeck (2000)	0.0308	5	34
Corbett et al. (2009)	0.0298	7	80
Wang et al. (2007)	0.0209	3	37
Eide et al. (2009)	0.0190	2	35
Corbett (2002)	0.0185	3	14
Corbett and Robinson (2001)	0.0185	2	7
Tzannatos (2010)	0.0185	2	28
Höfer (1998)	0.0185	2	4
Gallagher (2005)	0.0183	2	12

[a] *Local citation*: the number of citations within the pool of 338 papers
[b] *Global citation*: the number of total citations based on Scopus

A co-citation network consists of a set of nodes representing journal articles and a set of edges/links representing the co-occurrence of the nodes/articles in other papers (Leydesdorff 2011). Therefore, two publications are called to be co-cited if they appear together in the reference lists of other documents. That is if both document A and B are included in reference list of paper C, then A and B are co-cited. It is proven that papers which are more often cited together are more likely to present similar subject areas or be related (Hjørland 2013). The initial co-citation mapping with Gephi revealed that there are only 30 articles out of a total of 338 that have been co-cited by other papers within this sample.

The nodes of a network can be divided into clusters or modules where the density of edges is greater between the nodes of the same cluster compared to those of different clusters (Radicchi et al. 2004; Clauset et al. 2004; Leydesdorff 2011). Where nodes represent articles in a literature network, a cluster can be seen as a group of well-connected articles in a research area with limited connection to papers in another cluster or research area. Data clustering can be used as a classification tool for grouping of a set of given articles (Radicchi et al. 2004). Clustering allows for the topological analysis of networks, identifying topics, interrelations, and collaboration patterns. Modularity has received increasing attention from scholars turning it into a critical research field in social network analysis (Blondel et al. 2008).

The default modularity tool in Gephi is based on the Louvain algorithm, an iterative optimization model that aims to determine the optimal number of partitions that maximize the modularity index (Blondel et al. 2008). Applying this algorithm to the proposed 30-node citation network resulted in the creation of seven clusters. Papers of each cluster are cited together more often and these papers are more likely to present similar subject areas (Hjørland 2013). To identify the area of research focus for each cluster (i.e. characterizing/labeling of clusters), we carefully evaluated the contents and research areas of all papers. Table 9.9 summarizes the areas of research focus for each of the seven clusters. We recognize these seven clusters as

Table 9.9 Data clustering results

Cluster	Research area
1	Emissions (e.g. evaluation of emissions from vehicles, emissions mitigation strategies: their costs and benefits)
2	Eco-efficiency (e.g. berth allocation strategies, bunker consumption optimization, bunker levies, low carbon shipping)
3	Energy eco-efficiency (e.g. energy intensity and economic costs)
4	Climate change policy, regulation and carbon tax
5	Carbon footprint case studies
6	Ship mobility emissions (e.g. emissions from maneuvering ships, direct and feeder services)
7	Ship design (e.g. energy efficiency and cost effectiveness)

the primary areas of research focus within the context of green posts and maritime logistics. It is expected that research in all clusters as well an interdisciplinary multi-cluster research continue to grow within the next decade or so.

9.5 Conclusions

This chapter examined the evolution of the literature of green ports and maritime logistics by providing some author, affiliation and keyword statistics as well as identifying the primary research clusters through citation and co-citation analyses. Overall, while still in its early growth and expansion period, it is expected that the field will continue to grow in a number of directions as suggested by our data clustering results. Most of the research clusters have been shaped around emissions reduction, eco-efficiency, and the related environmental regulatory policy issues. This is not surprising given the global emissions reduction trends. It is expected that research in all clusters as well an interdisciplinary multi-cluster research will continue to grow as practitioners and governments face challenges that research can help solve.

Despite the interesting results of our literature mapping and data analysis, limitations do exist. The keyword structure was designed through a number of trials to ensure the most effective and feasible search space. However, there may still be some related works that this keyword structure has not captured. In addition, the literature mapping and network analysis methodology presented in this paper shows how a subject area can be objectively reviewed to identify the key papers and investigators. However, the methodology is not able to interpret the knowledge in these papers to explore the reasons why particular papers have been central to the development of the field. Future review efforts can focus on the development of tools and methodologies to address these limitations.

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Chapter 10
Economic and Environmental Trade-Offs in Water Transportation

Thalis Zis, Panagiotis Angeloudis and Michael G.H. Bell

Abstract In recent years slow steaming has resurfaced as a fuel saving measure allowing ship owners to significantly cut operational costs. Reduced fuel consumption leads to lower levels of greenhouse gases and pollutant emissions. Port authorities have considered offering incentives to ship operators that significantly reduce sailing speed in the port proximity, as a means to improve local air quality. This chapter conducts a literature review on emissions modelling methodologies for maritime transport and develops a framework that allows the estimation of pollutant emissions under different sailing scenarios. The chapter presents existing regulations and port initiatives that aim to reduce maritime emissions. The merits of localised slow steaming near the calling port for various case studies including different ship size, trip distance, sailing speed and fuel policies in place are examined. An activity based methodology is used to estimate fuel consumption and emissions savings during lower sailing speed operation for machinery on-board. Fuel price and the value of time lost govern the extent to which slow steaming and local speed reductions can be effective. The economic and environmental trade-offs occurring at different sailing speeds are discussed from the perspective of both the ship operator and the port authority considering the implications of regulatory policies such as the expansion of Emission Control Areas (ECA). The chapter concludes with a set of guidelines to port authorities on designing attractive speed reduction programmes, and recommendations to shipping companies on improving fuel efficiency across their schedule when such programmes are available.

Keywords Shipping emissions · Emission control areas · Speed optimization · Environmental trade-offs · Speed limits

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10.1 Introduction

The transportation sector accounted for 22 % of world CO_2 emissions in 2010 (IEA 2012), while the shipping sector alone was responsible for 2.2 % of the global amount in 2013 down from 2.7 % in 2008 (IMO 2014). This figure is relatively low considering that maritime transport moves 80 % of the world's trade by volume (UNCTAD 2013) and supports the argument that shipping is the most efficient mode of transport. However, cargo volumes continue to increase and as a result the environmental impacts of maritime transport are expected to gain interest in the future.

In addition to the contribution of the sector to climate change through the release of CO_2, there are concerns about other pollutant species emitted through maritime shipping. Of particular interest are sulphur, nitrogen and particulate matter emissions. The shipping sector is responsible for between 5 and 8 % of the global anthropogenic SO_2 emissions (Eyring et al. 2005) whereas its share of NO_x emissions was estimated at approximately 8.5 % in 2000 (Koffi et al. 2010) although there are other estimates that this figure reaches 15 % (Corbett et al. 2007). In the latter study, it is also estimated that PM emissions from shipping accounted for 64,000 fatalities near European, East and South Asian coastlines in 2002, a number which could increase with the expected growth in shipping activity.

Over the last decades there have been many attempts to reduce the growth of total emissions from the sector, with the International Maritime Organisation (IMO) playing an active role in developing a number of regulations and policies covering a broad range of important factors that affect the footprint of each ship, including fuel quality, engine efficiency and hull designs. Research has been carried out on emissions at both the microscopic (i.e. focusing on specific ship elements such as engine, ship design etc.) and macroscopic levels (i.e. approaching the problem from a systems perspective such as fleet deployment). Regulations have been set up to address the environmental consequences of maritime shipping at the global level dealing with CO_2 emissions and at a more regional level addressing pollutant emissions near coastlines, inland waterways and ports.

This chapter commences with a review of the literature on shipping emissions, the main modelling methodologies used to estimate the sector's footprint and ways of reducing the environmental impacts of maritime transport. The existing regulatory framework that is concerned with air emissions from maritime shipping is presented and operational practices and technologies that affect fuel consumption are discussed. The chapter then expands on existing studies by highlighting the economic and environmental trade-offs that emerge when emission reduction measures are adapted by the relevant stakeholders (regulators, shippers, port authorities). It is shown that to design efficient emissions reduction measures the perspective of all stakeholders has to be accounted for. The chapter finishes by providing recommendations for further research on the trade-offs amongst different pollutants and on specific questions with regards to impacts of the coming regulation on sulphur content. The potential benefits of including the maritime sector in emissions trading systems are also discussed.

10.2 Literature Review

This section presents previous research on the environmental impacts of maritime shipping. The research spans from efforts to create global emission inventories for the sector to operational problems of optimising sailing speeds across particular routes and dedicated studies of monitoring pollutants in coastlines.

10.2.1 Shipping Emissions Modelling

Pollutants emissions are the result of fossil fuel combustion in vessel engines. Most modelling methodologies calculate the emissions generated either as a function of the ship activity or the bunker sales in a specific region and subsequently multiplying this figure with appropriate emission factors. The former type is known as a bottom-up approach while the latter is a top-down approach. The selection of which approach is most appropriate to model the fuel consumption of a given system depends on the available data; however there are examples where intermediate approaches are preferred. In each case it is important to use accurate emission factors to convert the fuel consumption to pollutant emissions.

10.2.1.1 Bottom up

The term bottom-up is used to denote the approach of examining the contribution of each individual actor to a system. In the context of emissions modelling, a bottom-up approach considers the fuel consumption of each engine operating in a ship at each phase of each journey (cruise, manoeuvring, anchorage and at berth) and adds this fuel consumption for all engines, vessels and journeys to estimate the system's performance and emissions contribution. The necessary data to build the emissions estimate of a particular system (fleet) involves the technical specifications of each vessel (engine power installed, hull efficiency) and the operating patterns (sailing speed at sea, manoeuvring profiles at each port, hours spent stationary at anchorage and turnaround time at each port) at each activity phase.

Notable applications of bottom-up studies include the updated global emissions from ocean shipping based on activity data and vessel information from the Lloyd's ship registry (Corbett and Koehler 2003), the construction of an emissions inventory for marine vessels operating within 200 nautical miles of the US shoreline and inland waterways (Corbett and Fischbeck 2000) and the energy use and emissions generation of vessel activity in North America (Wang et al. 2007). In an era where vessel activity can be retrieved through data of shipping companies, port authorities and Automatic Identification System (AIS) the use of bottom-up methodologies can provide realistic estimates of emissions generated through shipping.

10.2.1.2 Top Down

A top-down approach decomposes a system by reducing it to its compositional subsystems. Top-down approaches in emissions modelling use data on the overall fuel consumed within a system and then match this consumption to the expected activity that caused it. Many studies are based on fuel sales statistics where the underlying hypothesis is that the fuel sold has been consumed under typical conditions. Such approaches could be used for the construction of large scale emission inventories (large areas, fleets and periods examined) but one key weakness in the context of marine emissions are the poorly documented sources of fuel statistics and the lack of validation (Corbett and Koehler 2003). When a top-down approach is used to estimate the emissions contribution of a particular country, fuel sales data are not sufficient as vessels within the examined country may be using fuel bought elsewhere.

Corbett et al. (1999) have used a top-down approach to construct a geographically resolved inventory for sulphur and nitrogen emissions using fuel data from 1993 and accounting for vessels of registered gross tonnage above 100. It has been argued that top-down methodologies are less appropriate to construct emission inventories from international transport (Peters et al. 2009). Due to limited data on vessel activity from earlier years top-down methodologies could be used to estimate emissions generation in the past. Endresen et al. (2007) used fuel sales data spanning a period from 1925 to 2002 to model carbon and sulphur emissions from oceangoing vessels taking into account the technological progress during this period (higher fuel efficiency, sailing speed, improved fuel quality etc.).

10.2.2 Emissions Reduction

A number of studies where emissions inventories have been constructed have been presented. Another recurring theme in the literature is the potential for fuel consumption and/or emissions reduction through operational practices, technologies or regulation. The relationship between sailing speed and pollutant emissions has been extensively researched. Ship operators are reducing sailing speed at times of increased fuel prices, a practice commonly known as slow steaming which has re-emerged in recent years following the recession of 2008. Corbett et al. (2009) examined the potential of slow steaming for various containership routes and showed that carbon emissions could be reduced by up to 70 %. Cariou (2011) illustrated that slow steaming can have environmental benefits despite the increase in fleet size operating to meet demand at lower sailing speeds. Psaraftis and Kontovas (2010) examine trade-offs between operating costs and environmental benefits of slow steaming.

Speed optimisation to minimise operating costs also has environmental consequences through the fuel consumption reduction (Wang and Meng 2012). A sensitivity analysis on different slow steaming scenarios and the resulting savings per shipment in carrier costs and CO_2 emissions was conducted by Maloni et al. (2013). Hvattum et al. (2013) developed an algorithm for the vessel speed optimisation problem to minimise fuel consumption along a fixed sequence of port calls.

10.2.3 Relevant Regulation and Port Initiatives

In the past the majority of the shipping fleet used to run on bunker oil with sulphur content up to 4.5 % (Corbett et al. 1999). In recent years there have been many regulations forcing the use of low sulphur fuel in certain areas. The IMO has set the maximum allowed content of sulphur in fuel and established Emission Control Areas (ECA) where tighter limits apply (IMO 1997) progressively in the coming years. The first four ECAs were the North Sea, the Baltic Sea, the majority of US and Canada Coasts and the US Caribbean ECA. The latter two have set limits on PM and NO_x emissions forcing marine vessels with diesel engines on-board to comply with standards set by MARPOL VI of the IMO. Apart from including additional pollutant species in the regulated areas, existing ECAs could be expanded or new ones added.

In the European Union, vessels in inland waterways and ships at berth are mandated to use ultra-low sulphur content fuel (0.1 % sulphur) or alternatively use technology (e.g. cold ironing, use of scrubbers) that results in the same reduction of sulphur emissions (European Commission 2005). A similar policy is applied in California waters in a radius of 24 NM of the California baseline (CARB 2012) where all machinery must use ultra-low sulphur fuel. These regulations are summarised in Table 10.1.

In addition to the introduction of regulated areas, the IMO developed the energy efficiency design index (EEDI) which is a ratio of the CO_2 emissions per ton mile of transported cargo. In 2013 acceptable values of EEDI were introduced which varied depending on ship type and characteristics. Older vessels of lesser fuel efficiency that now need to comply with the EEDI may need to change their operating patterns to do so (for instance through slow steaming).

Table 10.1 Existing regulation on sulphur content for bunker fuel

Operation	Sulphur content (%)			
	2005–2012	2012–2015	2015–2020	2020–
Within ECA	1.5	1	0.1	0.1
Outside ECA	4.5	3.5	3.5	0.5
European port at berth and inland waterways	0.1			
California within 24 NM	NA	0.1		

10.2.4 Port Specific Policies and Initiatives

Most of the aforementioned regulations affect the emissions along the journey of a vessel or part of it. Emissions of maritime shipping near ports may be influenced by the sulphur content restrictions and the lower speeds near the port, but there are additional port-specific policies and initiatives that target marine emissions at the port. In 2008 the International Association of Ports and Harbors (IAPH) launched the Worlds Ports Climate Initiative which provides support to member ports in reducing their greenhouse gas emissions. In Europe the European Sea Port Organization (ESPO) has developed a set of soft measures that allow port authorities to monitor qualitatively their progress in improving their environmental performance.

Port authorities around the world have adapted agendas seeking to improve local air quality in the vicinity of the port. The port of Singapore is rewarding vessels that are using low sulphur fuel by offering discounts in the port tariff. A similar policy is present in the port of Rotterdam for vessels using LNG as fuel. The port authorities of Gothenburg and Antwerp have invested in technologies that reduce emissions such as cold ironing (e.g. the provision of electric power to vessels at berth for their hostelling demands). Perhaps the most notable examples of port authorities with environmental action are the port of Los Angeles (POLA) and the port of Long Beach (POLB). In addition to the regulations in place by CARB, they are offering monetary incentives to ocean-going vessels that cut their sailing speed to 12 knots in the proximity of the port (20 or 40 NM). This scheme is known as the Vessel Speed Reduction Programme (VSRP) and it was marketed as a NO_x emissions reduction measure by the Californian port authorities. Despite the program being optional, participation rates in the first years have surpassed 90 and 80 % in the 20 and 40 NM zones respectively. Participating ship operators have noted however that the monetary compensation offered by the ports is not sufficient to cover the costs of complying with VSRP (Linder 2014).

10.3 Methodology

This chapter adapts an activity based methodology that models fuel consumption at the different phases of a journey for each engine on-board each vessel. Necessary data include the technical specifications of a vessel and the journey details (sailing speed, time spent at berth). The methodology uses established emission factors to estimate the pollutant emissions generated.

10.3.1 Fuel Consumption Per Trip

Each vessel operates in one of three different modes during a trip; cruise, manoeuvring and in-port berth activity. Typically on-board vessels there are three types of engines: main engines, auxiliary engines and auxiliary boilers (Zis et al. 2014). The propulsion requirements during cruise are powered by the dedicated main engines. The main engines are switched off during manoeuvring and when the vessel is at anchorage or at berth. The auxiliary engines on-board cover the electric requirements during any phase of the trip (cruise or berth) and tend to have increased engine loads during manoeuvring.

The boilers are fired whenever the main engines are switched off in order to maintain the temperature of the fuel and the propulsion engines at the desired levels. The energy demands of boilers vary depending on the ship, the calling port and the weather. The fuel consumption FC_{trip} (kg) for a journey is given by Eq. 10.1.

$$FC_{trip} = FC_{cruise} + FC_{manoeuvering} + FC_{berth} + FC_{anchorage} \tag{10.1}$$

where D denotes the distance travelled (NM), FC_{cr} the fuel consumption (kg) per NM during cruise, FC_m and FC_b the fuel consumption (kg/hour) during manoeuvring movements and at berth respectively for periods t_m and t_b (hours).

The fuel consumption during cruise per NM can be estimated by Eq. 10.2.

$$\mathrm{FC_{cr}} = 10^{-3} \cdot \left(\mathrm{SFCO_{main}} \cdot \mathrm{ELl_{main}} \cdot \mathrm{EP_{main}} + \mathrm{SFOC_{aux,cr}} \cdot \mathrm{EL_{aux,cr}}\right) \frac{1}{\mathrm{V_s}} \tag{10.2}$$

where $SFOC$ stands for the Specific Fuel Oil Consumption of each engine (*main* denotes the propulsion engine and *aux* the auxiliary engine), EL refers to the fractional engine load (%) of the MCR of the engine and EP to the nominal power (kW) installed for each engine. $SFOC_{main}$ and EL_{main} are functions of V_s. The general rule of thumb used in the industry is that EL_{main} relates to V_s by a power law (known as the propeller law) as follows:

$$\frac{EL_1}{EL_2} = \left(\frac{V_1}{V_2}\right)^{\mathrm{n}} \tag{10.3}$$

The value of the exponent n depends on the ship type, weather and sailing speed. Frequently a cubic relationship is used (n = 3) but when greater accuracy is required the values of Table 10.2 should be used.

Fuel consumption at berth per hour can be estimated through Eq. 10.4.

$$FC_b = 10^{-3} \cdot SFOC_{aux,b} \cdot EL_{aux,b} \cdot EP_{aux} + FC_{boilers} \tag{10.4}$$

Table 10.2 Variations of the propeller law

Ship	Exponent n
General (valid at low speeds)	3
Low speed ships (tankers, bulk carriers)	3.2
Medium-sized ships (feeder containerships, reefers)	3.5
Large high-speed ships (containerships)	4
Large containerships (extreme weather)	4.5

Source MAN Diesel (2009)

Table 10.3 Specifications of the examined containerships

Class	Capacity (TEU)	Nominal speed V_S (knots)	EP_{main} (kW)	EP_{aux} (kW)
Feeder	1000–2500	17.0	10,000	1900
Panamax	5000–7000	23.0	35,000	9000
New panamax	10,000–13,000	24.6	62,000	15,000
ULCV	15,000–18,000	25.5	80,000	23,000

Similarly, the fuel consumption during manoeuvring is

$$FC_m = 10^{-3} \cdot SFOC_{aux,m} \cdot EL_{aux,m} \cdot EP_{aux} + FC_{boilers} \tag{10.5}$$

This work assumes a universal average engine load of auxiliary engines during cruise and hoteling 30 and 23 % of the MCR respectively (Kontovas and Psaraftis 2009). For $EL_{aux,m}$ and $FC_{boilers}$ fixed values suggested in the emissions inventory of vessels calling in the port of Los Angeles are used (POLA 2013). Finally, the t_m is assumed fixed at 0.5 h during arrival and departure. The examined vessels are containerships of 4 different size-classes and their technical specifications are given in Table 10.3.

10.3.2 The Role of Sailing Speed

Propulsion engines are tuned to operate at the optimum level of efficiency (between 70 and 85 % of MCR) where the $SFOC_{main}$ takes its lower value as seen in Fig. 10.1. Figure 10.1 presents typical SFOC curves of a large 2-stroke engine in an ULCV and a smaller 4-stroke engine of a feeder vessel.

A significant speed reduction would result in lower EL_{main} and consequently fuel consumption despite the fact that the $SFOC_{main}$ would increase as seen in Fig. 10.1. The fuel consumption per NM of an ULCV is plotted for various V_S in Fig. 10.2.

It is evident that the total fuel consumption per NM is rapidly dropping at lower V_S. Figure 10.2 shows that at very low V_S the fuel consumption of the auxiliary engines can surpass that of the propulsion engines which is explained due to the longer time of operation per NM and the fact that the $EL_{aux,cr}$ is unaffected by the change in V_S.

Fig. 10.1 SFOC curves as functions of engine load

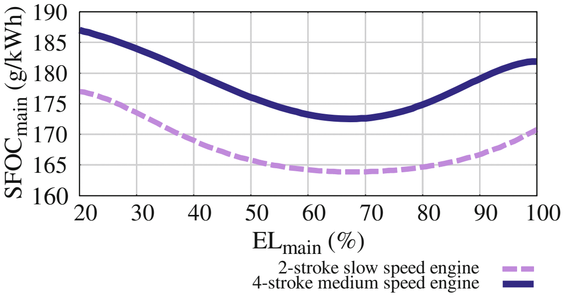
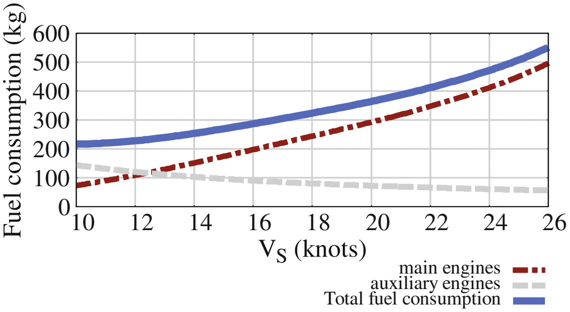


Fig. 10.2 Fuel consumption per NM at different V_S



10.3.3 Emissions Factors

Emission factors are ratios that are used to convert energy or mass to pollutant emissions. In maritime transport the emission factors are defined as ratios of mass of pollutant per mass of fuel burned and will be used as such in this chapter $\left(\frac{\text{gram of pollutant}}{\text{gram of fuel}}\right)$. The most common marine emission factors have been developed through a study of Lloyds Register Engineering Services during 1990–1995 when on-board data were collected for 50 representative sea vessels (Lloyds 1999). This study was expanded by Trozzi and Vaccaro (1998) who compared fuel consumption and emission factors used in the literature and proposed two activity-based methodologies for emissions estimation. A similar expansion to this methodology was conducted by ENTEC for the European Commission with increased importance in the role of the engine load to the main and auxiliary machinery (European Commission 2002). Finally, the Environmental Protection Agency (EPA 2000) has also set emission calculation standards and developed load correction factors for operation at very low loads.

The two methodologies of ENTEC and EPA were compared in the seminal paper of Dolphin and Melcer (2008) where it was shown that while the two are consistent, the EPA model fails to accurately depict the role of engine size, type and fuel type. The pollutant species modelled in the majority of these studies include CO_2, SO_2, NO_x, CO, volatile organic compounds (VOC) and particulate matter

(PM) emissions. In recent years there has been increasing focus on Black Carbon (BC) emissions from shipping due to its dual nature as a climate forcing agent and a local pollutant (Flanner et al. 2007).

This chapter will examine CO_2, SO_2 and NO_x emissions using values suggested by the IMO. A value of 3.17 is frequently used for CO_2 which is found by multiplying the carbon fraction of the fuel (86.4 %) with the relative molecular masses of CO_2 and C e.g. $\left(\frac{44}{12}\right)$. In a similar manner the SO_2 emission factor can be found by multiplying 0.02 with the sulphur content present in the fuel used. Nitrogen emissions vary depending on the engine speed and the IMO suggests a value of 0.087 for slow speed engines (large 2-stroke engines) and 0.057 for medium speed (4-stroke engines, auxiliary engines).

10.4 Analysis

The methodology of the previous section shows that there are significant fuel savings from sailing at lower speeds. This section will contrast the effectiveness of fuel switching and localised speed reduction schemes environmentally and economically.

10.4.1 Speed Reduction Near Ports

The following analysis assumes that each measure is compulsory and that the ship operator aims to minimise the cost of compliance without compromising the overall trip time. The critical parameters are the overall trip length D (NM) from port to port, the policy zone length z (NM), the nominal speed of each vessel V_S, the fuel cost and the speed limit V_l near the port.

10.4.1.1 Ship Operator Perspective

Considering that a ship operator would have to reduce V_S to V_l for the last z miles of an overall trip distance D, the time lost t_{lost} (hours) in the policy zone can be found by

$$t_{lost} = \frac{z}{V_1} - \frac{z}{V_s} \tag{10.6}$$

In order to ensure no time delay, the ship has to increase the sailing speed to V^* before entering the regulated area. If a maximum time delay t_{max} (hours) to the total trip time is allowed the necessary speed can be calculated as

$$V* = \frac{V_s \cdot V_l \cdot (D - z)}{V_1 \cdot D - z \cdot V_s \cdot V_l \cdot t_{\max}} \tag{10.7}$$

The necessary speed will increase for longer policy zones and stricter speed limits and decrease for very long journeys as there is additional distance to make up for the lost time. It should be noted that there is a maximum speed V_{max} that a vessel can sail at when the propulsion engines are working at the MCR.

$$V_{\max} = V_s\sqrt{[\mathrm{n}]}\frac{100}{EL_s} \tag{10.8}$$

The baseline conditions consider an ULCV travelling a distance of 1000 NM and entering a speed limit of 12 knots. A sensitivity analysis is performed for D, V_l, t_{max} and vessel type and $V*$ is plotted as a function of z in Fig. 10.4.

Figure 10.3 shows that different specifications of vessel speed reduction programmes near ports (policy length, speed limit) result in different behaviours for participating vessels (depending on port of origin and vessel specifications) and thus port authorities should consider tailoring such programs according to the visiting fleet and network connections.

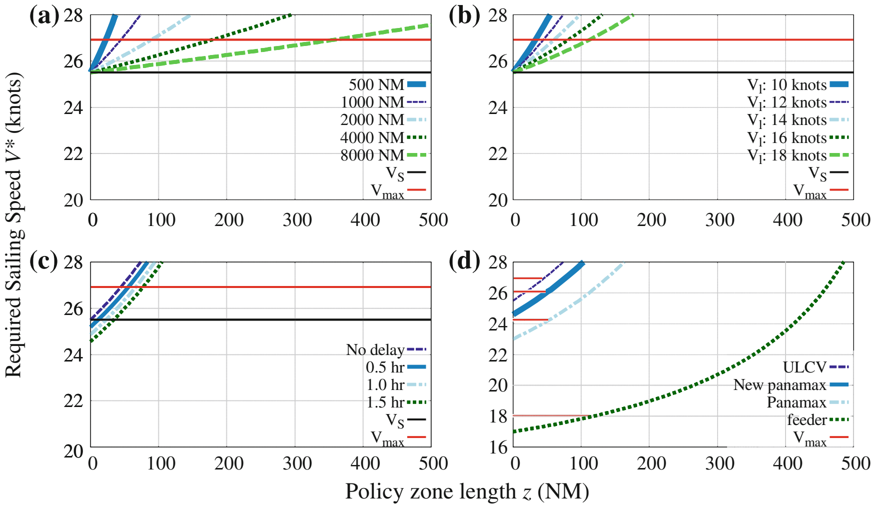


Fig. 10.3 Effects of policy zone length z (NM) to required vessel speed V^*(knots) for different: **a** trip distance D (NM), **b** speed limit V_l (knots), **c** allowed delay t_{max} (hours), **d** vessel type

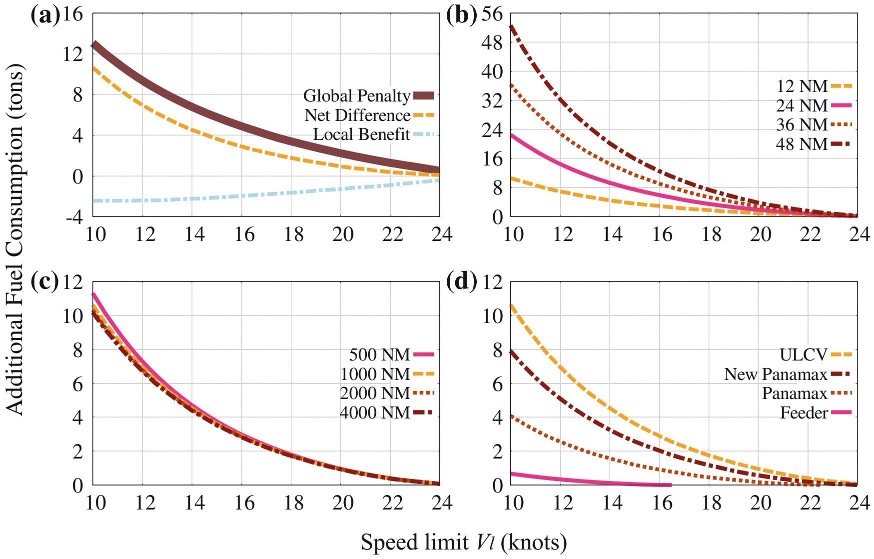


Fig. 10.4 Sensitivity analysis on difference in fuel consumption: **a** baseline scenario, **b** different zone length z (NM), **c** trip distance D (NM), **d** vessel type

10.4.1.2 Environmental and Economic Trade-Offs

The previous section examined the change in sailing speed along the journey caused by a speed reduction scheme near the port. The local benefits in emissions reduction enjoyed in the proximity of the port are offset by the additional fuel consumption due to the speed increase whilst at sea. The overall fuel consumption (from port to port) will increase and as a result assuming the same fuel price, the operating costs increase and there are more pollutants emitted globally.

The orange dashed curve gives the total additional fuel consumption for the baseline case (ULCV vessel in a trip of 1000 NM and a policy zone of 12 NM) for various speed limits. In Fig. 10.4a the local savings enjoyed in the proximity of the port are contrasted with the additional fuel consumption due to the speed increase outside the zone. The remaining graphs show that the policy zone length plays an important role in the additional fuel consumption globally, whereas the overall trip distance does not affect the global change as much. As expected, the larger ships complying results in additional emissions overall (but also more important local savings near the port) (Fig. 10.5).

Apart from the economic trade-offs of a complying decision, there are emission trade-offs occurring as well. As the localised speed reduction schemes aim to reduce NO_x emissions, which have more severe consequences in residential areas, it can be shown that NO_x savings in the port proximity are 'traded' with additional CO_2 released in the whole trip. For the baseline scenario of a policy zone of 12 NM, a

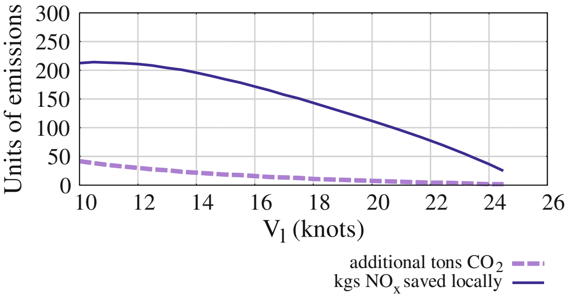


Fig. 10.5 CO_2 (tons) trade-off with local NO_x (kg) savings

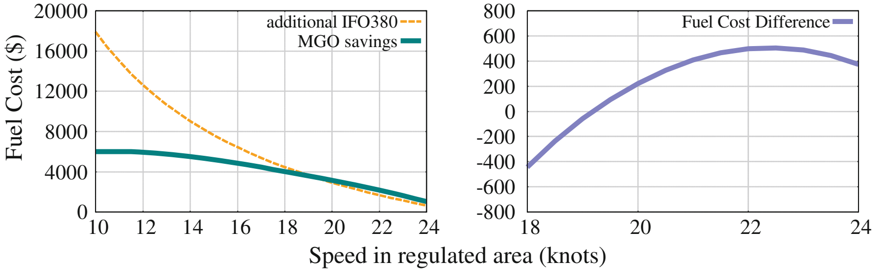


Fig. 10.6 Economic trade-offs and fuel price

trip distance of 1000 NM and a ULCV sailing normally at nominal speed the resulting trade-offs is plotted in Fig. 10.6.

Under the hypothesis that no time is to be lost, it is clear that the local savings in pollutant emissions near the port come at a significant cost due to the additional fuel required and higher greenhouse gas emissions. Finally, if a local speed reduction zone is to be adapted by a port authority and does not have a compulsory character, the analysis conducted allows the calculation of a monetary incentive that would convince ship operators to participate under different scenarios of z, D and V_l and ship calling.

10.4.2 Trade-Offs from Fuel Switching

There are areas where the use of low sulphur fuel is mandatory. The resulting SO_2 emissions are proportional to the sulphur content and therefore the emission savings are easily calculated. However, low-sulphur fuel is more expensive and therefore the SO_2 savings come at a high cost. Ship operators that seek to minimise costs may resort to speed differentiation in the different areas. For example, considering the CARB requirement of using fuel with 0.1 % sulphur in the last 24 NM of a journey the ship operator may choose to reduce the sailing speed for this distance and offset the delay with a speed increase earlier. The overall fuel consumption will increase due to the change of speeds; the ship will burn less of the expensive fuel. Considering again a baseline case of a trip of 1000 NM and fuel costs of $650 per ton of Heavy Fuel Oil (HFO—380) and $1200 per ton of Marine Gas Oil (MGO) the total fuel cost per trip is plotted in Fig. 10.6 for various sailing speeds in the 24 NM regulated area.

In the examined scenario depicted in Fig. 10.6, it is clear that it is in the economic interest of the ship operator to reduce its speed within the regulated area from 25.5 to 22.5 knots for fuel savings of $510 per trip. It is also seen that despite the increasing savings in MGO for very lower speeds, beyond 19.2 knots the increased fuel consumption of HFO during the trip is larger and thus leads to losses. Considering that in California the VSPR have a speed limit of 12 knots, it is clear that the overall fuel costs of the trip would increase and thus the ships complying with both regulations would be worse off. With different fuel prices, trip distance, policy zones and vessel types the optimal sailing speeds at the different segments would change.

10.5 Conclusions and Recommendations for Further Research

This chapter examined the economic and environmental trade-offs occurring when emissions reduction measures affect part of the journey in maritime transportation. The results highlight that there cannot be a universal policy/measure that is optimal for each vessel, port of origin and port of destination combination. The global environmental balance is sensitive and can be offset by one action that improves the air quality in the proximity of a coastal area or a port. The framework presented can be applied for the estimation of local savings in pollutant emissions for different values in the key parameters of the policy. The methodology considers the ship operator's perspective and the necessary changes in operation that allow the ship to arrive on time and at the minimum fuel costs while complying with the policy in place.

The overall trip distance does not significantly affect the additional emissions generated for arrival without time penalties and compliance to the scheme. Very large policy zones increase absolute emissions significantly and port authorities should carefully consider the length of the zone depending on the number of residents affected at each distance. Larger ships should be targeted primarily due to the bigger overall distance involved (allowing greater flexibility in sailing schedule) and the greater quantity of pollutants per call.

This work can be expanded by considering a shipping network where some of the proposed measures are compulsory and assessing the environmental impact. For example, the environmental benefits enjoyed in the regulated areas could be contrasted with the globally induced burdens due to increased sailing speeds. The impact on a more local scale near other ports where no such measures are forced could also be investigated. The next steps in this work involve the comparison of the local savings in the regulated areas with the global savings that would be enjoyed if the time lost for compliance in the regulated area was instead invested in slow steaming across the whole journey.

One of the weaknesses of the current model is that the economic analysis is very narrow and only considers the view of the ship operator. A thorough economic analysis can greatly enhance the suggested methodology by including the social costs and benefits of emissions reduction in residential areas and by considering the implications of the maritime and port sectors entering emissions trading schemes. Finally, the potential modal shift from maritime to other modes of transport due to the additional costs of emissions reduction measures and policies has to be considered as this would negatively affect the environmental balance given that shipping is the most fuel efficient mode.

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Chapter 11
The Economic and CO_2 Emissions Performance in Aviation: An Empirical Analysis of Major European Airlines

Chikage Miyoshi and Rico Merkert

Abstract The sustainability of aviation in global supply chains is of increasing importance to airline management and policy makers. With mounting environmental pressures and market volatilities, airlines need to find strategies for simultaneously managing their economic and environmental (emissions) performance, two objectives that can support but also contradict each other. This chapter aims to evaluate the relative performance of airlines' carbon and cost efficiency and how this relationship has changed over time. We compute and compare the carbon efficiency of 14 major European airlines for the period of 1986–2007. As jet fuel is the most important resource in the aviation supply chain, we examine whether there is a relationship between fuel prices and carbon efficiency. We also test whether unit cost, distance flown and load factors have an impact on airline carbon efficiency. The results show that the fuel prices and their volatility have affected and improved carbon efficiency of airlines. Our findings also confirm previous anecdotal evidence suggesting a significant negative relationship between carbon efficiency and unit cost.

Keywords Carbon efficiency · Fuel price · Unit cost · Airlines · Sustainability · Aviation supply chain

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11.1 Introduction

As a result of the liberalisation of most aviation markets, the advent of Low Cost Carriers (LCCs), the global financial crisis and the austerity measures in many countries as well as high fuel prices volatility cost control is very high on the agenda of any element in the aviation supply chain. It is also widely acknowledged that airlines contribute to Carbon Dioxide (CO_2) emissions and other green house gases (GHGs), and hence climate change. CO_2 is one greenhouse gas with a long atmospheric lifetime (100–1000 years), whereas NO_x has a much shorter lifetime in the atmosphere which depends on the time and location of the emission (Dressens et al. 2014a). The International Panel on Climate Change (IPCC) (1999) reported that aviation emissions such as CO_2 and water (H_2O) affect climate directly through fossil fuel conversion (Dressens et al. 2014b). Additional indirect effects include the production of ozone in the troposphere, alteration of methane lifetime and modified cirrus cloudiness. While the current share of aviation carbon emissions in total carbon emissions is still relatively low, forecasts suggest that aviation demand and hence CO_2 emissions from aviation are expected to grow faster than the global economy (Gudmundsson and Anger 2012). Also the relatively stronger impact of burning fossil fuels at high altitude (twice as strong as burning the same fuel at ground level; Lee 2010) contributes to raising concerns. The sustainability of aviation in global supply chains is therefore of increasing importance to airline management and policy makers.

With the mounting environmental pressures and market volatilities (demand, fuel prices and foreign exchange rates), airlines need to find strategies for simultaneously managing their economic and environmental (emission) performance, two objectives that can support but also contradict each other. Volatile fuel prices and carbon emission concerns have the potential to impact on operational practices (with fuel cost representing 40 % of the total industry costs; Halstead 2008), fuel and carbon permission hedging but also on fleet choice in order to improve their fuel efficiency (which reduces both fuel cost and emissions). One would assume that cutting CO_2 would at least in the short run incur costs, particularly capital costs (i.e. depreciation of new aircraft). However, new and fuel efficient aircraft might also become cheaper to operate and therefore overall more cost efficient (Miyoshi 2014). Since 2008 these trade-offs have (at least for the European context) become even more complex with legislation being adopted that regulates the inclusion of aviation in the EU Emission Trading Scheme (EU ETS; European Commission 2006). This scheme is the first implemented international market base mechanism (MBM) that aims for GHG emissions reduction. This legislation initially applied to all flights from/to the EU but was later suspended for flights in 2012 within non-European countries (European Commission 2013) due to the strong objections by non-EU carriers and countries. As a result of a ‘stop the clock’ decision (Decision no. 377/2013/EU; European Commission 2013) in April 2013, for the period 2013–2016 only emissions from flights within the European Economic Area fall under the EU ETS. The ultimate aim is a global MBMs through the

International Civil Aviation Organisation (ICAO). The global MBMs led by ICAO are expected to be finalised in 2016 and implemented by 2020 (European Commission 2014; ICAO 2014).

It is because of the first evidence from and experience with the EU ETS that we focus particularly on European airlines and analyze whether carbon efficiency impacts on their financial performance and vice versa. The analysis presented in this chapter applies a two stage methodology. In the first stage, we estimate the carbon efficiency of major European airlines over a period of 22 years (1986–2007) and also show how unit costs, load factors and stage lengths of these airlines have changed over the same period of time. In the second stage a number of different regression models are applied to evaluate the relationships between carbon efficiency and the other three measured variables of airline performance, namely unit costs, load factors and stage lengths. We extend Boyd and Pang's (2000) approach of linking energy efficiency with productivity further by (a) also considering cost efficiency and (b) applying the models to the airline context.

The remainder of this chapter is organised as follows: Sect. 11.2 discusses the results of our literature review. Section 11.3 details the methodology with regard to the estimation of carbon efficiency and Sect. 11.4 discusses the results. The regression models are then specified in Sects. 11.5 followed by Sect. 11.6 presenting both the cross sectional and longitudinal results. Finally, Sect. 11.7 concludes the chapter and provides suggestions for further research in this area.

11.2 Literature Review

Previous studies have not only focussed on assessing the environmental impacts of airlines' carbon emissions (e.g. Lee et al. 2010), but increasingly also on the underlying economics. While some papers aimed at estimating the cost and implications of those emissions to the wider economy (Bates et al. 2000; Tol 2005; Zhang et al. 2010) and demand (Macintosh and Wallace 2009), others focused on the impact of regulations that will to be imposed on the aviation industry to reduce the levels of carbon emissions. For example, Brueckner and Zhang (2010) applied a theoretical airline emission charges model to the aviation industry and found these emission charges would alter airlines choices and hence determine fares, flight frequencies, load factors and thus aircraft fuel efficiency.

Carbon emission efficiency can be defined as the ratio of output or capacity offered to the market to carbon (CO_2) tonnes/kg emitted. In the context of this chapter carbon emission efficiency is the ratio of available tonne-kilometer (capacity of an airline which includes passenger, freight and mail) to the total amount of CO_2 emitted. Less CO_2 per available tonne-kilometer (ATK) translates therefore by definition into more carbon efficient production. In order to estimate carbon emissions we use established conversion rates as aircraft carbon emissions are directly related to fuel consumption: According to European Commission (2009) and IPCC (1999) 3.156 kg of carbon dioxide is produced when one kg jet fuel (Jet kerosene type A, which is usually used for commercial jet aircraft) is burnt. Previous studies have found that carbon efficiency is improved by increasing load factors, seat density (per aircraft) and stage distance flown (Babikian et al. 2002; Lee et al. 2004). Miyoshi and Mason (2009) found that there are not only large differences at the airline and route level but also more systematically between different markets and airline business models in terms of emissions levels.

In addition, external shocks such as the 9/11 terrorist attacks and the global financial crisis have impacted on demand and hence unit cost, fuel efficiency (Oum et al. 2005) and hence indirectly also carbon efficiency. Zou et al.'s (2014) econometric results suggest for U.S. airlines that fuel efficiency can result in significant cost saving and hence improved cost efficiency. Morrell and Dray (2009) have further shown that high fuel prices having an influence on aircraft fleet turn over, which may in turn have potential impacts on carbon efficiency of the relevant airline fleet. Merkert and Hensher (2011) have further revealed that the fleet mix (fleet commonality) has a significant impact on airlines' cost efficiency.

For the European context, Albers et al. (2009) applied a scenario of € 20 per ton emitted CO_2 to individual routes in the EU. Their results indicate that at this price of CO_2 per tonne, the EU ETS would provide little incentives to European airlines to change their strategies or implement major route reconfigurations. Along the same lines, Boon et al. (2007) argued that the proposed allocation mechanism would only have a very small impact on the airlines' profitability. Contrary, Scheelhaase et al. (2010) showed that the proposed EU ETS would indeed not only impact on the cost structure of European airlines, but also result in competitive disadvantages of European airlines compared to non-European carriers. This is also due to the success of cost pass-through highly depending on market conditions and other factors (Forsyth et al. 2007). Morrell (2009) argued that airlines would instead increase aircraft size as a result of EU ETS incentives for doing so and hence reduce overall CO_2 emissions. First empirical results of the EU ETS scheme and its impact on the allocation of air traffic in Europe and CO_2 emissions are shown in Alonso et al. (2014). The importance of the initial allocation of allowances/permits and the need for maintaining a high price of those carbon permits to make the EU ETS scheme cost effective was studies in great detail (Derigs and Illing 2013; Miyoshi 2014; Sgouridis et al. 2011; Vespermann and Wald 2011). Some recent studies also looked at equity and the EU ETS, focusing on perceived differences of cost-benefit distribution among the groups participating in the scheme (Agusdinata and DeLaurentis 2011; Miyoshi 2014).

What most of the previous studies have in common is some hypothetical element in the models. We aim to show by using empirical data why carbon management, along with fuel management has become an important strategy for airlines. Particularly in the European context where there is a requirement to offset carbon emissions through allowances, carbon efficiency is expected to have an impact on airlines' cost efficiency over time.

11.3 Methodology and Sample

Our analysis aims to address the following questions: (1) Has airline carbon efficiency been improved as a result of the rise in jet fuel prices?; (2) Does carbon efficiency impact on airline unit cost and vice versa?; (3) Which airline types have acted to improve the efficiency of their operations and which options are available to less efficient airlines for improving their carbon efficiency? In this chapter we aim to relate the carbon emission efficiency [kg carbon per available tonne km (ATK)] of 14 European airlines to input factors such as fuel price, unit cost per ATK, distance flown and load factors. The impact of each factor is tested empirically using data from 1986 to 2007. Initially, we intended to include EBITDA and yield per ATK into the analysis, but the regression results came out insignificant.

In the first stage of our analysis, the carbon efficiency is estimated for each individual airline for the relevant 22 years. This estimation is based on traffic and fleet data of the Association of European Airlines (AEA) from 1986 to 2007 and aircraft performance data of BADA by Eurocontrol (2007). The approach used to estimate the carbon emissions per airline over the relevant period builds on Miyoshi and Mason (2009). Traffic and fleet data include both passengers and cargo services in all regions that are served by the analysed 14 AEA European airlines (see Table 11.1). Unit costs by airline were collected from ICAO data and the airline's annual accounts. Unit cost per ATK was adjusted using AEA traffic data to keep the consistency with the carbon emissions data. Fuel prices were provided by the US Energy Information Administration and adjusted for inflation. All cost and price data were converted into USD and are presented in 2007 prices.

In the second stage a number of different regression models are applied to evaluate the relationship between fuel efficiency and the other three analysed variable of airline performance, namely, unit cost, load factors and stage lengths.

11.4 Results of Carbon Emission Estimation

The results of the estimation model of carbon efficiency (kg/ATK) as well as key performance and cost data are summarized in Table 11.1. This table shows the emissions and characteristics of each individual airline for three of the analysed 22 years. Our results suggest that over the past two decades, the fuel efficiency of airlines if measured as the amount consumed per passenger km has improved by some 27 % between the years of 1986 and 2004 (which is on average an improvement

Table 11.1 Characteristics of major European airline used in this analysis in 1986, 2000 and 2007

Airline	Carbon (kg)/ATK	ATK (000s)	Cost/ATK in USD 2007 prices	Average distance flown (km)	Overall load factor
	1986				
AF	1.12	5,375,691	112.3	3812	0.69
Alitalia	1.18	2,303,808	127.1	3848	0.68
Austrian	187.4	2,570,000	–	1745	0.45
British Airways	1.04	6,383,762	116.1	4296	0.64
CSA	–	–	–	–	–
Finnair	2.63	306,985	316.7	5168	0.56
Iberia	1.87	1,733,388	201.5	3798	0.66
Iceland air	0.36	226,718	131.6	3461	0.74
KLM	0.75	4,301,744	91.5	4334	0.69
Lufthansa	1.01	6,731,665	126.2	4257	0.65
Olympic Airlines	1.66	641,902	–	4660	0.43
SAS	1.72	1,284,207	308.8	5123	0.7
TAP Portugal	1.13	564,936	177.2	3857	0.57
Turkish Airlines	10.68	54,523	–	2214	0.41
	2000				
AF	0.86	14,938,403	71.3	5833	0.75
Alitalia	1.06	5,400,617	123.9	6775	0.74
Austrian	1.14	1,197,893	176.1	7334	0.7
British Airways	0.88	18,807,401	69.6	6352	0.67
CSA	2.85	182,650	373.7	5084	0.66
Finnair	2.12	809,644	201.1	6017	0.64
Iberia	1.38	4,271,167	105	5255	0.61
Iceland air	1.35	397,842	139.2	4245	0.64
KLM	0.54	10,841,927	58.9	6253	0.81
Lufthansa	0.86	17,446,598	57	6245	0.77
Olympic Airlines	1.72	730,797	–	6581	0.6
SAS	2.13	1,840,884	290	6444	0.8
TAP Portugal	1.27	1,028,345	133.7	4686	0.64
Turkish Airlines	2.05	1,191,476	221	5674	0.62
	2009				
AF	0.83	19,747,187	88.9	6672	0.75
Alitalia	1.17	4,664,015	152.1	6960	0.76
Austrian	1.29	1,853,430	157.6	6944	0.8
British Airways	0.79	18,428,721	76.6	6770	0.67
CSA	4.49	228,186	590.6	6078	0.6
Finnair	0.99	2,258,194	139.9	6875	0.57
Iberia	0.94	6,184,564	109.1	6064	0.67
Iceland air	2.82	289,136	314.7	4340	0.67

(continued)

Table 11.1 (continued)

Airline	Carbon (kg)/ATK	ATK (000s)	Cost/ATK in USD 2007 prices	Average distance flown (km)	Overall load factor
KLM	0.45	12,919,687	109	7063	0.81
Lufthansa	0.84	21,505,167	78.8	6389	0.78
Olympic Airlines	1.79	473,224	248.7	6178	0.57
SAS	2.06	1,978,370	284.9	7175	0.76
TAP Portugal	1.12	2,135,885	116.8	5308	0.59
Turkish Airlines	1.94	1,873,634	174	5298	0.68

Source Own analysis based on AEA (2009), ICAO (2010) and Eurocontrol (2007)

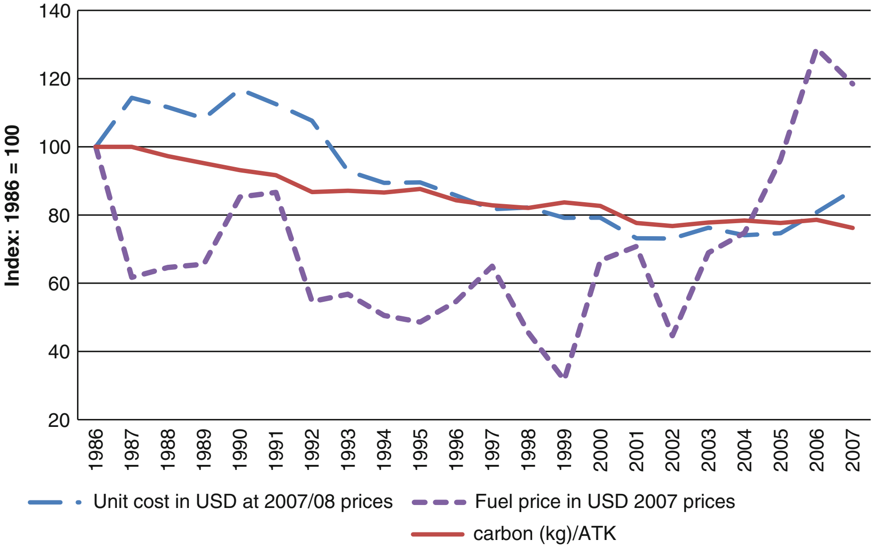

Fig. 11.1 Fuel price, unit cost and carbon emission levels of major airlines from 1986 to 2007. *Source* Data from Annual accounts, AEA, ICAO, Eurocontrol and US Energy Information Administration

of 2 % per year). The average distance flown has increased by 21 % and the average number of passengers carried per flight was up by 5 % over the same period of time.

Figure 11.1 exhibits the carbon efficiency trend in terms of the weighted average carbon emission (kg) in relation to available tonne km for all 14 individual AEA airlines over the analysed period. Figure 11.1 also illustrates that unit cost and carbon emission have decreased steadily until 2004. Overall, the level of carbon emission (kg) per ATK also fell by 20 %. At the same time (between 1986 and 2007) unit cost per ATK also fell by some 13 %. In contrast, the fuel price

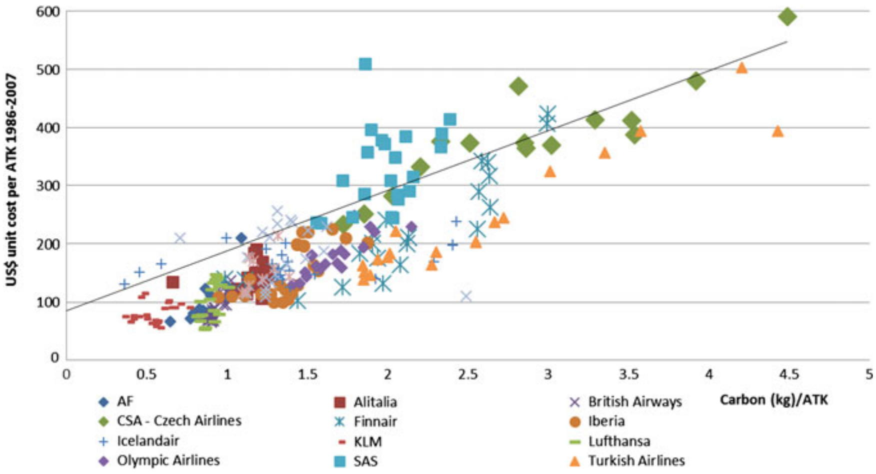

Fig. 11.2 Airline unit cost in relation to Carbon (kg)/ATK from 1986 to 2007. *Note* The observations of relative unit cost (in 2007/08 USD prices) and carbon emission (kg)/ATK are plotted for each of the 14 airlines and in each year from 1986 to 2007

has fluctuated somewhat unpredictably due to several shocks: the Gulf war in 1990–1991, SARS in 1997, September 11 in 2001 and the fuel price jump in 2004. Carbon emissions slightly increased shortly after each of these events, in line (the time lag appears to be quite short) with the increase in fuel price.

Unit costs dropped substantially during 1900 and 2000 by 40 %, but started to move up again from 2001. It is likely that this effect has been caused by the increase of the price of the key input, that jet fuel. Interestingly, since the sharp increase of jet fuel price in 2004, the unit cost rose despite a fall in carbon emissions. Although the unit cost and carbon efficiency have improved by about 20 % over the 22 years considered, there are differences across the analysed airlines.

Despite the volatility of fuel prices, Fig. 11.2 clearly illustrates the strong correlation between unit cost and carbon efficiency from 1986 to 2007. However, it also shows the variation across airlines and their transformation over the two decades. For example, whilst KLM, Lufthansa, Air France, and IcelandAir appear to have relatively stable (slightly decreasing) low carbon emissions per ATK, Czech Airlines and Turkish Airlines are associated with both higher levels of emission per ATK and a higher increase of these levels. Interestingly, SAS is one of the few airlines that have neither changed unit costs nor carbon efficiency over time; a similar observation can be made for Olympic Airlines and Finnair.

As the differences across the analysed airlines are hard to read in the way the results are plotted in Fig. 11.2, we have also plotted them in relation to carbon efficiency and for the two years of 1986 and 2007 only. As shown in Fig. 11.3, nine out of the 14 airlines have improved their carbon efficiency over the analysed period.

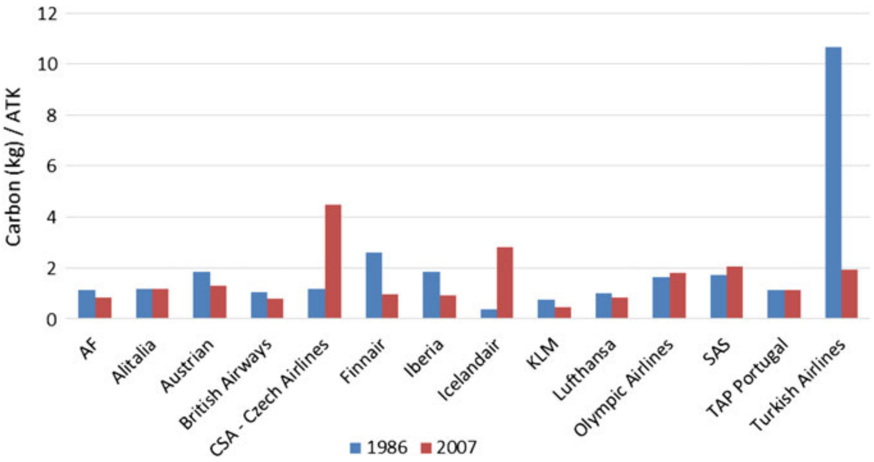

Fig. 11.3 Carbon efficiency of our analysed airlines in 1986 and 2007

11.5 Methodology of Evaluation of Relationships Between Carbon Efficiency, Unit Cost and Fuel Price

Based on the results of the descriptive analysis, we aimed to test the suggested correlation and hence the following three hypotheses were formulated: (1) unit costs have a significant positive impact on carbon emission efficiency; (2) carbon efficiency has been affected by the change in fuel price; (3) the carbon and cost efficiency are different across airlines, and change over time. In order to evaluate these relationships, the following regression model (Eq. 11.1) was specified with carbon efficiency as the dependent variable:

$$\begin{aligned}\ln Carbon_{it} &= \alpha + \beta_1 \ln Fuelprice_t + \beta_2 \ln Unitcost_{it} + \beta_3 \ln Distance_{it} \\ &\quad + \beta_4 Loadfactor_{it} + vi\end{aligned} \tag{11.1}$$

where $Carbon_{it}$ is the carbon emission (kg) per available tonne km (ATK) of airline i in year t (higher values mean less efficiency), $Fuelprice_t$ is the fuel price in year t in USD 2007 prices, $Unitcost_{it}$ is the unit cost per ATK for airline i in year t (in USD in 2007/08 prices), $Distance_{it}$ is the weighted average distance flown by for airline i in year t, and $Loadfactor_{it}$ is the weighted average load factor of for airline i in year t.

Based on our literature we argue that load factor and distance flown will most likely have an impact on carbon efficiency (Babikian et al. 2002; Lee et al. 2004; Mason and Miyoshi 2009; Zhang et al. 2010). What is less likely and hence more interesting, is whether fuel price and unit cost have an impact on carbon efficiency (as a result of fuel hedging and other factors an increase in fuel cost does not necessarily immediately result in an increase in unit cost).

In a first stage, the results of the pooled data were estimated using an OLS regression model. Since we found that Model 1 is associated with some degree of heteroskedasticity and because also the results of a Durbin-Watson d Test (value of 0.545) suggested some autocorrelation, two further regressions were used in a second stage, to see whether the results would differ from the simple OLS regression model.

In terms of those two additional regression models the first one is designed to determine differences across the different airlines while the second focuses on the differences over time. The results of both of these regression models are tested by means of the restricted F test.

11.6 Regression Results

11.6.1 Regression Results with Respect to Different Airlines

The results of both the OLS and the two GLS regression models used in this chapter are summarised in Table 11.2. In the airline specific (dummy) OLS model, all independent variables are statistically significant with an R^2 of 0.855 and a Durbin-Watson value of 0.754. This model appears to be a better fit compared to the pooled model, as the restricted F-value is 139.6 for 13 numerator df and 266 dominator df, and hence highly significant. However, as the Durbin-Watson test is below D_L, the GLS (Generalized Least Squares) methods appear to be most appropriate for our sample.

The most significant finding, which is consistent across all three models, is that unit costs have a negative impact on carbon efficiency. As Model 2 produced the best results in terms of R^2 and Durban Watson values we will focus our discussion on the results derived from that first GLS model. Its results suggest differences across airlines but also general trends such as negative impacts of Fuel price (−0.066) and Load factor (−0.353) on relative carbon emissions. The higher the fuel price and load factors the lower the relative carbon emissions (CO_2/ATK), which is as expected. Unit cost (0.318) and the Distance flown (0.296) have positive relationships with the dependent variable and therefore, negative relationships with carbon efficiency (the higher the relative cost, the more is emitted per ATK and hence the lower the carbon efficiency). In addition to these cross airline findings, the first GLS model also allowed for longitudinal analysis. The results suggest that some airlines improved their carbon efficiency over time, while others did not. Since the model uses the airlines as dummy variable (by estimating how much impact each airline has on the overall carbon efficiency), the results allow us broadly to divide the airlines into three different groups:

1. Relatively carbon efficient: Air France (coefficient of 0.074), BA (0.076), Lufthansa (0.083), Austrian (0.083), and Alitalia (0.088);
2. Slightly less carbon efficient: TAP (0.104) and Iberia (0.109);

Table 11.2 Estimation results of three regression models with Carbon kg/ATK as dependent variable

	OLS		GLS			
	Base model (model 1)		Airline (model 2)		Year (model 3)	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Constant	−4.966***	−7.327	−1.526***	−4.256	−0.740*	−1.966
$Fuelprice_t$	−0.085**	−1.961	−0.066**	−2.088		
$Unitcost_{it}$	0.716***	24.323	0.318***	5.582	0.646***	14.312
$Distance_{it}$	0.356***	4.7545	0.296***	2.831	−0.003	−0.024
$Loadfactor_{it}$	−1.586***	−8.266	−0.353	−1.265	−1.138***	−4.363
AF			0.074***	4.581		
AY			0.133***	7.096		
AZ			0.088***	5.297		
BA			0.076***	4.628		
FI			0.124***	6.974		
IB			0.109***	6.343		
KLM			–	–		
LH			0.083***	5.247		
OA			0.116***	5.454		
CSA			0.184***	8.010		
OS			0.083***	3.550		
SK			0.130***	6.574		
TK			0.169***	8.667		
TP			0.104***	5.760		
1986					−0.038	−1.413
1987					−0.021	−0.991
1988					−0.002	−0.074
1989					−0.009	−0.448
1990					−0.007	−0.356
1991					−0.004	−0.190
1992					0.006	0.287
1993					0.028	1.429
1994					0.023	1.231
1995					0.011	0.564
1996					0.008	0.435
1997					0.028	1.482
1998					0.007	0.375
1999					0.040	2.082
2000					0.031	1.637
2001					0.021	1.087
2002					0.062***	3.200
2003					0.015	0.257
2004					0.072	1.194

(continued)

Table 11.2 (continued)

	OLS		GLS			
	Base model (model 1)		Airline (model 2)		Year (model 3)	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
2005					0.015	0.825
2006					–	–
2007					0.005	0.259
The F test	212.8***		25.368***		10.991***	
N	280		270		272	
R^2	0.756		0.632		0.516	
DW	0.545		1.951		1.927	

Note *$P < 0.1$; **$P < 0.05$ and ***$P < 0.01$
Source Own analysis

3. Carbon inefficient: Olympic Airlines (0.116), SAS (0.130), Finnair (0.133), Turkish Airlines (0.169), and CSA (0.184).

Interestingly, these results are consistent with the results presented in Fig. 11.2. It is implied that the group of relatively carbon efficient airlines have been efficient in terms of carbon emissions and unit cost over time compared to the other airlines in Groups 2 and 3. KLM is the most efficient airline in Fig. 11.2 with respect to these parameters. However, in the empirical regression model the dummy variable of KLM had to be excluded due to multicollinearity. SAS, Finnair, Turkish Airline and CSA belong to the high unit cost and high carbon emission group. This can be explained by the fact that these airlines have been relatively less exposed to competition with Low Cost Carriers compared to Group 1 airlines.

11.6.2 Regression Results with Focus on Changes Over Time

Model 3 (GLS) aimed particularly at identifying the changes of carbon efficiency over time, for example as a result of technology improvements, changes in regulations and exogenous shocks such as SARS and 11 September 2001. Because of the low value of tolerance, the variable Fuel price had to be excluded in this third model. As in model 2, the results suggest that 'Unit cost' have a positive impact on carbon emissions and a negative relationship is revealed for 'Load factors'. Several year dummy variables (1986, 1992, 1999, 2000 and 2004) are marginally statistically significant. The year dummy of 1986 suggests a negative impact on the relative level of carbon emissions (and hence a positive impact on carbon efficiency). It is worth noting that, in 1986, the fuel price dropped dramatically because of oversupply and falling oil demand after the oil crisis in the 1980s. The other four years have a positive impact on carbon emissions. This means the carbon efficiency dropped in these years and may be a result of air transport demand declining after external shocks such as the Gulf war, SARS in 1997 and September 11 in 2001. Because of the drop in demand following these events, carbon efficiency declined. However, the results of Fig. 11.1 indicate some improvement of carbon efficiency after those events. This suggests that there may be time-lags between these events and carbon efficiency, which would be similar to the findings of Morrell and Dray (2009) who investigated the timing of aircraft turnover and re-engineering in relation to oil price peaks. In terms of their carbon efficiency we argue that airlines hope to swiftly respond to unexpected events by reducing capacity and operating costs in the short term. However, it often takes some time to implement those changes due to the institutional (e.g. schedule, slots, airport agreements) governance of air operations. In addition, fleet changes and renewal that would be required to bring about meaningful improvements in carbon efficiency do require a substantial capital outlay and are often subject to extensive internal decision making processes and external negotiations. Some airlines are locked into their fleet choices despite more efficient aircraft becoming available because of financial, organisational or indeed political reasons.

11.7 Conclusions

This chapter aimed to analyse the link between carbon efficiency and economic performance, namely unit cost (as most airlines key economic objective is cost minimisation) of major European airlines (covering both short-haul and long-haul carriers). Longitudinal impacts of fuel price, load factors and stage length were also investigated. Our results suggest that over the past two decades, carbon efficiency (which is also a proxy for fuel efficiency) of major European airlines has been improved by 20 % and unit costs have come down by 13 %. The change in fuel price has affected and improved carbon efficiency of airlines. When exogenous events occurred that reduced air transport demand and increased fuel prices, airlines cut capacity in order to improve their efficiency and reduce cost. Hence, carbon efficiency dropped initially after those events. Our key finding is that there is a significant negative relationship between carbon efficiency and unit cost. Improvements in carbon efficiency directly relate to cost management. The importance of carbon cost management is hence evidenced.

However, external demand and fuel price shocks as well as operational/travel disruptions such as the ash clouds resulting from the 2010 Eyjafjallajökull volcano eruption are unpredictable and uncontrollable, yet they have substantial impacts on both costs and carbon efficiency. The best ‘contingency’ practice is therefore continuous improvement of carbon efficiency and cost. In order to further improve carbon efficiency and hence sustainability of transport, airlines need to further improve operational practices (larger aircraft, different altitudes, more fuel efficient landing approaches etc.) and where possible also renew or re-engine their fleet. Different timelines are associated with the accomplishment of these measures as decision-making processes and the impact of capital investment (financial and human resources) result in time lags. In addition, fleet renewals require large investments. Not all airlines can implement this strategy promptly due to potentially weak cash flows and/or not strong enough balance sheets. Such airlines need to focus flight operation strategies that can improve carbon efficiency. The different results among airlines might have also been caused by differences in the airlines' organisation, institutional environments, and levels of competition with LCCs in their respective markets.

In the future, once the EU ETS is fully implemented we foresee that due to the cost of carbon being internalised into airlines' cost structures, the revealed carbon efficiency/unit cost relationship will become even stronger. Once a global MBM is implemented this will have not only an impact on European carriers but on airlines around the world. Carbon and fuel management strategies will therefore become even more crucial in the sense of operational best practices and technology improvement.

Further research into carbon and cost efficiency of airlines should investigate differences in airlines' fleet plans, labour cost and financial performance. In addition, the time lag of carbon efficiency improvements should be studied in greater detail. Finally, while the sustainability of the aviation supply chain largely depends on the carbon efficiency of airlines, there are numerous other players in that supply chain which also face cost and environmental challenges. The environmental footprint of airports is for example of increasing interest to regulators and stakeholders. The amount of emissions produced from airport activity is substantial and includes not only aeronautical sources, but also emissions resulting from airport surface access by passengers and employees (Ison et al. 2014; Miyoshi and Rietveld 2015; Miyoshi and Mason 2013), terminal buildings and other facilities. For example, in the London Gatwick airport context CO_2 emissions from passenger surface access are the second largest after aircraft emissions (BAA London Gatwick Airport 2009). Future research may hence consider extending our cost/carbon efficiency analysis to the airport context.

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Conclusion

Chapter 12
The Future of Green Logistics and Transportation

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Abstract The field of green supply chain management is rapidly growing and maturing. Significant room still exists for development in the field including those identified in this book in the context of green logistics and transportation. In this chapter we briefly review some of the important directions for future research in three areas of (1) green logistics network development, (2) green land transportation, and (3) green air and water transportation.

Keywords Sustainable supply chain · Green logistics · Green freight transportation · Green passenger public transport

12.1 Green Logistics Network Development

Opportunities abound for additional research in formal modeling and general study of green logistics and supply chain networks. One message we hope readers gained from this book is that achieving sustainability necessitates the development of resilient supply chains whose sustainability performance remains unaffected or lightly affected in the face of disruptive events (see Chap. 3). Logistics and supply chain sustainability research requires moving beyond a static analysis and performing a dynamic evaluation where supply chain sustainability can be examined in multiple disruption scenarios. Research and investigations in this context require identifying the related sustainability performance metrics, developing innovative

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robustness measures and multi-objective optimization methods to explore tradeoff solutions within a reasonable time tolerance, and completing dynamic sustainability analysis at the strategic, tactical and operational levels.

Dynamic sustainability analysis can also focus on the behavioral component of designing the distribution networks and delivery services (see Chap. 2). Different delivery and pickup alternatives provide different utility levels, and consumers choose alternatives so as to maximize their utility, subject to various constraints such as what transport modes they have available to travel to collection/delivery points (CDPs). The design of CDP networks can have impacts on the environmental footprint through reducing failed deliveries and allowing for consolidation of delivery schedules. A full environmental assessment of the end-to-end supply chain would require considering these pickup movements. This activity is where the mode choice of the customer making the pickup and their trip chaining behavior needs to be taken into consideration. Thus, distribution network design modeling efforts should incorporate the dynamics of the behavioral influences and their environmental consequences. Integrating behavioral responses and their associated environmental impacts into the conventional delivery models while considering the location, quality and price of the CDP and delivery offerings can become a formidable challenge and an avenue for future research in this area.

Another important, interesting and challenging topic is the development of "city logistics" for a global optimization, instead of partial/local optimization, of freight logistics and urban transport activities considering various aspects of environment, congestion, safety and energy consumption (see Chap. 4). Achieving the three city logistics goals of mobility, sustainability, and liveability requires the participation and cooperation of private and public sectors as well as residents. Advanced information systems such as Information and Communication Technology (ICT) and Intelligent Transport Systems (ITS) play a critical role in data collection and storage as well as information sharing among the city logistics stakeholders. The history of city logistics is relatively short and more research and investigations are required to evaluate and recognize the true economic, environmental and social benefits of innovative solutions. This whole topic linking public with private logistics management and techniques may provide ample 'technology transfer' and know-how between the two groups. Although the goals may be different (cost minimization or profit maximization versus serving the public and public well-being), the tools, methods, and research approaches can be evaluated and applied in both environments.

12.2 Green Land Transportation

Land transportation is very critical since much of the transportation implications from an environmental and business perspective are tied into this general mode. For example, freight vehicles contribute a substantial amount to the supply chain environmental burdens. The need for the development of decision support tools for evaluation and selection of environmentally conscious transportation fleets is evident (see Chap. 5). Future research in this area can focus on methodologies to develop and filter sustainability factors and attributes based upon which the environmental performance of transportation vehicles can be assessed. In particular, a technique, other than asking for expert opinions, may be helpful in narrowing down the initial factors. Secondly, the complexity of modeling efforts in this area may make it difficult for managerial acceptance of the technique. Clear, transparent, and easy-to-understand directions and support systems will be required. The development and availability of decision tools is only one dimension for land transport selection. Industrial or public sector differences may arise. How organizations make these decisions and their behaviors are additional dimensions for decision making. The roles of suppliers and customers and their needs in transportation fleet selection help to broaden the perspective across the supply chain. These additional dimensions are life cycle characteristics that can provide a broader and yet clearer picture of the true impact of these systems.

Many vehicle-related initiatives and advanced engine technologies can be used to improve the environmental performance of freight and passenger public transport systems (see Chap. 7). There have been substantial innovations in alternative fuels, utilization of different transport modes and larger capacity trucks, and City Logistics initiatives such as urban consolidation centers and low emission zones that help significantly reduce the emissions impacts from freight vehicles and public transport systems. Partnerships between public and private sectors are necessary to foster best practice for reducing the environmental impacts from freight and passenger transports. The argument here is that transportation fleet vehicle characteristics and decisions are only part of the solution. The extended infrastructural requirements and how these vehicles play a role in that are important. Matching vehicle to transportation environment and simulation or decision tools to help in this problem provides ample opportunities for future research directions.

One strategic message in this book is that we must look beyond final end product use to understand the full story of transportation utilization (i.e., passenger and freight movement) as well as the sourcing of energy that defines emission outcomes in the full production-consumption life cycle of transportation facilities and services. We must recognize that the greening of the supply chain entails establishing a greater appreciation of how alternative transport initiatives are influenced by and influence the shapes of our cities and regions and the demands on the use of alternatives means of transport. It is not just product or delivery vehicle, but the many dimensions of environment, infrastructure, controls, technology, and policies.

Importantly, the choices made by individuals and organizations on what modes of transport to use for specific tasks are made in the context of the entire origin-destination task, which often includes multiple destinations (see Chap. 8). This applies to both passenger and freight activity, and hence ongoing research and application must recognize the more holistic nature of people and freight movement and measure the greening of the full activity and not just the part that is defined by a main mode movement. Travel does not begin and end at a rail interchange, any more than it begins and starts at a bus stop or a port or airport. The recognition of the entire supply chain is a minimum recognition of the real impact that specific modal preferences and activities have on the environment.

A focus on road and rail track may miss an opportunity to improve the performance of the existing road and rail network without necessarily adding to that network. A primary refocus should be on the efficiency of hubs as interfaces to improve the efficiency and effectiveness of current intermodal activity and future opportunities. This perspective reinforces the view that modal competition is overemphasized to the neglect of the greater gain from viewing transport modes as complementary within the supply chain. It also suggests that the location of existing major hubs needs to be reappraised, be they intermodal terminals or warehouses. It may be more effective and less expensive to relocate such hubs than invest heavily in transport infrastructure to resolve a problem created in the first instance by the location of the hub. This perspective, which is not often subscribed to, will ensure that the prejudices (and associated emotional ideology) that often exist in promoting one mode over the other will be reflected on as an inappropriate basis for ascribing greenness.

12.3 Green Air and Water Transportation

The literature of green port and maritime logistics is still in its infancy (see Chap. 9). A comprehensive review of the existing literature identified seven clusters of research including studies on (1) port and maritime emissions, (2) eco-efficiency such as berth allocation strategies and bunker consumption optimization, (3) energy intensity and economic cost analysis, (4) environmental regulations, (5) carbon footprint case studies, (6) ship mobility emissions, and (7) ship construction/design. Clusters 1 and 2 have been the most popular and cluster 4 is the oldest amongst all, which is not surprising given the global trends in regulating anthropogenic carbon emissions from industrial activities. Research in all clusters is rapidly evolving and we expect many more multi-cluster studies which may require contributions from multiple disciplines such as business and economics, environmental science, and maritime and civil engineering.

In water transportation, fuel consumption and emission generation levels (e.g. CO_2, sulphur, nitrogen and particulate matter emissions) are dependent on multiple influencing factors such as port regulations, operator behavior, near-port sailing and streaming speed, and vessel specifications (see Chap. 10). For example, while the trip distance may not have considerable influence on emissions generation, significant fuel savings can be obtained from sailing in lower speeds, especially speed reduction of vessels near ports. Development of more effective environmental regulations and sailing policies by port authorities (e.g. sailing and streaming speed limits, policy zone and number of residents affected, fuel type and quality, vessel and ship size and engine characteristics) can help achieve green water transportation. Future studies should consider the adoption of multiple measures to investigate the environmental performance of maritime shipping under a range of policy schemes at the departing and arriving ports.

In the context of air transport, studies show that the carbon efficiency of major European airlines has been improved by 20 % in average while air transport costs have fallen by about 13 % over a 22 year period (see Chap. 11). Changes in air transport demand and cost figures, in particular fuel price, are identified as primary influencing factors for improved carbon efficiency. The market demand and fuel price volatility requires airlines not only to closely monitor their operational practices, but also to continuously review their fleets and investment decisions. We recognize this as a fertile direction for future research from both airlines cost/ emission tradeoff perspective and a supply chain perspective that air transport can be used as an express and environmentally friendly transport mode, especially in situations where lead-times play a critical role in material and product distribution.

12.4 Conclusion

Overall, we believe that the contents of this book provide a robust roadmap for further investigation in the area of green logistics and transportation. The observations and research directions provided in different chapters of this book can be integrated for the development of innovative solutions for greener multi-modal supply chains.

The book represents a point in time for a particular part of humanity's complex situation. The book is a very small part of the journey as we seek to become a more sustainable society, in this case from a transportation perspective. The developments and directions proposed here are only for a small fraction of potential research topics, just within green transportation and logistics. There are journals and other books dedicated to the topic, but we felt that this book was needed to provide ample opportunity to expand our understanding and further make progress. It is not only this generation, but future generations of people, systems, and society that will be influenced by the decisions we make today. Transportation and logistics decisions are ones that will cover generations, and hence making them greener and more sustainable is the least we can do for our social and environmental progress. Thank you for taking the time to read this chapter and the book.