Lecture Notes in Mobility

Gereon Meyer
Sven Beiker *Editors*

Road Vehicle Automation 4

Springer

Lecture Notes in Mobility

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Preface

You are holding the fourth volume of the Road Vehicle Automation book series in your hands, a journey that started when one of the very first symposia on this topic was held at Stanford University in 2013. Back then, an evolutionary development path, building on and further extending the achievements in advanced driver assistance systems, appeared to be the most probable introduction scenario of highly automated driving. Level 3 automation seemed to be feasible in the less complex environment of a motorway, as it would require just vehicle-based sensor systems, whereas the more revolutionary path of level 4 and 5 automation, covering a whole trip including urban areas, was considered pure utopia.

This notion is beginning to change fundamentally, right now. It is becoming obvious that level 3 automation would mean quite a lot of handovers from manual to automated driving and vice versa with uncertainties about driver's attention. At the same time, solutions for interpretation of traffic scenes improve, e.g., combining and fusing information from multiple sensor systems—both in the car and the environment, pattern recognition using machine learning and big data analysis, and connectivity of the vehicle with others and the infrastructure. In fact, it is uncertain now, which of the two paths—evolutionary or revolutionary—will unfold sooner. What remains certain, though, is the need to further develop technologies, study human factors, harmonize legal frameworks, and—last but not least—to validate the safety of automated and connected driving at all levels.

The chapters of this book are comprehensively covering political, legal, human factors, business, and technology-related aspects of connected and automated driving. They are based on oral and poster presentations of the Automated Vehicles Symposium (AVS) 2016 in San Francisco, California (USA). We are extremely grateful for these contributions and particularly appreciate the efforts of breakout session organizers to summarize the discussions they chaired in additional, jointly authored papers. Furthermore, we are happy to note that some authors who had contributed to previous volumes of Road Vehicle Automation have written chapters again. This provides the researchers, engineers, and decision-makers who are reading this book the opportunity to follow the developments in this rapidly evolving field in a unique way.

It should be noted that the Road Vehicle Automation books are now considered an important and relevant reference in their field. The chapters of the first three volumes have been downloaded more than 100 thousand times in the meanwhile, and access to the books is provided by several hundreds of libraries on all continents.

We would like to thank the organizers of the AVS 2016, the Transportation Research Board (TRB) and the Association for Unmanned Vehicle Systems International (AUVSI), for the continuing partnership. Our particular thanks go to Jane Lappin, Steve Shladover, and Bob Denaro from TRB for their support. Last but not least, we would like to thank Jan-Philip Schmidt and Petra Jantzen from Springer and Diana Tobias from VDI/VDE-IT for all their help during the editorial process.

And of course we are looking forward to the Automated Vehicle Symposium 2017 in San Francisco to connect with the automated driving community again, exchange latest findings in the field, and plan the fifth volume of this series as the next step in documenting what is arguably the greatest transition the automobile has seen since its invention more than 125 years ago.

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May 2017

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Introduction: The Automated Vehicles Symposium 2016

Steven E. Shladover, Jane Lappin and Robert P. Denaro

Abstract The 2016 Automated Vehicles Symposium built on the successes of the predecessor meetings, with an even larger and more diverse roster of participants and a broader selection of breakout sessions. The plenary and poster presentations and breakout discussions continued to provide the meeting participants with the most up-to-date and authoritative information about the current international state of development of road vehicle automation systems, making this the essential meeting for industry, government and research people interested in the subject.

Keywords Road vehicle automation · Road transport automation · Automated vehicles · Autonomous vehicles · Self-driving vehicles

1 Overview

The 2016 Automated Vehicles Symposium was organized and produced through a partnership between the National Academies of Science and Engineering Transportation Research Board (TRB) and the Association for Unmanned Vehicle Systems International (AUVSI), continuing the pattern established by the 2014 and 2015 Symposia. This meeting was organized to serve their constituencies' interests

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in understanding the impacts, benefits, challenges and risks associated with increasingly automated road vehicles and the environments in which they operate. It brought together key government, industry and academic experts from around the world with the goal of identifying opportunities and challenges and advancing automated vehicle (AV) and highly automated driving (HAD) research across a range of disciplines.

The symposium took place over five days, 18–22 July, with three days of core activities and ancillary sessions on the first and last days. The morning plenary sessions included presentations from the public sector, automakers and suppliers and research institutes and the afternoons were devoted to twenty-two breakout sessions for deeper investigation and discussion of selected topics. Receptions and poster sessions followed the close of the breakout sessions on Tuesday and Wednesday afternoons.

The breakout sessions were each organized by committees of volunteers to address a wide range of topics. Three of the breakout sessions spanned both afternoons of the Symposium, providing more time for exploration in greater depth and breadth:

- Public Transport and Shared Mobility
- Human Factors in Road Vehicle Automation
- Law and Policy as Infrastructure (Legal Issues)

The other nineteen breakout sessions covered a single afternoon each:

- Impact Assessment
- Enabling Technologies
- Safety Assurance
- Future Challenges for Automated Trucks
- Traffic Signal Control with Connected and Automated Vehicles
- Methods for Assessing Market Acceptance, Adoption and Usage of AVs
- Ethical and Social Implications of Automated Vehicles
- Early Implementation Alternatives for Automated Vehicles: An Interactive Scenario Planning Session
- "AV-Ready Cities" or "City-Ready AVS?"
- Design and Operational Challenges/Opportunities for Deploying Automated Vehicles on Freeways and Managed Lanes
- Reducing Conflict Between Vulnerable Road Users and Automated Vehicles
- Behavioral Experiments for Modeling Adoption and Use of Automated Vehicles
- Aftermarket Systems (ADAS-Related)
- Policy Making for Automated Vehicles: A Proactive Approach for Government
- Effects of Vehicle Automation on Energy- and Carbon-Intensity
- Cyber Security and Resilience Challenges and Opportunities for Self-Driving Vehicles

- Physical Infrastructure, Work Zones, and Digital Infrastructure
- Traffic Flow of Connected Automated Vehicles
- Can our Research Processes Keep Up in an Age of Automated Vehicles and Other Transformational Technologies?

The symposium also involved several related meetings that occurred before and following the main meeting:

- U.S. DOT Listening Session
- National Cooperative Highway Research Program panel meetings
- SAE On-Road Automated Vehicle (ORAV) Standards Committee meeting
- Meetings of the TRB Automated Transit Systems Committee and a joint meeting of the Traffic Control Devices and Signing and Marking Materials Committees
- U.S.—Japan—EU Trilateral Working Group on Automation in Road Transportation

In keeping with TRB practice, the plenary and breakout sessions were planned and produced by volunteers whose expertise and interests informed the content of the sessions. In keeping with AUVSI practice, the production of the symposium was professionally managed by dedicated conference and logistics managers. The AVS16 Executive Committee reflected this mix of the two organizations.

David Agnew, Hyundai-Mobis, Member, AUVSI Board of Directors; Richard Bishop, AUVSI subject matter expert on automation; Richard Cunard, Senior Program Officer, Traffic and Operations Engineer, TRB; Bob Denaro, ITS Consultant, Chair, TRB Joint Subcommittee on the Challenges and Opportunities for Road Vehicle Automation; Jane Lappin, Toyota Research Institute, Chair, TRB Intelligent Transportation Systems Committee (AHB15); Steven Shladover, University of California PATH Program, Chair, TRB Vehicle-Highway Automation Committee (AHB30); Brian Wynne, President and CEO, AUVSI; Lindsay Voss, Senior Program Development Manager, AUVSI.

2 Symposium Attendees

Almost 1200 registrants participated in the symposium. Attendees represented a wide range of organizations from government and industry to the academic-, public-, and private-sector research communities. One of the strengths of the meeting was the breadth of interests represented, including industry, public agencies and academic/research organizations. The automobile industry was well-represented with many attendees from Original Equipment Manufacturers (OEMs) and their suppliers.

These participants represented disciplines ranging from engineering to psychology to law. Twenty-five countries (representing 21% of the meeting participants from outside the U.S.) and forty U.S. states were represented among the meeting participants. The largest delegation from outside the U.S. came from Japan, with 60 participants, while the UK, South Korea, Canada and Germany all had more than 20 participants. California, as the host state, had the largest number of attendees from within the U.S., followed by the national capital region (DC, Maryland, and Virginia) and Michigan.

3 Keynote Talks

The Honorable Anthony Foxx, the Secretary of the U.S. Department of Transportation, gave the opening plenary address, indicating the importance that the U.S. DOT now assigns to vehicle automation and to the Symposium. Secretary Foxx observed that automated vehicles are coming, so government agencies have the choice to act or react. He advocated taking a proactive approach to integrate AVs into the transportation system safely, involving government, industry and consumers. He stressed the importance of making sure that crashes caused by technology errors or malfunctions do not increase, but that he does not expect automated vehicles to be perfect. He also noted the importance of clearly defining the boundaries of responsibility between the federal and state regulatory agencies and ensuring consistency across the states, which DOT is trying to facilitate by working together with the American Association of Motor Vehicle Administrators (AAMVA). Secretary Foxx concluded by noting that we should not only be focusing on the excitement generated by the new technology, but should focus on the goal of ensuring a safe and efficient transportation system for people and goods.

Dr. Mark Rosekind, the Administrator of the National Highway Traffic Safety Administration (NHTSA) gave the second plenary address, NHTSA and the Future of Automated Vehicles, discussing his agency's concerns about the recent rise in annual traffic fatalities and the potential for automated vehicles to improve traffic safety with a fundamentally new goal of preventing crashes before they occur. He took a practical approach to HAD and said that there will be incidents with AVs and NHTSA will investigate all of them. He said that we have a unique opportunity to share data and learn from HAD incidents, whereas with manual vehicles drivers don't share such data. And finally, no single incident will derail efforts to launch new technology that is life saving. He said that he did not know how to express when HAD is "safe enough", but reiterated Secretary Foxx' comment that we "can't wait for the perfect". He discussed NHTSA's work on developing guidance for the industry and states regarding highly automated vehicles (HAVs) so that they will be better able to realize their potential for improving road safety. He noted the difficulty of determining when HAVs will be safe enough, but said that they should be significantly safer than current vehicles before they reach widespread use. New safety metrics will be needed to assess HAVs, as well as new and more nimble regulatory processes.

4 Plenary Panel Sessions

Bob Denaro organized and moderated a panel session of start-up companies to provide insights about the business opportunities that these entrepreneurs see in the automated vehicle space:

- Dr. Louary Eldata, CEO and Co-founder Quanergy Systems, Inc.
- Nalin Gupta, CEO, Auro Robotics.
- Sravan Puttagunta, CEO, Civil Maps.

5 Plenary Presentation Sessions

Recent Developments in Vehicle Automation Technology:

- Socially Acceptable AI-Based City Driving—Dr. Maarten Sierhuis, Director, Nissan Research Center Silicon Valley
- Automated, Connected Electric Vehicles—Dr. Jan Becker, Senior Director, Automated Driving, Faraday Future
- Bringing Autonomous Vehicles into Production: An Automotive OEM Perspective, Colm Boran, Autonomous Vehicle Platform, Ford Motor Company
- Truck Automation: Enabling ADAS and Beyond through Connectivity, Dr. Josh Switkes, CEO, Peloton Technology, Inc.

Identifying and Addressing Key Non-technological Research Questions:

- Ethics of Autonomous Vehicles: Beyond Weird Crash Dilemmas—Dr. Patrick Lin, Philosophy Professor, Emerging Technologies, California Polytechnic State University
- Are Consumers Ready and Waiting for Automated Vehicles?—Kristin Kolodge, Executive Director of Driver Interaction and Human Machine Interface (HMI), J.D. Power and Associates
- Automated Driving Law—Bryant Walker Smith, Assistant Professor of Law, University of South Carolina
- Human Factors Recommendations for Highly Automated Driving in the EU Project AdaptIVe—Marc Dziennus, Cognitive Psychologist, German Aerospace Center (DLR)
- Policy Developments and Automated Vehicles—Sarah Hunter, Head of Policy, GoogleX
- The Traffic Jam of Robots: Implications of Autonomous Vehicles on Trip-Making—Dr. Joan Walker, Professor, University of California, Berkeley

- The Right Role for Autonomous Vehicle Technology in Cities—Gabe Klein, Fontinalis Partners Special Venture Partner and National Association of City Transportation Officials Strategic Advisory Board and Seleta Reynolds, General Manager of Los Angeles Department of Transportation, President of National Association of City Transportation Officials

International Developments on Automated Vehicles:

- Connected and Automated Vehicles in the UK—Iain Forbes, Head of the Centre for Connected and Autonomous Vehicles, Department for Transport
- Example European Activities on Connected and Automated Driving: The ADAPTIVE and AUTONET2030 Use Cases—Dr. Angelos Amditis, Research Director, Institute of Communication and Computer Systems
- Connected and Automated Driving in the Netherlands; Challenge, Experience and the Declaration of Amsterdam—Tom Alkim, Senior Advisor C-ITS and Automated Driving, Ministry of Infrastructure and the Environment, The Netherlands
- i-GAME: From Platooning to Cooperative Automated Maneuvering—Dr. Jeroen Ploeg, Senior Research Scientist, TNO Automotive, The Netherlands
- CityMobil2: Four Years of Demonstrating Automated Road Transport Systems in European Cities—Dr. Adriano Alessandrini, Università degli Studi di Firenze
- Drive Sweden: A National Effort on an Automated Transport System—Jan Hellaker, Head of Automation, Lindholmen Science Park AB

Technological Challenges:

- Connected and Automated Standards Are Key to New Vehicle Technologies—Jack Pokrzywa, Director, SAE Global Ground Vehicle Standards
- Cybersecurity Challenges for Automated Vehicles—Dr. Jonathan Petit, Principal Scientist, Security Innovation, Inc.
- Safety Assurance for Highly Automated Driving: The PEGASUS Approach—Dr. Hermann Winner, Technische Universität Darmstadt

Public Agency Programs on Road Vehicle Automation:

- European Collaboration on Road Automation—Liam Breslin, Head of Unit Surface Transport, European Commission, DG Research & Innovation
- Latest Developments in SIP-adus and Related Activities in Japan—Hajime Amano, President, ITS Japan
- USDOT Automation and Smart Cities Research—Kevin Dopart, Program Manager, Connected Vehicle Safety and Automation, Intelligent Transportation Systems Joint Program Office, U.S. DOT
- U.S. DOT Smart City Challenge—Brian Cronin, Director, Office of Operations and Development, Federal Highway Administration
- Automated Vehicles: Accelerating Their Safe Arrival—Nathaniel Beuse, Associate Administrator, Vehicle Safety Research, National Highway Traffic Safety Administration

- Transportation as a System: DOE SMART Mobility—Reuben Sarkar, Deputy Assistant Secretary for Transportation, U.S. Department of Energy
- Automated Vehicles and the Environment—Karl Simon, Director, Transportation and Climate Division of the Office of Transportation and Air Quality, U.S. Environmental Protection Agency

6 Breakout Sessions

The breakout sessions provided opportunities for more in-depth consideration of specific topic areas among groups of people with focused interests in those areas. With smaller groups, they could be more interactive than the large plenary sessions, with ample opportunities for questions and answers and debates. The primary findings from the breakout discussions were reported back to the plenary group on the final morning of the Symposium, in four panels based on thematic groupings. Highlights of the outputs from some of those sessions are summarized here.

6.1 User-Related Automated Vehicle Issue Breakout Sessions

Reducing Conflicts Between Vulnerable Road Users and Automated Vehicles

This group discussed the need for pedestrians and bicyclists to be able to communicate their intent to the AVs so the AVs can anticipate their actions, as well as the AVs communicating their intent to the vulnerable road users (VRUs) using external lighting. They were also concerned about the multi-modal intersection of the future and how to accommodate pedestrians (noting that we cannot expect to eliminate traffic signals where interactions with VRUs are possible).

Methods for Assessing Market Acceptance, Adoption and Usage of AVs

This group was concerned about how to collect data about user attitudes when people don't really understand AVs and their capabilities. The vehicle usage experience needs to be understood before it's possible to get to questions about purchase and usage decisions. Pilot tests need to be leveraged for data collection about this, where people can actually experience the AV operations.

Behavioral Experiments for Modeling Adoption and Use of Automated Vehicles

A variety of approaches was catalogued for assessing traveler behavior. Standard questions are needed across experiments so that results can be compared, and this also needs collaboration with other AV disciplines for a coordinated, integrated approach (so that the questions can reflect the reality of how the systems perform).

6.2 Breakout Sessions on Specific Automated Vehicle Application Areas

Public Transport and Shared Mobility

There was interest in working on the first and last mile access challenge and how shared AVs could serve under-served populations. There is a need to measure, document and share best practices and assessments of impacts.

Future Challenges for Automated Trucks

Although driverless truck operations are important for the military, they do not appear to be urgent for commercial applications. The importance of standards for V2V technology for platooning was emphasized, but non-cooperative automation could also be applied for intermodal terminals and drayage applications. The group also discussed whether the US needs something analogous to the European Truck Platooning Challenge?

Aftermarket Systems (ADAS-Related)

How can after-market products facilitate market penetration growth for AV systems? There is a need to catalog aftermarket opportunities for progress, such as ADAS applications building on smart phones and aftermarket data acquisition systems to collect large bodies of real-world driving data.

6.3 Policy and Societal Issue Breakout Sessions

Law and Policy as Infrastructure

Road authorities were most interested in traditional regulation topics such as boundaries between federal and state authority. The framework for driver licensing needs to consider concepts of responsibility and control and how they change with automation.

Ethical and Social Implications of Automated Vehicles

Ethical decisions are not necessarily hard coded, but this appearance is sometimes given. Standards are needed for data sharing so that data can be shared more openly. We can learn from the experience in the bioethics field.

Policy Making for Automated Vehicles

A Proactive Approach for Government: There is a need to educate public agencies about AVs, especially by giving policy makers the opportunity to experience the technology directly. There is a risk of premature regulation. Long-term transportation plans need to recognize the “new normal” in technology and the need for new training paradigms.

6.4 Breakout Sessions on Planning for Automated Vehicles

Impact Assessment

It's important to consider both direct and indirect impacts, considering different impacts on different stakeholders over different time scales. A common assessment framework would be useful. Uncertainty poses significant challenges in predicting impacts.

Effects of Vehicle Automation on Energy- and Carbon-Intensity

The net effects of AVs on energy and carbon intensity are unclear because of different positive and negative influences. Standard driving cycles for assessing energy and emissions will have to be revised to account for smoother speed profiles achieved with automation.

"AV-Ready" Cities or "City-Ready AVs?"

AVs are starting to get onto the urban policy agenda, where they need to be seen as tools to help solve transportation problems. Challenges include lack of modeling tools and of qualified staff to work on the issues. Achieving benefits will depend on behavior changes.

6.5 Breakout Sessions on Technology Issues

Enabling Technologies

Five technology categories were reviewed against several application scenarios. A deeper dive is recommended for next time around.

Safety Assurance

We need an honest discussion with the public about setting realistic safety expectations for AV systems. A variety of approaches to safety were discussed. Gaining public trust is essential, but this probably depends on having open data bases to define test scenarios and on generally accepted standards for validation.

Cyber Security and Resilience Challenges and Opportunities for Highly Automated Vehicles

We need to be able to distinguish cyber-attacks from failures, since they are not the same. Consumer expectations do not match expert thinking on the subject. Vehicle-roadway cooperation can promote opportunities to detect threats. Research is needed to understand the attack surfaces.

7 Breakout Sessions on Operational Issues for AVs

Design and Operational Challenges/Opportunities for Deploying Automated Vehicles on Freeways and Managed Lanes

Many managed lanes are already close to capacity, so there are concerns about how they could accommodate more traffic with additional categories of users. Better tools and models are needed to predict impacts, especially in mixed traffic environments. Deployment scenarios need to be defined for both new and converted managed lanes.

Traffic Flow of Connected Automated Vehicles

Current models don't represent AV performance adequately, including topics like lane changing, other aspects of driver behavior, and communication latency.

Traffic Signal Control with Connected and Automated Vehicles (CAVs)

This was a discussion of research needs, including topics in understanding user characteristics (including VRUs), control strategies that incorporate vehicle dynamics, human factors and infrastructure adaptations. Signals could have different levels of automation.

8 General Cross-Cutting Observations

As the field of road vehicle automation has advanced and the level of knowledge of the issues has grown over the past several years, the areas of emphasis within the Automated Vehicles Symposium have shifted. In this most recent meeting, several general observations are worth noting:

- More attention was devoted to the lower and intermediate levels of automation than in previous years, perhaps based on recognition that these will be the practical outcomes in the relatively near future. There also seemed to be a clearer recognition of the differences among the levels of automation.
- The presentations and breakout sessions covered a wider range of topics in the non-technological areas, with a broader range of stakeholders and expertise represented. However, the mirror image is that there was less on technological issues, which meant that the few technology-oriented breakout sessions were over-crowded.
- There appeared to be a substantially enhanced recognition of the difficulties that need to be resolved to reach the higher levels of automation, leading to more realistic deployment predictions. It was refreshing to hear multiple speakers admitting how difficult it's going to be resolve their issues and how important it will be for people in different countries and different stakeholder communities to work together on resolving them.

- With the increased level of knowledge among the meeting participants, more discussions were building on an established knowledge base, with less need to fill in background information.
- More subtle and intelligent questions were asked in the discussions (not just the obvious ones), again indicating the growing sophistication of the meeting participants.
- There was a sense of urgency in solving the technical and non-technical issues as market forces are pulling HAD into the market along with the authorities encouraging deployment but at the same time releasing guidance and regulations to manage this huge transition in transportation and mobility.

Part I
Public Sector Activities

Latest Development in SIP-Adus and Related Activities in Japan

Hajime Amano and Takahiko Uchimura

Abstract In 2014, Japanese government initiated a research and development program on connected and automated driving systems. Progresses made in the first half of this 5-year program are described in this paper. For the second half of the program, large-scale field operation tests are being planned. Objectives, scope and opportunities for international participants during the field operation tests are introduced. Expected applications of connected and automated driving technologies to overcome societal challenges in the Japanese context, such as aging and declining population, are also described.

Keywords Automated driving · Dynamic map · Connected vehicles · Human factors · Field operation test · Inclusive society

1 Overview of the SIP-Adus Program

Japanese national program on connected and automated driving systems started in 2014. The program name, SIP-adus, stands for Cross-Ministerial Strategic Innovation Promotion Program, Innovation of Automated Driving for Universal Services.

Connected and automated driving will be realized integrating a variety of technologies. On-board technologies are already in product level competition. Auto manufacturers are demonstrating their technologies and announcing near future products. Therefore, scope of SIP-adus, as a government funded project, does not include on-board technologies nor development of prototype automated cars.

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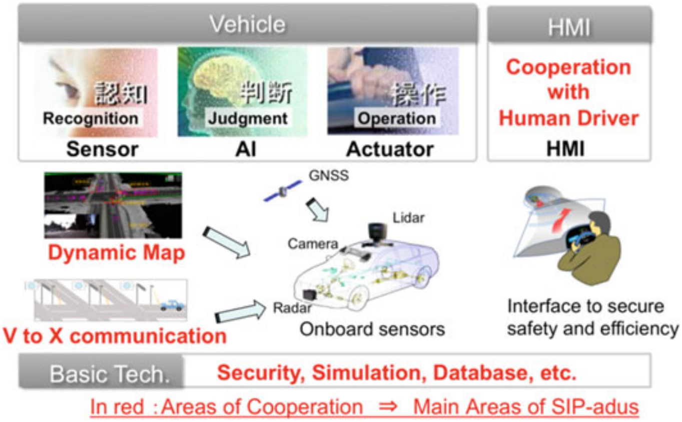

Fig. 1 Technologies for connected and automated driving

The program is focusing on platforms to be shared among stakeholders. Those are Dynamic Map, Connected Vehicles, Human Factors, Impact Assessment, Next Generation Transport and Cyber-security (see Fig. 1). Under the SIP-adus, more than 20 research projects are being conducted. Integrating results from those projects with active participation of auto manufacturers and research institutes, a large-scale field operation tests will be conducted from September 2017 through March 2018 (Morishita 2016; Kuzumaki 2016).

2 Progress of SIP-Adus in the Focus Areas

2.1 Dynamic Map

The Dynamic Map is composed of layers with different time frame; static, semi-static, semi-dynamic and dynamic. SIP-adus developed a prototype of the static database of the Dynamic Map and the location-referencing framework for dynamic data was also developed.

On a screen capture of the Dynamic Map viewer to evaluate the database and the location referencing, three-dimensional model of the road environment is shown over the measured data (see Fig. 2). Dynamic data of other road users, such as cars and pedestrians, are shown as yellow symbols.

It is emphasized that combination of cooperation to build shared common database and competition in the service operations with additional proprietary data. Based on the achievement through the SIP-adus, a company named ‘Dynamic Map Planning’ was founded to create a business model in line with the concept of balancing cooperation and competition. Survey companies, digital map

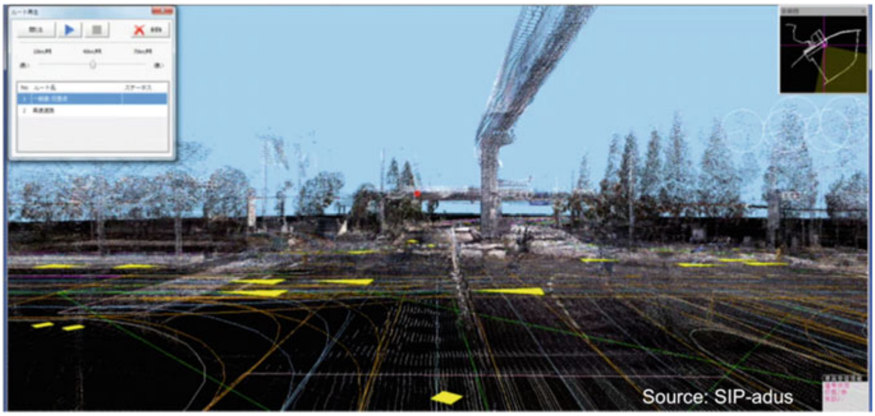

Fig. 2 Prototype dynamic map—viewer

suppliers and 9 Japanese major auto manufacturers joined. Targeting 2017, this company will be transformed into a real business entity (Shirato 2016).

2.2 *Connected Vehicles*

Evolution of connected and automated vehicles will be realized by integrating built-in features of driving assistance, getting more and more popular in the market, and cooperative systems, already in nationwide operation for more than 6 years in Japan. In other words, cooperative system is an essential part of the automated driving. Examples of connected services recently deployed are described in this section.

The Traffic Signal Prediction Systems or TSPS is a good example to mitigate traffic congestion at signalized intersections. Phase and timing of traffic signals are broadcast at the intersections. On-board system judges safe and most efficient speed and acceleration or deceleration timing (see Fig. 3). The system has already been installed and used by manually driven cars. 5–9% reduction of waiting time at red signal and about 10% reduction of fuel consumption are observed.

Today, more than 90% of highway toll is electronically collected in Japan after 15 years of operation. Using the same spectrum, nationwide deployment of roadside equipment for cooperative services was completed 6 years ago at 1600 locations. Safe driving assistance, traffic information provision and dynamic route guidance are available. The new services such as dynamic toll charging to guide drivers to less congested route with lower toll incentive, and freight operator support, utilizing probe data from the trucks are expected to start soon (Amano 2016).

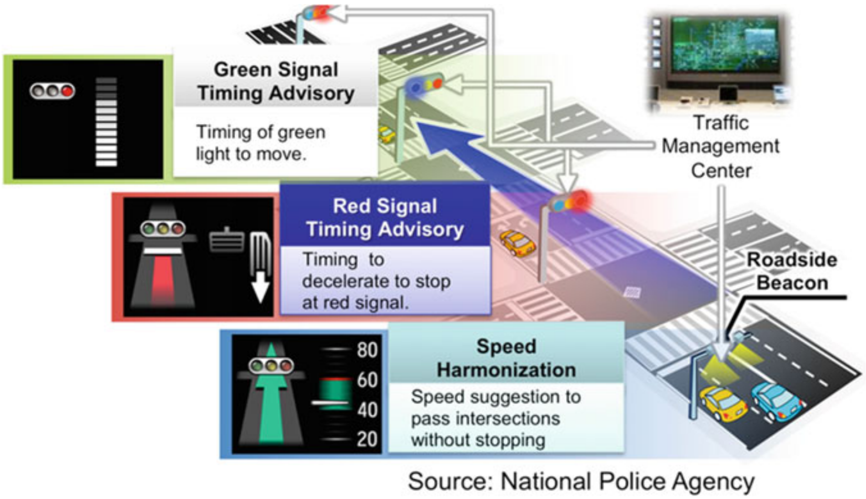

Fig. 3 Traffic signal prediction systems (TSPS)

2.3 *Human Factors*

Human factors are also important area. At SIP-adus, for the first phase, the focus of attention was transitions of roles between vehicle control system and human driver. Important cases are identified and a series of events, which trigger transition, are being analyzed along the timeline in each case. Then, the scope has been extended to cover the interactions between automated vehicles and surrounding road users and the society. Categories of issues on Human Factors are shown in Table 1 (Kitazaki 2016).

2.4 *Next Generation Transport*

Applications of automated driving technologies to public transportation is investigated at SIP-adus. The Advanced Rapid Transit will be deployed for the Tokyo Olympic and Paralympic Games in 2020. Tokyo Metropolitan Government and Keisei Bus Co., Ltd. released a Bus Rapid Transit deployment plan, including the ART system, in the waterfront area, where facilities for the Olympic and Paralympic Games are located. Keisei Bus is the operator of the system. The operation will start in 2019 (Amano 2016).

Table 1 Human factors—categories of issues

Interaction between	System use	
Vehicle–driver	A-1	Understanding system functions
	A-2	Understanding system states
	A-3	Understanding system operations
	A-4	Understanding system behavior
	Driver's state	
	B-1	Driver state with automation
	B-2	Transition from automation to fully manual
	B-3	User benefits of automation
Vehicle–surrounding road users	C-1	Communication between the autonomous vehicles and surrounding drivers
	C-2	Communication between the autonomous vehicle and surrounding vulnerable road users
	C-3	Mediation between formal rules and traffic efficiency
Vehicle–society	D-1	Social value and acceptance of the autonomous vehicles
	D-2	Liability
	D-3	Licensing

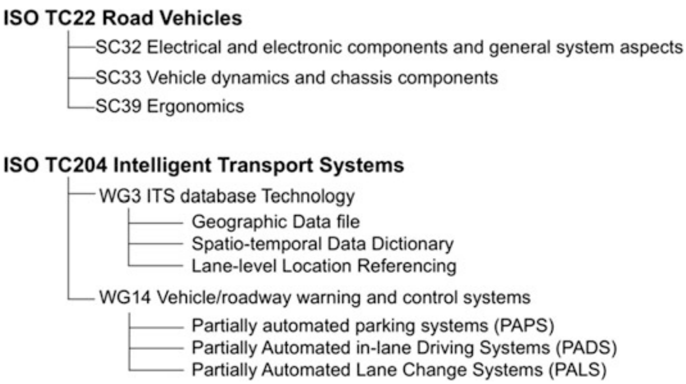

Fig. 4 Standardization at ISO

2.5 Standardization

Results of SIP-adus activities are input to the international standardization body (see Fig. 4). At ISO TC204 and TC22, Dynamic Map, system design and human factors are actively discussed. SIP-adus with other related activities in Japan is one of the contributors to those discussions (Shibata 2016; Uchimura 2016).

3 Large-Scale Field Operation Tests as a Platform for International Cooperation

Large-scale field operation tests are planned under SIP-adus program starting September 2017 through March 2018. Outline of the field evaluation tests is described in this section. Participation to the field operation tests is open to any qualified organizations. International participation is also welcome (Minakata 2016).

3.1 Objectives

The expected outcome the field evaluation tests is to provide auto manufacturers and research institutes with internationally shared platform to devise harmonized specifications and framework for connected and automated vehicles deployment, with active participation of international stakeholders.

Both technological excellence and harmonization in technical specifications are important aspects of the field operation tests. In addition, it is also recognized that feasibility and sustainability of practical operations should be taken into account.

3.2 Outline of the Field Operation Tests

3.2.1 Focus Areas

More than 20 projects are being conducted under SIP-adus. Achievements from those projects are integrated into 5 focused themes of test operations.

Those are:

- *Dynamic Map*: Prototype Dynamic Map of 3-dimensional high-resolution digital map data with road geometry and surrounding structures is evaluated. Semi-dynamic information such as traffic congestion and road closure is also included. Prototype data exchange scheme for generating, maintaining and distributing Dynamic Map is evaluated, too.
- *Human Machine Interface*: Drivers' understanding of the operational status of automated vehicles, readiness of the driver to take over the control of the vehicle under a variety of scenarios are measured and evaluated. Means of interactions of the automated vehicle with other road users are also investigated.
- *Information security*: Vulnerability against a variety of simulated cyber attacks is evaluated in a closed test environment. Counter measures are also evaluated.

Fig. 5 Field operation test site

- *Pedestrian accident reduction*: Applications of vehicle to pedestrian communication technologies to prevent cognitive mistakes and remind potential dangers are evaluated.
- *Next generation urban transportation*: Advanced Rapid Transit system with connected and automated technologies is evaluated from service level point of view for challenged passengers.

Demonstration of the connected and automated vehicles is also planned to promote proper understanding of new technologies for the general public, fostering social acceptance of deployment of those systems.

3.2.2 Test Sites

Three types of test environment are assigned. About 300 km stretches of expressways are selected surrounding Tokyo Metropolitan area, including Joban expressway, Tokyo Metropolitan expressway, Tomei expressway and Shin-Tomei expressway. For arterial road testing, Tokyo waterfront area is selected, where major facilities of Tokyo Olympic and Paralympic Games are located. In addition, for controlled environment testing, test facilities at Japan Automobile Research Institute will be used (see Fig. 5).

3.2.3 Resources

SIP-adus program will make all the arrangement among related national and local government agencies and road operators for the participating parties to use those test sites. Overall management of the field evaluation tests is also under the SIP-adus program. Shared databases essential for the objectives to be fulfilled, such as Dynamic Map for the entire test sites, will be built and distributed to the participating parties including follow up access to the updates for free. However, vehicles, drivers, supporting staff for safety of the vehicles and other road users, and necessary insurance coverage must be provided by the participating parties at their own cost.

3.2.4 Regulations

Test vehicles must comply with the Safety Regulations for Road Vehicles under the Road Traffic Act. Operation of the test vehicles must follow Road Traffic Act. The human driver monitors the surrounding traffic and the vehicle's condition at all times. In the event of an emergency, the driver operates the vehicle as necessary. In addition, the National Police Agency released Guidelines for Public Road Testing of Automated Driving Systems in May 2016. Participating parties are required to follow the guidelines.

3.3 Opportunities and Requirements for Open Participants

In the light of the objectives of the field operation tests, participation to the field operation tests is open to any auto manufacturers and research institutes as long as they meet the regulations and arrange necessary resources by themselves. Because it is important for the international players to work together to develop harmonized technical specifications and feasible operational framework, all the participating parties are required to submit test reports according to the guidelines set by SIP-adus. However, any proprietary data related to on-board technologies are not required to share. Only generic information to enhance technical specifications of common platforms and practical feasibility of deployment will be required.

4 Societal Values to Be Created with Connected and Automated Vehicle Technologies

4.1 Challenges for the Japanese Society

The key message from SIP-adus is 'Mobility Bringing Everyone a Smile'. We envision an inclusive society, where connected and automated driving technologies provide everyone with mobility to fully exercise his or her capacity, enabling sustainable development of the society (Amano 2016).

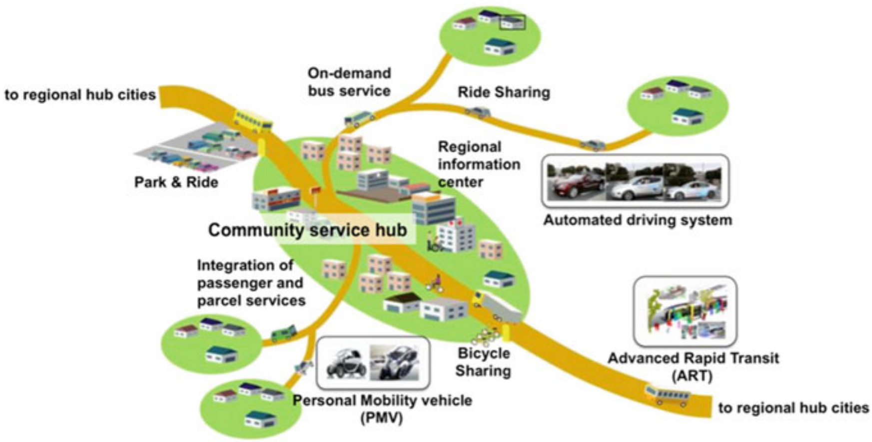

Fig. 6 Cluster of villages

4.2 Mobility for Enhanced Quality of Life and Socio-economic Activities

In 2014, Japanese government compiled a Grand Design towards 2050, where three types of cities are defined. In rural areas where most serious population decline is projected, small villages are connected to a basic social service hub with transportation and information network to maintain combined population of 10,000. We will have 5000 clusters of this kind (see Fig. 6).

Middle size cities are integrated to have combined population of at least 300,000, connecting to each other within one hour of travel. Population of 300,000 is necessary to maintain high-level education, medical care and employment opportunities. We will have 60–70 of reginal hubs (see Fig. 7).

Mega-cities like Tokyo become more concentrated center for competitive edge in global economy. Industries across the country are integrated by high capacity and efficient transportation for both people and goods and connected to the global operations. For the Japanese society to be sustainable, comprehensive transportation network is essential. For the transportation to be sustainable, innovative technologies such as connected and automated systems and social innovations are essential.

SIP-adus is expected to significantly contribute for the Japanese Society to overcome those challenges.

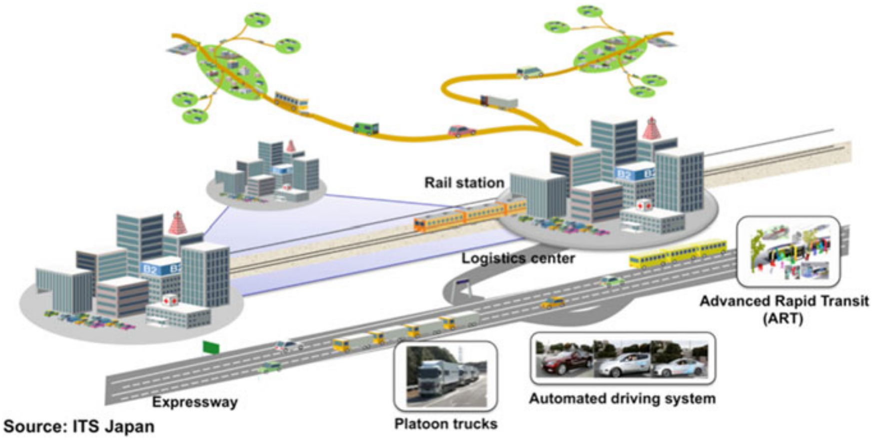

Fig. 7 Integrated regional hub

5 Conclusion

SIP-adus is a 5-year research program on connected and automated driving. Since it started in 2014, a variety of achievements have been made in more than 20 projects. Those results are integrated and evaluated through a large-scale field operation tests from September 2017 to March 2018. The field operation tests are designed to be an internationally shared platform to devise harmonized specifications and framework for connected and automated vehicle operations. It is anticipated that outcome of SIP-adus will create an inclusive society with enhanced mobility and it is disseminated to the other part of the world.

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Connected and Automated Driving in The Netherlands—Challenge, Experience and Declaration

Tom Alkim

Abstract The first half of 2016 The Netherlands had the presidency of the European Union and they have taken this opportunity to put Smart Mobility (connected and automated driving) on the agenda. During this presidency three events were organized: The EU Truck Platooning Challenge, The Experience and The Declaration of Amsterdam. In this chapter the events and their relation are described.

Keywords Connected and automated driving · Truck platooning · Declaration of Amsterdam

1 Dutch EU Presidency

The first half of 2016 The Netherlands had the presidency of the European Union and they have taken this opportunity to put Smart Mobility (connected and automated driving) on the agenda (Alkim et al. 2016). Several initiatives were organized by a working group consisting of the Ministry of Infrastructure and the Environment, Rijkswaterstaat (the national road operator) and the RDW (the Dutch type approval authority). This group came into live 3 years ago when Dutch Minister Melanie Schultz Verhaegen announced that she would like to see The Netherlands take a pro-active stance towards automated driving and become a frontrunner in this field. To realize this ambition three main events were organized to coincide with the Dutch presidency of the European Union: The EU Truck Platooning Challenge, The Experience and The Declaration of Amsterdam.

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Fig. 1 Trucks from all European OEMs at the arrival in the Rotterdam Harbor, 6 April 2016

2 EU Truck Platooning Challenge

The EU Truck Platooning Challenge was organized to demonstrate for the first time in history that it is possible to drive in Truck Platoons across borders on public roads in real traffic. All 6 European Truck manufacturers participated with either 2 or 3 truck platoons. The purpose was not to show the technical feasibility, to some level this is being taken for granted, but to make it legally possible to do so. After all, each country has slightly different rules and regulations making it a challenge to come up with a harmonized exemption. The day after the arrival of all platoons in the harbour of Rotterdam (April 6th 2016, see Fig. 1) a Truck Platooning Conference was organized to discuss future steps to take in order to make cross border (and multibrand) platooning a reality in Europe within 5 years.

2.1 Lessons Learnt

Although the EU Truck Platooning Challenge was not a research project it provided a unique opportunity to gain experience and accumulate knowledge regarding cross border truck platooning on public roads with mixed traffic. Several sources, such as the exemption procedures themselves, interviews with the drivers, a stakeholder consultation and aerial footage, have been used. In line with the learning by doing approach the Truck Platooning team wants to share their lessons learnt and provide building blocks for future European truck platooning corridors and initiatives. Hence the booklet, which can be downloaded from the EU Truck Platooning Challenge website (www.eutruckplatooning.com). Given the fact that the analyses are not scientifically based the results need to be taken as a contribution to the discussion around the truck platooning concept development and as building blocks for future Real Life Cases and deployment initiatives. The synthesis of the lessons learnt is presented around three themes.

1. Were the expected risks justified? Expected risks regarding traffic safety and infrastructure were identified based on the analysis of the requirements and recommendations of the nineteen exemptions. The results of the interviews with the drivers and the aerial footage are combined with five expected risks:
   - Increased chance of accidents/disturbance in traffic flow due to behaviour of the truck platoon as a single vehicle entity
   - Increased wear and tear on roads/bridges due to the truck platoon as a single vehicle entity
   - Limitations of the platooning system in complex traffic situations
   - A truck driver unfamiliar with the platooning system not knowing how to deal with the transition of control
   - Failure of the system in specific infrastructural situations: tunnels, slopes and curves
2. Benefits of the truck platooning concept. The expected benefits of truck platooning are: improved traffic safety and throughput, fuel savings, reduction of emissions and lower labour costs.
3. The European Truck Platooning Challenge is meant as a starting point for building cross border truck platooning corridors. The analysis of the exemptions showed that the national approaches differ substantially. The question is where does one start to get closer to cross border harmonisation and interoperability—obviously, selecting focus points is important.

2.2 Next Steps

In addition to the H2020 call for multi-brand platooning in Europe, where Rijkswaterstaat is one of the consortium partners, there are also some “real life cases” identified in The Netherlands. The purpose of these real life cases is to incorporate truck platooning in the day to day operational business of companies. In several workshops approximately twenty corridors and interested private partners have been identified and they are currently in the process of exploring the possibilities to start using trucks with platooning technology by 2018 (www.eutruckplatooning.com).

Fig. 2 Scene from the experience with participating vehicles

3 The Experience

An event called “The Experience” was organized where all transport Ministers were driven in automated vehicles from their meeting venue at the Scheepvaart Museum (where the Declaration of Amsterdam was signed) to the Innovation Expo at the EYE Museum (see Fig. 2). This allowed them to experience first hand what’s already available and what will become available in the short term. Judging by the amount of media attention and the smiles on all faces it was a big success and a great addition to the Declaration of Amsterdam (see Fig. 3).

4 Declaration of Amsterdam

On April 14th 2016 all European Transport Ministers gathered in Amsterdam for the informal Transport Council where the Dutch had put Smart Mobility on the agenda for the first time in history. The highpoint of this meeting was signing the Declaration of Amsterdam in which the Member States, European Commission and ACEA (European OEMs) are committing themselves to work together on coordinated and harmonized steps towards connected and automated driving in Europe (see Fig. 4).[1]

[1]The Declaration itself can be found here: https://english.eu2016.nl/documents/publications/2016/04/14/declaration-of-amsterdam.

Fig. 3 One of the participating vehicles driving through a tunnel in Amsterdam

It contains shared objectives, a joint agenda and specific actions for Member States, the European Commission and the industry.

Shared objectives:

- Work towards a coherent European framework for the deployment of interoperable connected and automated driving, which should be available, if possible, by 2019
- Bring together developments of connected and automated driving in order to reach their full potential to improve road safety, human health, traffic flows, and to reduce the environmental impact of road transport
- Adopt a "learning by experience" approach, including, where possible, cross-border cooperation, sharing and expanding knowledge on connected and automated driving and to develop practical guidelines to ensure interoperability of systems and services
- Support further innovation in connected and automated vehicle technologies to strengthen the global market position of European industry
- Ensure data protection and privacy

Joint agenda:

- **Coherent international, European and national rules**: the aim is to work towards the removal of barriers and to promote legal consistency. The legal framework should offer sufficient flexibility to accommodate innovation, facilitate the introduction of connected and automated vehicles on the market and enable their cross-border use.

Fig. 4 Family picture of the informal transport meeting, 14th April 2016

- **Use of data**: data generated through the use of connected and automated vehicles can serve public and private value-added services. Clarification is needed on the availability for public and private use and responsibilities of the parties involved.
- **Ensure privacy and data protection**: respecting existing legislation on privacy and data protection, the conditions for the (re-) use and sharing of data generated by connected and automated vehicles need to be clarified.
- **Vehicle-to-vehicle and vehicle-to-infrastructure communication**: in order to maximize benefits in road safety and environmental performance, it is essential to ensure that new services and systems are compatible and interoperable at European level and to coordinate investments towards reliable communication coverage, exploit the full potential of hybrid communications, where relevant, and improve the performance of location accuracy, benefiting in particular from the use of GALILEO and EGNOS.
- **Security**: in the light of the increase in cyber-threats and serious vulnerabilities, it is essential to ensure security and reliability of connected and automated vehicle communications and systems. Common trust models and certification policies should be developed to prevent risks and support cybersecurity, whilst ensuring safe and interoperable deployment.
- **Public awareness and acceptance**: it is important to manage societal expectations, to raise awareness and increase acceptance and appreciation of connected and automated vehicle technologies.

- **Common definitions of connected and automated driving**: common definitions of connected and automated driving should be developed and updated, based on the Society of Automotive Engineering levels (SAE levels) as a starting point.
- **International cooperation**: it is important to develop and maintain close cooperation with other regions, particularly the US and Japan, to work towards a global framework and international standards for connected and automated vehicles.

Next steps:

With the Declaration of Amsterdam the intention was to initiate a continuous series of high level strategical meetings between the Member States, European Commission and Industry. The next meeting was hosted by The Netherlands on February 15th 2017 (www.eutruckplatooning.com) and Germany, Sweden, Spain and Austria have expressed their interest to organize the next meetings which will take place twice a year.

5 Knowledge Agenda

In the spirit of the Declaration of Amsterdam the Dutch want to share their knowledge and this is done primarily through the knowledge agenda for connected and automated driving. To ensure that the modest budget for research is spend on topics that haven't been researched or on questions that haven't been answered yet we have created an overview of available reports, papers and presentations in different domains: Legal, Technical, Human Behavior, Impact and Deployment. Dissemination is done through a publicly available website: http://knowledgeagenda.connekt.nl/engels.

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Policymaking for Automated Vehicles: A Proactive Approach for Government

Baruch Feigenbaum, Ginger Goodin, Anita Kim, Shawn Kimmel, Richard Mudge and David Perlman

Abstract During the 2016 Automated Vehicle Symposium, the authors organized a policy focused breakout session that included a discussion with public agency representatives, industry leaders, and policy experts about the challenges, opportunities and priority actions policy-makers should consider to prepare for the adoption of automated vehicles. The industry panel highlighted a number of policy actions including the appropriate role of government, data and education needs. The public agency discussion settled on a few key themes including the need to improve public education and outreach, conduct information sharing, enhance communication with industry, consider near and long-term impacts, and focus on early deployment opportunities.

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1 Introduction

Automated vehicles (AVs) are currently being tested on public roadways in several states and are attracting an increasing amount of public attention. Although automated vehicles hold the potential to provide significant benefits such as increased vehicle safety, improved mobility for the elderly and disabled, and reduced vehicle emissions, they also introduce great uncertainty around new safety risks and impacts to the broader transportation system. Legislators, public agency officials and other public sector decision-makers are eager to better understand how policy tools can be used to manage these potential benefits and risks while promoting innovation.

During the 2016 Automated Vehicle Symposium, the authors organized a policy focused breakout session and convened a group of public agency representatives, industry leaders, and policy experts. The session included three parts: an industry focused panel discussing perspectives on AV technology development and deployment; a public agency panel centered on key issues facing public agencies that are either experiencing or wanting to enable testing of automated vehicles on their roads; and an interactive discussion on identifying policy strategies for public agencies to encourage the benefits of automated vehicles, while also steering away from potentially negative outcomes.

Panelists engaged in a candid discussion regarding the challenges, opportunities and priority actions policy-makers should consider to prepare for the adoption of automated vehicles. The discussion highlighted insights from those developing the technology and their views on what public agencies should be doing with respect to AVs. The public agency representatives were chosen for their respective expertise on the topic of AVs and included several 'early adopter' states that have enacted AV-specific legislation or have allowed AV testing through other policy instruments. Having these early innovators provided an opportunity to share lessons learned and best practices based on their experience.

Several themes and topics emerged as priority policy issues for both industry and public agencies. In particular, the session highlighted the following suggestions for policy-makers:

- Understand the risks of premature regulation and avoid legislation that may stifle development of technology
- Focus on education and outreach efforts for the public, public agency staff, legislators and policy-makers to inform them of the technology
- Consider early deployment opportunities in cities and test bed opportunities
- Assess not only near term challenges but the long term issues around transportation planning and infrastructure investment

This chapter summarizes the discussion from the session and provides a synthesis of discussion themes and findings.

2 Policy Perspectives: Industry and Consumer Perspectives

Understanding the perspectives of industry and consumers is critical to the public policy discussion. Policy priorities for AVs have been largely driven by industry due to the rapid pace of private sector innovation and investment. This investment is due to anticipated consumer demand, and these consumers are now beginning to form real opinions about whether they support the technology. As a result, public agencies must work closely with industry and consumer interest groups to fully achieve safety, mobility, energy, and quality of life benefits.

The industry and consumer perspectives were explored through a discussion with four panelists representing diverse stakeholders, including automobile manufacturers, consumers, energy independence advocates, and technology and transportation network companies (TNC):

- Paul Scullion, Association of Global Automakers
- Jill Ingrassia, American Automobile Association (AAA)
- Robbie Diamond, Securing America’s Future Energy (SAFE)
- David Strickland, Self-Driving Coalition for Safer Streets

Panelists highlighted a number of policy actions related to the appropriate role of government, data needs and management, and public agency education. Panelists generally agreed that there is some role for government, though there was some variation in opinions of how aggressive an approach government should take at this point. Some argued that government action should not stifle innovation, while several panelists recognized the need for the government to be involved in areas where it has traditionally played a role, for example, ensuring safety.

While the panelists agreed that policy actions (in particular legislation and regulation) can be premature if there is insufficient data to support decision-making, they identified a number of near term issues where states and localities could play a needed role. State and local governments could be active in their existing role with respect to driver licensing, vehicle registration, and roadway operations. It will be important to not only assess how these areas may pose barriers for automated vehicles, but also to understand how they may need to be modified to accommodate the technology. For example, some laws may prohibit the use of automated vehicles in certain contexts (e.g. distracted driving laws) and those laws may need to be revisited to maximize the benefits from the technology. Overall, panelists agreed that public agencies at every level of government should evaluate existing regulations and laws to determine whether they present barriers to automated vehicles.

With respect to the federal government’s role, panelists discussed the challenges with ensuring the regulatory process keeps pace with the rapid development of automated vehicle technology. Currently, there is an emerging patchwork of state legislation across the nation and this is one area where the Federal government can provide leadership. This could include consideration of Federal preemption tools. In particular, vehicle testing and certification is an area where states would not have the technical expertise to support.

Panelists also discussed the importance of having the necessary data to support decision-making and policy development. Issues around data ownership, data sharing and collection must be addressed at the federal, state, and local levels. One panelist advocated for data driven policy making, but also suggested that there is a general dearth of data to support decisions regarding automated vehicles. States are originators of a wealth of data that NHTSA uses to analyze fatalities and crashes. The data systems in each state could be improved to increase public safety by modernizing the crash data collection process and digitizing crash reporting.

Public and public agency education emerged as a major theme throughout this panel discussion and the overall session. A recent crash involving a Tesla vehicle, demonstrated the challenge in how automated vehicle technologies are being described to the public and the publics' understanding of the technologies current limitations and capabilities. All panelists agreed that although it is too early for definitive policies on driver training, educating the public is a near term priority. As part of this process, agencies will need help in asking the right questions to inform next steps. Panelists cited the need for educating agency personnel as well, including making investments in road infrastructure and in developing city planning strategies for land use, transit, last mile, road user allocation, congestion pricing, incentives, and parking.

The perspectives of this panel provided insights and policy recommendations on how decision-makers can best accelerate deployments and take an approach that considers the value proposition to consumers, especially on government roles, data, and public and public agency education.

3 Real Policy Challenges from Real Agencies

Several states have enacted legislation explicitly allowing automated vehicle testing or operations to occur on their roads. At the time of the session, a panelist commented that state legislatures had introduced approximately 35 legislative proposals since the beginning of the year regarding automated vehicle technology, testing, and deployment. The purpose of the second panel discussion was to convene representatives from all levels of government—federal, state, regional, and local—to discuss their insights and experiences with AVs. The panel included several 'early adopter' states where AV testing is currently occurring, including California, Nevada, Texas, and Virginia.

Panel members included:

- Bernard Soriano, California Department of Motor Vehicles
- Tracy Larkin-Thomason, Nevada Department of Transportation
- Nathaniel Beuse, National Highway Traffic Safety Administration

- Karla Taylor, Austin Transportation Department, City of Austin, Texas
- Keith Jasper, Northern Virginia Transportation Authority
- Mike Alexander, Atlanta Regional Commission

Public agencies face a set of unique issues and challenges as part of their public mission to ensure safety while enabling innovation. Panelists agreed that automated vehicles introduce new challenges in this area and acknowledged that public agencies are racing to assess their policy options and preparedness regarding the technology. Overall, the public agency discussion settled on a few key themes including the need to improve public education and outreach, conduct information sharing, enhance communication with industry, consider near and long-term impacts, and focus on early deployment opportunities.

Several panelists noted that both the public and political leaders in their state are enthusiastic about the future of automated vehicles and attracting testing activity, but also highlighted gaps in understanding of automated vehicle technology and functionality. They emphasized a need for education and outreach from industry and public agencies, particularly at the federal level, to build not only awareness, but also a level of comfort with automated vehicles among members of the public who may be concerned about their safety. Ultimately, the public and public sector decision-makers will need to be better informed in order to make decisions about automated vehicles. Panelists suggested that safe and thoughtfully executed demonstrations of automated vehicles will play a significant role in this, as experiencing the technology directly is critical for developing an informed opinion. Such demonstrations could focus on near-term deployment opportunities, including low-speed automated shuttles. Panelists also highlighted a need for more comprehensive education among drivers about the functionality of available automated features, particularly level 1, 2, and 3 systems that are available now or will be available in the near future.

Though expanded opportunities to experience automated vehicles will help build informed support for the technology, panelists also acknowledged a need for greater information sharing between industry and government so that public agencies can make thoughtful policy decisions. Some agencies will need to understand how automated vehicle developers assure the safety of their systems while others will need to understand how automated vehicles interact with existing infrastructure. Public agencies and industry will need to forge new partnerships in order to promote data and information sharing. Certain agencies may be well-suited to play the role of facilitating these relationships and coordination between a variety of entities from industry and the public sector (from industry, vehicle manufacturers and developers, suppliers, TNCs, and insurance companies; from the public sector, DMVs, state and local DOTs, state and local law enforcement, state insurance regulators, regional planning agencies, and federal regulatory and oversight agencies, among others).

Panelists also highlighted the challenges of crafting policies that address the long-term impacts of automated vehicles, particularly on travel and land use. Some planning agencies are beginning to model scenarios for automated vehicle adoption and use, but acknowledge that additional data will be needed to do this comprehensively. In the meantime, agencies can implement policies now that are not specific to automation, but could ultimately address some of the long-term opportunities and challenges of the technology. For example, policies that integrate mobility options can, in the near-term, focus on linking transit trips with trips provided by transportation network companies. In the long-term, these policies could facilitate integration between transit and automated vehicles.

Overall, panelists recognized that in numerous states, legislatures are acting to regulate automated vehicle testing and/or operations in an effort to attract the significant private sector activity occurring in this field. Given this motivation among legislators, encouraging innovation while also ensuring public safety represents a challenging balance for public agencies.

4 The Future Is a Choice: Policy Levers for State and Local Agencies

Within the broad and diverse policy landscape for automated vehicles, state and local governments play an important role, and have a range of policy levers they can use to promote social interests. As automated vehicles become more widely deployed on public roads, what policy tools can they use to mitigate potentially negative impacts and/or incentivize positive ones?

4.1 Potential Policy Levers for State and Local Agencies

An interactive discussion centered on the range of policy levers available to state and local agencies to reach desired outcomes with respect to automated vehicles. Approximately 60 attendees participated in the interactive discussion of potential policy levers and joined an informal voting process.

A list of policy levers for automated vehicles and connected vehicles (CV) are shown in Table 1 and were adapted by the session planning committee using in-progress research for NCHRP Report 845 (Zmud et al. 2017).

4.2 Near-Term Policy Actions for State and Local Agencies

The 16 potential policy levers encompass economic, regulatory and planning actions by state and local governments. Drawing from audience participation and feedback, two clear winners emerged for action now and over the next three to five years:

Table 1 Potential state and local policy levers for AVs and CVs

Technology	Policy lever
Automated vehicles	Enact legislation to stimulate AV testing through either legalization of testing or by funding testing activities Establish, codify and enforce AV operator/owner/passenger requirements, including operator training and licensing, to promote safe operation Accelerate AV market penetration by subsidizing equipped vehicles; both original equipment and after-market retrofit of conventional vehicles Subsidize shared vehicle services to support ridesharing and transit, including paratransit, to minimize growth in travel demand or maximize accessibility Create economic incentives, such as pre-tax transit benefits, to support market penetration of shared AVs near transit nodes, urban centers, and commercial centers Implement land use regulations and parking requirements to increase development density in support of market penetration of shared AVs at transit nodes, urban centers, and commercial centers Increase public and stakeholder awareness through education, communication and outreach, to stimulate consumer action, supportive public investment, and conducive political environment Increase public agency knowledge and capabilities to capitalize on widespread deployment of AVs and maximize societal benefits Grant AVs—including transit and commercial vehicles—privileged access (HOV/managed lanes, signal priority, parking access) to encourage adoption Restructure liability regimes, including insurance requirements, to accelerate market penetration Apply road pricing, including tolling, parking pricing, and emerging applications of distance-based pricing, to minimize growth in travel demand or maximize accessibility
Connected vehicles	Accelerate CV market penetration by subsidizing equipped vehicles, both original equipment and after-market retrofit of conventional vehicles Invest in CV infrastructure in collaboration with private sector to accelerate V2I deployment Enact legislation to stimulate CV testing by funding testing activities Implement new contractual mechanisms with private service providers, including shared data arrangements, to advance connectivity

- Increase public and stakeholder awareness through education and outreach to stimulate consumer action, supportive public investment and conducive political environment.
- Increase public agency knowledge and capabilities to capitalize on deployment of AVs.

There was also strong support for investing in CV infrastructure in the near term, including common data platforms and traffic management systems. Participants expressed support in the mid to longer term for modifying driver licensing, restructuring liability regimes, and looking for opportunities to grant AVs privileged access to lanes or parking.

Actions that involve government subsidies for equipping vehicles—be it AVs, CVs or specifically shared AVs—did not fare well in the informal voting.

5 Synthesis and Conclusions

The panel discussion reflected the considerable uncertainty about the pace with which automated vehicles might be deployed and what the likely impacts of such deployment might be. All panelists acknowledged how this uncertainty creates challenges for making informed policy decisions for automated vehicles, particularly as one tries to balance the benefits and risks of this emerging technology.

This uncertainty extends to political and public agency leaders and the public in general. While interest in automated vehicles continues to grow, confusion and misinformation are also a part of the conversation. Given the scale and scope of change implied by automated vehicles this is not surprising, but it does raise concerns about the ability of public policy to implement effective near-term policies. In addition, standards, the regulatory process and related legislation and regulations are of particular concern.

In this context, what should policymakers do to achieve a proactive approach towards automated vehicles? The session revealed several key findings that may be important for policymakers as they consider different strategies for addressing automated vehicles. These include the following:

- Automated vehicles have become an important and growing part of the public conversation regarding transportation. Political leaders, public agency staff, transportation planners, law enforcement, the general public and others will need to be coordinated with and included.
- Timely and effective education of the public and public agencies is critically important to address misinformation and manage expectations.
- Considerable uncertainty exists regarding the pace and nature of technology development and regarding the potential impact of these new technologies on transportation in general and on society itself.
- Despite the desire from a growing number of state and federal leaders to act, real risks exist from premature regulation or well-meaning legislation.
- One clear role for government is to review existing regulations and laws to assess whether they pose barriers to automated vehicles and to determine how they may need to be modified to maximize the benefits of the technology.
- Cities are likely early adopters of this new technology and could provide early deployment opportunities.
- Now is the time to begin incorporating these new futures into the long-term transportation planning process, however, is is challenging for incorporating changes into a process that remains traditional in underlying assumptions and models.

- Policymakers will need to accept the "new normal" of a world that includes dramatic new forms of mobility. The pace of change is likely to speed up for the foreseeable future and remaining flexible will be important.

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Part II
Human Factors and Challenges

Impact Assessment

Satu Innamaa, Scott Smith, Isabel Wilmink and Nick Reed

Abstract Automated vehicles can potentially transform the world's road transportation system. Direct impacts include traffic safety, transport network efficiency, energy/emissions and personal mobility. Second order indirect impacts, such as the possibility of increased travel leading to more congestion and emissions, are of significant concern. This chapter discusses the direct and indirect impacts by applying systems thinking to the impacts of automated vehicles, presenting two case studies related to different aspects of automation: low speed shared shuttle and truck platooning.

Keywords Impact assessment · Direct impact · Indirect impact · Automated driving · Automated shared shuttle · Truck platooning

1 Introduction

Automated vehicles can potentially transform the world's road transportation system. Benefits realized could include traffic safety (automobile crashes are a leading cause of accidental deaths), transport network efficiency (most cities experience

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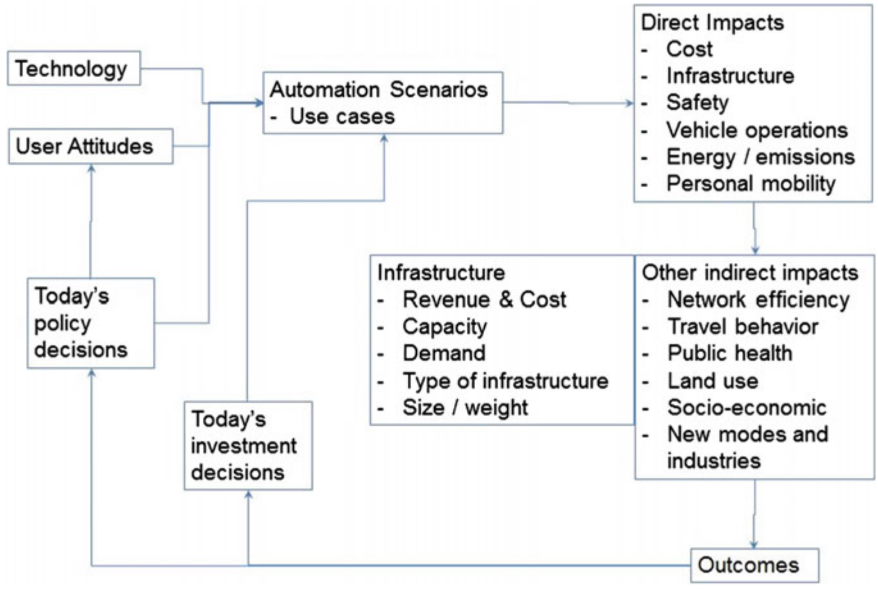

Fig. 1 Applying systems thinking to automated vehicles' impacts

significant traffic congestion), energy/emissions (oil consumption, air pollution and greenhouse gas emissions are of worldwide concern) and personal mobility (new mobility options for non-drivers). Automated vehicles are being introduced into a complex transportation system. Second order impacts, such as the possibility of increased travel leading to more congestion and emissions, are of significant concern.

Direct and indirect impacts related to automated vehicles can be defined by applying systems thinking to the impacts of automated vehicles (see Fig. 1). It is essential to identify the most important direct and indirect impacts and the main linkages between them. Information on these impacts and their outcomes will enable decision makers and researchers to address the investment and policy decisions needed today to make desired outcomes more likely. The purpose of this chapter is to discuss the direct and indirect impacts of road traffic automation and present two case studies related to different automatization of road transportation and their impacts.

2 Direct and Indirect Impacts

Figure 2 (based on Smith et al. 2015) depicts the impact areas. Direct impacts are those which have a relatively clear cause-effect relationship with the primary activity or action. They are generally easier to capture, measure and assess in a field

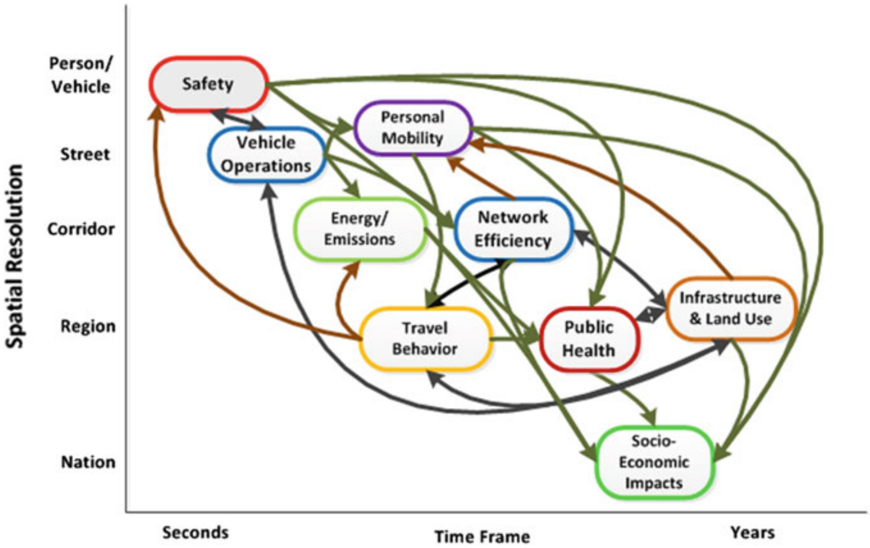

Fig. 2 Direct and indirect impacts

operational test, and are often (though not always) immediate to short-term in nature. In Fig. 2, they are in the upper left, and include safety, vehicle operations, energy/emissions and personal mobility. The others are indirect impacts. Indirect impacts can be characterized as secondary, tertiary, or still further removed from the original direct impact. Indirect impacts summarize the broader effects of the individual direct impacts and are produced as the result of a path/chain of impacts, often with complex interactions and external factors. They are typically more difficult to measure and are longer than the time horizon of a field test.[1] Impacts are described below.

Safety: Ultimately, safety is measured as fatalities, injuries and property damage for vehicle occupants and other road users. Other road users may include pedestrians, bicyclists, slow-moving vehicles, construction workers and first responders. Nearly all AV applications, ranging from Level 1 collision avoidance systems to Level 5 self-driving vehicles, have potential safety impacts. A challenge with safety assessment is that actual crashes are rare events; therefore, proxy measures are often used. These measures may include traffic violations, instances where a human driver must take control of the vehicle, exposure to near-crash situations, and responses to near-crash situations.

Vehicle Operations: Vehicle operations include acceleration, deceleration, lane keeping, car following, lane changing, gap acceptance: all affect highway capacity.

[1]This explanation is inspired by that of direct and indirect environmental impacts of road development in 'Roads and the Environment—a Handbook' (World Bank 1997).

Relevant automation applications include those, which provide longitudinal and/or lateral control with respect to the road and other vehicles.

Energy/Emissions: Energy and emissions includes both the energy consumption of the vehicle through a driving cycle, and tailpipe emissions of pollutants including greenhouse gases. The direct energy/emissions impacts come from the change in the driving cycle.

Personal Mobility: Mobility from a user's standpoint includes journey quality (comfort), travel time, cost, and whether the travel option is available to someone (e.g., a non-motorist). It also includes equity and accessibility considerations. The higher levels of automation will have the most significant impacts, by providing mobility for non-motorists and enabling multi-tasking. These include first mile/last mile services and accessibility applications. Challenges in measuring personal mobility impacts include the variety of sub-populations who may be affected in different ways, and the difficulty in assessing the actual value of automation to a person based on survey data. In the context of a fleet operation (trucking or transit), it is the direct impact on labor. Is the driver still needed? What are the implications of automation for driver productivity (ability to multi-task or reduced fatigue)?

Network Efficiency: Network efficiency refers to lane, link and intersection capacity in a regional transport network. It also refers to travel time and travel time reliability. Improved safety may improve network efficiency via reduced incident delay. Also, changes in vehicle operations (e.g., car following) will affect network efficiency.

Travel Behavior: A traveler may respond to AV options, including new service offerings, by changing travel behavior. There may be more trips. Modes and destinations may change. Higher-level automation applications that have a significant effect on personal mobility or labor could have a significant effect on travel behavior.

Public Health: Automation may impact the health of communities, via safety, air pollution, amount of walking and bicycling, as well as access to medical care, food, employment, education and recreation.

Land Use and Infrastructure: Automation may affect the use of land for transport functions (e.g., parking, road geometry). Longer-term land use changes may include location and density of housing, employment and recreation. Automation may also affect infrastructure assets required in several ways:

- Number of lanes and lane widths
- V2I infrastructure used by automation
- Size and weight implications of changed fleet composition
- Effect of travel behavior changes on trip making

Socio-Economic Impacts: Improved safety, use of time, freight movement, travel options for non-motorists, public health, land use and effects of changed emissions (including climate change) will have longer term economic impacts. Automation may also have substantial impact on labor markets and industries.

3 Use Case: Low Speed Shared Shuttle

Within level 4 of the Society of Automotive Engineers (SAE) J3016 standard (SAE 2016), one can classify two different broad varieties of automated vehicle. The first is a vehicle that is human driven some of the time but capable of operating without the need for driver input or attention on particular roads. The second variety is vehicles that are designed never to have a human driver in normal operation; these are capable of navigating a route and safely dealing with any hazards it may encounter. However, these vehicles are geo-fenced, restricted to specific areas of operation and cannot operate in an automated manner outside of those areas. An example is the Heathrow Ultra Personal Rapid Transit system, which began operation 2010 and transports passengers in fully driverless pod vehicles between Terminal 5 and one of two user selected car parks using dedicated infrastructure. As software and sensors improve, automated vehicles of this nature are starting to be operated in more complex, unsegregated environments. By constraining the task, the technical requirements to deliver a workable solution are simplified and creating a vehicle capable of meeting the specification is commensurately more achievable. As a result, low speed shared shuttle vehicles operating in unsegregated pedestrian or low speed traffic environments have begun to emerge.

A prominent project in the development of low speed automated shuttle vehicles was called CityMobil 2, which ran from 2012 to 2016. Automated shuttle vehicles were demonstrated operating on fixed routes in seven European cities (CityMobil2 2016). This project was led by University of Rome, La Sapienza with 45 partners and tested two different types of automated passenger shuttle to demonstrate their viability in supporting urban mobility. More than 60,000 passengers were transported over the course of the project. Following the example set by CityMobil 2 is the GATEway (Greenwich Automated Transport Environment) project in Greenwich, London (Reed 2015). This initiative is led by TRL and co-funded by UK government and industry. It will see seven automated shuttle vehicles, each capable of carrying six passengers, tested as a pseudo-service in the city to explore public trust and acceptance of automated vehicles.

The impact of this service will be assessed in a number of ways. Firstly, there have been workshops with a range of different stakeholder groups to explore their hopes and fears about the introduction of automated vehicles to the city; secondly, participants from these stakeholder groups will be invited to experience the use of the automated shuttle vehicles and their pre- and post-trial attitudes to the system will be explored. Finally, there will be a longer period of continuous daily operation of the shuttle service where longitudinal changes in attitude and use of the vehicles will be assessed.

In the workshop held at the Automated Vehicle Symposium 2016, the direct and indirect impacts of low speed shared automated shuttles were explored and the topics discussed are presented in the following sections.

3.1 Assumptions

The following assumptions were made about likely early deployments of low speed shared shuttles:

- They would be integrated with existing city transit networks where travel demand was high and options for new travel systems dependent on significant infrastructure (e.g. tram, light rail) are costly.
- Infrastructure requirements to deploy the vehicles would be minimal.
- They would be relatively low cost to the user (possibly subsidized)—similar or lower cost than a comparable bus fare.
- Although they may operate cautiously, the vehicles drive in a manner that is at least as safe as (and likely significantly safer than) a human operator.
- Vehicles would be electrically powered and accessible for wheelchair users and travelers with push-chairs, luggage etc.

3.2 Direct Impacts

Perhaps the fundamental impact of these vehicles operating as a service is that they would increase connectivity to transport hubs, increasing mobility options and potentially reducing the use of private cars to satisfy travel needs. Research is needed to confirm whether this would indeed be achieved in a commercially viable manner. Workshop attendees agreed that the use of these vehicles would increase options for those with additional travel needs, such as disabled and/or elderly people.

An anticipated direct impact was that the use of low speed shared automated vehicles would increase safety for road users. This assumption needs to be validated with such vehicles operating as an integrated part of the transport network. There was also a suggestion that because the automated vehicles behave consistently and predictably and are powered electrically, active travel modes (walking/cycling) would be more appealing. However, it is possible that fewer would choose active travel modes if low cost, flexible, on-demand automated vehicle options were available.

A further impact discussed was the potential for energy use and emissions to reduce through consolidation of travelers onto public transport services. However, discussions suggested the opposite effect could also occur if overall mobility increased. Operation of the vehicle services would also create employment opportunities in the maintenance and management of the vehicle services.

3.3 Indirect Impacts

The planning and use of land in city environments was seen as the most important indirect impact of these vehicles, with the opportunity to reclaim space allocated to car parking for alternative uses if low speed shared automated vehicles could be used to meet mobility needs. The potential for residents' health to improve through better air quality if automated electric vehicles displaced combustion engine vehicles for transportation was also discussed.

The ability to connect currently underserved areas with the wider transport network through the deployment of low speed automated vehicle services may have important socio-economic effects, enabling better access to education, employment and healthcare for residents. Consequently, the desirability of those areas may increase, leading to speculation that current residents may be priced out of the market—an unintentional adverse consequence of the vehicle services.

3.4 Future Research

The workshop discussions highlighted that whilst some direct and indirect impacts can be foreseen, there is a need for further research to gain a better understanding of the implications of low speed automated shuttle vehicle deployment. Research projects like CityMobil 2 and GATEway have demonstrated the technical feasibility of operating these vehicles. Further work is required to show how they can genuinely work as an economically viable and fully integrated component of city transport services. This should cover topics such as reliable, secure collection of payments; ensuring occupant safety and comfort (including sharing in a confined space); what size of vehicle/number of passengers is optimal for a particular use case; and how to design route provision to achieve social equity.

4 Use Case: Truck Platooning

The second use case is about truck platooning. Several tests with truck platooning have already taken place (for instance, the recent European Truck Platooning Challenge, see Rijkswaterstaat 2016) and more are planned.

To discuss potential impacts, a use case was defined in which platooning trucks have SAE level 4 automation functions. Platoons can be formed on the fly, with trucks from different brands and different haulers. Legislation concerning driving and resting times has been revised. This means that part of the trip, the driver is not considered to be driving, and so the vehicle can be on the road longer before a stop is required. The physical and digital infrastructure have been adapted to enable safe and efficient driving in mixed traffic—there will still be manually operated trucks and cars on the same road. Adaptations can be, for instance, that platoons communicate their path to vehicles that are nearby or that are merging onto the highway.

4.1 Direct and Indirect Impacts of Truck Platooning

What kind of impacts can be expected? There have been several studies on the impacts of platooning on energy use and emissions, but other impacts are usually only described in very general terms ('improved safety is expected'). Even if not a lot of quantitative data are available from studies, insight into the possible impacts can be given using the categories of impact described in Sect. 2. The DRAGON project, commissioned by the Conference of European Directors of Roads (CEDR), is now underway and one of the use cases in this project explores the impacts of truck platooning in 2030 (Wilmink et al. to be published). The DRAGON truck platooning use case is slightly different than the one discussed here, as several different levels of automation are assumed to be present on the road (instead of the level 4 vehicles assumed here), but the impacts described are very similar. A summary:

Positive *safety* impacts are expected, due to the presence of full automation or at least advanced driver support systems, which help prevent accidents where, for instance, the driver was distracted. There is, however, a risk of dangerous maneuvers of merging vehicles encountering a platoon.

Substantial *energy use and emission* reductions per distance travelled have been measured on the road, primarily in controlled tests (see, e.g. Tsugawa 2014; Davila 2013). Whether the reductions can be as large in real-world driving depends on the ability of trucks to find other trucks to platoon with (which needs the fleet managers' and drivers' willingness to cooperate), traffic conditions and safety considerations (would platoons have to split up often, to ensure safe driving for all traffic?).

Personal mobility may be affected if the truck drivers are able to engage in non-driving activities.

Truck platooning can also have a positive effect on *network efficiency*, especially when trucks not only communicate with the other vehicles in their platoon, but also with other road users and the infrastructure. Also, the trucks drive closer together and so take up less space. However, in busy traffic, truck platoons can be in the way of other traffic, resulting in disturbances that affect road capacity negatively. But, improved safety means less accident-related congestion.

For overall *travel behavior*, there are a lot of uncertainties about the impacts. The number of drivers needed could decrease and asset utilization could be improved. This could lead to a reduction of the transport costs, leading potentially to more freight miles on the road network, and less freight miles by other modes of transport (e.g. rail, waterways, air).

If the emissions are reduced, pollutant concentrations along roads will be reduced and this has a positive effect on *public health*. However, the reduction of emissions per vehicle could be canceled out by the increase in mileage due to lower transport costs.

Impacts on *land use and infrastructure* are also unclear. Some expect dedicated infrastructure for platooning trucks at some time in the future, but in the short term platoons are expected to use the existing infrastructure, possibly with a few modifications such as ramp metering or warning signs on on-ramps, to ensure merging vehicles are not hindered by platoons. This means that upgraded communications infrastructure may be needed for V2V and V2I communication. Another infrastructure issue is the question whether truck platooning will have significant impacts on infrastructure elements such as the pavement (extra ruts because of precise lane keeping?) and bridges and viaducts with long spans (load effects of heavy vehicles driving closely together). Regarding land use, transport companies and/or distribution centers may relocate to locations more suited to truck platooning.

Socio-economic impacts also need to be explored more thoroughly. On the cost side, it has been remarked that the costs of the system (at least C-ACC) are small compared to the costs of a truck. There may be an impact on the labor market when fewer drivers are needed—but in many regions, driver shortages are expected within in the next decade and this could mean lower investment costs for driver training. On the other hand, drivers operating a truck platoon may need additional training to ensure safe and efficient operation.

4.2 Future Research

During the breakout session, there seemed to be consensus on the direction of the direct impacts. There was more uncertainty about the indirect impacts. Members of the audience also discussed how field tests could be set up and the performance indicators that they would like to measure and derive for truck platooning. The following performance indicators were mentioned:

- Safety indicators, initially by determining surrogate or proxy measures such as the number of near-crash situations and changes in the behaviour of other vehicles around the platoons
- Fuel consumption
- Vehicle utilization (share of time that truck is in use)
- Driver productivity, including the share of time spent driving, working but not driving, resting
- Need for truck parking areas (which may be reduced if there is less need for trucks to stop)
- Type of trucks and what they're carrying

A baseline would be existing trucking operations. Participants thought that a two-stage field test may be appropriate. The first field test would be focused on vehicle operations (fuel consumption, safety), working with vehicle manufacturers for measurements. The second test would be focused on user issues, for which it would be useful to work with fleet owners.

In order to scale up results from field tests, especially to analyze network efficiency, traffic simulations could be used, especially to explore the impacts in mixed traffic of various compositions. There are some challenges that need to be addressed in order to achieve realistic simulations, for instance the need for real-life descriptions of the microscopic behavior of automated vehicles, realistic representations of manually driven conventional vehicles and the interactions between automated and manually driven vehicles. In particular, we need more information on their lateral behavior. See (Calvert et al. 2017) for more information.

5 Discussion

This chapter discusses the direct and indirect impacts of automated vehicles by presenting two case studies related to different aspects of automation: low speed shared shuttle and truck platooning. It is based primarily on discussion at the AVS2016 breakout session on Impact Assessment.

In addition to the specific impact areas and two case studies, discussed earlier, several themes emerged from the session:

- Firstly, impact mechanisms are complex and far-reaching. The impact mechanisms include interactions between direct impacts to indirect impacts, and they vary from short-term impacts to very long-term ones.
- It is necessary to keep in mind that most important impacts are different for different people—a positive impact for one can be negative for someone else.
- It is also essential is to clearly define the use cases and context. This means defining the environment, the time scale, perception, and other parameters. It is a challenge to consider future uncertainty in today's policy and infrastructure decisions.

For future research, it was understood that whilst some direct and indirect impacts can be foreseen, there is a need for further research to gain a better understanding of the implications. For example, for the low speed shuttles further work is required to show how they can genuinely work as an economically viable and fully integrated component of city transport services. In addition, more research is needed for the indirect impacts of truck platooning.

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The Digital Driver of the Future—User Experience Research on Generation Z in Germany

Evin Bahar Guenes, Katharina Hottelart and Patrice Reilhac

Abstract Future vehicle drivers will use cars differently than today, since increasingly connected and automated cars will offer a totally new driving experience. Valeo tries to find out how a positive driving experience of tomorrow can look like, but the challenge is that users today are not always aware of what they will need, especially when it comes to situations they have never experienced before. This paper shows that it is not enough to ask people what they would want in their future cockpit in order to find out their possible needs. Instead, one needs to understand what might impact their way of driving such as their way of living in a digital age, commuting and communicating. Understanding the user experience of users being born and raised in a digital era and being part of a generation highly-connected such as the Generation Z will help to create intuitive vehicle cockpits for automated and connected cars. With this background, a UX research study of Generation Z was conducted including ethnographic research and classical qualitative market research methods, exposing the future digital driver's needs.

Keywords Ethnographic research · Self-determination · Artificial intelligence · Automated driving · Connected driving

1 Introduction

In recent years, companies increasingly integrate customers' needs in an early stage of the product design process, thereby considering users as collaborative partners to have sustainable success in the market. With the rapid advancement of technologies

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and the pressure of product development getting shorter, companies within the high-tech industries tend to neglect what people really need. As a consequence, users are unsatisfied with products or services and even worse, avoid technologies which could have improved their way of living, if the products were designed in a user-friendly manner. One example in the automotive industry is the hesitation to adopt new technology in the field of automated and connected driving (Giesler 2016). A seamless Human-Machine-Interface is perceived as a key solution to enhance the driver's safety as well as to increase the consumer's acceptance in this field. This already has been proved, e.g. in a study conducted by Valeo in collaboration with the Fraunhofer Institute (Reilhac et al. 2016; Diederichs et al. 2015). However, there are still other aspects which need to be researched further, thinking of a possible de-motorization in mature automotive markets like Germany, especially among younger generations living in urban areas (Kalmbach et al. 2011) and how to win this user group. In order to have sustainable success in the automotive market, OEMs and suppliers are challenged to find out what the future generation might need and what this generation might perceive as a positive driving user experience. Against this background, a qualitative end-user study was conducted by Valeo to understand what the future generation such as the hyper-connected Generation Z might perceive as a positive driving user experience and how it might reflect in the future vehicle cockpit. Understanding Generation Z's needs is important for designing intuitive vehicle cockpits of automated and connected cars in two ways: (1) This user group has little to no driving experience and is currently more in the role of a passenger, which helps to identify potential pain points and values of automated cars from a different perspective, since the driver becomes more a passenger in the future car. (2) This group is born and raised within a highly connected world, which might shape the users' needs for future mobility differently than other generations. Exploring Generation Z's unspoken and spoken needs in terms of future mobility can show how vehicle cockpits of automated and connected cars might look like in the future. Accordingly, the end-user study deals with the following question: What can we learn from young people's experiences in a digital and highly connected world today about vehicle cockpits of the future? At the end, the study helps to anticipate needs of future vehicle drivers.

2 Methodology

2.1 Target Group

Recently, a lot of publications have appeared in the media about different habits and needs of generations such as Generation Y and X and how companies can adapt to their different needs. Increasingly Generation Z is in focus as well. While there seems to be no common agreement on when this generation was born (scientists dealing with Generation Z say they were born by end of 1990 and beginning of

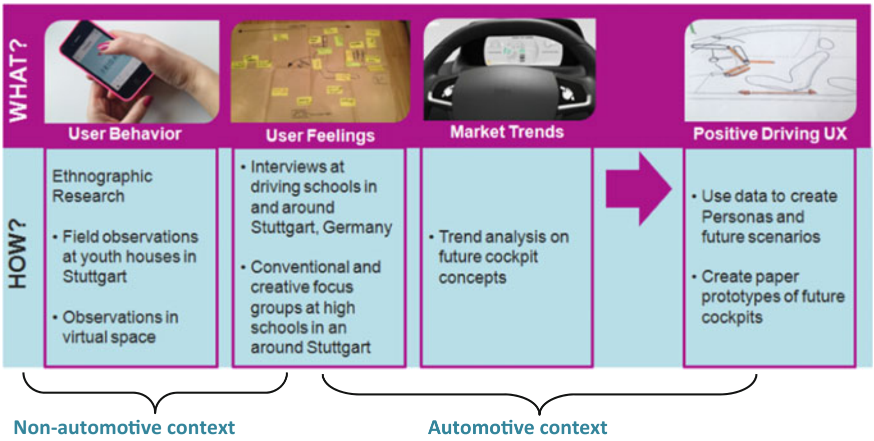

Fig. 1 Study approach for creating a positive driving user experience

1995 (Scholz 2016)), the attention of the media lays more on their distinctive characteristics: being socialized in early childhood with the internet and digital media, different than their former Generation, Generation Y, which came into touch with the internet at a later stage in their lives. This study refers to Generation Z between the age of 15 and 21, living mainly in and around the city of Stuttgart, Germany.

2.2 *Study Approach*

One part of the study, as can be seen above (see Fig. 1), is detached from the automotive context. It deals with Generation Z's digital culture to understand how Generation Z uses new technology today, what it means to them and how they are using it in specific contexts. To study the digital culture, ethnographic research was used, which has its roots in Social- and Cultural Anthropology. It is a holistic, qualitative approach to study human behavior and interactions of humans in their natural environment (Givens 2015). Its purpose is not only to understand the behavior itself, but the relevance of the behavior for the actor and his social environment. Classic ethnographic research makes use of participant observation, where the researcher is not just a passive observer, but a participant observer who takes part in the interactions of the studied group. With this empathy driven approach the researcher tries to see and understand the world through the eyes of the target group. It is also a way to uncover unspoken needs, since the researcher doesn't have to rely only on what people say about their habits but can discover unconscious habits of studied persons. To understand how connectivity and digital media is present in the daily life of Generation Z and how it affects their way of

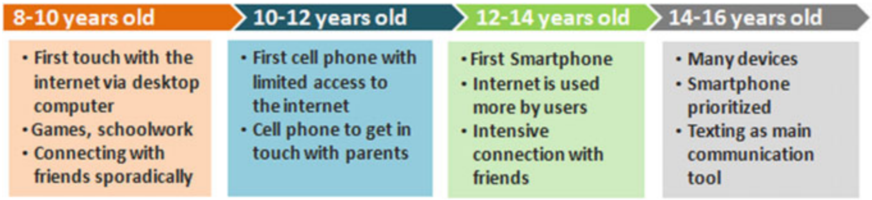

Fig. 2 Generation Z's consuming behavior of display based devices per age phase

communicating and interacting with each other, field observations were conducted. The observations took place in summer 2016 for about 5 days in youth centres in the city of Stuttgart, Germany, where teenagers spent their free time, meeting up with friends, having group activities such as cooking, dancing, playing card games or computer games. Understanding Generation Z's digital culture helped to identify their unspoken needs for future vehicle cockpits.

The other part of the study contains automotive topics. 10 focus group discussions were conducted in high schools in and around Stuttgart also in summer 2016. In each focus group 5–8 pupils took part. Thus, overall 65 respondents took part in the research. Besides topics concerning their consuming behavior of digital devices, topics like mobility behavior and expectations on future mobility were discussed. Here, the interdependence of culture and technology became visible for Valeo.

To translate the study findings into user needs for future cockpits, Personas were created. These are fictional and generalized representations of ideal customers. It is a tool used in the field of marketing, sales, product and services to understand specific needs, behaviors, and concerns of different user groups better (Martin and Hanington 2012). Identifying different types of Generation Z Personas based on ethnographic research and focus groups was necessary, since no generation is homogeneous in terms of interests, lifestyle or opinions on specific topics, and no needs are homogenous.

3 Study Results

3.1 Digital Culture

3.1.1 How Does Generation Z Use New Technology and When Did the Hyper-connectivity Start?

The figure (see Fig. 2) shows at which age the study participants came into touch with the internet and what they were using it for.

As the focus group sessions revealed, the study participants came into touch with the internet by the age of between 8 and 10 years mainly using it for online games or doing research for school. Connecting with friends was not in focus and took place only sporadically via Facebook or Skype. Their hyper-connectivity started when they had their first Smartphones (between age 12 and 14), which means that from this time on they would use it on a daily basis for several hours anywhere and whenever they would feel the need. According to the study participants, today they are using more than 3 display based devices in average on a daily basis (e.g. the Smartphone, the laptop, gaming consoles etc.). Nevertheless, they would prioritize the Smartphone over all, since it would fulfill many functions (such as a music player, communication and research tool) and could be taken anywhere.

3.1.2 What Does Connectivity Mean to Generation Z?

If you ask Generation Z, they say connectivity means to strengthen and to extend social interactions as the focus group discussions showed. They don‘t understand people‘s preconceptions on young people to be stuck on their Smartphones even when they are with friends, lacking social skills and being reputed not to communicate in a normal manner anymore. On the contrary, they think connectivity and especially Smartphones help to be closer to the social environment. Friends and family can be met spontaneously for example with help of group chats on WhatsApp where appointments can be made up quickly and staying up to date about each other is much easier since experiences can be shared anytime anywhere through pictures and videos. The Smartphone can also help to reach people speaking other languages, as could be observed at the youth centres. By using Google translator or searching for pictures on the internet that support their thoughts, German and Syrian teenagers were able to extend their communication.

Furthermore, they can decide more specifically with whom they want to interact. They see where their friends are and with whom they are on Snapchat and decide to join or not. They decide to encapsulate themselves either in inconvenient situations (e.g. when they want to avoid unintended conversations/eye contact with people they don’t know or don’t like), or to relax in the noisy train by using their Smartphones, hearing music or surfing on the internet. Another area where targeted social interaction can be seen is when people get into touch with people they haven’t met in personal before.

To get into touch in the virtual before physical space is perceived by the study participants as a normal way to get to know someone. Checking out peoples’ profiles (e.g. on Instagram or Facebook) and peoples’ friends would be usual to get an idea of how their characters might be. Also flirting seems to be more convenient for the study participants to take place in virtual space rather than physical space. Nevertheless, the youngsters are aware that the virtual space is not always representing reality and are trying to avoid hasty conclusions based on people’s self-presentations on virtual space.

Generally, it was surprising that the studied group distinguished their generation’s way of using new technology and attitudes towards digital life with the younger ones. According to them, today’s younger kids (e.g. their younger siblings or kids under their class grades) are stuck on their display based devices such as

Smartphones and tablets, even when they'd be with their friends. Many study participants stressed that they wouldn't want their children to be such virtual and digital life addicted. They would want them to take more part in "real" life, enjoying childhood by playing outside rather than playing with tablets, Smartphones and computers. Just like elderly people having preconceptions on Generation Z, the studied group prejudges the generation coming after them.

3.1.3 What Does It Mean to Generation Z to Be Disconnected?

Forgetting their Smartphones at home and being disconnected is a pain point, especially when the users are alone on the run. According to the study participants, they then don't have the possibility to check where to get from A to B with public transportation and are not available for family and friends. But the worst thing for the users would be to have no music with them. Surfing on the internet, watching videos or checking social media would be a secondary problem, since usually the participants try to save mobile data volume.

3.1.4 What Does Virtual Space Mean to Generation Z?

The virtual and real space is blending more and more, which can be seen from two perspectives. One is that the real world can be incorporated in virtual spaces e.g. in open world games (such as in the Game Grand Theft Auto) or virtual spaces where people create virtual identities and environments (such as in Minecraft or Secondlife). The other way round is to incorporate the virtual world into real world spaces as the trend of augmented reality shows. For the mainstream user, virtual worlds and the real world are separated from each other, meaning virtually created people and environments are not reality. But there are users who don't differentiate so much between these two worlds (not just within Generation Z but in general). This was discovered through an ethnographic study we conducted in the virtual space, where extreme users were interviewed and observed online (whether as avatars or real persons in social media or in games). Within these extreme users there are for example gamers who like to explore virtual created worlds (virtual world explorers) and gamers who create environments as well as avatars (virtual world creators). Chat interviews via Facebook, WhatsApp or directly in the games showed, that they have different interests: While the virtual world explorer is more interested in getting inspired or wants to escape daily grind by diving into other worlds, the virtual world creator is more interested in being creative and sharing it with other users whether to earn money or to get recognition for their work (e.g. blogging and modeling as avatars, creating whole fantasy cities etc.). Of course one can also be the other, and they might also have common interests, such as socializing with other users as avatars or as real persons. Since extreme users can also be early adopters, it was worth studying their perspective on virtual space to create an enhanced digital experience in the future car.

Mainstream users of virtual space, as the focus group discussions revealed, think that an enhanced digital experience can also have negative sides, such as a displaced reality perception or social exclusion. Devices such as Virtual Reality-glasses, for example, are linked to social isolation. The study participants preferred to be "accessible" for their social environment rather than being in their own worlds and would like to see the reactions of people they are watching a movie or playing games with. All in all, virtual space is seen as an important part of their life, but they enjoy it with caution.

3.2 Mobility

3.2.1 Interest in Driving

As the focus group discussions at the high schools show, there's a high interest in taking the driver's license as soon as they reach the required minimum age, no matter how is the availability and quality of local public transportation. As main reason for taking the driving test as soon as possible the participants mentioned that they might need it for their work later on. They would furthermore like to get it before finishing school, since afterwards they might lack of time, visiting university or work. Besides that, many participants could imagine to use a car for making road-trips to other cities and for vacation. Generally, the driving license and the car itself are perceived as a necessity to be more flexible. "Driving fun" was more a secondary value for the participants, but still a reason. It is worth mentioning that this outcome relates to study participants living mainly in and around the city of Stuttgart and the preferences might change in bigger cities such as Berlin.

3.2.2 Expectations on Future Mobility in General

The study participants were quite optimistic on future mobility, since a safer, easier and greener mobility is expected. A safer mobility is linked to their expectation of improved driving assistance systems, which might derive from the fact that they are confronted with that topic in the media such as TV spots of carmakers but also by family members who use assistance systems in their cars. Also the participants were quite confident that car accidents go back to human failure and that technology might support reduce human error. Easier mobility is expected since individual and public transportation might be better coordinated to each other. People might have more options to travel from A to B and make use mobility mix. Linked to this, a greener mobility is also expected, since cars might be used more efficiently e.g. through car sharing and electric cars that reduce pollution. Some also mentioned connected and automated cars as game changers for a greener mobility because of a possibly well coordinated traffic with less traffic jams.

Table 1 Expectations towards connected and automated driving

Positive expectations	• More comfort • Safety increases • Time for being productive (work) • More possibilities for entertainment • Coordinated traffic and greener mobility
Negative expectations	• Car might be controlled by hackers • Possible technology failure • Loss of driving-fun • Loss of self-reliance (less agility) • Automated and manually driven cars in the same traffic can be a risk (human as a risk factor) • Car makes morally questionable decisions
Other expectations	• Driving license might still be needed, even if cars drive fully automated (but other skills might be required to handle the car) • Car is connected, so privacy should be secured

3.2.3 Expectations on Automated and Connected Cars

In almost every focus group at least one participant mentioned connected and/or automated driving as form of future mobility. However, the participants' understandings of connected and automated cars were different. Mostly the study participants linked connected and automated cars to vehicles being connected to each other, driving all with the same speed and same driving style in the automated mode. Some participants mentioned the Tesla Model S as an example for an automated car. However, they didn't differentiate between semi-automated and highly automated functions or didn't know about different automation levels. But to understand their feelings towards highly automated and connected cars, the focus group moderator showed two videos. In one video principles of connected driving were described and in the other an example of a highly automated car like the Mercedes F015 concept car was shown. Based on these videos, the study participants expressed different expectations towards automated and connected cars (see Table 1). Some of the expectations are already known from other end-user studies, such as negative expectations like loss of driving fun, possible technology failure or ethical problems when it comes to cars prioritizing life's of different road users. But there also some quite unexpected topics for a younger user group: For example, their major concern on cars that might be controlled by hackers as new doors for terrorists. Another surprising expectation and wish was to have a strong data security and transparency on what happens with the collected data such as their driving behavior, routes they drive or in-car interactions etc.). Somehow Generation Z is concerned that their cars become public spaces because their cars are connected to the environment. They wish that everything that happens in the car stays in the car. However, as we will see in the next chapter, the users' privacy should not only be secured against the external environment, but also against the car's internal environment.

3.2.4 Expectations on Driver-Car Interaction

The most crucial part of the vehicle cockpit is how drivers interact with their cars. Future cars will be self-learning and much more intelligent, so the driver will have consequently other possibilities to interact with the car not just in terms of the way he gives commands but also how much commitment the car needs from the driver. To understand what Generation Z thinks of future driver-car-interactions, this topic was also discussed during focus group sessions. As a stimulus, the focus group moderator showed an extract of the 1980s TV show “Knight Rider”, where a driver communicates with his intelligent car in a natural way. After watching the video, the participants were asked to tell what they were thinking about a car that learns permanently new things and about the way the driver interacts with his car. During the discussions quickly the question emerged from the participants’ sides, if this car was some kind of Artificial Intelligence. Having this in mind, positive as well as negative expectations on self-learning and intelligent cars were then discussed in the group sessions. It turned out, that the participants were quite skeptical towards cars being able to improve their intelligence on their own, e.g. through using external data from the physical but also virtual environment. Besides general negative associations like machines manipulating its drivers, philosophical questions emerged as well, such as how much the car should be able to learn e.g. perceptions on the “good” or “evil” and about emotions. Especially cars developing emotions were major concerns from the participants’ sides, since emotions would make them more human. And being human would mean to become a risk factor in the traffic, because they wouldn’t act rational anymore. Besides that, there was almost no interest in cars communicating human-like or having conversations with drivers, since it would be strange to talk to a machine and too far from reality. This preference of machine-like AI’s over human-like AI’s is surprising, since OEM’s assume the more Anthropomorphism is integrated in the design, the more trust drivers have. However, even if the participants didn’t like the idea that cars talk to drivers like a humans, they liked the idea of cars being capable to understand commands via natural speech. According to the study participants, it would mean to have less distraction, having the possibility to interact with the car hands-free (e.g. for using the GPS, making phone calls or any other functions which lead to distraction). All in all, the participants could imagine that an Artificial Intelligence could have a great value on the driver’s safety, if the car’s intelligence is limited to driving related tasks. However, also in the context of an intelligent car, data security was discussed. Some participants didn’t like the idea that the car collects data about the driver, his interests, messages and what is talked in the car. The data could be misused or could accidently be accessible to other passengers or people they are sharing the car with (such as with other family members, which wouldn’t be surprising for people who just got their driving license).

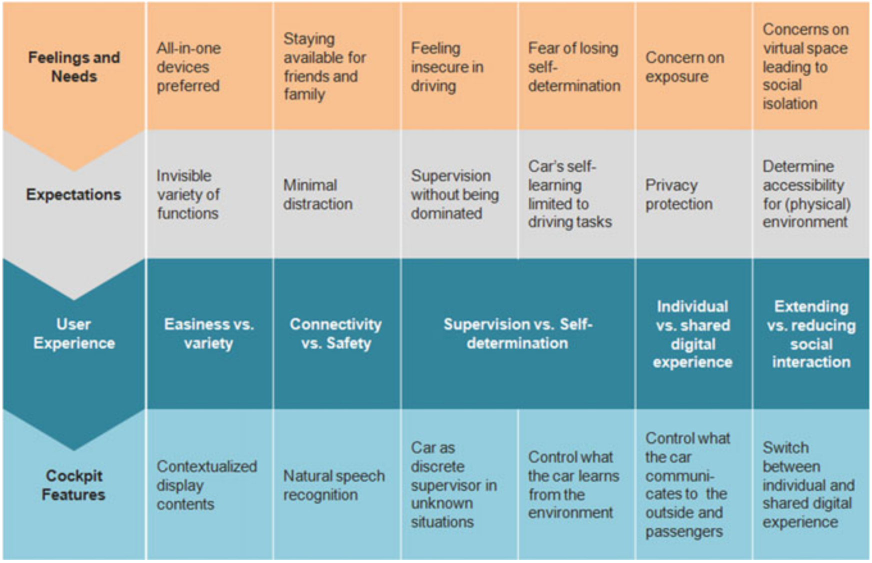

Fig. 3 Deriving cockpit features based on the study findings

4 Implications for the Future Cockpit

Studying Generation Z's experiences with new technology and their expectations on future mobility revealed different types of Generation Z users. These Personas, e.g. titled "The Novice Driver", "The Gamer", and "The Efficient", helped Valeo to translate the qualitative research data into cockpit features for automated and connected cars that meet the future driver's needs (see Fig. 3).

The study participants expect to have electronic devices (such as their Smartphones) that fulfill different tasks while being easy to use. So are they expecting their future cockpit to be: fulfilling different tasks but being uncomplicated to use, without many knobs and switches and without information overload. It's obvious that the future cockpit will be clean, with contextualized display contents, reducing distraction as much as possible. Reducing distraction is especially a need for the mainstream user among the Generation Z: "The Novice Driver", who gets easily distracted because of his lack of driving experience. Even if the car would drive in the automated mode, the user wouldn't want to enjoy his digital life in the car the same way he is experiencing mobile connectivity today with his Smartphone. He would rather prefer to use the car as a supervisor, who shows how to drive correctly in unknown situations. Connecting with friends and family would still be important in the car, but in a more discrete way. Secondary tasks would be possible depending on the cognitive overload the driver is having, which requires driver monitoring systems in the cockpit and predictive analytics. Different than "The Novice Driver", "The Efficient" would be more open for secondary tasks, but entertainment wouldn't be in focus of his needs during automated driving. This user would rather use the automated mode for both being productive and for relaxing in the car, rather than killing his time with media entertainment. This cockpit would require more dynamics: It wouldn't only change its physical appearance (e.g. a steering wheel which turns into a keyboard or a passenger screen that turns into a second monitor just like in the office), but also its display contents depending on the use case (e.g. a "business mode" would not allow a shared screen with passengers, while the "private mode" would). However, for an enhanced and shared digital experience in the future cockpit in terms of entertainment, one can learn from the identified virtual space extreme user "The Gamer". The future cockpit will enable drivers and passengers to use the car as a tool, to merge virtual and real life. Not only the car's environment is turned into a virtual field (e.g. augmented reality on windshields turning the road into a open world game and other cars into space shuttles), but also the car's inside, e.g. when the interior is turned into a "room-escape-game" with 3-D-body movement trackers enabling the players to pick holographic items, which are helping them to "escape".

Besides these different focuses of Generation Z Personas in terms of a positive driving UX, they also have commonalties: While one was already described above, such as easiness while having a variety of options, another key experience is self-estimation. Not just in terms of having the possibility to overtake control when the car drives it-self (which is nothing new) but in terms of securing the driver's data privacy and in terms of keeping self-reliance towards an intelligent system. The future driver will need full transparency and control on what the car learns about him and his environment to make sure the car's actions stay predictable. Also he will need to control what the car communicates about the driver to his environment (e.g. to other passengers in the car and the outside world). The future cockpit will for example be equipped to detect who sits in the car, preventing to expose private stuff of the driver to unintended persons. Incoming messages and phone calls will probably never be shown in the car's center or middle console to keep the user's privacy save. Furthermore, having the possibility to individually adjust how far-reaching the car's intelligence is, such as adjusting if it goes beyond the basic knowledge related to traffic will be relevant for the future driver. The need for control above the system also reflects in the target group's preference in terms of communicating with the future car: The future driver will have the option to give commands via natural speech, while the machine communicates like a machine, letting the human being human.

5 Conclusions

As this paper reveals, the hyper-connected Generation Z can show how a positive driving user experience can be created for automated and connected cars. But what does distinguish their way of thinking from other user groups?

Since the very first discussions on self-driving cars, loss of control and lack of trust towards the system is a major concern in terms of user acceptance. And this will stay a hot topic to discuss, but in a slightly different context. Generation Z wants to keep the lead. Not necessarily in terms of keeping physical control to steer the car (although this is very attractive for the driver-to-be's), but in terms of losing self-reliance and self-determination through technologies such as Artificial Intelligence that might overwhelm them as human beings. This doesn't mean that they aren't convinced that Artificial Intelligence can contribute to driver's safety, but they are not interested in having cars extending their intelligence beyond driving related tasks, such as learn to have emotions. The question is, if this might derive from the fact that they perceive cars as simple means a tool to get from A to B rather than having an emotional link to the car, or if this skepticism is simply deriving from science fiction and horror movies they see on artificial intelligence manipulating humans? In any way, independence seems to be an important topic, at least for the German Generation Z. Further research is needed how to create Human-Robot-Relationship, which fulfils the need to relieve the driver without stealing his self-determination.

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Reducing Conflict Between Vulnerable Road Users and Automated Vehicles

Justin M. Owens, Ryan Greene-Roesel, Azra Habibovic, Larry Head and Andrés Apricio

Abstract This chapter presents a summary of AVS 2016 Breakout Session 14, Reducing Conflict Between Vulnerable Road Users and Automated Vehicles. The session was scheduled to run for 90 min with approximately 60 min devoted to a panel of four speakers and 30 min of general discussion. The four speakers presented on a range of issues related to the intersection of VRUs and AVs. Key points included the need to develop usable, cross-cultural methods for pedestrians and AVs to communicate, the need to identify areas of opportunity and challenge relative to the current state of driver/VRU interactions, the need for further development and human factors testing of pedestrian-enabled mobile technology, and the importance of ongoing field testing.

Keywords Automated vehicles · Vulnerable road users · Human factors · Intersections · Design · Portable devices · Perception · Behavior

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1 Introduction

Human drivers frequently come into close proximity with vulnerable road users (VRUs) such as pedestrians and cyclists at intersections and midblock crossings, and must decide how and when to proceed. The decision whether to stop, yield, or perform some other action to avoid conflict is influenced by the ability of the driver and VRU to detect and anticipate each other's actions, as well as by social norms, environmental conditions, visibility, roadway design, law enforcement, pedestrian traffic volume, and other factors.

Semi—and fully-automated vehicles (AVs) will face a variety of challenges when encountering VRUs, including localization of the VRU and prediction of the his/her intent and direction of movement. However, AV systems also present opportunities for greater predictability and safety for vehicle/VRU interactions. This breakout session was developed to explore how AVs can more effectively communicate with road users outside the vehicle and vice versa, the challenges posed by VRU conflicts across a variety of driving scenarios, how connectivity and advanced features can predict and help avoid future conflicts, and how yielding norms can be established in an automated future.

To accomplish this, the organizers invited speakers from a range of geographic areas and research specialties to present talks related to the topic at hand, after which there was a panel discussion with audience involvement. In Sect. 2 we present summaries of the presentations, followed in Sect. 3 by highlights of the discussion that was generated during the panel portion of the study.

2 Issues and Solutions

2.1 Presentation Summaries

2.1.1 Vulnerable Road Users in the Age of Automated Vehicles: How to Ensure Safe Interactions?

Dr. Azra Habibovic, a Senior Researcher at the Swedish ICT, discussed the topic of how to better understand and encourage positive communication and interaction between VRUs and AVs, with the core message that understanding each other's intent is crucial for safe and pleasant interactions between road users. In this context, active communication signals (e.g. gestures, eye contact, vocalizations, and vehicle control behavior) and passive communication signals (e.g. distance, speed, age, engine sound, etc.), must be taken into consideration. These signals are bidirectional and dependent upon proper interpretation, and are mediated by environmental and roadway conditions including weather, traffic, visibility, and ambient noise, which can favor certain methods of interaction or interfere with others.

While the proper use and interpretation of these communication signals are critical for safe vehicle-pedestrian interactions, challenges arise when attempting to evaluate the potential for their inclusion within an AV framework. In particular, independent researchers rarely have access to cutting-edge AV technology, and the development of functional prototypes is time–and cost-intensive.

As an example of the kind of research that can be performed within these constraints, Dr. Habibovic described a series of studies conducted to determine the emotional valence of a variety of pedestrian/driver interactions. In one study variant, a right-hand drive (nonstandard) vehicle was fitted with a "dummy" steering wheel on the left (standard) side and participant reactions to a confederate "driver" were recorded; in some scenarios, no "driver" was present at all. In this and related studies, participant pedestrians rated eye contact with the driver as promoting calm interaction, while apparent driver distraction led to pedestrian stress and ratings of an unpleasant interaction. The lack of a visible driver also resulted in stress and ratings of an unpleasant interaction, which may be expected as this scenario was contrary to the expectations of pedestrians in the current driving environment.

In general, pedestrians require informational support about the status of automated vehicles, including current operation mode (manual vs. automated) and imminent behavior (e.g. "about to start," "about to turn," "about to yield," "resting," etc.).

An example vehicle-pedestrian interface was demonstrated using the Automated Vehicle Interaction Principles (AVIP) project, a concept designed to illustrate a potential universal, visual communication interface for AVs.[1] The AVIP interface consists of an outward-facing LED light bar affixed to the top of the vehicle windshield that uses distinct patterns of light to communicate the vehicle's status and intent to pedestrians. Initial testing with pedestrians found that this interface may alleviate the stress and unpleasant interactions associated with absent or distracted drivers. Future research on this technology is intended to extend testing in scope and functionality.

2.1.2 The Current State of Vehicle-VRU Interactions

Dr. Justin Owens, a senior researcher in the Center for Vulnerable Road User Safety at the Virginia Tech Transportation Institute, presented an overview of how drivers and VRUs currently interact. Driver/VRU interactions can be informative for AV design, both in cases where drivers and VRUs interact positively (and may be informative to AV system design) and in cases where the interaction breaks down (cases where AVs may offer potential improvement).

At a fundamental level, driver/VRU interactions nearly always result in a successful negotiation, with these negotiations based on laws, social norms, and

[1] As of this writing, a video demonstration of the AVIP project may be viewed at www.youtube.com/watch?v=MU74wK_RlTo.

driver/VRU perceptual abilities and skill. On rare occasion, however, breakdowns in negotiation lead to a crash, with often tragic consequences given the vulnerability of the non-driver. These breakdowns are often caused by one or a combination of human factors issues, a sampling of which were discussed in the context of potential improvements with automated and/or connected technology.

One important human factors issue is visibility, which is critical to the safe avoidance of VRU; a driver must be able to both see and identify other road users in time to react properly. Pedestrian/cyclist night visibility is a serious safety concern, as 72% of pedestrian fatalities occur in the dark (NHTSA 2016). Current countermeasures to reduced visibility include roadway, intersection, and personal lighting, reflective clothing or other materials, night vision, and educational interventions. Visibility is a domain for which automated and connected technologies may provide significant safety improvement with the advent of advanced machine vision, LIDAR, V2P communications, etc. Conversely, pedestrians and cyclists need to be aware of the presence of the vehicle; if future vehicles lack headlights producing light in the visible spectrum, particularly if combined with quiet operation from electric motors, this could pose a serious problem.

The choices of crossing location and when to initiate crossing are also a serious factors in pedestrian crash risk, as 78% of pedestrian fatalities occur in urban areas and 71% occur at non-intersections (NHTSA 2016). The tendency of pedestrians and cyclists to overestimate their own visibility to drivers (Tyrrell et al. 2004; Wood et al. 2010) may affect these crossing decisions, as may distracted walking, when pedestrians may not attend to their surroundings to the extent necessary to maintain spatial awareness. AVs equipped with advanced sensing technologies may allow improved detection in these cases beyond human capabilities, and application-centered notifications delivered via pedestrian smartphones may also assist in alerting pedestrians to potentially unsafe behaviors.

Social factors, particularly variations in cultural norms across and between countries, present a challenge for current drivers and VRUs (especially during travel in unfamiliar locations) and could pose a similar challenge to AVs given the assumption that vehicle control algorithms may be universal. Further, much of the every-day interaction between drivers and VRUs may be based in mutually-understood social gestures (such as a horizontal wave gesture meaning “proceed” or a vertical wave of “thanks”) that may not be easily duplicated in an AV interface, although as seen in Dr. Habibovic’s previous talk efforts are underway to develop such interfaces.

Finally, a range of challenges and opportunities face the design of AVs concerning pedestrians with disabilities. As mentioned above, the silence of electric vehicles continues to be a challenge for vision-impaired pedestrians; this may be exacerbated at night if traditional headlights become obsolete. Pedestrians with mobility impairments may need additional crossing time at intersections, which could affect algorithms controlling traffic flow (this point was discussed further by Dr. Head later in the session). Similarly, pedestrians with cognitive impairments may face novel challenges in determining when it is safe to cross a roadway without traditional human-based social interactions.

In sum, while the current scope of interactions between AVs and VRUs is generally very safe and positive, there are areas of challenge—particularly around the limits of human perception and performance—where advanced vehicle technologies may provide a tangible safety benefit. On the other hand, there are scenarios, particularly those involving social interaction, where AVs may pose unique challenges to VRUs. A major challenge facing future work on the interactions between AVs and VRUs will be to improve upon what already (mostly) works while reducing the burden on both VRUs and vehicle occupants.

2.1.3 Connected Pedestrians at Signalized Intersections in a CAV Environment

Dr. Larry Head, the Director of the Transportation Research Institute at the University of Arizona, focused on the fundamental question of the role of traditional traffic signals in future roadways, and, if they are unnecessary for safe traffic flow, how pedestrians will be able to integrate with AVs in a safe manner.

As one potential set of tools for enabling the safe flow of pedestrians in automated intersections, Dr. Head discussed the Multi-modal Intelligent Traffic Signal System (MMITSS) project sponsored though a Pooled Fund study (FHWA, MCDOT, Caltrans, VDOT, and other states). The focus of this project is on dynamic mobility applications, and incorporates components of Intelligent Traffic Signal Control (I-SIG), Signal Priority (TSP, FSP, PREEMP), Mobile Accessible Pedestrian Signal System (PED-SIG), and Real-time Performance Observer (PERF-OBS). This technology is based on connected vehicle and pedestrian infrastructure that utilizes DSRC/Wi-Fi/LTE based wireless communications.

An example use case was described as involving a pedestrian walking, on a sidewalk, toward an intersection. As the pedestrian travels along the sidewalk information from the MAP is used to refine the pedestrians position. When the pedestrian arrives at the intersection, s/he would use a smartphone application to request a pedestrian interval to cross the street. The pedestrian's location is estimated using a corrected GPS position and transmitted to a server based on a high-fidelity map of the area. The server then sends a pedestrian signal request to the appropriate traffic signal controller. The smartphone application can relay real-time information to the pedestrian, including signal timing status and countdown duration. One notable technical challenge to this approach is the limited precision on smartphone GPS. Two ongoing implementations were discussed, the MMITSS Ped App and the Savari SmartCross.

2.1.4 PROSPECT: PROactive Safety for Pedestrians and CyclisTs

Mr. Andrés Aparicio, Product Manager at Applus IDIADA, presented a summary of the ongoing "PROactive Safety for Pedestrians and CyclisTs" (PROSPECT) project funded by the Innovation and Networks Executive Agency of the European

Commission.[2] The goal of this project is to significantly improve the effectiveness of active VRU safety systems by expanding the scope of situations addressed by the systems and improving overall system performance. Key aspects of the project include:

1. Understanding of relevant VRU scenarios. This aspect incorporates macro-level statistical and in-depth analysis of crash factors, including national statistics from specifics countries and weighting across the EU, as well as naturalistic urban observations at hotspots in a variety of EU cities.
2. Improved VRU sensing including enhanced VRU coverage and improved sensor and situational analyses such as advanced machine learning techniques for vision sensors.
3. Advanced system control strategies including accident avoidance by combining steering and braking and advanced actuator concepts.
4. A validation phase including testing in realistic traffic scenarios (reproduced in controlled environments) and user acceptance tests addressing the influence of false warning and incorrect interventions and predictive models of acceptance.

Four demonstration vehicles have been developed, as well as a mobile driving simulator. In addition, pedestrian and cyclist dummies including a propulsion system are in development to allow more realistic testing.

In addition, Mr. Aparicio presented an update on upcoming Euro NCAP standards that will include assessments of automatic emergency braking (AEB) for pedestrians and cyclists in 2016 and 2018, respectively. The "Assessment methodologies for forward-looking integrated pedestrian safety systems" (AsPeCSS[3]) project was conducted in coordination with the NCAP standards update to "develop harmonized test and assessment procedures" including a methodology for balancing active and passive safety benefits, methods for active safety testing, and methods to adapt passive safety test conditions from pre-crash actions.

3 Discussion and Future Directions

Following the scheduled presentations, the audience engaged in a spirited discussion with the panel. Highlights of the discussion and outstanding questions for future consideration are presented below:

- What are the consequences of advanced AV/Pedestrian systems that require smartphone applications for pedestrians who do not have smartphones? Further, what happens if pedestrians who do have smartphones and rely on such systems forget their phone, the battery dies, or the equipment malfunctions?

[2]Further information on the PROSPECT project may be found at www.prospect-project.eu.

[3]Further information on the AsPeCSS Project may be found at www.aspecss-project.eu.

- Relatedly, it was suggested that the burden should not be on pedestrians to carry devices to communicate with vehicles. Perhaps planners should design future city spaces to accommodate pedestrians, and cars should be parked outside the cities (the discussant cited a previous plenary presentation on reclaiming city space for pedestrians).
- Where does the onus of responsibility fall in a vehicle:VRU conflict? Is it up to the pedestrian or car to yield or to detect? If the responsibility falls to the vehicle, what is to stop pedestrians from taking advantage of such a system by behaving irresponsibly?
- If drivers have the option to turn off vehicle systems, what can be done to overcome their desire to do so? How can we reduce false positives and increase consumer acceptance?
- How effective are pedestrian/cyclist detection systems in the dark? Radar is not affected by dark conditions, but may not provide precise identification of VRUs. Camera performance may suffer during night driving and/or inclement weather such as fog or rain. It was suggested that nighttime and inclement weather performance assessments could be included as part of system evaluation.
- One interesting suggestion was that AVs could lead to higher-order mode shifts by making roadways more appealing to pedestrians and cyclists by slowing vehicles down and reducing conflicts.

In this session, panelists and the audience discussed a wide range of topics relevant to the future of interaction between AVs and VRUs, particularly pedestrians and cyclists, and identified a variety of topic areas of both opportunity and challenge. Takeaway points included the need to develop usable, cross-cultural ways for pedestrians and AVs to communicate, the need to identify areas of opportunity and challenge relative to the current state of driver/VRU interactions, the need for further development and human factors testing of pedestrian-enabled mobile technology, and the importance of ongoing field testing. We believe that this topic is highly relevant and important for the acceptance and safe integration of automated vehicle features in the near and long-term future.

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Part III
Ethics, Legal, Energy and Technology Perspectives

Model Legislation for Automated Driving

Bryant Walker Smith

Abstract This book chapter proposes model bills to clarify the legal status of automated driving at both the state and federal levels in the United States. The chapter briefly describes this current status, critiques my earlier legislative language, identifies other relevant efforts, presents the model state bill, and then presents the model federal bill. These models principally address the legal status of automated driving rather than the range of other relevant issues. Since they are likely to evolve, current versions are available at newlypossible.org/modellaws.

Keywords Automated driving · Automated vehicles · Autonomous vehicles · Self-driving vehicles · Driverless vehicles · Legislation · Model state policy · Legality · Regulation · National highway traffic safety administration · NHTSA · Motor vehicle safety · Exemptions · Levels of automation

1 Introduction

In 2012, I offered model statutory language to clarify the legal status of automated driving under the vehicle codes of US states. In the intervening five years, automated driving has progressed rapidly. This progress has touched not just the technologies for automated driving but also the relevant applications, business cases, and legal frameworks. Accordingly, for this book chapter, I have revised my model language for US states and added model language for the US Congress. These model bills provide a starting place for a government that wishes to clarify the legal status of automated driving within its jurisdiction.

The state bill is an improvement over my original model as well as over the laws actually enacted in several US states. It is intended to clearly, succinctly, and fairly address a wide range of automated driving applications and business cases. It also aims to facilitate uniformity—and even some collaboration—among the various states.

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The federal bill is entirely new. It is intended to swiftly address arguable inconsistencies between the existing federal motor vehicle safety standards and particular applications of automated driving. These include truly driverless vehicles that lack conventional input devices like brake pedals and truly personless vehicles that are not designed to carry humans at all.

There are two important caveats to these model bills.

First, like their predecessor, the bills suffer from their own (or, more correctly, my own) sins of commission and omission. Automated driving's continued evolution will reveal more issues, inconsistencies, and ambiguities. For this reason, current and past versions of these model bills are available at newlypossible.org/modellaws.

Second, although the bills principally address only the legal status of automated driving, there are many other issues related to automated driving that governments can and should address. For example, governments that wish to promote automated driving might consider the strategies described in How Governments Can Promote Automated Driving. And every government should consider how to prepare for the dramatic challenges and opportunities associated with automation and connectivity more generally.

This chapter is more modest in ambition. It summarizes the legal status of automated driving, critiques my previous model state bill, discusses other models, presents the new model state bill, and finally presents the model federal bill.

2 The Legal Status of Automated Driving

In assessing whether automated vehicles can be lawfully sold and operated, the key inquiry is whether those activities are prohibited by any law rather than whether they are expressly permitted by any law. This inquiry in turn requires an exhaustive examination of every law potentially relevant to automated driving.

At the international level, two treaties contain provisions that are at least arguably in tension with automated driving. Only the treaty that does not bind the United States has been amended with a view toward lower levels of automation. However, the other treaty can be reasonably interpreted in a manner consistent with automated driving. This interpretation finds further support in the lackluster effort to amend the treaty even as parties such as the United States and the United Kingdom have moved to embrace automated driving in their domestic laws.

At the federal level, the US federal motor vehicle safety standards (FMVSS) do not require that humans actively drive their vehicles but may require that these vehicles can be actively driven by these humans. My 2012 analysis did not consider how developers of truly driverless vehicles that lack traditional driver devices such as brake pedals might certify those vehicles under safety standards that reference those devices. (It should have). However, this issue has been thoughtfully examined in correspondence between Waymo (now Google) and the National Highway Traffic Safety Administration as well as in a report by the Volpe Center.

At the state level, vehicle codes are generally consistent with a range of automated driving activities. These codes contain various provisions that require both vehicles and their drivers to be reasonably safe, and they define driver in a broad way that could conceivably include a mere user of an automated vehicle. However, the codes do not expressly require drivers to monitor the driving environment or to physically manipulate the steering wheel, accelerator pedal, or brake pedal. New York, which provides that "[n]o person shall operate a motor vehicle without having at least one hand … on the steering mechanism at all times when the motor vehicle is in motion," is a notable exception.

Since Nevada became the first to do so in 2011, many states have enacted laws specific to automated driving, and many more have considered or are considering them. California has developed what is by far the most detailed legal framework for automated driving, but some of these details (such as the statutory definition of driver) are in tension with particular visions of automated driving. After initially prohibiting automated driving other than for testing, Michigan enacted a set of laws that are collectively incomprehensible. Florida declared automated driving to be lawful, but the interaction between this declaration and other legal provisions is unclear. In several states, specific automated driving developers are pursuing special legal frameworks for their particular automated driving applications.

Substantial automated driving activities are also occurring in states without laws specific to automated driving. States including Texas, Washington, and Pennsylvania have no such laws, and Arizona has only an executive order.

Municipalities are also contributing to the discussion of automated driving. Several, for example, have enacted resolutions encouraging local development and deployment or are collaborating on specific automated driving projects.

3 Prior State Language

The statutory language I suggested in 2012 was coherent but overly complex. It addressed several common provisions that could apply to automated driving in adverse or ambiguous ways. It also anticipated a diverse set of automated driving technologies and applications—but attempted to manage this diversity through an excessively intricate framework that relied excessively on administrative rulemaking.

My earlier definition of driver offers a central example. Automated driving laws of a similar vintage generally defined the driver as (to quote California's) "the person who is seated in the driver's seat" or the person who "causes the autonomous technology to engage." This language, while generally sufficient for on-road testing that was occurring at the time, applied uncomfortably to deployments. Under these definitions, for example, a person might qualify as a driver even if asleep at home (or, to use a popular media example, while drinking in a tavern).

In contrast, the model language provided a more elaborate nested definition of driver depending on the particular circumstances of operation. Under this language, the driver could be the company that manufactured or insured the vehicle, the human who actually or presumptively initiated automated operation, the owner of the vehicle, or even a person who hacked the vehicle. This was unhelpfully complex.

In an effort to increase the flexibility and resiliency of the legal framework, the language also delegated many details to a state's department of motor vehicles. This delegation, however, could strain any such department and, if replicated across many states, any developer interacting with these departments. The flexibility did not justify the complexity.

4 Other State Models

Other recent efforts offer potential inputs to or models for state legislation. For example:

1. The National Highway Traffic Safety Administration (NHTSA) developed a model policy for states in cooperation with the American Association of Motor Vehicle Administrators (AAMVA). The US Department of Transportation published this model policy as part of the 2016 Federal Automated Vehicles Policy.
2. SAE International defined concepts relating to automated driving in SAE J3016 (2016). The document's delineation of the levels of automation, description of the operational design domain, and definition of other key terms has influenced bills introduced in several states. The model bills adopt or adapt SAE's definitions of automated driving system, dynamic driving task, and remote driver.
3. Marc Scribner of the Competitive Enterprise Institute proposed state-by-state language to exempt platoons from certain following-distance requirements. Particular language I had suggested is incorporated in the model state bill.
4. At the request of General Motors, Michigan enacted a law expressly authorizing and regulating automated ridesharing projects undertaken by or with the participation of a motor vehicle manufacturer. Legislators in other states subsequently introduced similar bills.
5. The Uniform Law Commission (ULC) recently concluded a study on whether to draft a uniform law on highly automated vehicles and appears likely to proceed toward a multiyear drafting process.

Other models are likely to emerge—or to exist without ever emerging publicly. The two models that follow may provide a public foundation for future efforts.

5 Model State Bill

1. **Background**
    a. It is the intent of the Legislature to facilitate the development and deployment of automated driving in a way that improves highway safety.

b. The Legislature hereby finds that the automated operation of an automated vehicle under the conditions prescribed herein is consistent with article 8 of the Convention on Road Traffic because automated driving systems perform the operational and tactical functions otherwise performed by conventional drivers and have the potential to advance an object of the Convention by significantly improving highway safety.

2. **Implementation**

a. The Department of Motor Vehicles and the Department of Insurance may make rules, issue interpretations, and take other lawful actions to administer and enforce this Act.

3. **Definitions**

a. Automated driving provider means the natural or legal person that for the purpose of registering an automated vehicle warrants that the automated operation of such vehicle is reasonably safe.
b. Automated driving system means the hardware and software that are collectively capable of performing the entire dynamic driving task on a sustained basis.
c. Automated operation means the performance of the entire dynamic driving task by an automated driving system, a remote driver, or a combination of automated driving system and remote driver. Automated operation begins at the moment of such performance and continues until the moment that a driver or operator intentionally terminates such performance for a reason other than a reasonable perception of imminent harm.
d. Automated operation insurance means an insurance policy that covers damages to the person or property of another arising from the automated operation of an automated vehicle without regard to fault.
e. Automated vehicle means a motor vehicle with an automated driving system, regardless of whether the vehicle is under automated operation.
f. Automated vehicle owner means the owner of the automated vehicle, as the term owner is defined in this Title.
g. Automation continuation guarantee means a surety bond or cash deposit that specifically covers diminution in the value of an automated vehicle arising from revocation of that vehicle's registration.
h. Dedicated automated vehicle means an automated vehicle designed for exclusively automated operation.
i. Drive and operate each mean as provided in the vehicle code, except that an automated driving system exclusively drives and operates a vehicle under automated operation.
j. Driver and operator each mean as provided in the vehicle code, except that an automated driving system is the exclusive driver and operator of a vehicle under automated operation.
k. Dynamic driving task means all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and

waypoints, and including without limitation controlling lateral vehicle motion, controlling longitudinal vehicle motion, monitoring the driving environment, executing responses to objects and events, planning vehicle maneuvers, and enhancing vehicle conspicuity.

l. Participating agency means the Department of Motor Vehicles, an administrative agency of another state that shares automated vehicle registration information with this State, or an administrative agency of the United States that shares automated vehicle registration information with this State.
m. Remote driver means a natural person who performs part of or the entire dynamic driving task while not seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices.

4. **Driving licensing**

   a. A person who uses an automated vehicle without driving or operating such vehicle shall not be required to hold a driving license.
   b. A remote driver shall hold a driving license that is valid in this State.
   c. A remote driver who is employed, contracted, or compensated as such shall hold a commercial driving license that is valid in this State.

5. **Vehicle registration**

   a. An automated vehicle owner may register an automated vehicle in this State regardless of whether such owner is a resident thereof.
   b. An automated vehicle owner shall register an automated vehicle in this State if such vehicle travels more than 80% of its miles therein as measured on a calendar year basis.
   c. Registration of an automated vehicle may be granted, maintained, and renewed only if, by means of a current electronic record automatically retrievable by any participating agency, an automated driving provider:

      i. identifies such vehicle by vehicle identification number;
      ii. describes the capabilities and limitations of such vehicle's automated driving system;
      iii. provides proof of automated operation insurance for such vehicle;
      iv. provides proof of any required automation continuation guarantee for such vehicle;
      v. represents to each participating agency that it believes the automated operation of such vehicle to be reasonably safe;
      vi. represents to each participating agency that clear and convincing evidence supports such belief;
      vii. warrants to the public that the automated operation of such vehicle is reasonably safe; and
      viii. irrevocably appoints each participating agency as a lawful agent upon whom any process may be served in any action arising from the automated operation of such vehicle.

d. The Department of Motor Vehicles may decline, suspend, revoke, or decline to renew the registration of any motor vehicle that it determines to be unsafe, improperly equipped, insufficiently insured, noncompliant with any vehicle registration requirement, or otherwise unfit to be operated on a highway.
e. Registration of a motor vehicle shall create no presumption as to the safety of such vehicle or its equipment.

6. **Equipment**

a. This Title's vehicle and equipment provisions shall be interpreted to facilitate the development and deployment of automated vehicles in a way that improves highway safety.
b. An automated vehicle shall be reasonably safe.
c. An automated driving system shall be reasonably safe.
d. Any provision of this Title requiring equipment necessary only for the performance of the dynamic driving task by a human driver shall not apply with respect to a dedicated automated vehicle.

7. **Rules of the road**

a. This Title's rules of the road shall be interpreted to facilitate the development and deployment of automated vehicles in a way that improves highway safety.
b. Automated operation of an automated vehicle in accordance with this Act and in a reasonably safe manner is lawful.
c. An automated driving provider shall take reasonable steps to ensure reasonable compliance with all provisions of this section while an associated automated vehicle is under automated operation and shall be liable as would a driver or operator in case of noncompliance.
d. A motor vehicle shall not be operated on a public highway if it is unsafe, improperly equipped, insufficiently insured, noncompliant with any vehicle registration requirement, or otherwise unfit for such operation.
e. An automated vehicle that is under automated operation shall not be deemed unattended unless it is not lawfully registered in this State or another, poses a risk to public safety, or unreasonably obstructs other road users.
f. An automated vehicle that is under automated operation shall not be deemed abandoned unless it is not lawfully registered in this State or another, poses a risk to public safety, or unreasonably obstructs other road users.
g. Any provision of this Title restricting the use of electronic devices by a driver or operator shall not apply to the automated operation of an automated vehicle.
h. Any provision of this Title requiring a minimum following distance other than a reasonable and prudent distance shall not apply to operation of any nonleading vehicle traveling in a procession of vehicles if the speed of each vehicle is automatically coordinated.

i. Any natural or legal person who in willful or wanton disregard for the safety of persons or property initiates, continues, or impedes the automated operation of an automated vehicle shall be guilty of reckless driving.

8. **Insurance**

   a. The automated driving provider shall maintain automated operation insurance for each automated vehicle in an amount that is not less than the amount of third party liability insurance specified in this State's financial responsibility statute.
   b. The automated driving provider shall maintain an automation continuation guarantee for each automated vehicle in an amount that is not less than $10,000, except that this requirement shall not apply if the automated driving provider is also the automated vehicle owner.
   c. This Act does not displace any other insurance requirements.

9. **Penalties**

   a. Unless otherwise provided by this Act or by the laws of this State, a natural or legal person who fails to comply with any provision of this Act shall be liable for a civil infraction and fined not more than $1000 for each day of each violation.

10. **Miscellaneous**

   a. The effective date of this Act shall be 30 days after its enactment.
   b. The provisions of this Act are severable, and a declaration that any part thereof is unconstitutional or otherwise invalid shall not affect the part that remains.

6 Model Federal Bill

1. **Background**

   a. It is the intent of Congress to facilitate the development and deployment of automated driving in a way that improves highway safety.
   b. Congress hereby finds that the automated operation of an automated vehicle under the conditions prescribed herein is consistent with article 8 of the Convention on Road Traffic because automated driving systems perform the operational and tactical functions otherwise performed by conventional drivers and have the potential to advance an object of the Convention by significantly improving highway safety.

2. **Definitions**

a. Automated driving system means the hardware and software that are collectively capable of performing the entire dynamic driving task on a sustained basis.
b. Automated operation means the performance of the entire dynamic driving task by an automated driving system, a remote driver, or a combination of automated driving system and remote driver.
c. Automated vehicle means a motor vehicle with an automated driving system, regardless of whether the vehicle is under automated operation.
d. Conventional driver means a natural person who performs part of or the entire dynamic driving task while seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices.
e. Dedicated automated vehicle means an automated vehicle designed for exclusively automated operation.
f. Dynamic driving task means all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints, and including without limitation controlling lateral vehicle motion, controlling longitudinal vehicle motion, monitoring the driving environment, executing responses to objects and events, planning vehicle maneuvers, and enhancing vehicle conspicuity.
g. Remote driver means a natural person who performs part of or the entire dynamic driving task while not seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices.

3. **Engineering judgment**

a. Section 30111 of this Title is amended by striking:"The Secretary of Transportation shall prescribe motor vehicle safety standards. Each standard shall be practicable, meet the need for motor vehicle safety, and be stated in objective terms."and inserting:"The Secretary of Transportation shall prescribe motor vehicle safety standards. Each standard shall be practicable, meet the need for motor vehicle safety, and be stated in objective terms. A standard is stated in objective terms even if it specifies a test procedure that involves conditions or produces results that cannot be precisely replicated."

4. **Automatic exemptions**

a. A dedicated automated vehicle shall be exempt from any provision, including any requirement, specification, procedure, or portion thereof, of a motor vehicle safety standard or bumper standard prescribed under this Title if:

   i. such provision applies to motor vehicle equipment necessary only for the performance of the dynamic driving task by a conventional driver; and

   ii. such standard, including any change thereto, was promulgated prior to the effective date of this Act.

b. A dedicated automated vehicle that is not designed, intended, or marketed for human occupancy shall be exempt from any provision, including any requirement, specification, procedure, or portion thereof, of a motor vehicle safety standard or bumper standard prescribed under this Title if:

   i. such provision applies to motor vehicle equipment necessary only for the protection of human occupants of the vehicle on which such equipment is installed; and
   ii. such standard, including any change thereto, was promulgated prior to the effective date of this Act.

5. **Discretionary exemptions**

   a. Section 30113(d) of this Title is amended by striking:"A manufacturer is eligible for an exemption under subsection (b)(3)(B)(ii), (iii), or (iv) of this section only if the Secretary determines the exemption is for not more than 2,500 vehicles to be sold in the United States in any 12-month period." and inserting:"A manufacturer is eligible for an exemption under subsection (b)(3)(B)(ii) or (iii) of this section only if the Secretary determines the exemption is for not more than 2,500 vehicles to be sold in the United States in any 12-month period."
   b. Section 30113(e) of this Title is amended by striking:"An exemption or renewal under subsection (b)(3)(B)(i) of this section may be granted for not more than 3 years. An exemption or renewal under subsection (b)(3)(B)(ii), (iii), or (iv) of this section may be granted for not more than 2 years." and inserting: "An exemption or renewal under subsection (b)(3)(B)(i) of this section may be granted for not more than 3 years. An exemption or renewal under subsection (b)(3)(B)(ii) or (iii) of this section may be granted for not more than 2 years. An exemption or renewal under subsection (b)(3)(B)(iv) of this section may be granted for not more than 5 years."

7 Conclusion

The model bills presented above provide a foundation for efforts to clarify the legal status of automated driving at the state and federal levels. This foundation is promising, but it will not be perfect. As automated driving technologies, applications, and business cases continue to evolve, new issues may emerge. For this reason, current versions of these model bills are at newlypossible.org/modellaws.

The Environmental Potential of Autonomous Vehicles

Aaron Hula, Lisa Snapp, Jeff Alson and Karl Simon

Abstract Automated vehicle technologies are rapidly developing, and their emergence on the automotive landscape will likely be transformative in nature. Autonomous vehicles could provide better access to mobility that is not only significantly safer, but also potentially cheaper, cleaner, and more efficient. These technologies could play a leading role in addressing the enormous challenge of climate change, yet their ultimate environmental impact is an open question whose answer will be influenced by a large array of decisions yet to come. We have an opportunity now, while policy is in its infancy, to shape the direction of autonomous vehicles to ensure that the transformational change they will bring is overwhelmingly positive for the environment.

Keywords Autonomous · Automated · Self-driving · Environment · Energy · Greenhouse gasses · Emissions · Electrification · Car sharing · Automated · Connected · Fuels

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1 The Challenge Ahead

In October 2012, the Environmental Protection Agency, along with the National Highway Traffic Administration and California Air Resources Board, finalized a national program for light duty greenhouse gas emissions and fuel economy through model year 2025.[1] These standards are expected to nearly double new vehicle fuel economy from the baseline model year 2011, reduce greenhouse gas (GHG) emissions on the order of 6 billion metric tons, and save consumers money (Regulatory Impact Analysis 2012; Memorandum to the Docket 2016). These standards are expected to be met largely through improvements in gasoline engine technology, and did not attempt to include the potential impacts of autonomous vehicles.

While the fuel savings and emission reductions from the National Program are substantial, they are only a first step towards larger greenhouse gas reductions that will be necessary to address long term climate change. Already, the average atmospheric CO_2 concentration of 401 ppm in 2015 is likely the highest level for at least the last 800,000 years (IPCC 2013), and the past 15 years have been 15 of the 16 warmest years on record (NOAA: Global Climate Report—Annual 2015). Extreme temperatures and other events in the U.S. could lead to thousands of deaths and trillions of dollars in economic damage (Melillo 2014).

Figure 1 illustrates projected GHG tailpipe and upstream emissions from light duty vehicles under three scenarios through 2050 (Environmental Protection Agency 2016). The upper “Business-as-Usual” curve assumes that there are no major regulatory or other changes in the light-duty sector after 2025. The middle “4.5% per year reduction” curve assumes that the average annual stringency increase reflected in the National Program GHG standards for model year 2012–2025 continues through model year 2050. The bottom curve reflects a trajectory fitted to achieve a 72% reduction in light-duty vehicle GHG emissions from 2010 levels in 2050. This corresponds to the minimum global GHG emission reductions required to stabilize atmospheric GHG concentrations around 450 ppm and to limit global temperature rise to below 2 °C, as estimated by the Intergovernmental Panel on Climate Change (IPCC 2013).

The business-as-usual scenario demonstrated in Fig. 1 will not provide long-term GHG emission reductions. However, change is clearly coming to the automotive industry. The advent of autonomous technologies, the explosion of ride-hailing and ride-sharing innovations, and the increasing capacities of, and interest in, electric vehicles are all shaping a new and exciting transportation future. The challenge industry and policy makers face in shaping this future is to ensure that these technologies develop such that they improve the environmental profile of mobility.

[1]NHTSA’s CAFE standards for model years 2022–2025 are not final, and are augural. NHTSA is required by Congress to set CAFE standards for no more than 5 years at a time.

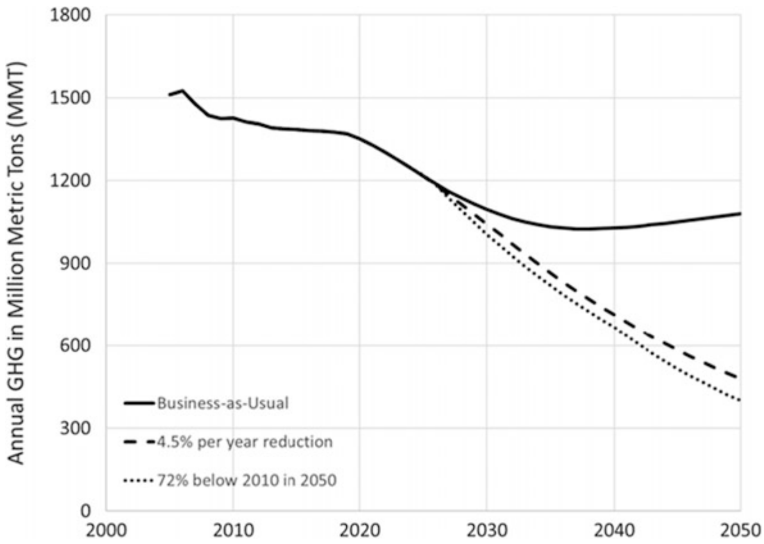

Fig. 1 Light duty vehicle tailpipe and upstream GHG emissions through 2050

2 The Environmental Impacts of Connected and Autonomous Vehicles

Connected and autonomous vehicles have the potential to reshape transportation and, with it, the environmental impact of moving people and goods. There are many aspects of an autonomous future that will change the impact of transportation, but the overarching question is relatively straightforward: will system efficiency improvements resulting from autonomous technologies reduce the overall environmental impact of transportation, or will the impacts of increased travel demand overwhelm any efficiency improvements and result in increased emissions and other environmental negatives?

The amount of research investigating the environmental impacts of autonomous vehicles has been limited to a handful of prominent studies (Brown et al. 2014; MacKenzie et al. 2014; Stephens et al. 2016), most of which are only able to conclude that there is a very wide range of possible outcomes. Technology design and an array of market and policy forces could result in outcomes ranging from significant reductions to drastic increases in emissions. For example, a recent study by the U.S. Department of Energy (MacKenzie et al. 2014) concluded that fuel use and related emissions could be reduced by 60%, or could increase three-fold. The largest factor potentially increasing the environmental impact of autonomous vehicles is that they could make driving easier and cheaper, inducing dramatic increases in travel demand and, hence, fuel consumption. New user groups that are currently unable to drive will also likely increase travel demand, and higher speed travel may also become a reality. In the worst case, poetically termed the “dystopian nightmare" by MacKenzie (Stephens et al. 2016), vehicle miles travelled would skyrocket, while the lack of a comprehensive regulatory approach would prevent many of the potential benefits of autonomous vehicles from materializing.

There is, however, a much more positive road autonomous vehicles can take. Connected and automated technology can facilitate more efficient vehicles, electric powertrains, shared mobility, smoother traffic flow, and even a reshaping of how we design, live, and move in our urban areas. Research suggests that energy and GHG emissions could be drastically reduced without sacrificing personal mobility (Greenblatt and Saxena 2015; Alonso-Mora et al. 2016). Achieving this vision will require researchers, engineers, and policy makers to maintain a clear and constant focus on energy and environmental considerations during every stage of development. Here, we consider four important aspects of the developing CAV market with environmental and energy implications.

2.1 Fuel Economy

Federal regulations will approximately double new vehicle fuel economy by 2025, but autonomous vehicles have the potential to go much further. Vehicle acceleration, speed, braking, following distance, and routing decisions can all be optimized to provide more efficient travel with autonomous vehicles. If autonomous vehicles can reliably lead to near zero collisions, as many experts anticipate, vehicles could become substantially lighter as fewer safety features are needed. Finally, as more vehicles become connected and automated, vehicle platooning could lead to improved aerodynamics. All of these advances could lead to substantial improvements in fuel economy. At the same time, they raise many important questions, such as which factors should drive the vehicle optimization and decision-making protocols that will affect the energy these vehicles consume, and how to test and measure these vehicles. It will also be important to consider how autonomous vehicles will interact with non-autonomous vehicles, especially during early transition years.

2.2 New Mobility Options

The power of the smartphone is already changing how we use transportation, and has huge potential, especially in conjunction with autonomous vehicles. New app based mobility options can increase vehicle occupancy through ride-sharing, enable development of flexible transit systems that are responsive to demand, provide right-sized vehicles for specific trips, and enable a shift from private vehicle ownership to transportation as a service. They can also help promote the use of public transit by integrating personal and public transportation options. All of these opportunities can make personal mobility more available and affordable, and reduce energy use and emissions (Alonso-Mora et al. 2016; Martin and Shaheen 2011). The factors that influence how people harness these tools and their effect on transportation choices is an important area for further research.

2.3 The Urban Environment

Currently, our cars are parked about 96% of the time (Jonas et al. 2015), and cities reflect that with a plethora of parking spaces, lots, and garages. With a more efficient transportation system including autonomous vehicles and shared mobility, our cities could slash the amount of driving dedicated to finding parking and recapture infrastructure for recreational, residential, and commercial use without reducing personal mobility. Municipalities could focus on creating livable, walkable spaces designed for people instead of cars, reducing the need for transportation further. To shift today's car-centric focus to shared mobility, research into the barriers to, enablers of, and effects of such a transition on local economies, mobility, and the environment is strongly needed. We need to understand the lessons learned by cities already incorporating new mobility options, including pilot cities such as those participating in the Department of Transportation's Smart Cities Challenge, and begin to apply these lessons learned more broadly as soon as possible. Because of the long lifetime of infrastructure, we need to ensure that the infrastructure we put in place in the near future will enable this emerging transportation paradigm in an environmentally-protective, people-friendly way, rather than reinforcing outdated systems that require driving, encourage parking, and generate sprawl.

2.4 Fuels

Even with a more efficient transportation system based on efficient autonomous vehicles, ride-sharing options, and improved urban design, the fuels utilized by our transportation system could have a large environmental impact. This will particularly be true if, as some predict, vehicle miles travelled increase in the future. Fortunately, many experts feel that autonomous and electric vehicles are mutually reinforcing: the high level of electrification of autonomous control systems naturally extends to the powertrain, and, in return, shared mobility and automated recharging can make electric vehicles more attractive. Paired with low carbon electricity, electric autonomous vehicles could provide substantial GHG emissions savings. Yet, to realize this will require low carbon electricity options, an increased charging infrastructure with careful planning of charging station locations and types, convenient payment options and affordable pricing structures, and a better understanding of the range and recharging needs for both a shared-mobility and a private-ownership model.

3 The Path Forward

Transformational change in personal transportation seems imminent, driven by a convergence of demographic, technology, and economic factors. The CEO of one major domestic automaker recently stated, "The automotive industry will see more changes in the next five years than in the previous 50 years" (Mary Barra 2016). A second automaker CEO said "[t]he next 20 years will see a radical transformation of our industry" (Bill Ford 2014). It seems highly likely that we are indeed on the cusp of transformational change in the light-duty vehicle sector.

However, it is clear that we do not yet understand what that transformation will ultimately mean for the environment. There is currently very little focus on the potential environmental impact of autonomous vehicles. We need to continue existing research, encourage better data collection, examine experiments already happening in our cities, and coordinate discussions between technology and policy decision makers in the U.S. and abroad. We need to understand what key decision points will lead to positive, and to negative, environmental outcomes. As the technology develops, the time is now to identify and address environmental concerns and to encourage technology and policy options that enable better environmental outcomes.

Autonomous vehicles and other new transportation technologies present the opportunity to improve mobility and move towards a transportation system that is safer, cheaper, and has a lesser impact on the environment. These revolutions in transportation could allow us to fundamentally rethink how we move, how we design our cities and homes, to slash the approximately 8 billion h a year Americans spend stuck in traffic (McLean 2016), and reduce the 30 billion h Americans spend commuting each year (Ingraham 2016). They have the potential to improve lives, encourage sustainable economic growth, and significantly reduce emissions that contribute to climate change. We need to begin working towards these goals today.

Autonomous vehicles and other transformational technologies are already with us and beginning to disrupt all aspects of the transportation sector. Researchers, engineers, policy makers, and consumers will soon face many decisions that will eventually shape the future of transportation and its impacts on the environment. The authors strongly encourage further research and coordination to understand the impacts of the technologies themselves, and the external factors that will influence the ultimate environmental impact of autonomous vehicles and other transformational technologies. The results of this research must be incorporated into the design decision process as both the technology and related policies develop. Encouraging the inclusion of all relevant information on the environmental impacts of transformational transportation technologies is critical for the development of a robust market for transportation solutions that improves not only lives, but also the environment.

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Energy Impact of Connected Eco-driving on Electric Vehicles

Xuewei Qi, Matthew J. Barth, Guoyuan Wu, Kanok Boriboonsomsin and Peng Wang

Abstract Transportation-related energy consumption and air quality problems have continued to attract public attentions. A variety of emerging technologies have been proposed and/or developed to address these issues. In recent years, electric vehicles (EVs) are deemed to be very promising in reducing traffic related fuel consumption and pollutant emissions, due to the use of electric batteries as the only energy source. On the other hand, recent research shows that additional energy savings can be achieved with the aid of Eco-driving system in a connected vehicle environment (e.g., Eco-approach at signalized intersections). However, most of the existing eco-driving research is only focused on the internal combustion engine (ICE) vehicles thus far. There is still lack of convincing evidence (especially with real-world implementation) of how these connected eco-driving technologies impacts the energy efficiency of EVs. To fill this gap, this chapter provides a real-world example of quantifying the energy synergy of combining vehicle connectivity, vehicle automation and vehicle electrification, by designing, implementing and testing an eco-approach and departure (EAD) system for EVs with real-world driving data.

Keywords Electric vehicles · Eco-driving · Vehicle automation · Connected vehicle · Energy impact · Traffic signals

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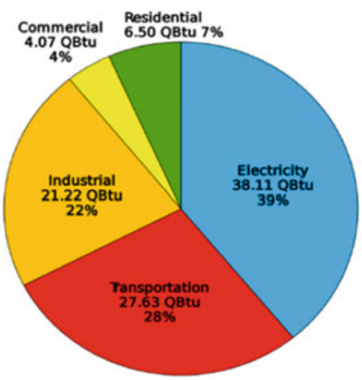
1 Introduction

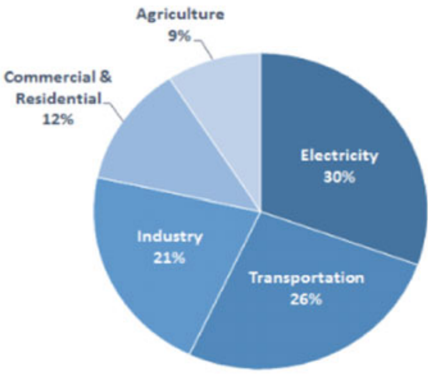
In recent years, a significant amount of transportation-related fossil fuel consumption and greenhouse gas emissions have created an increasing amount of public concern. Tailpipe emissions from vehicles are the single largest human-made source of carbon dioxide, nitrogen oxides, and methane in transportation related activities. Vehicles that are stationary, idling, and traveling in a stop-and-go pattern due to congestion in urban areas emit more pollutant emissions and greenhouse gases (GHGs) than those traveling in free-flow conditions. The resulted air quality degradation is very serious in some major cities of U.S. as well as other developing countries (e.g., China).

In addition to improving air quality, reducing transportation-related energy consumption and greenhouse gas (GHG) emissions has been a common goal of public agencies and research institutes for many years. In 2014, the total energy consumed by the transportation sector in the United States was as high as 23.70 Quadrillion BTU which is 28% share of the total energy (U.S. Energy Information Administration 2015) (see Figs. 1 and 2). The U.S. Environmental Protection Agency (EPA) reported that nearly 26% of GHG emissions resulted from fossil fuel combustion for transportation activities in 2014 (U.S. Environmental Protection Agency (EPA) 1990) (see Fig. 1a, b).

Altogether, the transportation-related impacts on air quality, climate change, and energy consumption have motivated researchers from different technical backgrounds to develop different ways to reduce vehicle emissions and energy consumption. In recent years, with the rapid development of vehicle related technologies, such as connected vehicle (CV) technology as well as automation technology, there is now a common vision for future vehicles that will be



a) Energy Consumption 2014 [1]



b) Total U.S. Greenhouse Gas Emissions 2014 [2]

Fig. 1 Total U.S. energy consumption and greenhouse gas emissions by economic sectors **a** Energy Consumption 2014 (U.S. Energy Information Administration 2015). **b** Total U.S. greenhouse gas emissions 2014 (U.S. Environmental Protection Agency (EPA) 1990)

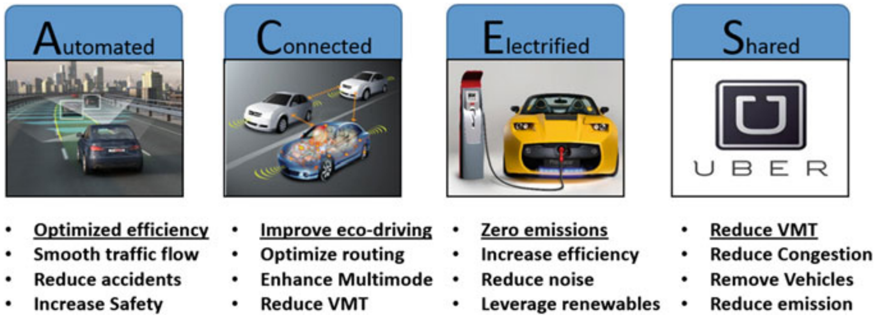


Fig. 2 Key features of future vehicles

automated, connected, electrified and shared. As can be seen in Fig. 2, for each of those features, multiple benefits can be identified (as listed in the figure) in terms of safety, mobility and environmental impact. However, reducing energy consumption and emissions are the only benefits that can be achieved in all four of these features. This is explained in more detail below:

1. **Automated**: Vehicle automation including automated vehicle dynamics control (i.e., adaptive cruise control (ACC)) and automated powertrain operations (i.e., power-split control for PHEVs), can be used to improve vehicle energy efficiency and reduce emissions. For example, eco-friendly adaptive cruise control (Eco-ACC) is designed to automatically control the vehicle speed profile when following a preceding vehicle smoothly to reduce unnecessary accelerations so that energy efficiency can be improved.
2. **Connected**: The recent development of Connected vehicle (CV) technology has brought a new revolution for the modern intelligent transportation system. In a CV environment, the V2V, V2I communications enables unlimited potential applications. For example, connected ecodriving technology is designed in a CV environment to encourage more energy efficient driving, such as reducing traffic congestion and unnecessary stop-and-go maneuvers at signalized intersections.
3. **Electrified**: In recent years, cleaner alternative energy sources are used to replace fossil fuels for vehicles, such as electricity from renewable resources (e.g., solar, wind) and hydrogen. With these alternative fuels, plug-in electric vehicles (PEVs) and fuel cell vehicles are designed. Transportation electrification is one of the more promising ways to reduce transportation related fossil fuel consumption and emissions; however, the massive adoption of PEVs is currently impeded by the limited charging infrastructure and the perceived limited driving range per charge (i.e., the so-called “range anxiety”) (Zhang and Yao 2015). There is still large room for improving PEV energy efficiency.
4. **Shared**: Vehicle Systems have emerged in the last two decades provide a variety of shared mobility options. Shared vehicle systems have had this tremendous growth due to advances in electronic and wireless technologies that

made sharing assets easier and more efficient. The main benefits of shared vehicle systems is to reduce vehicle miles travelled (VMT), thereby reducing vehicle energy consumption and tailpipe emissions.

As previously described, the adoption of electric-drive vehicles has the potential to play a significant role in addressing both energy and environmental impacts brought by on by today's transportation systems. Using electricity as a transportation fuel has a number of benefits. Electricity has a strong potential for GHG reduction, as long as it is generated from renewable sources such as solar and wind. Electric vehicles themselves have zero direct emissions, although generating the electricity to power the vehicle often results in indirect emissions at the power plants. If electricity is generated from the current U.S. average generation mix, EVs can reduce GHG emissions by about 33%, compared to today's ICE powered vehicles (US DOT 2010). If we assume 56% light-duty vehicle (LDV) penetration by 2050, this could provide a total reduction in transportation emissions of 26–30% (US DOT 2010). The huge potential benefits of EVs have already attracted significant interest and investment in EV technology. Since late 2010, more than 20 automakers have introduced BEVs or PHEVs. Within the United States, the government has allocated considerable stimulus funding to promote the use of alternative fuels (Skerlos and Winebrake 2010). The American Recovery and Reinvestment Act (ARRA) of 2009 provided over $2 billion for electric vehicle and battery technologies, geared toward achieving a goal of one million electric vehicles on U.S. roads by 2018 (Canis 2011). Many states also have committed themselves to promoting EVs. For example, California has taken a number of legislative and regulatory steps to promote electric vehicle deployment and adoption, such as the Zero Emission Vehicle and Low Carbon Fuel Standard regulatory programs and rebates for purchasing electric vehicles (Elkind 2012). With this momentum, it is not difficult to see that in the near future EVs may gain significant market penetration, particularly in densely populated urban areas with systemic air quality problems.

This chapter is aimed at investigating the synergy energy benefits of vehicle electrification, vehicle automaton and vehicle connectivity by designing, implementing and testing a connected ecodriving technology for EVs. Researchers have proposed several eco-driving systems that are capable of optimizing EV energy efficiency under different driving conditions. An eco-friendly optimal adaptive cruise control (ACC) was developed in (Flehmig et al. 2015). It calculates an energy optimal trajectory for an EV when following another slower vehicle in traffic. (Frank e al. 2013) designed an Android application to inform the driver about the energy efficiency by calculating and showing an eco-score based on a fuzzy system. A novel torque vectoring control system that can optimally distribute the torque by considering the efficiency characteristics of EVs was proposed in (Koehler et al. 2015) and 10% of energy efficiency improvement was identified. Despite the above efforts on eco-driving systems for EVs, only a few are focused on the eco-approach and departure (EAD) system which takes advantage of signal phase and timing (SPaT) information broadcast via infrastructure-to-vehicle

(I2V) communication. (Miyatake et al. 2011) applied a dynamic programming (DP)-based model to develop eco-driving systems for EVs along signalized arterials. The proposed model was tested in simulation with very limited signal phase conditions. In a recent study (Zhang and Yao 2015), the authors developed an EAD system for EVs based on their own EV energy consumption estimation model, where the validation was also conducted in a simulation environment under 4 scenarios with different signal phases. In this chapter, an EAD system for EVs was developed and evaluated in two different automation levels: manual driving with assistance via human-machine interface (HMI) and partially automated longitudinal control. Real-world driving data were collected for system evaluation, by comparing the energy and mobility performance to the baseline stage, i.e., manual driving without any assistance.

2 Connected Eco-driving for EV

2.1 Vehicular Movements at Isolated Intersections

Basically, there are 4 different *passing scenarios* for a vehicle to travel through an isolated signalized intersection. The velocity profiles of these 4 different scenarios are shown by the green, blue, red, and yellow lines in Fig. 3. It is also noted that all these trajectories have the same initial and final velocities, and same traveled distance (e.g., within the dedicated short range communication range). More specifically, these scenarios can be described as follows:

- Scenario 1 (cruise): the vehicle cruises through the intersection at a constant speed (green line)

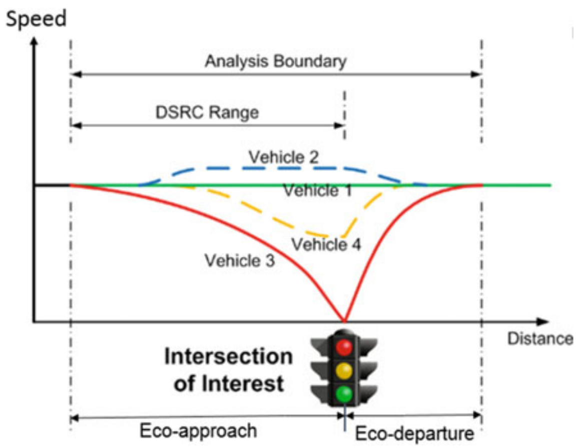


Fig. 3 Illustration of different vehicle trajectories traveling across an intersection

- Scenario 2 (speed-up): the vehicle speeds up to pass the intersection and then gets back to the initial speed after the intersection (blue line)
- Scenario 3 (coast-down with stop): the vehicle slows down and stops at the intersection (red line)
- Scenario 4 (coast-down without stop or glide): the vehicle slows down and passes the intersection at a mid-range speed, and then speeds up to its initial speed (yellow line)

For conventional gasoline vehicles, our previous research (Barth et al. 2011) has shown that, even though all these scenarios cover the same distance with the identical initial and final velocities, the associated fuel consumption and emissions may vary greatly. Vehicle 1 (or Scenario 1) uses the least fuel since it does not need to accelerate or make unnecessary deceleration. Vehicle 2 (or Scenario 2) consumes more fuel than vehicle 1 since there is a slight acceleration and deceleration before and after the intersection. Vehicle 3 (or Scenario 3) might use the most amount of fuel since it has to decelerate to a full stop, idle for a certain period, and then accelerate from a stop to a desired final speed. Finally, Vehicle 4’s (or Scenario 4’s) fuel consumption may be comparable to Vehicle 2’s since both vehicles have a slight speed up and slow down during their trips, although the acceleration occurs at a relatively lower speed.

Therefore, when a gasoline vehicle is traveling through a signalized intersection, its velocity profile could be optimized to achieve minimum fuel consumption for each of the 4 scenarios. Similarly, the velocity profile of an EV can also be optimized to achieve minimum energy consumption by taking into consideration of its distinctive characteristics (e.g., regenerative braking). This is the basic idea behind the vehicle trajectory planning algorithm described in the following.

2.2 *Optimal Vehicle Trajectory Planning*

In this study, a vehicle trajectory planning algorithm (VTPA) is designed for generating an optimal velocity profile based on real-time SPaT information. Among all the possible velocity profiles with which a vehicle can safely travel through an intersection, the VTPA can choose the velocity profile that has minimum tractive power requirements, in order to minimize energy consumption. The required tractive power of a vehicle depends on the instantaneous velocity and acceleration under the point mass assumption, as given by:

$$P_{tract.} = Av + Bv^2 + Cv^3 + M(0.447a + g\ \sin\theta)v * 0.4471000 \qquad (1)$$

where M is vehicle mass with appropriate inertial correction for rotating and reciprocating parts (kg); v is instantaneous speed (miles/hour or mph); a is acceleration (mph/s); g is gravitational acceleration (9.81 meters/second^2 or m/s^2); and θ is road grade angle in degree. Here, the coefficients A, B, and C are associated with rolling resistance, speed-correction to rolling resistance, and aerodynamic drag, respectively, which can be determined empirically.

As suggested in our previous work (U.S. Energy Information Administration 2015), there are numerous ways to accelerate or decelerate from one speed to another, such as constant acceleration and deceleration rates, linear acceleration and deceleration rates, and constant power rates. A family of piecewise trigonometric-linear functions is selected as the target velocity profiles (for both approach and departure portions), due to its mathematical tractability and smoothness. For more details of the algorithm, please refer to (U.S. Energy Information Administration 2015).

2.3 MPC-Based EAD System for Partially Automated Driving

In this study, the designed VTPA is integrated with a model predictive control (MPC) scheme to develop a partially automated EAD system for EVs (see Fig. 4). For each optimization time horizon of the proposed system, the control objective is to follow the pre-calculated optimal vehicle trajectory as close as possible. In addition, the receding horizon property of MPC allows the system to better handle unpredicted disturbances. The system diagram is provided in Fig. 4.

A nonlinear point mass model (longitudinal dynamics) (Kamal et al. 2013) is adopted in this work:

$$\dot{x} = v, \tag{2a}$$

$$\dot{v} = -\frac{1}{M} C_D \rho_a A_v v^2 - \mu g - g\theta + u_f, \tag{2b}$$

where x is position of the vehicle; v is velocity; M is mass; θ is road gradient ($\theta = 0$ in this work); g is acceleration of gravity (i.e., 9.8 $\mathrm{m/s^2}$); u_f is braking or traction force per unit mass (i.e., the acceleration/deceleration generated from vehicle propulsion); C_D is drag coefficient; ρ_a is air density; A_v is frontal area of the

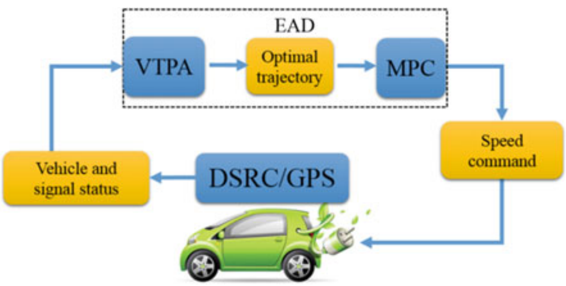


Fig. 4 The system diagram of MPC-based EAD for EVs

vehicle; and μ is rolling friction coefficient. The values of C_D, ρ_a, A_v, and μ can be found in (Kamal et al. 2013). When implementing MPC, Eq. (2a) needs to be discretized as follows:

$$x(t_0 + (k+1)\Delta t) = x(t_0 + k\Delta t) + v(t_0 + k\Delta t)\Delta t, \tag{3a}$$

$$\begin{aligned} v(t_0 + (k+1)\Delta t) = v(t_0 + k\Delta t) \\ + (-\frac{1}{M} C_D \rho_a A_v v(t_0 + k\Delta t)^2 \\ - \mu g - g\theta + u_f(t_0 + k\Delta t))\Delta t, \end{aligned} \tag{3b}$$

where t_0 is starting time, Δt is sampling period, and k is time step. For brevity, we denote $x(t_0 + k\Delta t)$ as $x(k)$, $v(t_0 + k\Delta t)$ as $v(k)$, and $u_f(t_0 + k\Delta t)$ as $u_f(k)$ in the remaining parts of this work.

As stated above, the MPC is designed to follow the optimal vehicle trajectory. Therefore, the objective function is defined as the sum of squared differences between the modeled and reference velocities. We also consider box constraints for the velocities, acceleration/deceleration and jerk values. In summary, the optimal control problem based on MPC can be formulated as:

$$\begin{aligned} \text{argmin}_{u_f} \quad & \sum_{k=t}^{t+l} [v(k) - v_r(k)]^2, \\ \text{subject to} \quad & \text{the discritized dynamics } (3), \\ & v_m \le v(k) \le v_M, \\ & |u_f(k)| \le u_M, \\ & |u_f(k+1) - u_f(k)| \le du_M, \end{aligned}$$

where t is current time; l is optimization horizon; $v(\cdot)$ is velocity computed by the MPC; $v_r(\cdot)$ is reference velocity; v_m is minimum allowable speed, which is set to 0 in this work; v_M is maximum allowable speed (usually the speed limit); u_M is maximum acceleration/deceleration constrained by the vehicle propulsion power; and du_M is the user-defined maximum jerk (mainly for driving comfort). We use 0.1 s as the time step and the control horizon of the MPC is set to 1 s, which means that there are 10 time steps to optimize for each control horizon. Note that as the dynamics in Eq. (3a) are nonlinear, the optimization problem at every time step of the MPC is non-convex.

3 Experimental Design and Data Collection

The field data for evaluation were collected at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia. The driving test was conducted from point "*A*" to point "*B*" with a length of 190 ft before the intersection and 126 ft

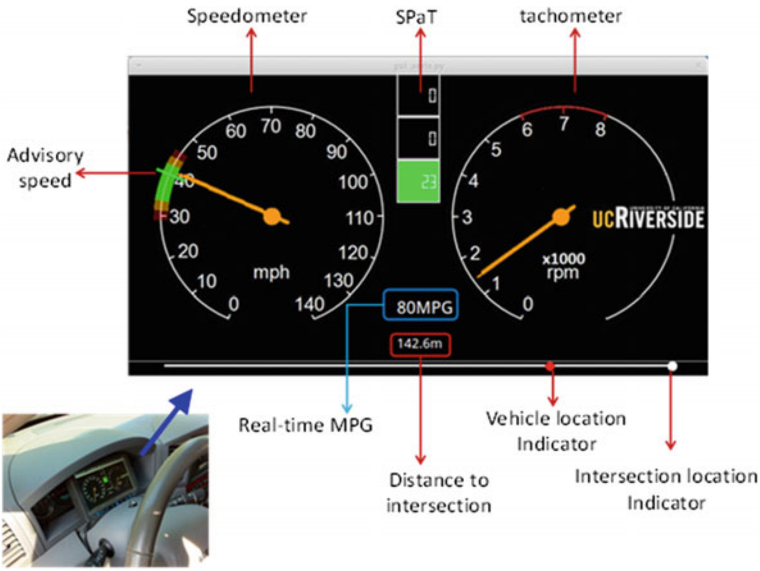


Fig. 5 Graphic interface for "manual-HMI-assisted" driving

after the intersection (see Fig. 5). In order to comprehensively investigate the energy and mobility benefits of the proposed system for EVs, we evaluated the system performance in 3 different stages as elaborated in the following:

- Stage I: "manual-uninformed" driving (MUD) as a baseline. In this stage, the driver approached and traveled through the intersection in a normal fashion without guidance or automation, stopping as needed without any guidance or automated vehicle control.
- Stage II: "manual-HMI-assisted" driving (HMI). In this stage, the driver was provided an enhanced dashboard which presented a recommended range of driving speed overlaid on a speedometer (see Fig. 5). This information can assist the driver to approach and depart the intersection in an environmentally friendly manner while obeying the traffic signal. The advisory speed profiles were generated using the VTPA described earlier.
- Stage III: "MPC-based (partially) automated" driving (MPC). No real-world testing has been conducted in this stage due to the limited resources. Instead, we evaluated the performance of the designed MPC-based longitudinal control system in a simulation environment developed in Matlab using data collected from the field testing. The optimal speed profile calculated by the VTPA was used as the reference input to the MPC model. The results from this simulation likely represent the upper bound of system performance.

To investigate different scenarios with respect to when a vehicle enters a signalized intersection, the field experiment was designed to have the test vehicle approach the intersection at different time instances throughout the entire signal cycle (i.e., every 5 s in the 60-s cycle). We call these different entering cases as "*entry case*" in the rest of this chapter. Furthermore, the test vehicle approached the intersection at different operating speeds (i.e., 20 and 25 mph). Therefore, a test matrix was designed, consisting of the operating speed along the vertical axis, and the *entry case* across the horizontal access. In this matrix, there are a total of 12 *entry cases* × 2 speed levels = 24 test cells. For the Stage I and Stage II experiments, a total of four drivers were recruited to conduct test runs. Each driver completed each of the test cells in the test matrix. Therefore, a total of 24 test cells × 2 stages × 4 drivers = 192 test runs were conducted. For each test run, data such as speed and distance to the stop bar were logged at 10 Hz and post-processed to determine energy consumption and other performance measures. It is noted that a hybrid vehicle (2012 Ford Escape) was used for the field study. The energy consumption was estimated by the EV energy consumption model (see Sect. 4) under the assumption that there would be no significant change in driving speed if an EV were used.

4 Energy and Mobility Benefits Analysis

4.1 EV Energy Consumption Estimation Model

A microscopic EV energy consumption estimation model developed in (Zhang and Yao 2015) was adopted to calculate the EV energy consumption based on the collected vehicle speed profiles. This model is designed for 4 different EV driving conditions: accelerating, decelerating, cruising and idling. The final model is presented as follows:

$$ECR = \begin{cases} e^{\left(\sum_{i=0}^{3}\sum_{j=0}^{3}(l_{i,j}\times v^{i}\times a^{j})\right)} & a > 0 \\ e^{\left(\sum_{i=0}^{3}\sum_{j=0}^{3}(m_{i,j}\times v^{i}\times a^{j})\right)} & a < 0 \\ e^{\left(\sum_{i=0}^{3}(n_{i}\times v^{i})\right)} & a = 0, v \neq 0 \\ \overline{const} & a = 0, v = 0 \end{cases} \tag{4}$$

where, ECR is energy consumption rate (Watt); $l_{i,j}, m_{i,j,}$ and n_i are coefficients for ECR at speed power index i (=0, 1, 2, 3) and acceleration power index j (=0, 1, 2, 3); v is instantaneous speed (km/h); a is instantaneous acceleration (m/s^2); $\overline{const}$ is the average energy consumption rate for idling. The coefficients in this model were obtained through curve fitting of real-world driving data and can be found in (Zhang and Yao 2015).

4.2 Energy and Mobility Benefits Analysis

Using the data collected in the field test, the designed EAD system for EVs were evaluated in terms of energy and motility benefits. The EV energy consumption model described above was applied to calculate the energy consumption associated with the collected vehicle trajectory data. Figure 6 indicates the change in *passing scenarios* due to the application of the EAD system for one of the drivers (Driver 1). For example, in *entry case* 4, Driver 1 passed the intersection with passing scenario 3 (which is the most energy intensive passing scenario) in both stages I and II, but he would have done so with passing scenario 2 in stage III if the proposed MPC-based longitudinal controller has been applied. It is observed that among the 12 *entry cases* of Driver 1, there are more scenario 3 in stage I than that in stage II or stage III due to the lack of recommended driving speed provided to the driver. In stage III, there would have been no passing scenario 3 with the aid of the MPC-based longitudinal controller.

Figure 7a, b show the energy savings and time savings of stage II ("HMI vs. MUD") and stage III ("MPC vs. MUD"), as compared to stage I, for Driver 1. Figure 6 shows clearly that most of the energy savings happen when the *passing scenarios* changes from scenario 3 to scenario 2 or scenario 4 (i.e., entry cases 3, 4, 5, 6, and 7 shown in Fig. 6). The biggest energy saving (45.3%) occurs in *entry case* 4 where the *passing scenario* changes from scenario 3 to scenario 2. The speed profiles for this entry case are given in Fig. 8a. As shown in the figure, when given the advisory speed profile through HMI, Driver 1 failed to follow it closely at the beginning, resulting in a switch from passing scenario 2 to 3, and therefore, trivial energy savings. For those *entry cases* where the three different stages are in the

Signal Phase	Entering Time(s)	Entry Case	MUD	HMI	MPC
Green	2	1	1	1	1
	7	2	2	2	2
	12	3	3	3	2
	17	4	3	3	2
	22	5	3	3	4
	27	6	3	3	4
Red	2	7	3	4	4
	7	8	4	4	4
	12	9	1	1	1
	17	10	1	1	1
	22	11	1	1	1
	27	12	1	1	1

Scenario 1 Scenario 2 Scenario 3 Scenario 4

Fig. 6 Changes in passing scenario in different stages (Driver 1)

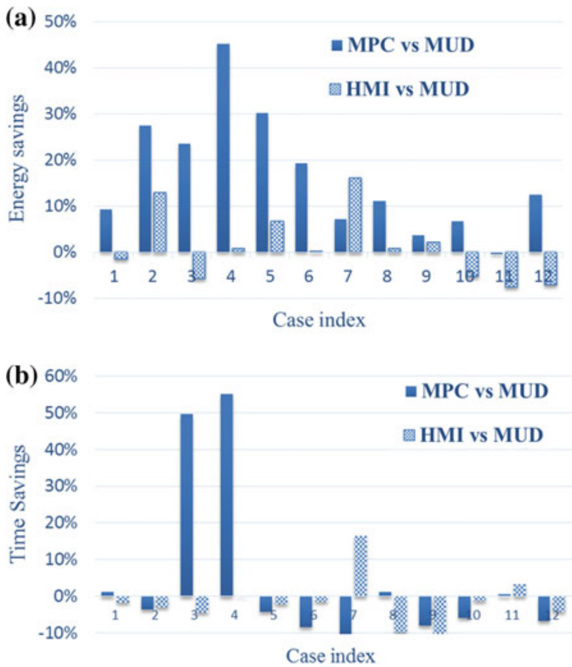


Fig. 7 **a** Energy and time savings for different entry cases (Driver 1)—Energy savings. **b** Energy and time savings for different entry cases (Driver 1)—Time savings

same *passing scenarios*, the energy savings are not as much and, for some entry cases of stage 2, turn negative because of variations in real-world driving.

From the mobility perspective, it is observed in Fig. 7b that most of the *entry cases* in stage II and stage III result in minimal time savings or even small time penalties except *entry case* 3 and *entry case* 4 of stage III where the passing scenario is 2. This can be well explained by Fig. 8b where the speed profile in stage I shows a more aggressive trend (i.e., exceeding the speed limit of 20 mph almost throughout) than either of the other two stages. Although stages II and III have longer travel times in this case, it is because of the uncharacteristic driving in stage 1 rather than the shortcoming of the EAD system.

To further analyze the energy benefits of the designed EAD system, a scenario change analysis was conducted using the driving data of all 4 drivers. The analysis covers all the scenario changes that happened in the field experiment. As shown in Table 1, most of the energy savings happen when the passing scenario changes from scenario 3 to scenario 2 or scenario 4 with the assistance of the EAD system. However, when the EAD system cannot change the passing scenario, there is not as much energy saving (on average) or even a negative saving (for scenario 3 between stage I and stage II) due to variations in real-world driving. This may suggest that the information disseminated by the HMI is not effective enough in assisting the manual driving and more comprehensive system design should be conducted to take into consideration the human factors aspect. One possible way to improve the

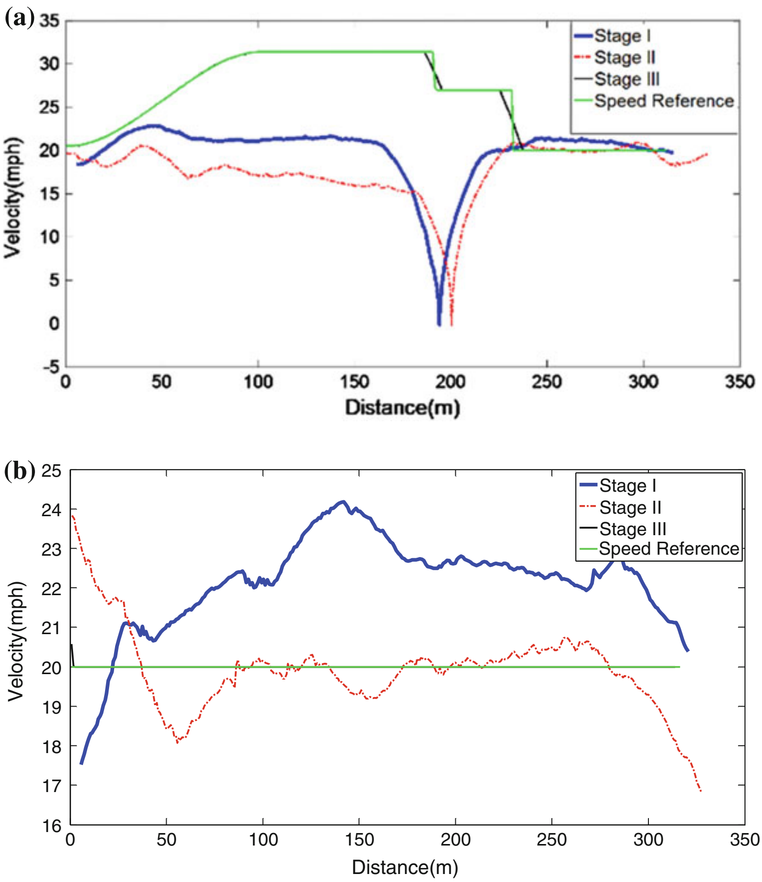


Fig. 8 **a** Speed versus distance for entry case 4 (Driver 1). **b** Speed versus distance for entry case 9 (Driver 1)

existing system is to disable the display of advisory speed when the system predicts that there will be no change in the passing scenario.

Finally, the average energy and time savings across all *entry case*s and all drivers were calculated and thus are provided in Table 2. It shows that the MPC based EAD system can achieve an average of 21.9% electricity savings along with an average of 10.7% time savings (mostly contributed by *entry case* 3 and *entry case* 4), while the driving assistance system with HMI achieves 12.1% energy savings on average but with compromise of travel time (increase of 3.2%).

Table 1 Scenario-change analysis

Stage	Scenario change	Energy savings		
		Min (%)	Mean (%)	Max (%)
I versus III	3 → 2	13.9	25.7	45.3
I versus III	3 → 4	10.3	19.1	27.0
I versus III	1 → 1	−16.0	7.3	11.3
I versus III	2 → 2	−15.5	5.9	10.9
I versus II	3 → 2	2.2	9.5	18.3
I versus II	3 → 4	1.2	3.8	13.9
I versus II	1 → 1	−6.7	1.1	6.3
I versus II	2 → 2	−15.1	0.9	5.1
I versus II	3 → 3	−10.3	−3.1	7.3

Table 2 Average energy and mobility improvement

Stage	Energy benefit (energy savings)			Mobility benefit (time savings)		
	Min (%)	Mean (%)	Max (%)	Min (%)	Mean (%)	Max (%)
II	−14.3	12.1	27	−13	−3.2	17.6
III	3.7	21.9	45.3	−28.1	10.7	55.1

5 Conclusion

Due to the lack of evidence of how vehicle automation, vehicle connectivity could influence the energy efficiency of EVs, this chapter provides numerical evidence of the energy synergy of combining vehicle connectivity, vehicle automation and vehicle electrification, by designing, implementing and testing an eco-approach and departure (EAD) system for EVs with real-world driving data. In this chapter, connected eco-driving system for EVs is developed and then evaluated in two different stages: driving assistance via HMI and partially automated driving. The analyses show that an average of 12 and 22% energy savings can be achieved in these two stages, respectively, compared to the baseline stage (i.e., manual driving without any assistance). To the best of our knowledge, this is the first research that reports the energy benefits of connected eco-driving system for EVs with real-world driving data at different automation levels. Potential topics for future research include improving the system performance by considering the human factors aspect in the design of the HMI and conducting real-world experiments with actual EVs under a variety of scenarios.

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A First-Order Estimate of Automated Mobility District Fuel Consumption and GHG Emission Impacts

Yuche Chen, Stanley Young, Xuewei Qi and Jeffrey Gonder

Abstract A first of its kind, this study develops a framework to quantify the fuel consumption and greenhouse gas emission impacts of an Automated Small Vehicle Transit system on a campus area. The results show that the automated mobility district system has the potential to reduce transportation system fuel consumption and greenhouse gas emissions, but the benefits are largely dependent on the operation and ridership of the personal rapid transit system. Our study calls for more research to understand the energy and environmental benefits of such a system.

Keywords Automated mobility district · Energy and emissions inventory · Benefits analysis

1 Introduction

"Automated mobility district" (AMD) is introduced as a term to describe a campus-size implementation of automated/connected vehicle technology to realize the benefits of a fully automated vehicle mobility service. An AMD is closely related to the past concepts of personal rapid transit (PRT) and group rapid transit (GRT) studied and implemented in the 1970s, with the primary difference being that

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PRT and GRT are captive to a guideway as opposed to operating on the existing roadway infrastructure (Yong et al. 2003; He et al. 2005; Advanced Transit Association 1988; Anderson 1994; Chen et al. 2017; Chen and Borken-Kleefeld 2016; Hu and Chen 2016; Chen and Meier 2016; Zhang et al. 2016). In the past decade, the term "automated transit network" (ATN) was coined and refers to largely the same concept, including both PRT and GRT, but broader in technical scope to reflect a wider array of automation technology that may allow the system to use existing infrastructure (vs. a completely dedicated guideway) (Anderson 1999, 1998; Borken-Kleefeld and Chen 2015; Chen and Fan 2014; Chen and Borken-Kleefeld 2014, 2013; Morrison and Chen 2011). An ATN remains primarily the same service concept as PRT, GRT, and the envisioned AMD with automated vehicles. All are characterized by driverless, on-demand transit that provides direct origin-to-destination service to either individuals or small groups. Although an AMD can be realized (and has been implemented) with PRT, GRT, and ATN systems on dedicated guideways, current automated vehicle-based reasoning envisions a system of automated taxis controlled and dispatched within a limited geographic area and using the existing roadway infrastructure.

A typical AMD system may have the following basic features:

1. **Fully Automated and Driverless Vehicles**. A National Highway Traffic Safety Administration level 4 or SAE International level 5 vehicle capable of all safety-critical driving functions, able to monitor roadway conditions, and pilot a vehicle for an entire trip. Such a design anticipates that the driver will provide destination input, but is not expected to be available for control at any time during the trip.
2. **Service is Confined to a Geographic Boundary That Encompasses a Relatively Dense Area of Trip Attractions, such as a Campus Area**. This may be a medical, academic, business park, or other type of campus. Such areas are typified by jobs, attractions, or other activities that draw people on a daily basis. Although residential land use is not prohibited, it is not the dominant land use within such a district. The geographic extent is limited, typically to **4–10 square miles**.
3. **Mobility within the District is Restricted to or Dominated by the AMD**. Within the district, access to end destinations is provided by automated vehicle service. Personal vehicles may or may not be prohibited, but at a minimum, the area is designed to be most efficiently accessed by the AMD, though other forms may be permitted.
4. **Multi-Modal Access to the Perimeter of the Area**. The perimeter (cordon line or membrane) of the AMD provides efficient opportunities for modal interface to the AMD through bus, light-rail, or other modes.

Challenges to providing efficient mobility to such campuses include:

1. **Amount and Proximity of Parking**: Many campuses are primarily accessed by private automobile even when other transit options are present. The quantity,

quality, and proximity of parking become policy issues, not only for mobility, but for policies that touch on benefits and compensation (e.g., reserved and named parking). The search for parking frequently contributes to vehicle miles traveled (VMT) within the campus and in vehicle-pedestrian congestion.

2. **Effective Intra-campus Circulation**: The geographic expanse of campuses of this size make walking impractical for most intra-campus circulation, since the majority of such trips will be greater than ¼ mile, a frequently used maximum boundary for pedestrian activity. Although many campuses have shuttles, their frequency and quality often prompt users to use personal vehicles to relocate within the campus if possible.
3. **Pedestrian/Vehicle Conflict and Congestion**: Academic campuses may limit or fully prohibit vehicle circulation interior to the campus boundaries to maintain an attractive pedestrian environment. As campuses grow, demands of efficient exterior access via automobile conflicts with intra-campus pedestrian movement, creating less than desirable conflicts for both modes and introducing safety concerns, primarily for pedestrians and cyclists.
4. **Efficient Access by Transit and Service Vehicles**: Medical, academic, recreational, and other campuses typically encourage and some require their clientele to access campus facilities using non-personal vehicle methods. Public buses, private shuttles, line-haul systems (rail and light-rail), ambulances, ride-hailing services (Uber/Lyft), etc., all provide options, but without an efficient intra-campus mobility system, such systems fail to provide full and efficient service to patrons for all campus destinations and for intra-campus trips.

An AMD system is conceived to address many of the issues above. Given the promise of an AMD system, to the best of the authors' knowledge, none of the existing literature addresses the fuel consumption and environmental impacts of such a system. As the first of its kind, this study developed a framework to quantify the fuel consumption and greenhouse gas (GHG) emission impacts of an automated small vehicle transit system on a campus area. The framework establishes a fuel consumption and GHG emission inventory, which takes into consideration the average vehicle fleet composite fuel consumption and GHG emissions of vehicles in specific speed bins and passenger vehicle and small transit vehicle average occupancy. The results show that such a system has the potential to reduce total transportation system fuel consumption and GHG emissions, but the benefits largely depend on the operation and ridership of the system. Our study also calls for future research to understand fuel consumption and GHG emission benefits of an AMD system.

The rest of the paper is structured as following. In Sect. 2, we introduce the background information for the case study. Section 3 describes the methodology, and Sect. 4 discusses the results of the case study. Section 5 presents the conclusions.

Fig. 1 Street map of Manhattan and map of KSU main campus (Yong et al. 2003)

2 Background

The city of Manhattan, Kansas, was selected as the study area for this project. The main campus of Kansas State University (KSU) and the surrounding community were selected as the impact area. The broad area beyond the Manhattan city limits and the KSU main campus was treated as an external area. The city of Manhattan is located in the heart of northeast Kansas' scenic Flint Hills. First settled in 1855, it is home to KSU. The Manhattan community encompasses approximately 11 square miles and has an estimated population of 44,800 as of 2001. The city's population for the year 2010 is projected to be 56,539. Maps of Manhattan and of the KSU campus are shown in Fig. 1.

KSU is a comprehensive research and land-grant institution, of which the main campus is located in Manhattan. The KSU main campus has a land area of 664 acres. The total student population enrolled (on campus only) in Fall 2001 was 21,929. The total faculty/staff number (full-time employees only) in Fall 2001 was approximately 2200. The KSU population, including students, faculty, and staff, amounts to approximately 50% of the population of Manhattan.

The definition of a PRT system has been debated over the past 30 years. Taxi 2000 Corporation, one of the major PRT developers in the United States since the 1990s, defines PRT as: "a personal rapid transit system of computer-controlled, three-passenger vehicles on slim guideways operating on-demand and nonstop direct to any station in the network" (Anderson 1994). An example of a PRT system is shown in Fig. 2. Anderson (1999) and other PRT experts contend that PRT systems are the only transit systems that offer many of the advantages of the automobile, and therefore are the only transit systems that are able to compete with automobile transportation. They predicted that, if appropriately designed and constructed, PRT systems would attract a considerable number of people who would ride it rather than using their own automobiles (He et al. 2005).

Fig. 2 PRT station design (He et al. 2005)

3 Methodology

In a Young et al. study, mobility benefits of installing PRT system on the campus site were analyzed with results shown in Table 1 (Yong et al. 2003). The table shows person miles (i.e., personal miles traveled [PMT]) per day and person hours (i.e., personal hours traveled [PHT]) per day for different travel modes and under various PRT operational modes. Specifically, "6 min," "3 min," and "2 min" refer to PRT systems operating at frequencies of 6, 3, and 2 min, respectively. Usually, more frequent PRT service makes it more attractive as a travel mode compared with other modes, which is confirmed by the observations in Table 1. As a continuation of the previous study, we establish a framework to model and estimate the fuel consumption impacts of a PRT system. The framework takes the PMT of passenger vehicles and PRT as input and uses average vehicle occupancy to convert PMT to VMT. For passenger vehicles' VMT (i.e., VMT driving on the road network), we disaggregate into VMT by different vehicle model year and type because those are important factors influencing fuel consumption on VMT. In addition, fuel economy data for each vehicle's model year, vehicle type, and average speed bin are prepared. Average vehicle speeds under each PRT operating scenario are captured

Table 1 Base level results for 't' PRT network

Person miles per day	No PRT	6 min	3 min	2 min
Driving on road network	40,131	38,352	36,621	35,807
Walking on sidewalks	20,216	18,814	16,770	15,681
Riding the PRT	0	3604	8169	10,279
Total	60,347	60,770	61,560	61,767
Person hours per day	**No PRT**	**6 min**	**3 min**	**2 min**
Driving on road network	2014	1927	1842	1805
Walking on sidewalks	5037	4688	4186	3923
In the parking lot	1877	1686	1532	1497
Riding the PRT	0	458	843	1035
Total	8928	8759	8403	8260

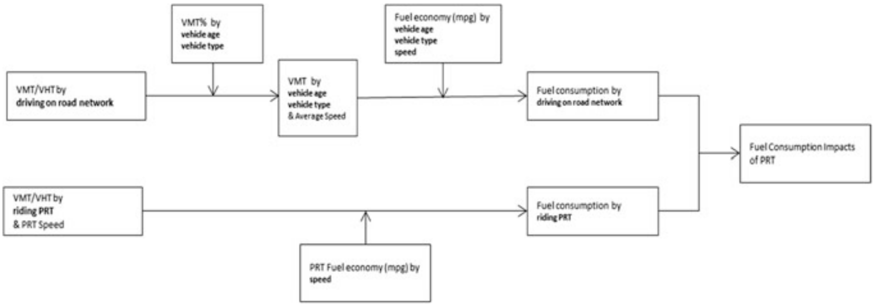

Fig. 3 Flow chart of the fuel consumption/GHG emission quantification framework

through dividing PMT by PHT. A fuel economy value for each vehicle type at the captured speed will be identified and applied to the corresponding VMT to calculate the total fuel consumption.

PRT fuel consumption is calculated based on the VMT as well as the PRT vehicle's fuel economy, assuming travel at 30 miles per h. The default speed for the system is 30 miles per h (Yong et al. 2003). We will estimate the fuel consumptions of various PRT vehicles assuming they are gasoline, hybrid electric, plug-in hybrid electric, and battery electric vehicles. Finally, the fuel consumptions of the vehicles driving on the road network and the PRT vehicles are summed together to quantify the fuel consumption impacts of a PRT system on the AMD (Fig. 3).

To support the implementation of the framework, some input data are needed.

- **Average Occupancy**: Average occupancy numbers for passenger vehicles and PRT are needed. The average occupancy for a passenger vehicle is assumed to be 1.13 persons per vehicle, which is based on 2009 National Household Travel Survey data (Santos et al. 2011). For PRT vehicles, there are usually two to four people per vehicle. In this study, we analyze the fuel consumption impacts under different PRT occupancy scenarios.
- **VMT Distribution/Fuel Economy**: To obtain the VMT distribution by vehicle age and vehicle type, as well as fuel economy data by speed, vehicle age and vehicle type, we used a set of fleet average fuel economy data that are based on a real-world fuel economy study conducted by University of California, Riverside (Barth and Boriboonsomsin 2008). Both the fuel economy study and PRT mobility study were conducted around 2005; therefore, the fuel economy data are perfectly suitable to be applied for the fuel consumption analysis. Although the fuel economy data were based on an average vehicle fleet in southern California, which is different from the location of this mobility study, we argue that it is still valid to study the fuel consumption impacts as long as the before and after fuel economy data remain the same. The University of California, Riverside study estimated speed-dependent fuel economy for an average vehicle at real-world driving and steady-state driving conditions. The fuel economy data for real-world driving are applied to VMT from vehicles driving on the road

network to estimate the fuel consumption, and fuel economy under steady-state driving conditions is applied to a PRT system vehicle.

- **Fuel Economy Benefits of Steady-State Driving**: For an average speed of 30 miles per h, the steady-state fuel economy is 36.0 miles per gal. versus real-world driving fuel economy of 25.9 miles per gal. for an average vehicle, according to the University of California study (Barth and Boriboonsomsin 2008). This equals a 40% increase in fuel economy for vehicles driving under steady-state conditions, e.g., a PRT vehicle. The GHG emissions benefit for steady-state driving at 30 miles per h is 30%.
- **PRT Vehicle Fuel Type**: We assumed the PRT vehicles use a gasoline combustion engine. Although a PRT vehicle can also be a hybrid electric vehicle or electric vehicle, we believe the fuel consumption benefits we find in this study can be seen as the upper bound of the benefits.

4 Results

We present the total system fuel consumption and GHG emissions under each PRT system operation as well as PRT average occupancy scenarios in Fig. 4. The blue bar represents fuel consumption of regular passenger vehicles. Shorter PRT boarding delay times generally lead to more people shifting from driving directly to campus to driving to a PRT station and taking a PRT vehicle to campus. But from the mobility analysis results, we observe that when the PRT boarding delay time drops from 6 to 3 min, it actually slightly increases PMT for regular vehicles (<1%), and significantly promotes PMT generated by PRT vehicles (>120%). When looking at total system fuel consumption, PRT vehicles operating at a 6-min boarding delay time have the lowest fuel consumption for the whole system. The dilemma is that making PRT too convenient and fast will actually induce travel demand and lead to higher PMT and VMT as well as higher fuel consumption. Similar patterns can also be observed for GHG emissions.

The fuel economy benefit of PRT gasoline vehicles is assumed to be 40, and 30% for GHG emissions, based on one study done in southern California. Recent studies have shown a higher potential for automated vehicles such as PRT vehicles in improving fuel economy and reducing GHG emissions, with estimates as high as a 90% improvement in fuel economy. We conducted a sensitivity study trying to understand how different improvements in fuel economy and reductions in GHG emissions for a PRT vehicle compared with a regular vehicle mean to the system's total energy. Figure 5 shows the relationship between PRT fuel economy and GHG emission reduction benefits versus total system fuel consumption and GHG emissions. One observation is that the total system fuel consumption and GHG emissions are reduced as the PRT vehicle's benefits increase. However, the marginal reduction in total system fuel consumption by increasing the PRT vehicle's fuel economy is higher for PRT vehicles operating at 2- or 3-min delay times versus a 6-min delay. The same observation is also true for GHG emission reduction.

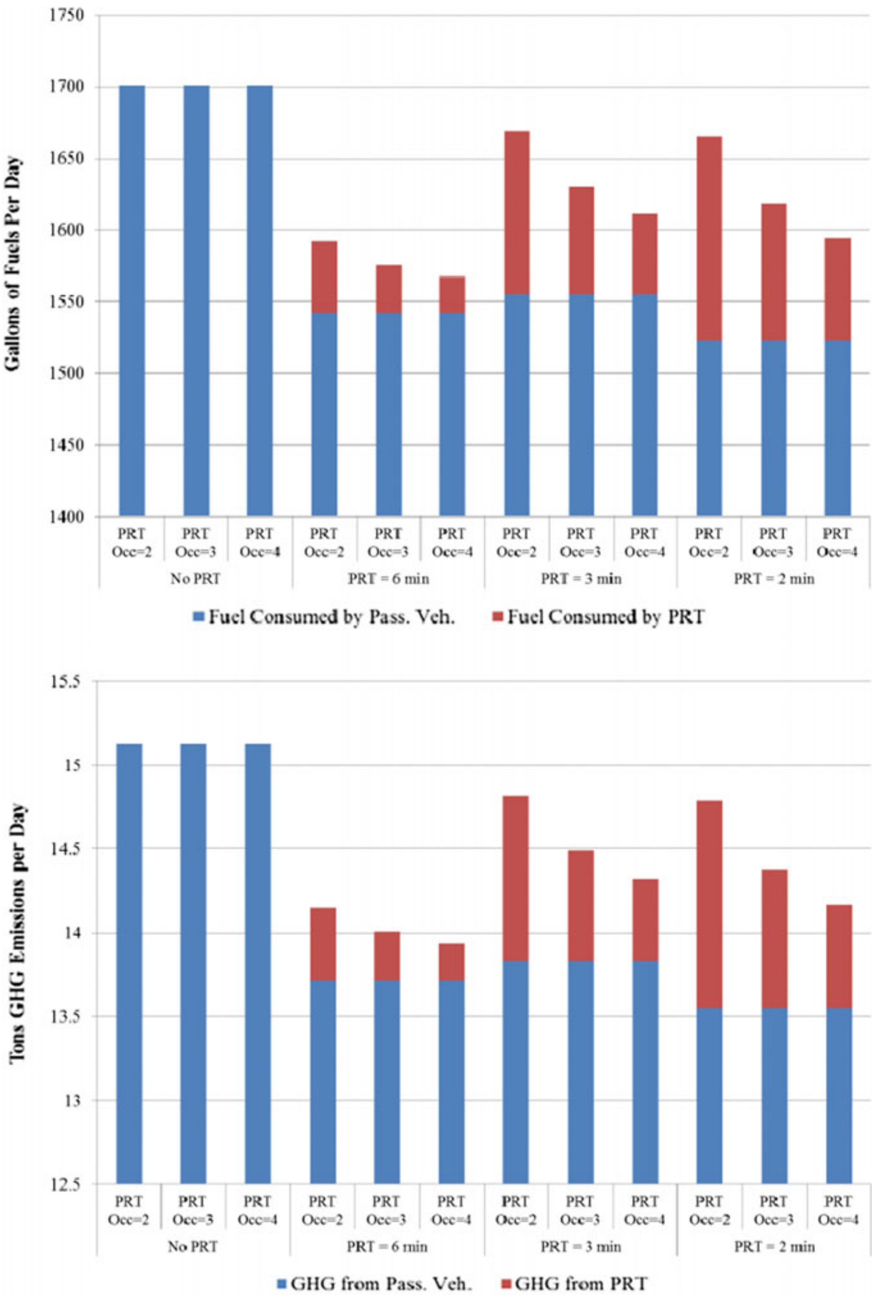

Fig. 4 Total system fuel consumption (*upper*) and GHG emissions (*lower*) under PRT operation and occupancy scenarios

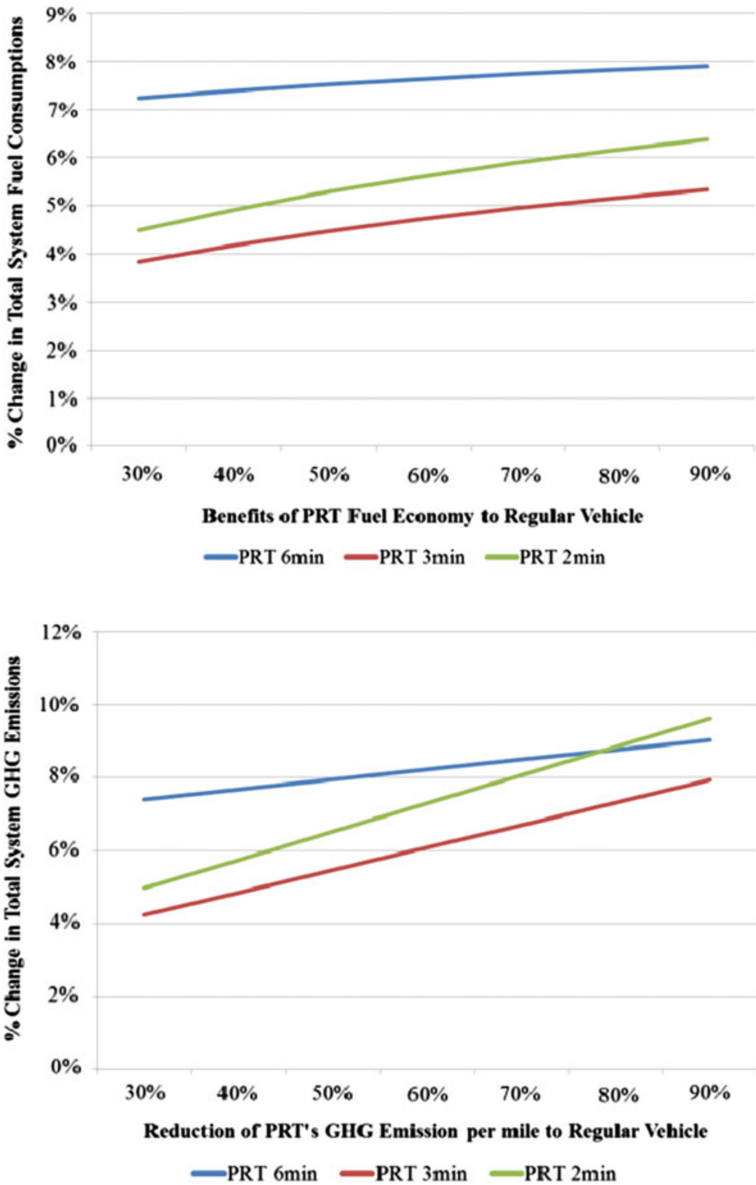

Fig. 5 Reduction in total system fuel consumption (*upper*) and GHG emissions (*lower*) under different PRT operating and fuel consumption/GHG emission benefits scenarios

5 Conclusion

Due to more new technologies available in personal mobility, how people travel and satisfy their travel demand might be significantly changed. In the meanwhile, the new technologies have potential to influence the fuel consumption and GHG emissions generated from people's travel. We propose a framework to quantify the fuel consumptions and GHG emissions of adopting a PRT system at a university campus. The PRT system is intended to replace some travel in the central area of the campus, which is usually highly congested. Our results show that the PRT system has the potential to reduce system fuel consumption due to fewer people driving vehicles to the central campus area, thus lessening fuel consumption, as well as higher fuel economy, which can be achieved by the PRT vehicles. However, the results are sensitive to the average occupancy of the PRT vehicles, as well as how much reduction in fuel consumption and GHG emissions the PRT vehicles could achieve. Future research could include:

1. Assume different fuel types of PRT vehicles and quantify the associated impacts to the total system fuel consumption and GHG emissions.
2. Expand the mobility and energy model framework to other similar AMDs and conduct region-specific analyses.

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Shared Automated Mobility: Early Exploration and Potential Impacts

Adam Stocker and Susan Shaheen

Abstract Automated vehicles, if shared, have the potential to blur the lines between public and private transportation services. This chapter reviews possible future shared automated vehicle (SAV) business models and their potential impacts on travel behavior. By examining the impacts of non-automated shared mobility services like carsharing and ridesourcing, we foster a better understanding of how current shared mobility services affect user behavior. This serves as a starting point to explore the potential impact of SAV services. Several key studies covering the topic are discussed. Although the future of SAVs is uncertain, this chapter begins the dialogue around SAV business models that may develop, which are informed by current shared mobility services.

Keywords Automated vehicles (AV) · Shared AVs · Business models · Social and environmental impacts

1 Introduction

Automated vehicles (AVs), broadly defined, are vehicles used to move passengers or freight with some level of automation (see Table 1) that aims to assist or replace human control. Many AV systems are already in operation today, but this is primarily for use in controlled, fixed-guideway systems like trains or airport people movers. AVs are currently being developed for use on public roadways, and many major automobile manufacturers and technology companies are racing to bring this technology to market. More advanced AV technology development began in 1977 in Japan (Forrest and Konca 2007), and it has subsequently included Germany,

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Table 1 SAE vehicle automation level definitions

Automation level	Description
Level 0	No automation
Level 1	Automation of one primary control function, e.g., adaptive cruise control, self-parking, lane-keep assist or autonomous braking
Level 2	Automation of two or more primary control functions "designed to work in unison to relieve the driver of control of those functions"
Level 3	Limited self-driving; driver may "cede full control of all safety critical functions under certain traffic or environmental conditions," but it is "expected to be available for occasional control" with adequate warning
Level 4	Full self-driving without human controls within a well-defined Operational Design Domain, with operations capability even if a human driver does not respond appropriately to a request to intervene
Level 5	Full self-driving without human controls in all driving environments that can be managed by a human driver

Italy, the European Union and the U.S. (Forrest and Konca 2007; Broggi et al. 1999; Dickmanns 2007; EUREKA Network 2013). From 2004 to 2007, the U.S. Defense Advanced Research Projects Agency sponsored the Grand Challenge AV races with large prizes (DARPA 2007). As of August 2016, over 30 companies around the world were developing AV technology (CB Insights 2016), including most major auto manufacturers and many technology companies. Most auto manufacturers, which have announced plans for AVs, already offer or plan to release vehicles with some automated features by 2017. Eleven companies are claiming to have a highly automated (Level 4 or higher) technology ready by 2020, with some declaring the vehicles will be on public roads at that time (Business Insider 2016). Researchers disagree on when AVs will become generally available, however. IHS Automotive (2014) projects Level 3 functionality by 2020, Level 4 by 2025 and Level 5 by 2030, with AVs reaching 9% of sales in 2035 and 90% of the vehicle fleet by 2055. Navigant Consulting (Navigant Research 2013) was even more optimistic, expecting 75% of light-duty vehicle sales to be automated by 2035, whereas the Insurance Information Institute (2014) claims that all cars may be automated by 2030. Predictions vary among experts, and executives at Audi believe fully automated vehicles are still 20–30 years away. Similarly, executives at Bosch believe full automation is beyond the 2025 time frame (Bankrate 2016).

Many believe that the proliferation of AVs could have an impact on the underlying urban fabric of cities. People around the world are increasingly living in urban areas. The United Nations estimates that 54% of the world's population resided in urban areas in 2014, and that proportion will increase to 66% by 2050 (United Nations 2014). This trend of increasing urbanization is putting tension on already congested urban roadways. Data from INRIX showed that 8 billion hours were wasted in 2015 in the U.S. alone due to traffic congestion (Inrix Technology, Inc 2015). As widely understood, there are major safety consequences of motorized vehicles that could be mitigated due to automation. The National Highway Traffic Safety Administration (NHTSA) (2008) found that 93% of crashes between 2005 and 2007 were human caused, while the New York Department of Motor Vehicles (2012) found a lower human attribution rate (78%). Motor vehicle deaths in the U.S. increased 8% between 2014 and 2015 with increases continuing into the first half of 2016, even when accounting for a change in vehicle miles traveled (National Safety Council 2016). If AVs could eliminate all human causes of crashes, accident rates could fall by as much as 80–90%, and motor-vehicle deaths could be greatly reduced.

1.1 Shared Mobility and Vehicle Automation

Shared mobility is the shared use of a vehicle, bicycle, or other low-speed mode that enables users to have short-term access to transportation modes on an "as-needed" basis (Shaheen et al. 2015). Shared mobility includes services like carsharing, bikesharing, scooter sharing, on-demand ride services, ridesharing, microtransit, and courier network services. Shared mobility services have been growing rapidly around the world. There were over 4.8 million carsharing members worldwide and over 100,000 vehicles as of 2014, a 65 and 55% increase, respectively, from two years prior (Shaheen et al. 2016). Ridesourcing services, like Lyft and Uber, are growing at a rapid pace as well. As of June 2016, Uber claimed more than 50 million riders worldwide had taken more than 2 billion rides total since its founding in 2009 (UBER Newsroom 2016a).

The advancement of AV technology and the growth of shared mobility services may provide important alternatives to conventional transportation and have the potential to alter the way in which people move around cities. A convergence of these two innovations is beginning to develop, with various small-scale shared automated vehicle (SAV) pilots emerging around the world. Many auto companies are partnering with, investing in, or acquiring mobility and mobility-related technology companies. These partnerships and business models are discussed at length later in this paper. There has been much speculation regarding the effects of shared automated mobility on traveler behavior, urban form, congestion, and the environment. While the impacts of such a system are unknown since no large-scale public SAV service exists today, there are many academic studies that explore potential SAV scenarios, the findings of which are presented in this chapter.

In this chapter, we review possible future shared automated vehicle (SAV) business models and their potential impacts on travel behavior and other transportation modes. This chapter includes four key sections: an overview of existing shared mobility business models and their impacts on travel behavior, current SAV developments and pilot programs, potential future SAV business models, and a summary of the current SAV impact literature and understanding.

2 Current State of Shared Mobility

To understand the possible business models and impacts that SAVs may have in the future, it is important to begin with a discussion of current models and the impacts of shared mobility systems. In the following section, we outline different business models in which shared mobility providers operate, and we define the shared modes encompassed under each business model. The three business models highlighted include: (1) Business-to-Consumer Service Models, (2) Peer-to-Peer Service Models, and (3) For-Hire Service Models. We conclude this section with a discussion of the modal impacts of shared mobility. Table 2 shows the many different shared mobility services grouped by business model. Select services are discussed further in this section.

2.1 Business-to-Consumer (B2C) Service Models

In Business-to-Consumer (B2C) service models, vendors typically own/lease and maintain a fleet of vehicles and allow users to access these vehicles via membership and/or usage fees (Shaheen et al. 2016). One example of a B2C shared mobility service model is carsharing. Carsharing offers consumers the benefits of a private vehicle ownership, while relieving them of the purchase and maintenance costs. Users can access vehicles owned by carsharing companies as part of a shared fleet on an as-needed basis. Members typically pay an initial or yearly membership fee and usage fees by the mile, hour, or a combination of both. B2C carsharing service models include roundtrip and one-way carsharing. In roundtrip carsharing, the vehicle must be returned to the original location, while in one-way carsharing the car typically can be parked anywhere within a designated service area, allowing point-to-point trip making. The roundtrip business model generally relies on both membership fees and fees per mile and hour driven. One-way (or point-to-point) carsharing is a relatively recent form of carsharing, emerging more prominently in 2012 (Shaheen and Cohen 2012). By January 2015, almost 36% of North American fleets were one-way capable, with about 31% of carsharing members having access to these one-way vehicles (Shaheen and Cohen 2015).

Table 2 Shared mobility business and service models

Business-to-consumer (B2C)	Peer-to-peer service models (P2P)	For-hire service models
• Carsharing • Bikesharing • Scooter sharing • Microtransit	• P2P carsharing • Hybrid P2P-traditional carsharing • Fractional ownership • P2P marketplace • Ridesharing	• Ridesourcing/TNCs • Taxis/E-hail • Courier network services (CNS)

2.2 Peer-to-Peer (P2P) Service Models

In P2P service models, companies supervise transactions among individual owners and renters by providing the necessary platform and resources needed for the exchange. P2P service models differ from B2C models since the company typically does not own any of the assets being shared under a P2P model. There are carsharing operators that use a P2P model, including Getaround and Turo (formerly RelayRides). Insurance during the rental is typically covered by the P2P carsharing organization. The operator generally keeps a portion of the rental amount in return for facilitating the transaction and providing third-party insurance. P2P carsharing companies are gaining momentum in North America, and there were eight active companies as of May 2015.

2.3 For-Hire Service Models

For-hire services involve a customer or passenger hiring a driver on an as-needed basis for transportation services. For-hire vehicle services can be pre-arranged by reservation or booked on-demand through street-hail, phone dispatch, or e-Hail via a smartphone or other Internet-enabled device. One shared mobility option that employs a for-hire service model are ridesourcing companies or TNCs (Transportation Network Companies). Ridesourcing services provide both pre-arranged and on-demand transportation services for compensation by connecting drivers of personal vehicles with passengers. Rides are typically booked via smartphone, and mobile applications are used for booking, payment, and driver/passenger ratings. Ridesourcing services first launched in San Francisco, CA in Summer 2012 (Lyft and Sidecar) and have expanded rapidly around the world with other major international players emerging including: Grab (Southeast Asia), Ola (India), and Didi (China).

2.4 Impact on Other Transportation Modes

Innovative transportation services introduced into an ecosystem of existing travel options will have impacts on the subsequent travel behavior of users. There is an existing body of research literature that has examined the impacts of different forms of shared mobility on user travel behavior and preferences. While additional research is needed to fully understand the impact of these services and the variation of impacts across different metropolitan areas and land-use contexts, we provide a brief overview of the existing impact understanding of key shared modes in Table 3.

Table 3 Shared mobility impacts overview

Shared mode	Key impacts
Roundtrip carsharing	From aggregate-level study of 6281 users (Martin and Shaheen 2011): • 25% of members sold a vehicle due to carsharing, and another 25% postponed a vehicle purchase • Reductions in VMT (27–43%) and in GHG emissions (a 34–41% decline) due to carsharing • Slight overall decline in public transit use and a notable increase in alternative modes, such as walking, bicycling, and carpooling
One-way carsharing	From recent study of car2go in five North American cities (Martin and Shaheen 2016): • 2–5% of members sold a vehicle due to one-way carsharing, and another 7–10% did not acquire a vehicle, depending on the city • Percent reductions in VMT due to car2go ranged from 6 to 16% per household and reductions in GHG emissions from 4 to 18% per car2go household • More car2go members reduce their public transit use than those who increase it, although the majority of members do not change their public transit use
Ridesourcing/TNCs	From early exploratory study in Spring 2014 of 380 users in San Francisco (Rayle et al. 2016): • If ridesourcing were unavailable, 39% would have taken a taxi and 24% a bus • Four percent entered a public transit station as their origin or destination • Forty percent of ridesourcing users stated that they had reduced their driving due to the service

3 Shared Automated Mobility

There has been an upsurgence of interest in the idea of automated shared fleets in the last few years. This interest is likely due to the highly publicized AV development space, as well as the popularity of ridesourcing services and the realization that operating cost per mile of mobility services may substantially decrease compared to current prices with automation. Many experts, companies, public agencies, and universities are at the initial stages of exploring the potential impacts of SAVs. In this section, we discuss recent developments, possible business models, and potential impacts of shared automated mobility services.

3.1 Current Developments and Projected Trends

Many pilots around the world have been employing automation to provide a shared mobility service. Thus far, most SAV pilots serving actual passengers involve either on-demand ride services or low-speed shuttles operating in controlled environments.

A couple of pilots have launched involving ridesourcing services and automated vehicles. Uber began testing an AV service open to frequent uberX customers in Pittsburgh, PA in September 2016 (UBER Newsroom 2016b). The company began with a fleet of 14 Ford Fusions and will add 100 Volvos by the end of the year. The SAV service requires an engineer to closely monitor the system at all times. Also during September 2016 in Singapore, nuTonomy and Grab partnered to offer a similar AV ridesourcing service in a 2.5 km^2 business district called "One North" (Tech Crunch 2016). If these types of AV ridesourcing services expand, the companies may begin to own or lease a portion of their own vehicle fleet instead of relying on personal vehicles owned by the drivers themselves.

There have been a number of automated shuttle service pilots around the world, although all are in the initial testing phase and operate in a low-speed setting. Most of these automated shuttles are in a vehicle testing phase. At present, only some are offering rides to passengers. The French company EasyMile has provided its EZ10 electric automated shuttle for over 10 pilots around the world including multiple locations throughout Europe, in addition to the U.S., Singapore, Dubai, and Japan. Local Motors has developed a shuttle named Olli that is a low-speed, 12-seat, automated electric shuttle that is similar to the EZ10. The company has a showroom and test site in National Harbor, MD where it will soon begin an on-demand ride service pilot with the shuttles. Olli pilots are planned to expand to Miami, Las Vegas, Denmark, and Germany at a later date (The Washington Post 2016). CityMobil2, a multi-stakeholder project co-funded by the EU, has been using EasyMile EZ10 and Robosoft Robucity vehicles in low-speed AV pilots serving passengers on short routes in seven European cities. All of the automated shuttle or bus pilots thus far have been small scale in nature. Thus, no significant impacts have been documented yet from these pilots. At the time of this writing, there are no SAV deployments with full automation, although many companies are beginning to discuss the idea of a shared and fully automated fleet.

3.2 *Potential SAV Business and Service Models*

As we have reviewed in previous sections of this paper, the development of SAV services will take time to mature. It will likely be a number of years until these services become widely available. SAVs have many hurdles, both technological and political, before they could become commonplace. Nevertheless, we can begin to speculate on the business models these services may employ based on current developments and existing knowledge about shared mobility services. Once vehicles have fully automated capabilities and are legal on public roads without any human supervision required (i.e., they can drive on public roads unmanned), shared mobility modal definitions and business models will begin to blur. For example, carsharing and ridesourcing start to look like very similar services, if their fleets are comprised of fully automated vehicles. Users of carsharing systems will no longer have to access a carsharing vehicle and drive themselves around. Instead, the

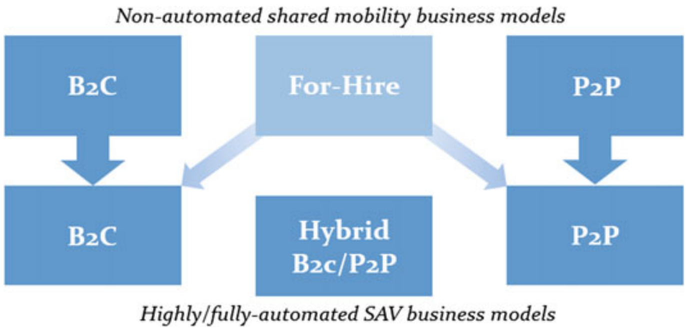

Fig. 1 Non-automated and highly/fully-automated shared mobility business models

vehicle will have the ability to drive up to the user on-demand and drive itself to a destination. This type of service is akin to ridesourcing services that exist today, with the advent of vehicle automation.

For-hire and B2C/P2P service models also begin to blur, as the distinction of whether or not a rider is "hiring" someone to drive the shared vehicle is unnecessary as vehicles no longer require a human driver. Instead, who owns the vehicle(s) and who controls the SAV network's operational decisions become the two most important factors in defining SAV business models (see Fig. 1). Table 4 outlines the potential SAV business models. Note that we intentionally do not make any distinction between the private- or public-sector with the following definitions and only differentiate between an individual and an entity. An entity could refer to private- or public-sector owners or operators in the business model definitions. Although we use the term B2C for simplification purposes, this could refer to a public entity as well. SAV business models will vary based on two key factors: (1) Vehicle Ownership (who owns the vehicle(s)) and (2) Network Operations (who controls the network operations). These aspects are expanded upon in Table 4.

As discussed earlier, for-hire business models blend into B2C and P2P models when considering fully automated vehicles. In a fully automated world, vehicle ownership scenarios include: (1) Business-owned (B2C), (2) Individually owned (P2P), or (3) Hybrid Business/Individually owned. The next aspect of the business model then becomes what entities or individuals are controlling the SAV network operations and their relationship to the vehicle owner(s). A SAV network operator controls fleet-level decisions, which may include one or many of the following responsibilities: booking, routing, payment, area of operations, fee structure, user data collection, membership decisions, conflict mitigation, vehicle maintenance, and insurance. Some of these responsibilities may instead fall partially or fully on

Table 4 Potential SAV business models

SAV business model title	Vehicle ownership and network operations	Description	Current non-AV example
B2C with single owner-operator	Business-owned vehicles (B2C), same entity owns and operates	Would employ a SAV fleet that is both owned and operated by the same organization	B2C carsharing operator (like Zipcar or car2go) that both owns and operates a SAV fleet
B2C with different entities owning and operating	Business-owned vehicles (B2C), different entity owns than operates	Two (or more) companies partner to provide SAV services	The current GM-Lyft partnership is an example where such a business model may emerge
P2P with third-party operator	Individually owned vehicles (P2P), third-party entity operates	A third-party would control network operations of a P2P fleet, likely taking some monetary contribution from the vehicle owner, user, or both, in exchange for their services	P2P carsharing or ridesourcing services, but where many vehicles on the network are fully automated
P2P with decentralized operations	Individually owned vehicles (P2P), decentralized peer-to-peer operations	Individually owned AVs where operational aspects are not controlled by any one centralized third party and are instead decided upon by individual owners and agreed-upon operating procedures, possibly facilitated by emerging technologies like blockchain	Arcade City, an Austin-based ridesourcing service that operates truly peer-to-peer services with no central intermediary
Hybrid ownership with same entity operating	Hybrid business/individually owned vehicles, Same entity that owns (some) vehicles operates	An entity that owns a portion of the SAVs in their fleet but also includes individually owned AVs that join the entity's shared fleet when individuals make their vehicles available for sharing on the network	Ridesourcing mixed-ownership fleet

(continued)

Table 4 (continued)

SAV business model title	Vehicle ownership and network operations	Description	Current non-AV example
Hybrid ownership with third-party operator	Hybrid business-/individually owned vehicles, Third-party entity operates	A third-party that does not own SAVs themselves but that brings online both individually owned and entity-owned AVs on a shared network of vehicles that they operate	Getaround (P2P carsharing company)/city CarShare (non-profit B2C carsharing organization) recent partnership in Bay Area

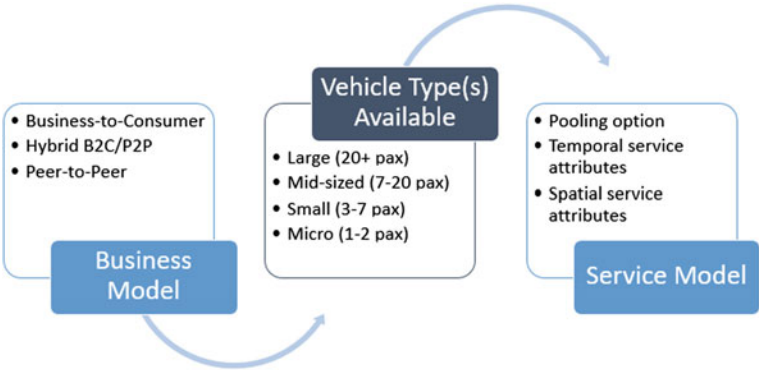

Fig. 2 Potential SAV service models

the vehicle owner(s) or another entity entirely, depending on the specific business model employed and case-by-case agreements. Ultimately, the vehicle owner(s) and network operator(s) would receive a portion of the user fees in return for their assets and services. The way profit is divided will vary by business model. We outline and describe a range of ownership-operations combinations that could possibly emerge in Table 4.

As illustrated in Fig. 2, differences in service attributes may depend on the type and capacity of SAV that is used, which is dependent on the business model employed. For example, large- and mid-sized vehicles with the capacity for many passengers, similar to most bus or shuttle services today, will likely not be employed under a P2P model because very few individuals will have the motivation to buy a large AV. P2P SAV options will likely be comprised of smaller vehicles that operate more point-to-point and on-demand services.

In the next section, we explore user preferences for SAV services by covering findings from the literature on the potential impacts of SAV services on travel behavior, other transportation modes, and the environment.

3.3 Research on SAV Impacts

The impact that SAV services may have on travel behavior, other transportation modes, the environment, and cities in general remains uncertain. In this section, we summarize relevant academic research on the potential impact of SAVs. As real-world deployment of SAVs has been extremely limited, most studies on the subject develop or modify existing models of travel behavior and include SAVs, with assumptions regarding their operations and vehicle types. Some have documented demographic trends over time and speculated at possible future scenarios based on expert projections. Other studies have surveyed potential users on their feelings toward the potential use of SAVs and relied on detailed analysis to assess possible impacts. Although most of the studies do not go into specific business model assumptions of SAVs, many of them include scenarios that span from no AV sharing (privately owned), to a shared vehicle fleet with no pooled option, to a pooled option SAV service to illustrate differences and impacts between sharing levels.

Chen and Kockelman (2016) modified an existing travel model to assess the potential modal shifts as a result of shared, automated, and electric vehicles (SAEV). In addition to privately owned non-automated vehicles and buses, their model predicted that the SAEV mode would comprise about 27% of all trips generated. The vast majority of these trips came at the expense of trips by private car (90%), with the rest derived from trips formerly made using public transit. Davidson and Spinoulas (2016) anticipated modal share changes under both moderate and aggressive AV growth scenarios projected to years 2036 and 2046. In their model, without automated vehicles, active transportation modes and public transportation gain greater modal share over time compared to private vehicles. The modeled proportion of trips made by AVs rose with a greater number of AVs in the fleet, as they became more attractive than other options due to speed, lower costs, and more direct service. A survey by Bansal et al. (2016) of residents of Austin, Texas found that full-time male workers are likely to use SAVs more frequently, while licensed drivers are less likely to use them at even a low cost per mile price point. More tech-savvy survey participants, who were categorized in this way if they had heard of Google's self-driving car project and considered an anti-lock braking system was a form of automation, were more likely to say that they would make the switch to SAVs. A positive relationship was found between the distance between home and work and SAV adoption rates. For participants familiar with ridesourcing services, switching to SAVs was tied to service cost compared to the cost of non-automated ridesourcing services. Sessa et al. (2015) created a survey for two scenarios: one where most AVs are privately owned and another where they comprise a fleet owned and operated by either a public or private entity. In the first scenario, sharing AVs takes place with a purely P2P model with no pooling available, while the latter scenario has a pooled option. Similar to the results of Davidson and Spinoulas (2016), in the first scenario, the greater the AV supply, the more trips passengers are expected to take in total, while also drawing some trips away from public transportation. In the second scenario, however, the third-party owned SAV fleet was determined to complement public transportation, drawing most of its trips away from private vehicle trips. This finding only holds in metropolitan areas, however, as the authors expect smaller cities and rural areas to see a rise in SAV usage but no notable change in public transportation use. These conclusions are based on the assumption that automation increases the ease by which users can switch between public transportation modes and the first- or last-mile to a destination, reducing the non-monetary costs of using public transportation.

Other studies assess the potential environmental impacts of SAVs. A study by OECD/ITF (2016) modeled the impact of replacing all car and bus trips within a mid-sized European city, representative of Lisbon, Portugal, with a portion of trips served by SAV fleets. Sharing of rides was taken into account in the modeling effort. The authors found that when these existing vehicle trips were served instead by a combination of SAV taxis and shuttle buses, emissions are reduced by one-third, 95% less space is required for public parking, and the vehicle fleet would only need to be 3% of the size compared to today's car and bus fleet. This study predicts total vehicle kilometers traveled would be 37% lower than at present, although each vehicle would travel 10 times the total distance traveled by current vehicles. Another study also found potential emission reductions due to SAVs. A study by Greenblatt and Shaheen (2015) found that a fleet of SAEVs with right-sizing of vehicles by trip, in combination with a future year 2030 low-carbon electricity grid, could reduce per-mile GHG emissions by 63–82% compared to a privately owned hybrid vehicle in 2030. The per-mile GHG reductions are 90% lower than a privately owned, gasoline-powered vehicle in 2014. Half of these emission savings are attributed to smaller right-sized vehicles based on trip needs. The study also found that if these vehicles are driven 40,000–70,000 miles per year, typical for U.S. taxis, fuel cell or electric battery vehicles are a more cost effective option than gasoline-powered vehicles. Despite the higher upfront cost of the alternative fuel vehicle, the per-mile cost of fuel is lower, so the savings can pay for the extra initial investment.

At present, the impacts of SAVs on behavior, other travel modes, and the environment are still uncertain. A number of studies predict a modal shift away from private vehicle trips due to SAVs under certain sharing scenarios. The impact SAV services may have on VMT and congestion is uncertain as well, with some studies predicting that roadway capacity may be freed up due to more efficient operations and right-sizing of vehicles.

4 Conclusion

The future of surface transportation is facing a notable transformation with AVs and shared mobility applications contributing. It is conceivable that AVs will become an emerging technology by 2020, a more accepted technology by 2030, and come to dominate ground transportation by 2050, similar to what mobile phones have done for the telecommunications industry. The kinds of business models and service offerings that may emerge, which include SAVs are not fully clear. The relationship between the AV owner(s) and SAV network operator (companies, municipalities, or individuals), as well as the vehicle types and service models employed will guide the development of SAV services. Some business models may prove more profitable or efficient than others. This will depend on many aspects including: technologies available, location, vehicle types used, ownership schemes, and many other factors.

If AVs become widespread, SAVs could probably constitute a sizeable portion of trips, although what percentage that may be is unknown and will likely depend on many different factors. The number of personally owned AVs in an area will likely determine, to some degree, the demand for SAV services. Impacts will also depend on levels of sharing and the future modal split among public transit, shared AV fleets, and shared (or pooled) rides. It is possible that SAV fleets could become widely used without very many shared rides, and single-occupant vehicles may continue to dominate the majority of vehicle trips made. It is also feasible that shared rides could become more common, if automation makes deviation more efficient, more cost effective, and less onerous to users. To date, most studies have not been able to deeply assess the propensity for shared rides, since SAV travel behavior data currently do not exist. Business models, travel behavior preferences, and public policy will be key components in determining how the SAV market and impacts unfold.

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Shared Automated Mobility and Public Transport

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Abstract Automated vehicle technology offers many opportunities to improve the quality of public transport. This chapter reviews key understanding and takeaways from an international workshop that took place in July 2016 at the Automated Vehicle Symposium in San Francisco, California, which focused on the ongoing development of shared automated mobility services and public transit. During the two-day workshop, speakers from the public and private sectors, academia, and non-governmental organizations presented key findings from their work. Discussion centered around the implications of the convergence of shared mobility and vehicle automation on the future development of public transport, funding, pilots, and policy implications.

Keywords Shared mobility · Automated vehicles · Connected vehicles · Automated transit · Carsharing · Ridesourcing · Transportation network companies · Microtransit · Impacts · Public policy

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1 Introduction

At present, over 50% of the world's population lives in urban areas, and this is projected to increase to 66% by 2050 (United Nations 2014). Since cities emit over 70% of the world's greenhouse gas (GHG) emissions (UN-HABITAT 2011), sustainability of urban mobility systems is paramount. The need for urban mobility improvements goes much beyond nation and city, with Pope Francis commenting recently that *The quality of life in cities has much to do with systems of transport, which are often a source of much suffering for those who use them.* Global trends indicate increasing growth and development in shared mobility, automation, and electrification. The convergence of these technologies and services points to notable disruptions in transportation for both people and goods (Greenblatt and Shaheen 2015; Stocker and Shaheen 2017). Furthermore, simulations of automated public mobility systems demonstrate that the energy efficiency of an electrified, centrally managed fleet greatly exceed private vehicle ownership (Chen et al. 2015; Greenblatt and Saxena 2015) Thus, the intersection of automated, electric, and shared mobility holds the promise of a "sweet spot" for sustainable urban applications, provided the right policy signals are employed to maximize the social and environmental benefits.

In September 2016, the National Highway Traffic Safety Administration (NHTSA) released its first iteration of their Federal Automated Vehicles Policy, which adopts the Society of Automotive Engineers' (SAE) International definitions for the six levels of automation (U.S. Department of Transportation 2016a). The definitions categorize automated vehicles (AVs) into levels of increasing automation, outlined in Table 1. One of the major distinctions drawn is between Levels 0–2 and 3–5, based on whether the human operator or the automated system is primarily responsible for monitoring the driving environment (U.S. Department of Transportation 2016a).

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Table 1 SAE vehicle automation level definitions (U.S. Department of Transportation 2016)

SAE level	Name	Description
Level 0	No automation	No automation
Level 1	Driver assistance	Automation of one primary control function, e.g., adaptive cruise control, self-parking, lane-keep assist or autonomous braking
Level 2	Partial automation	Automation of two or more primary control functions "designed to work in unison to relieve the driver of control of those functions"
Level 3	Conditional automation	Limited self-driving; driver may "cede full control of all safety critical functions under certain traffic or environmental conditions," but it is "expected to be available for occasional control" with adequate warning
Level 4	High automation	Full self-driving without human controls within a well-defined Operational Design Domain, with operations capability even if a human driver does not respond appropriately to a request to intervene
Level 5	Full automation	Full self-driving without human controls in all driving environments that can be managed by a human driver

Although the debate of when fully automated vehicles will be available for mainstream use is uncertain, the public transit sector has already harnessed fully automated vehicles for highly-responsive on-demand mobility in several applications. This includes categories of Personal Rapid Transit (PRT), Group Rapid Transit (GRT), Automated Transit Networks (ATNs), and Automated People Movers (APMs). These technologies are employed on campuses, such as the Morgantown PRT and Masdar City, in office parks like the Rivium Park Shuttle pilot, and at airports including Heathrow terminal 5, not to mention the APMs deployed at most major airports across the globe. As private vehicles are evolving toward highly and fully automated operations, automated transit is also evolving for use in mixed traffic. Where full automation was once limited to a dedicated guideway or segregated roadway, these systems are beginning to operate in shared environments–bringing both high reliability along with ease of access at public transit stations. This parallel perspective on vehicle automation for public transit brings to the forefront the management and supervisory control aspects that automated vehicle systems will require to meet the demanding needs of 24-7 public mobility applications and the tradeoffs in capacity, safety, congestion, and sustainability, which accompany mixed-use versus dedicated guideways implementations.

This chapter reviews key understanding and takeaways from an international workshop in July 2016 held in San Francisco, California, which focused on the present and future of shared automated mobility services and public transit. This two-day workshop was attended by over 100 individuals, representing the public and private sectors, academia, and non-governmental organizations. The chapter is organized into four sections, as follows: (1) updates on research pilot programs and testing sites, (2) program updates and funding opportunities, (3) public transport in the future, and (4) policy implications and research needs for public transport and shared mobility.

2 Updates on Research, Projects, Pilot Programs, and Testing Sites

Updates on research, pilot programs, and testing sites were provided in the areas of shared mobility and automation for public transport. In this section, we provide an overview of key highlights in shared mobility research and lessons learned from shared automated vehicle (SAV) testing sites and pilot programs.

2.1 Impacts of Shared Mobility

The carsharing industry has grown rapidly since the launch of the first carsharing operator in North America in 1994 (Martin and Shaheen 2016). In 2015, a total of 39 roundtrip and three one-way carsharing operators were active on the continent, providing access to shared fleets of vehicles for millions of drivers (Martin and Shaheen 2016). Carsharing operators are expanding their services and leveraging innovative technologies to improve the versatility of their carsharing systems. Zipcar, which launched in 2000 as a fleet-based roundtrip carsharing service, began deploying one-way carsharing in various cities across the U.S. in 2016. Many new carsharing services have launched innovative services in the past few years as well, including GM's Maven and BMW's ReachNow (formerly DriveNow), among others.

The discussion of the opportunities and challenges that will emerge as shared mobility converges with electrification and automation can be informed by the environmental and behavioral impacts observed from carsharing and other shared mobility services. A 2016 study on the one-way carsharing operator car2go in five North American cities found significant reductions in vehicle ownership, vehicle miles/kilometers traveled (VMT/VKT), and GHG emissions due to the availability of car2go in Calgary, San Diego, Seattle, Vancouver, and Washington, DC (Martin and Shaheen 2016). Researchers from the Transportation Sustainability Research Center (TSRC) at UC Berkeley conducted the study in partnership with the Federal Highway Administration (FHWA), San Diego Association of Governments (SANDAG), the City of Seattle, and Daimler AG's carsharing service, car2go. In total, car2go took more than 28,000 vehicles off the road in the five cities studied and prevented between 16 and 47 million VKT per city in 2015. The reduction in VMT/VKT per household in the five cities ranged from six to sixteen percent and the reduction in GHG emissions ranged from four to eighteen percent per household.

Table 2 Impacts of roundtrip versus one-way carsharing on vehicle ownership, VMT/VKT, and GHG emissions (Martin and Shaheen 2011, 2016; Shaheen et al. 2014)

Carsharing service model	Vehicles removed per carsharing vehicle	% Reduction in VMT/VKT	% Reduction in GHG
Roundtrip	9–13	27 (average)	34–41
One-way	7–11	6–16	4–18

The directional findings of the one-way carsharing study are consistent with findings from previous studies on roundtrip carsharing conducted by TSRC in 2010 and 2011. Table 2 summarizes the environmental impacts from these studies. Whether roundtrip or one-way, carsharing results in reduced household vehicle ownership, reduced VMT/VKT, reduced GHG emissions, an increase in alternative mode usage, such as walking or biking, and a decrease in public transit use (more pronounced for one-way carsharing) (Martin and Shaheen 2011, 2016; Shaheen et al. 2014).

Findings from a 2013 and 2014 bikesharing study conducted by TSRC in partnership with the Mineta Transportation Institute reveal that bikesharing reduces driving and taxi use. Half of bikesharing members reported a decrease in personal vehicle use (Shaheen et al. 2014). Yet the impact on public transit appears somewhat mixed. Bus use consistently decreased across all four cities within the study, albeit by different magnitudes ranging from a net decrease in use of three percent in the Twin Cities to a net decrease of 41% in Montreal (Shaheen et al. 2014). In contrast, respondents' urban rail use increased in the Twin Cities due to bikesharing (net increase of 12%), while the other three cities showed a decrease in urban rail usage, led by Washington, DC (net decrease of 41%). The study suggests that urban form, level of public transit service, and the availability of alternative modes and routes may ultimately impact the complementarity of innovative shared modes with public transit, a valuable lesson as AV modes emerge, whether shared or not. In the next section, we explore SAV testing and pilot programs across the globe.

2.2 *Shared Automated Vehicle Testing and Pilot Programs*

Cities across the world are exploring the viability of integrating SAVs in their public transit networks. AV testing facilities have grown in number and size in recent years, as both the public and private sectors seek opportunities to facilitate the development of AV technology in safe, controlled environments. These testing initiatives and pilot programs demonstrate the potential for integrating SAVs into the transportation ecosystem, while providing insight into the infrastructural, regulatory, and financial challenges that must be overcome and eventually resolved in advance of widespread SAV deployment.

2.2.1 AV Test Sites and Public Demonstrations

AV testing in controlled environments provides an intermediary step between the development and deployment of SAVs. The European Commission (EC) has provided uninterrupted funding for research and development work on the topic of automated urban transport systems since 2001, including the CyberCars, CyberMove, NetMobil, CityMobil, and CityMobil2 projects.

In 2014, the Contra Costa Transportation Authority (CCTA) launched GoMentum Station, the largest secure testing facility for connected and automated vehicle (CAV) technology in the US. GoMentum includes 5000 acres dedicated to fostering the convergence of CAV technology, innovation, and commercialization. As of July 2016, 2100 acres were available for testing to multiple partners, bringing together automobile manufacturers, communication companies, technology companies, researchers, and public agencies. GoMentum Station's newest partner, EasyMile, will launch an SAV pilot in 2017 in the Bishop Ranch Business Park in San Ramon, California. The 12-passenger AV will serve as a first- and last-mile solution that can alleviate congestion and reduce parking needs.

In the United Kingdom, the UK Autodrive Programme, one of three consortia funded by Innovate UK, is a three-year pilot of CAV technologies that launched in November 2015. In the M1 car development project, four full-sized automated Jaguar, Land Rover, and Tata vehicles will be tested on public roads in a series of increasingly challenging public tests. The Low Speed Autonomous Transport System (L-SATS) development project is designing and piloting a fleet of 40 low-speed automated pods in Milton Keynes. As of July 2016, the pods were in the process of being designed for personal on-demand point-to-point transportation in pedestrian areas. Finally, the cities program engages the public with a national longitudinal public attitudinal survey, congestion simulations, and a last mile service demonstration in Milton Keynes. In the next section, we explore SAV pilot design considerations.

2.2.2 SAV Pilot Design Considerations

Two of the most important performance metrics for SAV pilots are: system safety and throughput. AV pilots are subject to a number of environmental and operational constraints, including regulatory frameworks for vehicles and services, special requirements for infrastructure, human factors, and financial issues. Implementation pathways for SAVs differ whether such a system will be implemented as part of an existing multi-modal system or if a paradigm shift to a completely new system is envisioned. Four main factors contribute to the complexity of the system: speed, intersections, access, and behavior. While some SAV applications operate in completely controlled environments in which all four factors are regulated and predictable, most SAV pilots to date function in *semi-controlled* environments in which the pilot service is designed to integrate with the built environment and local regulations on a case-by-case basis. Cyclists, pedestrians, and other vulnerable

Table 3 Automated people movers in semi-controlled environments (Alessandrini 2016)

AV application	Speed	Intersections	Access	Behavior
Rivium AV shuttle	Controlled	Controlled	Semi-controlled	Semi-controlled
Dedicated bus lane	Controlled	Semi-controlled	Semi-controlled	Controlled
University campus AV shuttle	Controlled	Uncontrolled	Uncontrolled	Semi-controlled

users need to be considered, together with the integration of traffic management systems and interaction with manually operated traffic. Rethinking lane widths, parking, and other rights-of-way to accommodate both AVs and pedestrians in a simple and comprehensive manner is crucial to facilitating successful and informative pilot deployments and ultimately paving the way for fully automated vehicles, which are expected to operate in completely uncontrolled environments (Alessandrini 2016).

Table 3 provides three examples of fixed route public transit systems operating in semi-controlled environments: (1) 2getthere's first application of GRT in the Rivium business park in the Dutch city Capelle aan den Ijssel, (2) dedicated inner city bus lanes, and (3) automated shuttles on university campuses. The Rivium shuttle operates at grade on a designated fenced track. Such a system would appear to be under full control. In reality, however, the fencing does little to deter children and wildlife from entering the rights-of-way of the AVs, resulting in semi-controlled access to the AVs in practice.

With respect to the human elements involved, pilot deployments may need to be based on user requirement analyses or they may be innovation driven. The use cases and economic viability of SAV pilots must be carefully considered to ensure that they are deployed in markets with sizeable demand, which is appropriate for the particular level of service provided by the pilot system. Most AV shuttle manufacturers are still fairly small companies, so economies of scale restrict the maximum occupancy of the vehicles. The marginal benefit and added capacity of increasing the vehicle size diminishes after a threshold level is reached. Although current AV shuttles operate at relatively low speeds with capacity for about 10–20 passengers, growing demand and advances in technology are driving improvements in the versatility of SAV designs. For instance, 2getthere's newest third generation GRT vehicle is bidirectional, with obstacle detection on both sides of the vehicle and a maximum speed of 60 kph. This GRT shuttle is designed with eight seats and space for an additional 16 standing passengers, providing a maximum occupancy for 24 passengers. The regulatory environment for piloting SAVs is often fragmented. In the next section, we explore this issue.

2.2.3 Overcoming Regulatory Fragmentation

Documenting the safety and security of SAVs is vital to gaining the acceptance of potential users. However, industry, regulators, and the public are all grappling with the challenge of assessing the safety and risk factors of AVs in a standardized manner. Differing legal frameworks across nations and cities create further barriers to the deployment of SAV pilots. For example, regulations in Greece authorize AVs to operate in a demonstration without a driver on board but require remote professional drivers to monitor and control the vehicles via live camera streams broadcast from the AVs (Mercier-Handisyde 2016). In contrast, Germany requested an amendment to the Vienna convention in 2016 to require drivers to be present onboard when operating AVs (Alessandrini 2016).

This issue is highlighted through the work of the Transportation Research Board in sponsoring a research needs statement that identifies the need for a generic, systems- level hazard analysis of fully automated roadway vehicle technology operating a public transit service. Other safety analysis methodologies being applied to AV research and development initiatives worldwide include the vehicle-focused safety certification process, which is embodied by IEC 61508, and the corresponding ISO 62626 automotive functional-safety methodology. These machine automation methodologies derive safety integrity levels (SIL) that are directly relevant to manufactured automotive products, as driving automation is introduced by original equipment manufacturers (OEMs).

In the private sector, a San Francisco-based startup that uses smartphone sensors to measure driver behavior, called Zendrive, has identified the opportunity to leverage the billions of miles of human driver behavioral data it has collected to develop a quantitative and algorithmic approach to understanding and measuring AV safety. These data can be used to understand the many human, environmental, and vehicle risk factors associated with surface transportation and how they vary with respect to geography and time, among other factors. Zendrive has begun forming partnerships to develop this technology and market it to insurance providers, regulators, and original equipment manufacturers (OEMs). In the next section, we describe program updates and funding opportunities.

3 Program Updates and Funding Opportunities

The year 2016 marked a milestone in the development of SAV technologies in the US. Federal, regional, and local government bodies began taking initiative in identifying mobility needs and pursuing opportunities to enact positive change using vehicle automation and shared mobility solutions. Collaboration among government, researchers, and private companies is vital in making these opportunities a reality. In this section, we provide an overview of program updates and funding opportunities including: lessons learned from the US Department of Transportation's (USDOT) Smart City Challenge and Federal Transit Administration (FTA) Mobility on Demand (MOD) Sandbox programs, research opportunities identified by the Accessible Transportation Technologies Research Initiative (ATTRI), and funding opportunities with the National Cooperative Highway Research Program (NCHRP).

3.1 Beyond Traffic: USDOT Calls for Innovations in Transportation

In February 2015, US Secretary of Transportation Anthony Foxx and Google Chairman Eric Schmidt launched the Beyond Traffic Framework. The draft report, titled *Beyond Traffic 2045, Trends and Choices,* calls for an increase in mobility options in growing megaregions, emphasizing that the country's critical aging infrastructure is not equipped to handle the projected dramatic growth in population (U.S. Department of Transportation 2015). In response, the USDOT developed the Smart City Challenge, an unprecedented competition between medium-sized cities for $40 million in funding to revolutionize their transportation systems. Following the completion of the Smart City Challenge, the US FTA announced an opportunity for $8 million in federal funding for innovative projects to tackle mobility issues in public transportation (U.S. Department of Transportation 2016c). The challenges and solutions identified in the project proposals for both the Smart City Challenge and the FTA MOD Sandbox provide important insights for transportation providers across the US. Each of these initiatives is described below.

3.1.1 Automation in the Smart City Challenge

The USDOT launched the Smart City Challenge in December 2015, asking mid-sized cities across the US to develop comprehensive proposals for a smart transportation system that would serve underserved communities, employ shared data, and leverage electrification and automation in transportation to address the city's challenges. Out of a total of 78 applicants, the USDOT chose seven finalist cities. Each of the finalists met with Secretary Anthony Foxx and a team from USDOT. Each also received $100,000 to fund public outreach, the production of pitch videos, and intensive technical assistance from Federal experts and private sector partners.

From a public engagement perspective, the Smart City Challenge was widely successful. In the words of Secretary Foxx, "[The Smart City Challenge] will serve as a catalyst for widespread change in communities across America." The applications revealed that cities across the US are eager to get more information about automation technologies despite the uncertain regulatory environment. Eighty-two percent of the applications included AV concepts, many of which proposed use cases to leverage AVs to provide better transportation access to disadvantaged communities (U.S. Department of Transportation 2016b, d]. Forty-four of the cities proposed projects to test the use of SAVs (U.S. Department of Transportation 2016). Figure 1 displays the number of cities that proposed a variety of urban automation solutions in their Smart City Challenge applications.

In June 2016, Columbus, Ohio was named the winner of the Smart City Challenge. Columbus proposed connecting more residents to jobs by deploying six electric automated shuttles to connect a new bus rapid transit center to a major retail

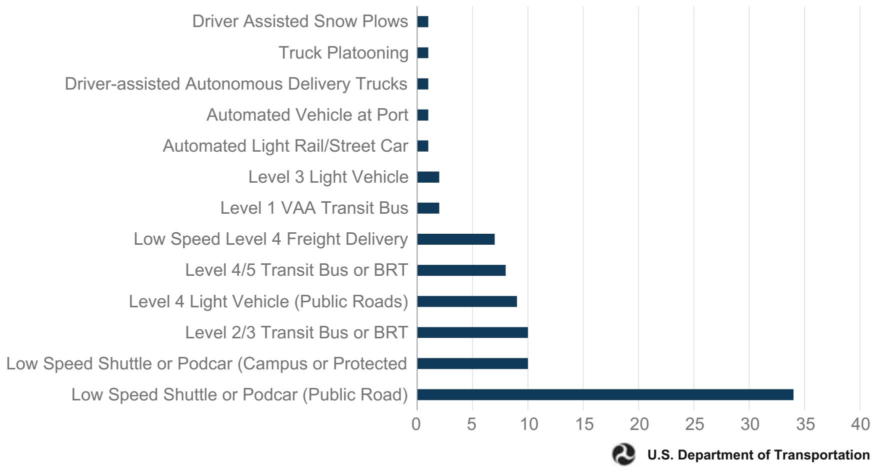

Fig. 1 Urban automation in the smart city challenge applications: 78 city analysis (Dopart 2016)

district (U.S. Department of Transportation 2016d). The other six finalists were redirected to apply for other federal grants to fund the initiatives proposed in their Smart City Challenge applications. Both Pittsburgh and San Francisco (SF) received Advanced Transportation and Congestion Management Technologies Deployment grants of $11 million, which were leveraged from their smart cities applications. The SF proposal includes a shared automated electric shuttle. Portland, Oregon's TriMet also received funding to integrate shared mobility options into existing trip planning app (U.S. Department of Transportation 2016b). In the next section, we describe the FTA MOD Sandbox initiative.

3.1.2 FTA Mobility on Demand (MOD) Sandbox: Changing the Transit Landscape

In May 2016, the FTA launched the MOD Sandbox program to support research and technology deployment pilot projects that promise to make notable improvements to the efficiency and effectiveness of public transportation, while enhancing safety and connectivity in America's transportation system (U.S. Department of Transportation 2016c). MOD embodies the guiding principles of the FTA by promoting data driven and platform independent solutions with a traveler centric, consumer focused, mode agnostic, and multimodal approach to mobility. The MOD Sandbox program was designed to empower regional public transportation providers (e.g., public transportation agencies, state/local government DOTs, federally recognized Indian tribes) with funding and a legal safe space with which to explore bold and innovative demonstration projects. Applicants were required to address equity and accessibility and include one or more strategic partner(s) in their proposals.

The FTA received 79 submissions for the MOD Sandbox from all types and sizes of communities in 33 states, with a variety of proposed partnerships and use cases (Valdes 2016). As of July 2016, the FTA was in the process of evaluating the project proposals, which had requested a total of $59 million in funding, ranging from $112,000 to $3.5 million (Valdes 2016). A number of proposals requested relatively small amounts of funding, demonstrating a larger need for regulatory approval than for money to move forward in implementing some of the proposed pilot projects. Eleven pilot projects, totaling $8 million, were selected. One project includes an automated shuttle in Arizona. The program includes a national evaluation to document understanding and share lessons learned. The FTA hopes to continue the MOD Sandbox program for years to come, potentially varying the focus of the program from year to year. In the next section, we describe the USDOT's ATTRI program.

3.2 Research Needs in Accessible Transportation Technologies

The Accessible Transportation Technologies Research Initiative (ATTRI) is a joint USDOT multi-year, multimodal, multi-agency research, development, and implementation effort co-led by the FHWA and FTA. ATTRI focuses on research to improve the mobility of travelers with disabilities through the use of intelligent transportation systems (ITS) and other advanced technologies. ATTRI identifies, develops, and deploys innovative transformative applications or systems, along with supporting policies and institutional guidance, to address the mobility challenges of travelers with disabilities, as well as veterans and older adults.

ATTRI is taking a collaborative approach by reaching out to various research teams, advocacy groups, and municipalities to identify the leading transportation barriers, needs, and technology issues for people with disabilities. ATTRI released a report assessing user needs in May 2016, which recommends four initial key focus areas for technological advancement: (1) smart wayfinding and navigational solutions, (2) pre-trip concierge and visualization, (3) shared use, automation, and robotics, and (4) safe intersection crossings (Pierce et al. 2016). ATTRI is an ongoing project that looks forward to launching several projects selected through a Broad Agency Announcement and other methods (Fig. 2).

Finally, we describe NCHRP funding opportunities and research initiatives below.

3.3 NCHRP Funding Opportunities and Research Initiatives

The National Cooperative Highway Research Program (NCHRP), a pooled fund program funded by state DOTs, has a $40 million budget for annual research

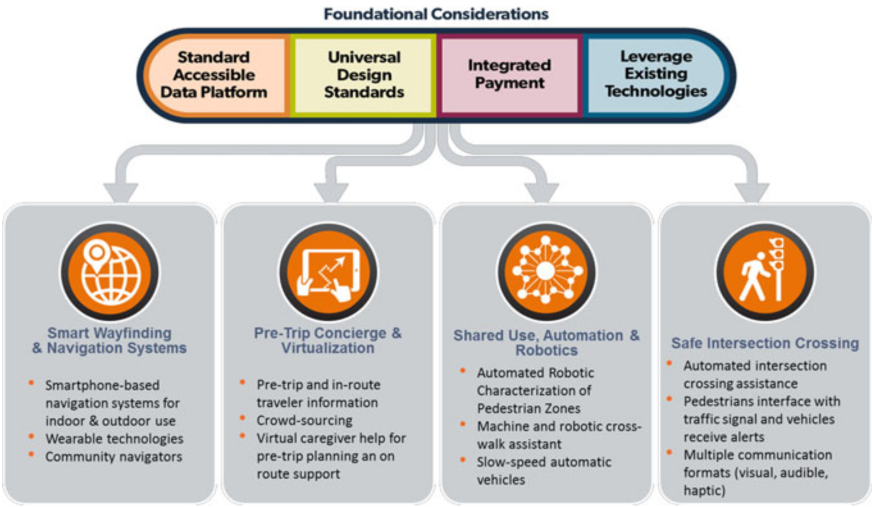

Fig. 2 ATTRI foundational considerations and key focus areas for application development (Pierce et al. 2016)

projects. A number of these projects focus on creating practical and actionable information for policymakers and agencies to help lay the pathway for the beneficial deployment of vehicle automation and shared mobility.

There are three main efforts underway as part of NCHRP. First, the NCHRP Legal Research Digest 69 looks at the legal environment for CAVs including: civil liability, insurance, sustainability, and more. Second, NCHRP 20-102 is an ongoing effort examining the impacts of CAVs on state and local transportation agencies. The project splits a \$3.5 million total budget into 20 discrete research and applied projects of \$100–\$400k. These projects include, but are not limited to: road markings for machine vision, impacts of regulations and policies for CVs and AVs on traditional public transit operations, cybersecurity implications, data management, effects on travel demand, and issues pertaining to truck freight operations. Third, the Partners in Research Symposium, hosted in Detroit, MI, in October and November 2016, was the first of a series of events convening public agencies, private companies, and researchers. These ongoing events identify research needs to help policy makers prepare for innovative mobility services and technologies. In the next section, we explore the future of public transport in light of CAVs and SAVs.

4 Public Transport in the Future

While there is notable uncertainty around the nature of vehicle automation and its rollout, there are a number of measures being undertaken to explore automation technologies and innovative service models to improve accessibility. With an eye to the future, we provide an overview of some key regional and local initiatives, applications of automation technologies for public transit, initiatives to innovate paratransit, and lessons learned from public-private partnerships (P3s).

4.1 Regional and Local "Automated Oriented Development" Initiatives

Drawing parallels to transit oriented development (TOD), Mayor Mirisch of Beverly Hills promotes the concept of Automated Oriented Development (AOD), an approach to urban development that leverages the benefits of AV technology to maximize mobility, while minimizing vehicle use. In line with this strategy, Mirisch is leading an effort to develop a fleet of automated municipal shuttles to provide transportation to and from a Beverly Hills future rail station, which is scheduled to open in 2023. The city expects the automated shuttles to improve mobility for older adults and handicapped residents, assist with tourism, and improve access to the downtown for residents. In the spirit of AOD, the city is planning to install loading and valet zones for the automated shuttles.

The Santa Clara Valley Transportation Authority (VTA) is also exploring approaches to leverage technology to prepare for a light rail expansion. In 2016, VTA launched an on-demand shuttle pilot called FLEX, which operated in a relatively small, defined service area including 130 pre-defined pickup locations. Users could hail a shuttle for point-to-point travel between any two stops using a custom-built smartphone app. Among the challenges encountered were: software issues, an early launch without enough demand, and a lack of partnerships with local businesses and residences. The potential causes of these problems include the lack of a soft launch (early testing), fares that were not competitive with other on-demand services, and a "committee-based approach" to project organization, which ultimately resulted in unclear project direction. The FLEX pilot concluded after six months. In the next section, we explore some technological opportunities for AVs in public transit.

4.2 Technological Opportunities Using AV Technology for Public Transit

The impact of AV technology on public transit can be viewed from the lens of market segments: captive riders (who do not have access to cars) and choice riders (those who have access to cars but use public transit because of benefits, such as constructive use of time or avoiding high parking costs). Level two automation for private autos is anticipated to reduce congestion and provide self-parking, detracting from the competitive advantages of public transit (Wadud et al. 2016). Level three automation includes amenities similar to public transit in terms of

Table 4 Potential increased capacity of exclusive bus lane using cooperative adaptive cruise control (Lutin 2016)

Average interval between buses (seconds)	Average spacing between buses (ft.)	Buses per hour	Seated passengers per hour
1	6	3600	205,200
2	47	1800	102,600
3	109	1200	68,400
4	150	900	51,300
5 (Base)	212	720	41,040

allowing for more productive use of travel time for eating, sleeping, or browsing the Internet, for example. Level four automation provides a viable alternative to public transit for captive riders, currently estimated at over 30 million people in the US (Lutin 2016). As a result, the impact of vehicle automation on public transit will most likely be large and significant.

Public transit agencies can benefit from a two-fold approach to integrating AV technology that includes both a technological (leverage automation on public transit vehicles to improve performance) and institutional (concentrate on markets best served) response. With respect to a technological approach, numerous automation technologies can be implemented in public transit systems including: lane-keeping, precision docking, cooperative adaptive cruise control (CACC), collision avoidance, and automated emergency braking. An analysis of the exclusive bus-only lane through the Lincoln Tunnel shown in Table 4 reveals a potential capacity increase of over 50%, if headways can be reduced from five to three seconds using CACC.

Technology can also create notable cost savings by reducing liability exposure. From 2002 to 2013, the total casualty and liability expenses for bus, paratransit, and vanpools exceeded $5 billion dollars (Lutin 2016). A research project led by the Washington State Transit Insurance Pool (WSTIP), in collaboration with Munich Re and researchers at the University of Washington, is testing active safety collision warning systems to reduce collisions. The study equipped 38 public transit buses at WSTIP member agencies with four aftermarket sensors to determine the potential to reduce the frequency and severity of collisions and the associated casualty and liability expenses (Lutin 2016). A preliminary analysis of 232 closed insurance claims from the years 2006 to 2015 reveals that 100% of the fatalities observed (six total) were collision-related, and 88% of injuries (335 total) and 94% of claims ($24.9 million total) resulted from collisions or sudden stops (Lutin 2016). The final results of this research will be available in 2017. In the section below, we explore the future of paratransit.

4.3 The Near Future of Paratransit

The paratransit market serves mostly older adults, which can include ambulatory passengers for whom providing convenience and care is expensive. Yet the demand for paratransit services is increasing as a growing number of veterans are filing for disabilities, and the aging Baby Boomer generation has increasingly pressing mobility needs (McGurrin et al. 2016). Furthermore, buses are typically cost prohibitive in the paratransit market due to low passenger volume (2.5 passengers/h) and have high maintenance costs (Mindorff 2016). Hybrids and vans are increasingly replacing buses in low-volume service areas.

The transition from car ownership to public transit and paratransit services tends to occur after the loss of a license or due to the high cost of vehicle ownership. However, the disabled and older adults face barriers to accessing transportation that include lack of signage, maps, and other information; navigational difficulties, such as lack of knowledge of transfers and public transit arrival times; and lack of handicapped-accessible infrastructure and pathways. Greater convenience can be introduced to public transit by integrating innovative technologies, such as smartphone vehicle location services and integrated routing and payment services. These services could attract more riders to public transit by lowering intermodal friction and providing a similar level of reliability to personal vehicle ownership.

The Disabled and Aged Regional Transportation System (DARTS), the paratransit service in Hamilton, Ontario, saw an increase in passenger trips from slightly over 400,000 in 2008 to approximately 650,000 in 2016 (Mindorff 2016). To cope with rising demand, DARTS has systematically planned the elimination of buses in its fleet from the end of 2016 through July 2017 by replacing 70 buses with hybrids and vans (Mindorff 2016). In addition, DARTS developed a suite of applications that seek to enable a more spontaneous and convenient experience for passengers that can rival personal vehicle ownership. Passengers can monitor the location of vehicles scheduled to pick them up and even sign up for a phone alert ten minutes prior to their pickup to assist them in making a smooth transfer. Additionally, analytics packages developed for back office providers are reducing costs through better prediction and management of cancellations. In the section below, we examine the role of P3s.

4.4 Integration of Public and Private Models

A growing number of public transit agencies have begun to pursue opportunities to offer flexible demand-responsive services, especially in areas where ridership is sparse. However, the process of building dispatching software and user interfaces to implement such services requires a large amount of time and resources, which agencies may not be able to access. On the other hand, many private sector transportation technology companies have created reliable on-demand dispatching software and service models that are widely applicable to the challenges faced by public transit agencies. In addition to technological expertise, these companies offer innovative business models that can be in line with actual travel demand in a market. In appropriate applications, P3s can be a powerful tool to improve access to public transit and reduce costs for public agencies in areas where ridership is too low to support traditional public transit services. Ultimately, the viability of P3s must be considered on a case-by-case basis. In the sections below, we explore two P3 partnerships related to the future of SAVs, as well as underscore the need for evaluation and flexibility in a range of land-use contexts.

4.4.1 Ridesourcing/TNCs Replacing Public Transit Service

In addition to rider applications and dispatching software, ridesourcing/TNCs, such as Lyft and Uber, also offer large, regionally distributed driver communities. When the available driver pool encompasses areas that public transit agencies have greater difficulty serving efficiently, partnership opportunities can arise.

Potential areas for cooperation within this context include both routes with lower transit ridership and first- and last-mile to public transit solutions. An example of the former is the current partnership between Lyft and the Livermore/Amador Valley Transit Authority (LAVTA). LAVTA had cut services and some public transit lines in recent years, but they still wanted to provide residents with a robust and affordable service. To tackle this challenge, LAVTA identified geographic areas within their jurisdiction for reduced-fare rides, then provided subsidies to Lyft accordingly. All this was conducted at lower cost than serving passengers using transit buses directly. First-mile/last-mile solutions can be similarly subsidized, as a way for public agencies to encourage line-haul mass transit ridership, while potentially alleviating some resources devoted to feeder systems.

Future opportunities for P3 s with TNCs include integrated payment systems and vehicle automation. SAVs will offer further opportunities by changing the cost curve dramatically, making it possible to bring affordable access across the transport network.

4.4.2 A Public-Private Pop-up Bus Service

Bridj, a microtransit start-up based in Boston, Massachusetts, is seeking to challenge the traditional model of static bus routes by creating pop-up routes that emerge with demand—as new travelers request rides the buses dynamically adjust their routes in order to most efficiently serve riders. Bridj operates under the premise of picking up and dropping off passengers within a seven-minute walk of the customer's origin and destination, with a target fare of 3–4 $.

Bridj has entered new markets by partnering with public agencies, like the Kansas City Area Transportation Authority (KCATA). In Kansas City, Bridj was responsible for managing the app/user interface of the Ride KC: Bridj service, assigning vehicle pick-up and drop-off locations, and routing. KCATA was the owner and operator of all public transit vehicles used by the Ride KC: Bridj service, and all drivers belonged to the same union as other bus drivers working for

KCATA. Key takeaways from the pilot include: (1) strategic and effective outreach efforts are essential to create community awareness and achieve a sustainable level of ridership, (2) many riders took no more than one ride, citing limited geographic and temporal service coverage as the two biggest barriers, (3) the most reported motivations for use of the Ride KC: Bridj service were better cost, comfort, and flexibility than alternative options (Shaheen et al. 2016).

4.4.3 Public-Private Partnerships with the Rise of Vehicle Automation

Vehicle automation will inevitably change the nature of conventional public-private relationships in transportation, which have been around for decades. As vehicle automation significantly changes costs of both public and private services, the nature of P3s will change based on geographies, densities, and existing infrastructure. How such costs and factors play out will inevitably depend on what makes sense at the local level. Some public transit agencies may opt to provide more flexible demand-responsive service in smaller vehicles themselves, while others may opt to pursue such systems through partnerships. Services will range between fixed and flexible routes, differ based on service areas, and vary upon scheduled or demand-responsive service schedules. OEMs may opt to maintain ownership of vehicles through a service rather than selling vehicles directly to customers. This could take the form of SAV fleets or as leased vehicles to individuals. The emergence of such SAV services could ultimately reflect a quasi-public transportation system. The ultimate nature of these hybrid systems and mix of public-private interactions will likely vary from city to city depending on the context.

Governments stand to benefit from piloting partnerships that explore the value of innovative transport services. Costs of new pilots can be a significant barrier, particularly the costs of extending pilots, as needed. It is critical that new partnerships and pilots have the time and space to grow, but it is equally crucial to rapidly assess performance through data understanding. Provisioning a way forward post-pilot is also essential. It is critical to ensure that knowledge transfer of lessons learned is a key pilot objective to ensure dissemination across the broader community. In the next section, we discuss future research needs and policy implications.

5 Policy Implications and Research Needs for Public Transport and Shared Mobility

We concluded the two-day workshop with an interactive discussion regarding policy implications and research needs for shared automated mobility and public transport. Seven major policy areas were explored: safety, efficiency, affordability, equity, user experience, ecology, and public-private integration.

Table 5 Summary of policy implications and research needs identified by the public transit and shared mobility breakout session

Policy area	Goals	Potential policy actions	Research needs
Efficiency	• Minimize delay • Maximize the user experience • Minimize costs	• Ensure flexibility for P3 s and procurement • Consider dedicated AV lanes • Explore new funding streams • Implement a single form of payment	• Willingness to pay for different service types • Labor and equity issues • Optimal vehicle design
Safety	• Interpersonal safety: prevent crime/negative experiences in vehicles (e.g., harassment, anti-social behavior, child safety) • Vehicle safety: reduce collisions, injuries, etc.	• Set safety targets and standards • Require on-board attendants • Vehicle design criteria (e.g., clear visibility, emergency button, surveillance)	• Acceptable collision rates • Cultural differences • Collision avoidance technology • Pickup/dropoff zone safety
Equity	• Provide access to jobs, education, and health care • Reduce social exclusion • Ensure equitable service • Provide free flow of data • Ensure "special needs" are met • Ensure affordability	• Require fare integration with equitable fare structures • Ensure equitable allocation of roadway capacity and curb space • Road pricing for efficiency • Prioritize improvements for paratransit • Enable testing/pilots • Provide AV-friendly infrastructure	• Labor issues as public transit is increasingly automated • Methods to ensure service optimization • Data sharing • Transition to AVs

Attendees of the workshop were divided into breakout tables for different policy areas. Each breakout table identified goals, potential policy actions, and research needs for specific policy areas. We present a summary for each policy area in Table 5.

6 Conclusion

As urban populations across the globe continue to grow, transportation providers are challenged with the growing need to adapt their infrastructure and public transit service models to create sustainable mobility solutions. Vehicle automation, electrification, and shared mobility offer numerous opportunities to improve the quality of public transportation systems. The integration of these technologies with public transit is being widely researched and tested, with a growing number of SAV pilot programs and funding opportunities emerging in recent years.

SAVs introduce opportunities to increase vehicle capacity and reduce per-mile costs of shared mobility, which could facilitate redevelopment in cities, such as repurposing of parking structures for affordable housing and parklets. However, the reduced costs of SAVs could cause a reduction in the use of public transit and a net increase in VMT/VKT due to induced demand, if left unregulated. While studies of shared mobility have shown a net reduction in public transit use, the behavioral changes in response to shared mobility are not uniform (Martin and Shaheen 2016; Shaheen et al. 2014; Alessandrini and Mercier-Handisyde 2016). Thus, continued efforts to understand the dynamics of the evolving transportation ecosystem are paramount in developing policies that can influence behavior and steer the impacts of SAV systems in a positive direction.

Programs like the MOD Sandbox, NCHRP, and ATTRI are providing funding opportunities to support the research and deployment of automated technology applications, while promoting knowledge transfer of research needs, best practices, and environmental and behavioral impacts learned from such projects. Unique challenges are presented for each new SAV pilot, as operating environments, service needs, infrastructure, and regulatory restrictions vary greatly across geographies and use cases. While researchers have begun to develop a standardized safety analysis framework, fragmented regulation remains a large barrier to the efficient scaling of SAV systems.

While AV technology and regulatory guidelines continue to develop, public transit agencies can take advantage of technological and institutional opportunities to begin adapting their services in response to automation. In addition to public SAV pilots and demonstrations, agencies are leveraging automation to improve safety, efficiency, and reliability of existing public transit. Aftermarket technologies installed on buses, such as lane-keeping, collision avoidance, and automated emergency braking, can greatly improve safety and lower insurance costs for public transit agencies. Incorporating demand-responsive technology helps provide convenient public transportation service that is competitive to personal vehicle ownership and other private mobility options.

Institutionally, public transit agencies can prepare for the maturation of automation with strategic analysis of markets where existing ridership is too low to justify operating a transit vehicle in favor of shared ride services. Agencies may benefit from concentrating public transit resources in corridors where congestion and parking costs are high, and where transit increases the capacity of a lane beyond that of a general traffic lane. In the appropriate circumstances, innovative partnerships between public and private transportation providers can improve access to on-demand mobility while increasing the coverage and connectivity of existing public transit networks. These considerations create a foundation with which to optimize the benefits of using SAVs as a replacement for public transit on bus routes with poor ridership and/or headways and for service to persons with disabilities, where appropriate.

The convergence of shared mobility, automation, and public transit is in its nascent stages. With careful research, cross-sector collaboration, and exploratory pilots, there lies great opportunity for shared automated mobility solutions to improve the quality and equity of transportation services. Ongoing research and testing is needed to scale these services in a range of land-use and operational environments, as well as to maximize societal benefits.

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Part IV
Vehicle Systems and Technologies Development

Safety Assurance for Automated Vehicles

Hermann Winner and Ching-Yao Chan

Abstract With the rapid progress in functional skills of automated driving, the question of how the safety of automated vehicles can be assured increasingly becomes a key factor to the introduction of automated vehicles (AVs) for public operations in real world environments. Until now, there have been no well-defined standards or commonly accepted procedures to validate the safety of automated vehicles. In a break-out session of the Automated Vehicles Symposium 2016 (AVS), different approaches to Safety Assurance from a variety of projects preparing for the introduction of AVs were presented. The session also included presentations with follow-up discussions on the requirements of safety assurance from societal perspectives and on the feasibility of satisfying such requirements within the current or expected technological constraints. A summary and some highlights of the session are provided below.

Keywords Safety assurance · Automated vehicles

1 Introduction

The performance of automated vehicles has continuously advanced. Some test cars can now operate safely for thousands of kilometers of automated driving. But even this is still far away from a truly verifiable demonstration of safety on the level of human driving. Safety assurance of automated driving is a currently unsolved challenge and has the potential to be a show stopper. So, researchers from different

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disciplines and backgrounds have aimed at building pieces of a strategy to assure safety. In the break-out session *Safety Assurance* of the Automated Vehicle Symposium 2016, the first one on this topic in this symposium series, these different perspectives and their current state of research were presented. The participants were able to obtain an understanding of the discussed methods and to engage in discussions to convey their points of view. The breakout session was organized to have two sub-sessions. The first session included four speakers followed by a panel discussion, and the second sub-session consisted of five presenters followed by a panel discussion as well. In addition to questions to and answers from speakers, the panel discussion was facilitated to identify the next steps for forming a strategy to achieve the goals and objectives of safety assurance. In total, nine presentations were given across two sub-sessions.

The high-level interest and active participation of attendees was very encouraging for a new break-out session. There were approximately 70 attendees based on the sign-up sheets (some attendees might not have signed in even though they were present) that included 35 individuals from private industries, 14 from academia, and 15 from government agencies/non-profit organizations.

2 Session Highlights

2.1 Dependability and Verification for Self-driving Cars—The Drive Me Approach (Jonas NILSSON, Volvo Car Corporation, Sweden)

The development of self-driving cars represents a paradigm shift for the automotive industry. This talk was based on experiences from the Drive Me project in Gothenburg (Sweden) and focused on the new challenges in safety and dependability brought by autonomy. In addition, the impact these challenges have on safety assurance and verification was elaborated. There is a lot of debate around automation levels, primarily aimed at describing the split of the driving task between man and machine. From a safety perspective, the great distinction is whether the responsibility for safe driving lies with the autopilot or the human driver. For traditional ADAS features, this is clearly on the driver. For self-driving cars, it is clearly on the autopilot. This paradigm shift implies that the vehicle must always be able to drive safely to a stop or hand over to the driver by mutual consent. This in turns implies that the vehicle must have redundant components to ensure that this is possible even in the presence of system faults (Fig. 1).

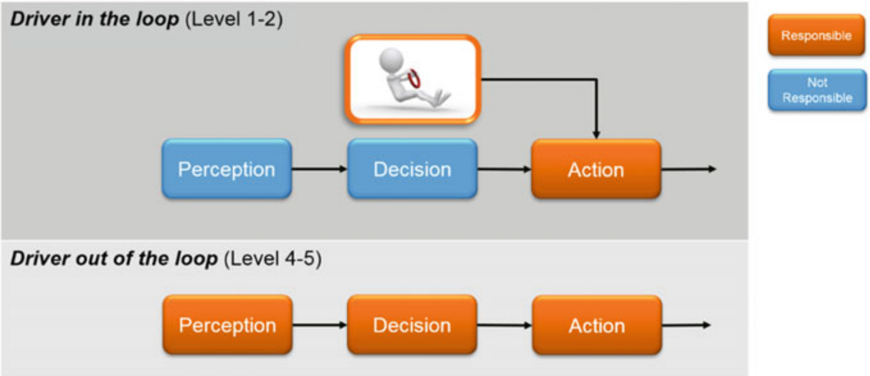

Fig. 1 The paradigm shift from level 1–2 to 4–5

2.2 *Concerning Safety Assurance on Automated Vehicle—Results and Discussion Based on the Projects in Japan—(Naohisa HASHIMOTO, National Institute of Advanced Industrial Science and Technology (AIST), Japan)*

Safety of automated vehicles depends on several aspects including sensors, algorithms, system architecture and human factors. Different automated vehicle projects can be categorized according to their objectives, and safety should be evaluated considering the characteristics of each category. For example, MTBF (mean time between failure) for level 4 automated vehicles, effect of human factor, which includes transition from automated to manual driving, for level 3 automated vehicles, and risk homeostasis theory for level 1 and 2 automated vehicles should be considered respectively. In addition, the main benefits of automated vehicles are improved safety and efficiency, thus any introduction scenario requires a taxonomy (environment, vehicle type, who drives, weather, etc.). For the future, being autonomous is fundamental and being cooperative provides better performance, therefore safety requirement levels or standards (for evaluation of automated vehicles) are necessary. This need was discussed and illustrated with lessons learned from the automated vehicle projects in Japan (see Fig. 2).

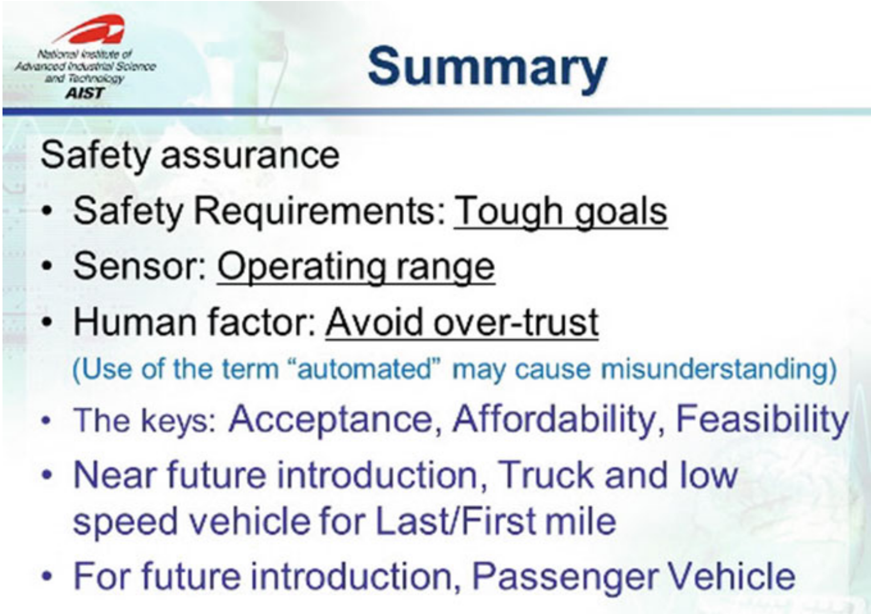

Fig. 2 Summary key figure of the presentation

2.3 Safety Assurance Based on an Objective Identification of Scenarios—One Approach of the PEGASUS-Project (Walther WACHENFELD, Technische Universität Darmstadt, Germany)

Assessing automation only by test-driving is not economically feasible ahead of market introduction. Thus, testing has to be shifted to other testing tools. These tools need information on relevance of scenarios to reduce the test effort. The key question is: What is of relevance when assessing automated driving? Within the PEGASUS project (www.pegasus-projekt.info/en/home) one primary goal is to answer this question for highly automated driving on motorways. The presentation proposes and discusses an objective identification of scenarios and their relevance for assessing safety.

Figure 3 summarizes the current state of a methodology to identify relevant scenarios for the safety assessment of automated driving. In focus are the metrics (M_*) that are used to reach objective decisions when following this methodology. Two approaches are proposed to capture the relevant scenarios. On the one hand the top down analysis starts with the final goal of the release of an automated vehicle (left upper corner of Fig. 3) to include relevant scenarios. On the other hand the bottom up analysis starts with different existing information sources that contain and generate a diversity of scenarios (left lower corner of Fig. 3). Both approaches

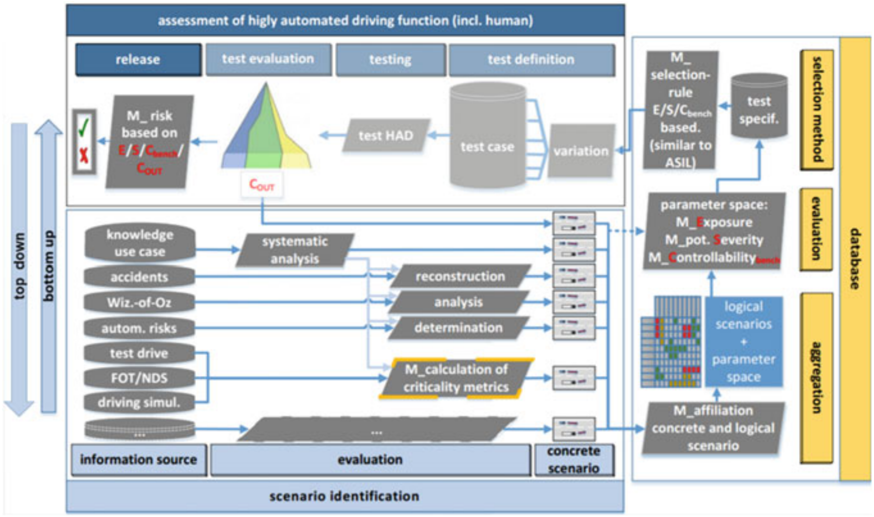

Fig. 3 Current state of the methodology to identify relevant scenarios

should lead to a database that summarizes in a standardized way the scenarios, their parameter spaces as well as an information on relevance for the assessment activities.

The aforementioned methodology is a proposed approach that is still under development improvement. The overall aim is to come to an acceptable common methodology and scenarios. This should **not** be seen to replace real-world driving but to complement it by enabling proofing ground tests, software in the loop tests and others that promise to help assessing automated driving's safety more efficiently.

2.4 Developing and Assessing Automated Driving (Lutz ECKSTEIN, RWTH Aachen University, Institute for Automotive Engineering (ika), Germany)

The assessment and certification of automated driving probably constitutes the most demanding challenge, which requires a sophisticated, collaborative approach. In this presentation, a novel approach to structure and visualize the interdependencies of challenges was proposed. The so-called 5-Layer-Model on automated driving, as illustrated in Fig. 4, depicts the interaction between five layers and the respective requirements and results on each of the layers: scientific evidence on the Human Factors Layer e.g. for level 3 Automated Driving will influence not only the functionality on the Technical Layer, but also rules on driving behavior on the Legal Layer, which again may influence the customer´s willingness to pay on the

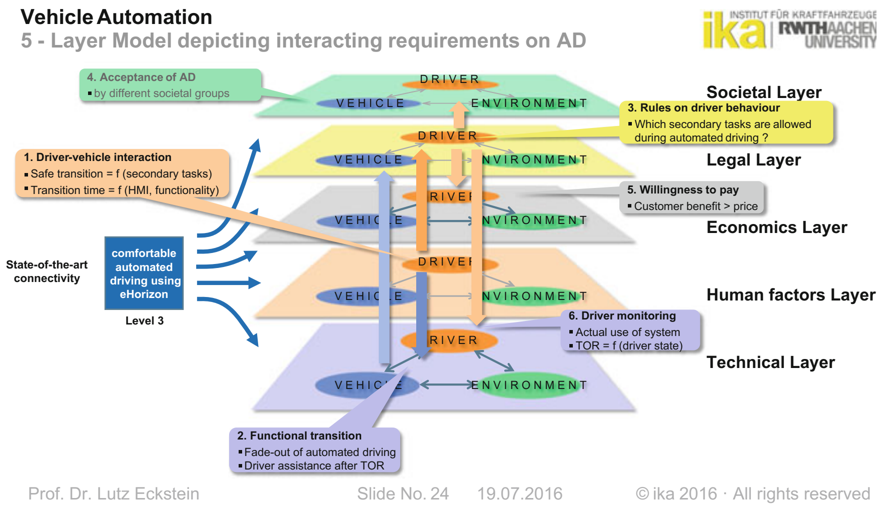

Fig. 4 5-layer model depicting interacting requirements on Automated Driving

Economics Layer. The Societal Layer is regarded as the top layer, since rules and regulations will only be adapted if the benefit of Automated Driving for society can be shown and is recognized (see Fig. 4).

Moreover, special emphasis is put on the question of assessment and certification on the way to automated driving, based on a continuous collection, abstraction and variation of relevant traffic situations. Finally, the contribution of different projects and especially of PEGASUS is described.

2.5 *Establishing Trust in Autonomous Vehicles—An Aerospace Perspective (Tim Allan WHEELER, Stanford University, Stanford Intelligent Systems Laboratory, USA)*

Autonomous vehicles and other emerging active driving systems require advanced science and engineering methodologies by which trust can be established. The certification of any automated driving system will require a combination of driving tests and detailed simulation studies to ensure system effectiveness and safety. This talk covered recent developments in collision avoidance in civil aviation, which allowed for the creation of rich encounter models based on a Bayesian statistical framework from which optimal collision avoidance strategies have been derived and validated (see Fig. 5).

The route to building trust lies in the creation of a scientific, unified, transparent framework to optimize and evaluate active driving systems. Civil aviation has an

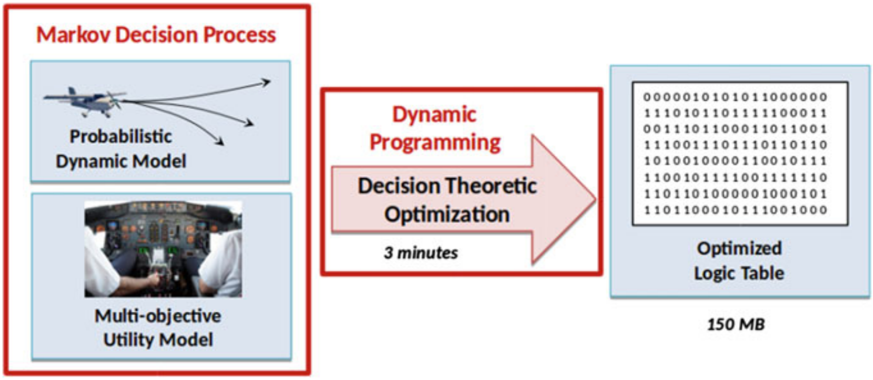

Fig. 5 The collision avoidance problem for aviation framed as a decision making problem

outstanding safety record, and one can use similar approaches in automotive safety validation. To this end we need a cross-industry standard model that is open, unified, and transparent.

2.6 Driving Autonomous Vehicles to Safety (Nidhi KALRA, RAND Center for Decision Making Under Uncertainty, USA)

The presentation raises the following questions: How safe should autonomous vehicles be before they are allowed on the roads? How do we (not) prove they are safe? How might our near-term safety choices affect the long-term evolution of the technology? These and other pressing policy questions are discussed. Suggestions are made to explore how adaptive regulations may be a promising way to answer the aforementioned questions.

2.7 Functional Validation and Performance Assessment of Automated Truck Platoons in Controlled Environments (Marcos PILLADO, Applus IDIADA, Spain)

Platooning of heavy duty vehicles (HDV) provides the opportunity to save fuel, increase safety and add road capacity. The COMPANION (Cooperative dynamic formation of Platoons for safe and energy-optimized goods transportation) project has developed and validated a system for creation, coordination and operation of platoons. A complete integration of the entire system was performed in the project

Fig. 6 Platoon under test

in order to make a global assessment of the full system. The testing methodology used for the validation and performance assessment of the platooning maneuvers and the on-board HMI in a controlled scenario, Fig. 6 shows the arrangement of three trucks platooning in Applus + IDIADA test tracks. The functional validation aims to identify the potential effects of failure conditions within vehicle components in a platoon prior to testing the system on public roads (if necessary define additional mitigations to be put in place to enhance safety) in order to ensure that previously identified safety requirements are capable of being satisfied. The analysis takes into account the defined pre-conditions and expected circumstances associated with the potential scenarios on public roads.

2.8 Challenges in Autonomous Vehicle Testing and Validation (Michael WAGNER, Carnegie Mellon University, USA)

Software testing is all too often simply a bug hunt rather than a well-considered exercise in ensuring quality. A more methodical approach than a simple cycle of system-level test-fail-patch-test will be required to deploy safe autonomous vehicles at scale. The presenter identifies five major challenge areas in testing according to the V model for autonomous vehicles and discuss promising potential solutions. While significant challenges remain in safety certification of algorithms that provide high-level autonomy themselves, it seems within reach to instead architect the system and its accompanying design process to be able to employ existing software safety approaches.

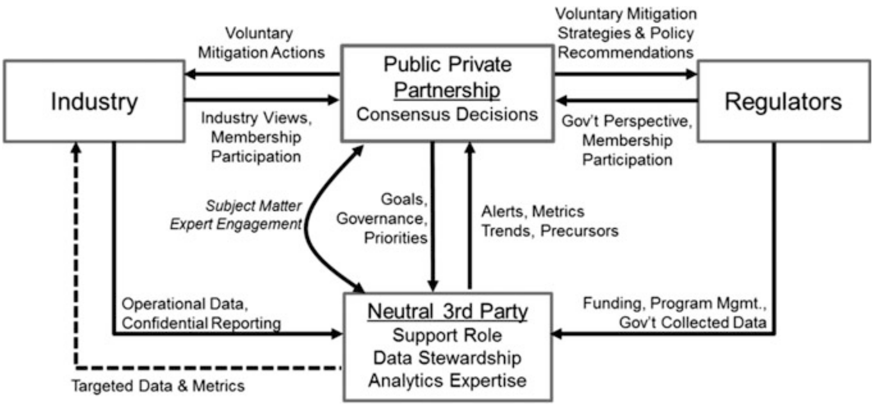

Fig. 7 Safety data sharing framework

2.9 Applicability of Lessons Learned from Aviation Safety Management System for Automated Vehicles (Andrew LACHER, Unmanned and Autonomous Systems Research Strategist, the MITRE Corporation, USA)

In January 2016, US DoT, NHTSA, and the automotive industry agreed to examine the existing aviation industry voluntary/anonymous safety information reporting systems to understand whether such an approach could be utilized in the auto sector. Safety data sharing is one of the components of a Safety Management System (SMS) which is a standard recognized throughout the aviation industry worldwide. Using SMS practices, the Commercial Aviation Safety Team (CAST, a combined industry/Government group) reduced the risk of commercial aviation fatalities in the US by 83% in 10 years.

One of the keys to the success of the data sharing initiative under CAST is the public-private partnership that was established with the regulator and the industry as equal partners (see Fig. 7).

Data is not shared by industry with the regulator but with a neutral 3rd partner with insights (e.g., benchmarks, specific safety mitigations, aggregated results) shared with the broader community to include industry participants, the regulator, and the general public.

As automotive vehicles become increasing automated, there are likely lessons from automated flying associated with human factors and cognitive science that could be leveraged to guide the system design of future road vehicles.

There may be some appropriate practices to be taken from the approach that the aviation community takes associated with pre-production approval and airworthiness of aircraft that could also be applied to highly automated vehicles and connected driving.

3 Summary of Panel Discussion

Selective major questions raised by participants and the corresponding comments and discussions are highlighted below.

- *What is the role of the driver for different levels of autonomy?*
  The experts explained the differing expectations but there was still an issue of potential confusion about whether customers would understand the differentiation. The challenges associated with driver hand-off was emphasized.
- *How can data for safety assurance be collected commonly and shared for the design of safety systems?*
  The German government has started a project to collect data for certification purposes.
- *How can learning systems be tested and why would monitoring unknown situations be useful?*
  There is no solution for the problem of unknown unknowns. One can have a run-time monitor to record a system's boundary and capabilities, then the behavior can be pre-identified to ensure the whole system behavior is safe. The monitor can tell whether I am in a known condition, rather than a safe condition; or if not, the system can issue a reasonable failsafe strategy.
- *How to communicate the fact that the AV cannot be shown to be perfect before introduction?*
  There is a fundamental difference between opinions and values. We should clearly explain the implications and have it accessible to the public. It is a communication problem, but mere communication is not enough. How a message is conveyed to the public greatly influences interpretation. There is a perception gap about what the testing is for. It is important to make the communication clear, so people could think through the problem more carefully.
- *Is there anything to be learned from the FAA to apply to autonomous driving?*
  The comparisons between the worlds of aviation safety and road safety were discussed concerning risk management and their financial resources for safety. The FAA ASIAS project could be used as a reference for an automotive data and safety reporting program.

4 Key Results

The following is a list of key points captured in the panel presentations and discussions.

A safe and fail-operational vehicle implies a lot of redundancy, which is not a current state-of-the-art practice in automobiles.

- Safety-related tasks must be clearly divided between driver and autopilot (or the designated automated driving functions).

- There are strong interdependencies between levels of automation and safety assurance approaches.
- Scenario-based testing needs a documented and traceable way showing where the tests are derived from.
- Databases and test methodologies must be developed and deployed step by step.
- A scientific, unified framework to optimize and evaluate the safety will lead to trust in automated driving.
- We cannot wait for a perfectly safe AD system. Instead, we should start with reasonable safety in order to offer improvements as soon as possible with the potential benefit of saving lives.

5 Next Steps

We present a list of next steps suggested by the panel participants.

- Creating open databases for test scenarios
- Establishing a safety management system (mimicking the model from aviation?)
- Developing scientific accepted validation methodology
- Standards, standards, standards, (***emphasis*** added by authors) … need to be established for validation (not for function)
- Convey realistic expectations about safety to the public

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Enabling Technologies for Road Vehicle Automation

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Abstract Technology is to a large extent driving the development of road vehicle automation. This Chapter summarizes the general overall trends in the enabling technologies within this field that were discussed during the Enabling technologies for road vehicle automation breakout session at the Automated Vehicle Symposium 2016. With a starting point in six scenarios that have the potential to be deployed at an early stage, five different categories of emerging technologies are described: (a) positioning, localization and mapping (b) algorithms, deep learning techniques, sensor fusion guidance and control (c) hybrid communication (d) sensing and perception and (e) technologies for data ownership and privacy. It is found that

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reliability and extensive computational power are the two most common challenges within the emerging technologies. Furthermore, cybersecurity binds all technologies together as vehicles will be constantly connected. Connectivity allows both improved local awareness through vehicle-to-vehicle communication and it allows continuous deployment of new software and algorithms that constantly learns new unforeseen objects or scenarios. Finally, while five categories were individually considered, further holistic work to combine them in a systems concept would be the important next step toward implementation.

Keywords Vehicle automation · GNSS · Deep learning · Local awareness · Hybrid communication · V2V

1 Introduction

Technology, user experience and legislation are three great challenges to overcome to be able to introduce high and full road vehicle automation (Dokic et al. 2015; Smith 2014; Meschtscherjakov et al. 2015). This paper highlights the findings from the Automated Vehicle Symposium 2016 in San Francisco with regards to enabling technologies for road vehicle automation.

The findings from this paper may function as a research road map by (i) exploring a wide range of technologies to enable road vehicle automation (ii) gain an understanding of how these technologies will need to work together to address needs of the applications, and (iii) realize the potential shortfalls in these technologies, ranging from pure technical capabilities through the conformance to the perspectives listed above.

To describe the underlying technologies we project the technologies onto one or several of the vehicle-highway automation scenarios, see Sect. 2. The incremental development and gradual introduction of ADAS pave the way for higher level of road vehicle automation in all the challenges listed above. However, from a holistic perspective, it is a huge difference between technology that support the driver and technology that is completely autonomous.

Automation is divided into six different levels, ranging from (0) no automation to (5) full automation as defined in the international SAE standard J3016[1] see description in Table 1.

2 Automation Scenarios

During the breakout session, technologies were presented and discussed with consideration to the following use-cases of automated vehicles (AVs), previously identified as having the potential to be deployed at an early stage.

[1] www.sae.org/misc/pdfs/automated_driving.pdf.

Table 1 Description of SAE level of automation

SAE level	Name	Description
Level 0	No automation	No automation
Level 1	Driver assistance	Automation of one primary control function, e.g., adaptive cruise control, self-parking, lane-keep assist or autonomous braking
Level 2	Partial automation	Automation of two or more primary control functions "designed to work in unison to relieve the driver of control of those functions"
Level 3	Conditional automation	Limited self-driving; driver may "cede full control of all safety critical functions under certain traffic or environmental conditions," but it is "expected to be available for occasional control" with adequate warning
Level 4	High automation	Full self-driving without human controls within a well-defined Operational Design Domain, with operations capability even if a human driver does not respond appropriately to a request to intervene
Level 5	Full automation	Full self-driving without human controls in all driving environments that can be managed by a human driver

Scenario 1: Required Connected Capability—A large western country decides that as of 2017 all newly manufactured vehicles must come with connected vehicle safety technology and that within a span of several phase in years all cars must be equipped or retrofit with the capability.

Scenario 2: Retirement Community—A small town (about 20,000) which is mostly a wealthy retirement community mandates that on a certain date that vehicles registered and traveling within the city limits must be autonomous vehicles.

Scenario 3: Mandated Platooning—Platooning { In 2020, The US government mandates platooning trucks or automated vehicles only in the far left lane for large sections of the US interstate highway system.

Scenario 4: Small City Taxi Service—A large corporation in conjunction with a medium size city, about 400,000, launches a driverless taxi service to service the entire metropolitan area.

Scenario 5: AVs in Hot Lanes—A large state plans to modify its hot-lanes so that to incentivize AVs, for example, providing specific time windows for AVs and offering free or reduced access fees. Initially the incentives are limited by taking into account the market penetration but they are expected to expand over the next couple of years until they become 24/7 for AVs.

Scenario 6: Delivery Platooning—In 2016, a large Nationwide US package delivery service deploys platooning technology (SAE Level 1 or 2 and Connected Vehicle technology) to its cross country fleet and starts organizing platoons. It has previously received government approval to optimize the work rules surround platooning truck drives.

3 Emerging Technologies

3.1 Position, Localization and Mapping

Positioning, localization and mapping have a mutual relationship and the performance of the overall navigation system, both nearby and far away, is dependent on their individual performance. State-of-art maps have 10 cm accuracy with detailed lane-level information and provide the basis for automated vehicles to be able to drive in a way recognizable by humans. To create such detailed maps, technologies such as swarm mapping (Kronfeld et al. 2008) and crowd sourcing are typically used.

Positioning is achieved through Global Navigation Satellite System (GNSS) and technologies such as GPS L1/L2, GLONASS, BeiDou and Galileo are among the most popular ones. However the accuracy of GNSS is typically in the range of meters. To achieve high accuracy positioning, differential positioning systems where a fixed base-station broadcast correction signals locally are used. The state-of-art positioning is accomplished by real-time kinematics (RTK) technology where accuracy of 1 cm can be achieved.

Since the GNSS-device needs to connect not only to the satellite but also to a ground-based reference station, the risk of disturbances is substantial. Other challenges within this field are for example the high computational load that is caused by the high definition maps and sensors. Open research questions are for example if the mapping should be made in each individual vehicle or in a powerful cloud-based computation platform.

3.2 Algorithms, Deep Learning Techniques, Sensor Fusion, Guidance and Control

Whereas positioning, localization and mapping take care of the navigation, the algorithms, deep learning techniques, sensor fusion, guidance and control handle the actual scene identification, threat assessment and behavior of the vehicle.

To date, computer-based vision systems are the most prominent approaches to road vehicle automation. However, 2D vision systems have difficulties to obtain depth in images and thus they are often fused with radar and lidar sensors (Hasch et al. 2012; Carlino et al. 2016). Maneuvering in a complex traffic environment requires deep understanding about the local environment and one of the most promising algorithms to achieve this is deep learning. Deep learning algorithms have shown to be particular useful in learning meaningful representations and patterns in large amount of data (Najafabadi et al. 2015). Deep learning algorithms use an hierarchical multi-level learning process where the complex high dimensional representations are learned based on lower dimensional representations in the subsequent layers in the hierarchy.

Deep learning can be used both to categorize data into previously unknown clusters/patterns i.e. unsupervised learning, or it can learn from labeled data if it is available in sufficiently large amounts.

One challenge in this domain is the lack of labeled training data which is a tedious and labor intensive work. The computational power required to train the networks is another challenge, although recently high performance multi-core platforms for training and execution are available. However, to constantly improve the performance of the computer vision-based system of vehicles that are already deployed will require (a) ways to collect new, unforeseen data that should be used to update the system, (b) high performance cloud-based computing to re-train the deep neural networks and (c) secure communication networks to support continuous deployment of the new software.

Vision Systems are also used for lane keeping guidance but suffer from lack of high assurance required for lane keeping guidance due to high entropy inherent in vision-based systems. More research is needed on sensors like radar for lane keeping and platooning guidance which can offer higher accuracy and precision for specific information required for vehicle dynamics control. Radar also has the potential for more assured lane detection if augmented with infrastructure improvements like using high Radar Cross Section (RCS) rectors instead of the prevalent painted lane guides.

3.3 Hybrid Communications

To improve the performance of automated vehicles, communication is one *sensor* that has a large potential to create a traffic system that is more efficient than that controlled by humans. Communication allows information exchange with objects or vehicles that are out of sight for the in-vehicle proximity sensors, making it possible to warn a vehicle about hidden threats or send out an early warning about a slippery road, a pot hole or a road construction. To cope with the dynamic and heterogeneous traffic system, a hybrid communication system is required. Dedicated Short Range Communication (DSRC) performs well with an update frequency of 10 Hz and a nominal transmission range of up to approximately 300 m. However, the physical channel quickly become congested when traffic increases resulting in low throughput and packet loss. To alleviate the load and to allow long range communication either infrastructure-based repeaters or road-side-units may be used to filter and relay the communication. Another solution could be to use a different communication technology e.g. 3G/4G/5G/LTE. In the European standard ITS-G5 (Chen and Englund 2014), the architecture allows communication with different physical layer technology, which allows for hybrid communication. Vehicular communication is highly standardized regarding the physical layer communication and there are significant standardization activities on applications, and the breadth of applications is considerable. However, to enable intelligent interaction and negotiation to allow vehicles to automatically change lane, in e.g. a platooning scenario, further investigation is needed (Englund et al. 2016).

3.4 Sensing and Perception

Hardware components for sensing and perception are developed hand in hand with software i.e. powerful dedicated hardware for image analysis in vehicles is developed in parallel with deep learning algorithms, see Sect. 3.2. Beside the rapid development of powerful, yet low cost camera (Sivaraman and Trivedi 2013), radar (Hasch et al. 2012) and lidar systems (Carlino et al. 2016) that can be used to recognize the close vicinity of a vehicle, wireless communication technologies that can provide information about non line-of-sight objects is also maturing. Communication systems for vehicular applications covers a broad range of technologies ranging from DSRC to cellular communication, efficient for different applications. The *degree* of collaboration may also vary depending on the application. For example, in a platooning system, safety critical information is shared among the platoon members which strongly affect the operational behavior of the vehicles. In a cloud-based system where vehicles share information about e.g. road conditions the shared information is less timely and the degree of collaboration on the operational level is lower. Instead, the collaboration on the tactical level such as route planning is more prominent (Aramrattana et al. 2015).

To enable high level of automation, sensing and perception of the environment are two major technical challenges. To date, fusion of vision, radar and lidar systems is the most common approach to achieve robust situation aware- ness. However, there are initiatives to allow pure vision-based systems to learn from e.g. driver behavior to drive vehicles (Xu et al. 2016; Shalev-Shwartz and Shashua 2016). To speed up this technology development, online databases from sensor readings are available (Cordts et al. 2016).

Other open research questions related to this domain are how to cover a wide dynamic range of the sensor systems and how to achieve robustness in terms of redundancy and thus, high reliability.

3.5 Technologies for Data Ownership and Privacy

Data ownership and privacy within Cooperative Intelligent Transportation Systems (C-ITS) and automated driving are two areas that are crucial for the development of road vehicle automation. As mentioned in the previous Sections, data from AVs may be shared for several reasons; route estimation; providing congestion and slippery road warnings; and gathering training data for centralized machine learning systems. Nevertheless, not only privacy of the ego vehicle or the driver is of interest but also personal data of people caught by the vision-based sensors of a vehicle must be handled with care. In Marín Pérez et al. (2015) and the references therein, recent findings on the development of security and privacy for vehicular networks are described. This topic is also addressed in the current work on the C-ITS platform in Europe with the objective to facilitate the convergence of investments and regulatory frameworks in the EU to deploy mature C-ITS services from 2019 and beyond. The results from the first phase of the C-ITS platform have on the one hand addressed the architecture to enable data sharing within C-ITS. However, on the other hand, the Cooperative Awareness Message (CAM) and the Decentralized Notification Message (DENM) are considered as private information and should be treated accordingly. Consequently, more research efforts are needed to regulate the privacy and technical development to create anonymized CAM and DENM messages.

Given that secure communication is established, cybersecurity and handling of security breaches are two important research fields. All components e.g. sensors, sensor fusion, data processing, communication, vehicles and infrastructure need to be considered to achieve resilient communication within road vehicle automation and C-ITS. One approach to create trust between road-users is proposed in Rosenstatter (2016). Here the validation of the actual shared data is the main goal instead of focusing on the validation of the source. A trust index is calculated depending on both historical behavior of the ego vehicle as well as on other vehicles and road infrastructure (location), in order to build a control system for a cooperative automated vehicle that is able to make more reliable and safe decisions. The system showed good performance while testing with data from the Grand Cooperative Driving Challenge 2016. Further research on how trust and reputation models can be shared among road users using cloud-based infrastructure is one future research topic that to a large extent also address data ownership and privacy.

4 Conclusion

This Chapter highlights discussions and findings during the breakout session, enabling technologies for road vehicle automation, convened during the Automated Vehicle Symposium 2016. In addition, the Chapter identifies future research directions that can address the shortfalls of the technologies. During the break out session it was primarily discussed how reliability of the systems need to be at a sufficiently high level to allow introduction of automated vehicles; this yields positioning, proximity sensors as well as software and algorithms. Currently, sensors provide accurate information however the computational power and the infrastructure for continuous deployment of software needs to be further studied. Consequently, cybersecurity is related to this field while handling the connectivity and on-line software updates over the Internet.

Another research field aims to complement proximity sensors with information that are not line-of-sight by using wireless communication. To handle challenges with end to end applications, hybrid communication solutions can utilize the most appropriate technology at any time by combining e.g. DSRC and cellular communication. Additionally, cybersecurity, data ownership and privacy will become crucial in the future traffic systems, particularly in light of the proposed rule-making from NHTSA, to have 50% of all light weight vehicles to be equipped with DSRC by 2021, and 100% by 2023, this will be readily dealt with.

As a final take-away, combining five technology categories—(a) positioning, localization and mapping (b) algorithms, deep learning techniques, sensor fusion guidance and control (c) hybrid communication (d) sensing and perception and (e) technologies for data ownership and privacy—with six scenarios—(1) required connected capability, (2) retirement community, (3) mandated platooning, (4) small city taxi service, (5) automated vehicles in hot lanes, and (6) delivery platooning—started but did not complete the consideration on what combinations of enabling technologies may practicably set the stage for a gamut of automated vehicle futures. Certainly, further scenario-based discovery of the synergies between the technologies has merit.

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Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions

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Abstract The integration of automated and connected vehicles on our existing road network is expected to impact traffic efficiency and safety. This upcoming new reality causes road operators, researchers, and policy makers to raise critical questions on the requirements and implications of automated and connected vehicles on the road infrastructure. We present a state of the art on this topic while considering both the digital and the physical infrastructure. A considerable research effort exists with respect to the digital infrastructure, while for the physical infrastructure it is scarce. Based on the state of the art, and a brainstorming workshop involving experts from different disciplines in the Netherlands, a detailed mind map is presented and recommendations for future research directions are suggested.

Keywords Automated driving · Physical infrastructure · Digital infrastructure

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1 Introduction

Following the rapid development toward vehicle automation and the desire for sustainability, there has been in recent decades considerable efforts to advance and develop the infrastructure for automated and connected driving. Lamb et al. (2011) present the Forever Open Road vision and scheme, redefining how roads can be designed, constructed, operated and maintained in the future, and present future research opportunities. “The Forever Open Road will be constructed from pre-fabricated elements, built and maintained using sustainable materials. It will have adaptable capacity provision (lanes, hard shoulder and central reserve), and built-in services and communication systems. It will measure its own condition, harvest energy, and clean and repair itself. It will communicate with vehicles and will allow for automated driving”. However, this vision holds many knowledge gaps and uncertainties that require comprehensive research in the field of physical and digital infrastructure.

The remainder of this paper is structured as follows: Sect. 2 reviews the state of the art on physical and digital infrastructure, followed by Sect. 3 which presents the results of the brainstorming workshop. Section 4 synthesizes the findings, and Sect. 5 presents the knowledge gaps and future research directions.

2 State of the Art

This state of the art reviews the existing literature on the topic of automated vehicles and infrastructure. The databases and search engines used were: Google Scholar, Scopus, Web of Science, and TRID. The keywords used were: “road infrastructure AND automated vehicles OR self-driving vehicles”, “road design AND automated vehicles OR self-driving vehicles”, “cooperative systems AND road infrastructure”, “digital infrastructure AND automated vehicles”, “physical infrastructure AND automated vehicles”. Only reports in English were included from 2000 onwards. The review resulted in the division into physical and digital infrastructure, as presented in Sects. 2.1 and 2.2, respectively.

2.1 Physical Infrastructure

The literature on the implications of vehicle automation on the physical infrastructure is scarce compared to that on the digital infrastructure. The literature found is categorized into geometric road design and structural pavement design.

2.1.1 Geometric Road Design

Several experts indicate that under the assumption that all vehicles are automated and connected, standards regarding the width of the road could be reduced. Hayeri et al. (2015) indicate that since lane keeping systems will guarantee that vehicles stay within their lanes, it would be possible to reduce the width standards of lanes, shoulders, clear zones, and medians. As a result an additional lane could be created, and possibly dedicated to platoons. However, clear zones for emergency or maintenance operation will still be required, but probably with narrower width, as automated vehicles will have precise positioning capabilities. Other studies (Somers and Weeratunga 2015; Lumiaho and Malin 2016) reached similar conclusions. Managed lanes (High Occupancy Vehicles (HOV) lanes and High Occupancy Toll (HOT) lanes) could be used as experimentation and first adoption areas for connected and autonomous vehicles (Hayeri et al. 2015).

Washburn and Washburn (2014) discuss in their report two factors that largely impact the road geometric design: vehicle performance and sight distance. Despite better braking technologies in autonomous vehicles, the need to consider human tolerance to the resulting forces, as well as energy consumption and emissions, limits the maximum acceleration rates used. With respect to sight distance, auto-mated vehicles would not perform better than humans in situations where the line of sight is limited, unless connectivity, i.e. V2X, is available.

McDonald and Rodier (2015) summarize the changes in freeway design that are expected as a result of the advancement in vehicle technology. Among these changes: (1) Lanes with higher speeds could be provided for automated vehicles, with dedicated off-ramps. These ramps could allow for vehicle speeds of 100 mph ($\sim$160 km/h), could be steeply banked and shorter becoming mini ramps integrated with arterials; (2) Trucks could be separated by type and speed, and restricted to drive during night-time; (3) Medians could be replaced and used to accommodate other modes of travel or even turned into park space; and (4) HOV lanes could be converted to dedicated lanes, assisting with initial transition to automated vehicles.

Nitsche et al. (2014), defined the requirements on the infrastructure regarding the use of highly automated driving based on a literature review, and a web questionnaire. Based on this, the factors that mostly influence the lane assistance systems were identified. These include lane markings, their visibility and harmonization. For the collision avoidance systems, the complex urban road environment and poor visibility due to bad weather are most challenging, and therefore, infrastructure-based warning systems, sufficient road friction coefficient, presence of wireless communication beacons, and pedestrian and bicyclist protection at intersections are important. For the speed control systems, lane markings, roadside V2I/I2 V, infrastructure-based warning systems for bad weather and poor visibility, and clear and consistent traffic signs, are important. However, these systems do not cover the whole range of subsystems in automated driving.

2.1.2 Structural Pavement Design

Precise positioning of vehicles would allow to reduce the width of the lane, while new wear patterns of the pavement would appear which would require changes to pavement design (Kornhauser 2013). This new reality might lead to redefinition of the speed limit and the way it is determined, for example dynamic speed limits based on the road and traffic conditions, and mix of vehicles (automated and traditional vehicles) via traditional driver information signs. Automated vehicles could be programmed to drive more evenly across the whole width of the driving lane, thus reducing pavement wear. This would prevent the increased damage that would result from precise positioning, but it also means that lanes could not be made narrower (Carsten and Kulmala 2015).

Chen et al. (2016) used the finite elements modelling approach to analyse the impact on the pavement rutting performance when implementing automated vehicles on a large scale. While the decreased wheel wander and increased lane capacity could bring an accelerated rutting potential, the increase in traffic speed would negate this effect. Therefore, whether the resulting effect is positive or negative, depends actually on the practical road and traffic conditions.

2.2 Digital Infrastructure

Studies in the literature address different aspects of the digital infrastructure. In order to achieve full advantage of vehicle automation, connectivity between vehicles, between vehicles and vulnerable road users, and between vehicles and the infrastructure are essential (Sanchez et al. 2016). To develop this connectivity, several challenges and milestones should be accomplished, in various areas, such as: affordable sensing technology, high-precision positioning, communication technologies and digital maps. The scientific papers found are categorized into: Sensors, connectivity and cloud; digital maps and road database; and exact positioning.

2.2.1 Sensors, Connectivity and Cloud

Rebsamen et al. (2012) explored the value of using existing infrastructure sensors (such as traffic cameras) to improve safety and efficiency of autonomous vehicles in a simulation experiment and a field test in an urban environment. The authors argue that infrastructure sensors can provide essential information regarding the surrounding environment of vehicles which sometimes (as in the case of occlusion by objects or other vehicles) can be missed by the vehicle on-board sensors.

Regarding connectivity, at level 4 automation, the requirements include: Speed limit beacons for controlling speed, magnetic nails/reflective striping for lane keeping, infrastructure-assisted merging and lane changing, aided by roadside units

(RSUs), safety and warning messages on unexpected queues and for enhancing traffic signal operation (Zhang 2013). Current radio advisories and ITS message signs would be obsolete in a fully connected environment where V2I and V2X will directly transfer the information to on-board units in vehicles (Hayeri et al. 2015). However, in case of no connectivity, ITS message signs would still be needed. To facilitate safe operation for bicyclists and pedestrians, and in case of connectivity failure, signals at intersections are essential.

Eltoweissy et al. (2010) introduce the term Autonomous Vehicular Clouds (AVCs), which are autonomous clouds of vehicular computing, communication, sensing, power and physical resources. The main aim of the AVC is to provide on-demand solutions to events that cannot be dealt with reasonably in a proactive way or with pre-assigned assets. Unique characteristics of the AVC are the autonomous cooperation among vehicular resources and the ability to offer a seamless integration and decentralized management of cyber-physical resources. Gerla et al. (2014) describe the evolution from intelligent vehicle grid to autonomous, Internet-connected vehicles and vehicular cloud. The Internet of Vehicles will have communications, storage, intelligence, and learning capabilities to anticipate the customers' intentions. The advantages of vehicular cloud, and the challenges it faces, such as latency in information transfer, emergency (such as earthquakes) and security situations (such as malicious attacks), are presented.

2.2.2 Digital Maps and Road Database

For automated vehicles, the road database is considered as the most fundamental element (Hu et al. 2013). These maps should be highly detailed (3D lane geometry), highly accurate (sub-meter absolute, decimeter-level relative), and richly attributed (lane-level attributes, position landmark, road DNA that provides robust and scalable positioning content). Lee (2016) proposed a design of a road database for self-driving vehicles which includes dynamic data (such as: temporary closure of roads) as well as static data on roads using the Entity—Relationship model. The authors extracted six entities and ten relationships as requirements for the road database. These entities are: location, node, link, waypoint, traffic light, and crosswalk. Other studies indicate the need for more information. Bauer and Mayr (2003) developed a road database system that takes into account for each location on the road the geometrical characteristics as in road construction planning, such as the curvature of the road. This detailed data of the road is needed in order to develop a Velocity Profile Planning Module, which adapts the speed of the vehicle based on the road design characteristics. Shields (2016) indicates that some in-vehicle control processes can be helped by reliable knowledge of the road network, including: (1) knowledge on pavement surface quality, curves, hills, speed limits, and lanes; (2) information about difficult weather conditions, blocked or hard-to-find elements such as some signs and traffic signals; (3) reduction in sensor recognition processing by providing guidance about non-moving road items, and improving relative positioning by using landmarks with reliable positions.

2.2.3 Exact Positioning of the Vehicle

The main challenges when it comes to cooperative systems between vehicles and infrastructure are exact geo-positioning of vehicles, the matching of events to the in-car map-database and the proper presentation to drivers in real time (Böhm and Scheider 2007). Furthermore, for cooperative systems targeting enhancing safety, lane-specific positioning and situational access and speeds are recommended. A major challenge in realizing this, is the necessary real time accuracy in positioning. This may be realized by fusion of several in-vehicle sensors, and calibration of the On-Board-Equipment at gantries along the road. A new approach for accurate positioning of automated vehicles which relies on combining multiple positioning methods and is based on Global Navigation Satellite System (GNSS) to obtain absolute position was recently introduced (Knoop et al. 2017). The method is called: 'Single Frequency Precise Point Positioning (SF-PPP)', and it uses a low cost receiver with single frequency, single antenna, and single GNSS constellation (GPS). The results of testing the method showed that it can reach an accuracy of 0.5 m in open area environments, while in more closed environments the accuracy level decreases to 0.5–3.0 m.

3 Brainstorming Workshop

The brainstorming workshop was held on February 9th, 2016 and involved 13 experts from different disciplines from the Netherlands, including vehicle automation, structural pavement design, traffic engineering, planning, safety, and geometric road design. The workshop was held to develop a mind map for research needs regarding the infrastructure for automated driving, following previous efforts on this topic (Alkim and Veenis 2015). During the workshop, each expert was first asked to think of two to three future research questions related to the infrastructure for automated driving. All questions were then collected and clustered to a number of identified sub-topics. Following this a mind map was created, as presented in Fig. 1, and each expert was asked to select four research topics that should be given priority. The top four clusters that resulted from this process, i.e. those that received the highest ranking, were chosen as building blocks for a research program. These include: (1) *Impact of automated driving on existing infrastructure*: What are the expected changes in loading of the infrastructure, due to automated driving? and how will this impact infrastructure maintenance?; (2) *Transitions*: What are the impacts of transitions (mixed traffic and mixed infrastructure) on the road geometric design? and how will this change over time?; (3) *Design from scratch*: What is the ideal design for a future infrastructure for automated driving? How would we design an infrastructure for SAE level 4 and higher in a greenfield situation?; and (4) *Business case and decision making*: What are the costs and benefits of automated driving? What is the timing, how will this impact decision making?

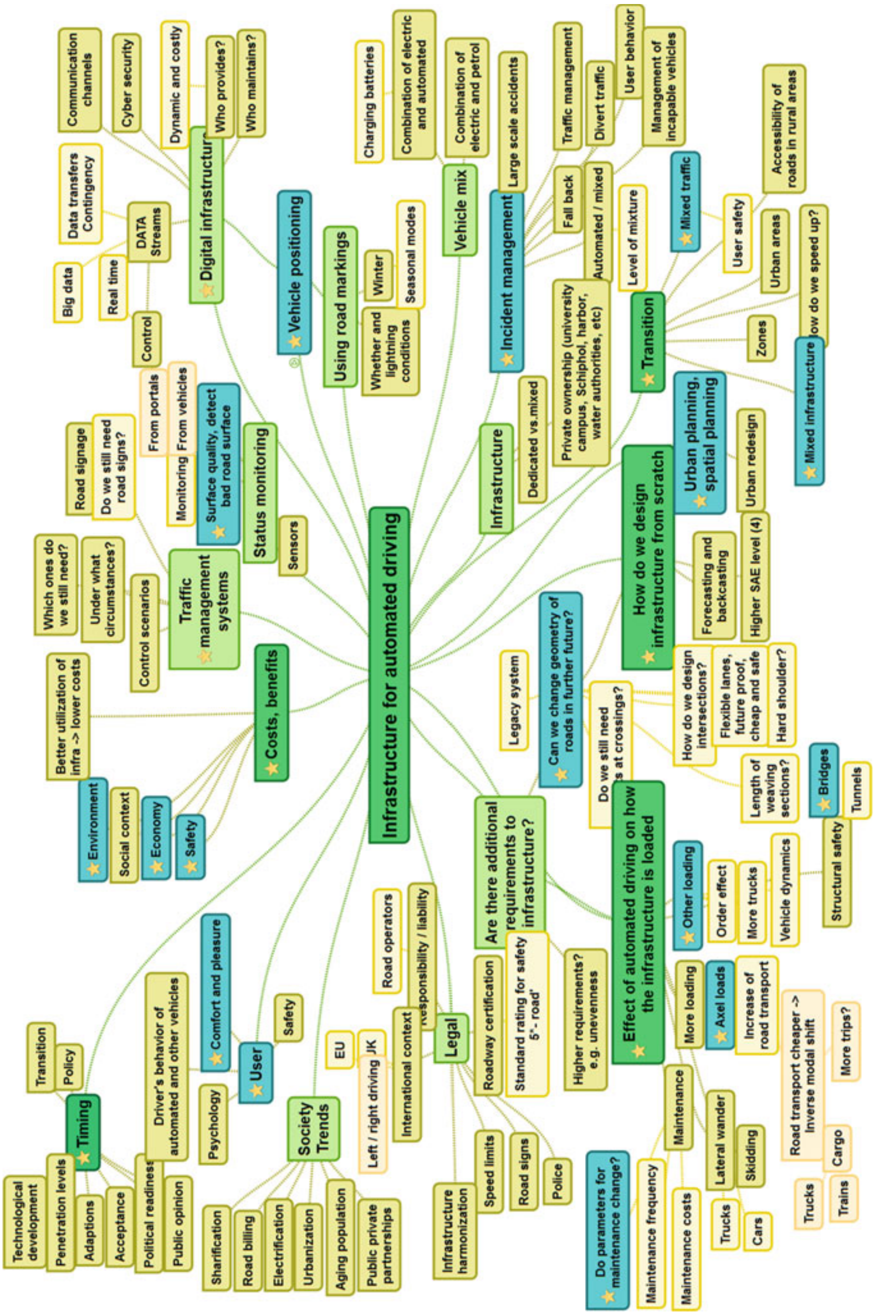

Fig. 1 Mind map for future research on infrastructure for automated and connected driving

4 Synthesis

The search for scientific literature on the topic of infrastructure and automated driving revealed that there is a considerable research effort with respect to the digital infrastructure, while for the physical infrastructure it is scarce.

With respect to the physical infrastructure it was found that the existing literature mostly assumes full penetration (100%) with automation level 4. There is a lack of studies which investigate the potential changes in the physical infrastructure in an intermediate stage of mixed traffic of automated and traditional vehicles. Many of these studies indicate the possibilities of reducing the cross section width standards. However, this would require careful investigation on the implications for the pavement maintenance, and traffic safety in case of emergency situations. It is also dependent on the development of precise positioning technologies, which again might have implications for the wear patterns of the pavement, and other pavement damage types, like ravelling. In reality, precise positioning of vehicles does not require big changes in the pavement design as in the frequency and costs of pavement maintenance. With respect to vehicle performance and sight distance, which are parameters that impact the design of the vertical and horizontal road alignment, it is not foreseen to be changed dramatically, as passenger comfort limits the acceleration forces that humans can tolerate. Furthermore, in case of only automation with no connectivity, vehicles would still have limitation of sight distance when there are obstacles, and by the road design itself (like crest curve or a bend). Several researchers suggest, as a first step, the possibility of using managed lanes as dedicated lanes for connected and automated vehicles.

With respect to the digital infrastructure, connectivity between the vehicles and the infrastructure, between vehicles, and between vehicles and other road users, such as vulnerable road users, is essential to utilize the full advantage of vehicle automation. This connectivity is currently not feasible. It requires advancement in several areas such as sensing technologies, precise positioning, and digital maps. The development of precise positioning is critical as the use of lane markings as orientation assistance for automated vehicles can be problematic in countries with severe weather conditions (such as the Nordic countries), and as a result of pavement wear. Researchers indicate the additional benefits of using information from infrastructure sensors which can be missed by the vehicles' sensors. Road signs and ITS message signs would be essential in case of connectivity failure, and in areas where vulnerable road users are present. For full deployment in real life there is a need for: real time and detailed digital maps (especially in hectic urban environments), video cameras monitoring, car sensors that work in all weather conditions, and connectivity. The developments of crowd sourcing for updating maps as currently done by some navigation companies will help to provide up-to-date maps. Also, as vehicles become more intelligent and equipped with sensors, this would speed up the maps' update process. However, it seems unlikely that this will be fast and accurate enough without considerable advancements in V2X communication and cloud computing.

5 Knowledge Gaps and Future Research Directions

Based on the reviewed literature several knowledge gaps with respect to the physical and the digital infrastructure are identified.

5.1 *Physical Infrastructure*

Since automated vehicles would have several new capabilities compared to traditional vehicles, such as shorter reaction times and precise positioning, this raises questions whether it would be possible to eventually have shorter merging/weaving configurations and on/off ramps, and whether we need longer lengths in intermediate stages, when we have mixed traffic. Similar questions can be raised with respect to the road width, especially the implications of reducing lane width on the traffic safety performance, and the safety perception of drivers/passengers, and regarding driver behavioural adaptation to conventional roads. It might be that transition zones will be needed between highways and city networks in case of switching driving modes (from automated to traditional driving), and in such cases, the question is how to design such transition zones.

In case the lane division on a road can be controlled via communication rather than markings in the fully automated situation, this opens new possibilities to narrow the lane width, which could eventually increase the capacity of existing roads. However, this might have implications for the deterioration of roads, and the required maintenance frequency. We still lack knowledge regarding the implications of this for changes in axle load distribution, order effect in asphalt damage development, load order due to platooning, increased or reduced deterioration, and the required adaption of design and maintenance approaches.

Knowledge is also lacking regarding the requirements that automated vehicles set for pavement conditions. How smooth/even does a road have to be for the sensors and software to function appropriately? What happens if a road does not meet those requirements? And should road authorities guarantee a certain level of performance for roads open to automated vehicles?

Since the transition to fully automated situation with 100% penetration rate will not happen overnight, but take several decades, questions are raised on how can we deal with mixed traffic (various levels of automation)? and whether the infrastructure should be separated for different levels of automation. Or, can roads be designed to safely mix vehicles at different automation levels?

The implication of automated vehicles on the safety of vulnerable road users in urban areas is a critical issue, and requires understanding of vulnerable road users behavioural adaptation. Only then we can develop safe urban design environments, and safe vehicle communication interactions.

5.2 Digital Infrastructure

Despite the relatively significant research efforts in the area of digital infrastructure compared to the physical infrastructure, there are still several knowledge gaps that are critical to the successful operation of automated vehicles and which require further research. Among these critical aspects, are the dynamic digital maps of the infrastructure and its surrounding. There is still knowledge gap regarding how accurate and detailed these maps need to be and the necessary details regarding the geometric design of the roads. What responsibility do road authorities have in providing these maps? A second critical issue is the research need to develop accurate and reliable positioning of vehicles, at a sub-lane level. With the development of digital maps, accurate positioning, and connectivity between vehicles, the question is raised whether there would still be a need for road signs and traffic management systems, to what extent, and how would this change with the increase in automation, and its reliability.

Automated vehicles will be equipped with many sensors which can monitor the infrastructure condition and feed it to other upstream vehicles. Sensors can also be incorporated in or around the road, to warn the approaching vehicles for risky situations like a pot hole, slippery road or accident. The question is, if the installations of road sensors are critical for the safe operation of vehicles, or whether the sensors installed in vehicles would be enough to gather and share that kind of information. Following this, the development of fusion methods of multi sensing and information for scene understanding and prediction will be needed. Furthermore, the huge amount of data created, which needs to be stored, shared and handled raises the question who will handle this large amount of data in the cloud? Finally, connectivity between vehicles and vulnerable road users in urban areas is still in its infancy and requires in the first stage a comprehensive understanding of the interactions between automated vehicles and vulnerable road users in different urban and rural design settings and different vehicle communication methods.

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Part V
Transportation Infrastructure and Planning

Understanding the Effects of Autonomous Vehicles on Urban Form

Sara Costa Maia and Annalisa Meyboom

Abstract Predicting the future impact of Autonomous Vehicles on infrastructure and urban form is critical for decision makers at all levels of government. The Autonomous Vehicle (AV) is a disruptive technology in transportation and its impact could resonate through all levels of society and government. The impact on infrastructure spending and decisions is one of the greatest reasons for understanding the potential outcomes of the technology but, in addition, the potential of the technology to play a positive role for the less advantaged members of society is large if there is proper direction of the technology as it is implemented. Auto makers view the technology as something which offers their customers a higher level of convenience and safety and, as such, they are in heated competition to develop this technology. In order to understand and speculate on the systemic urban impact of this nascent transportation technology, a comprehensive methodology is required. This paper will present, substantiate and describe such methodology. We base our proposal on existing future envisioning techniques for business decision making, precedent discussions on the impact of AVs, and on visionary traditions of architectural and urban design. We do not intend a precise method for future prediction, but rather a useful and robust tool that can be used by decision makers to take better informed decision on maximizing benefits and mitigating problems of new transportation technologies with regard to the quality of urban environments.

Keywords Autonomous vehicles · Urban planning · Methodology · Future visioning · Shell approach

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1 Introduction

One of the most determinant factors in the configuration of cities is arguably the modes and technologies that define urban transportation. Technological innovation is a critical aspect for consideration by transportation and planning professionals (Sussman 2005). Authors like Muller (1995) have also argued upon analytical research that there exists a "strong relationship between the interurban transportation system and the spatial form and organization of the metropolis".

We are now faced with the prospect of a new urban transportation shift, given the approaching feasibility of fully autonomous vehicles (AVs). The era of the AVs will likely foster a new and distinct urban model, which will be not only dependent of the technology currently under development, but also on the policies and urban planning decision to be taken in the early years of AV market penetration.

This chapter will provide decision makers with an understanding of the potential trajectories for the types of outcomes we may see for autonomous vehicles in our cities and outline what major aspects will influence these differing trajectories.

Understanding the full implications of introducing a new technology is no simple task. Since the beginning of the 20th century, when technology started to shift at very provocative rates, a multitude of researchers and enthusiasts have put efforts into envisioning the future scenarios enabled by new inventions. These speculations range from Villemard's hardly accurate illustrations for the year 2000 (Villemard 2017) to Nikola Tesla's technology-specific impressive predictions (Dommermuth-Costa 1994).

One of the developments of the work of McLuhan and Innis (Vassão 2008) is the assumption that any technology in itself carries unforeseen consequences, beyond its original purpose or content. Tenner, in the book "Why things bite back: Technology and the revenge of unintended consequences", also identifies a tendency towards the unavoidable ignorance of consequences, potentialities and developments of any technology (Tenner 1997).

McLuhan uses the invention of press as an example, pointing out its far-reaching role in the emergence of modern National States in Europe (McLuhan 1963). Despite its primary goal of accelerating the production of books, the press also allowed for standardization of education and imposition of a national language, besides supporting the advent of the Industrial Revolution. McLuhan points out that these consequences were already present in the conception of the press, but would only reveal themselves slowly in time. Analogously, the consequences of AVs are also present in their conception and revealing these consequences is an interesting and important exercise.

In the fields of architecture and urban planning, technology has also been involved in 20th-century visionary thinking to a similar extent that social issues were central to 19th century speculative design (Collins 1979). These visionary works, however, are of arguably different nature than Villemard's or Tesla's. Architectural visionary thinking is conceived as a statement, a utopian manifest, with little interest to predictive accuracy. They are not solely concerned with what cities will be, but with what they could be, and how it reflects values and ideas in a very intentional way. They aspire towards an improved reality according to the authors' particular ideals, and strive to influence the making of the world with such ideals.

Apart from the aforementioned modes of envisioning the impact of technologies, it can also be mentioned the abundant literature that offer technical/scientific predictions for certain technology's aspects, typically based on statistical models. For example, the journal Technological Forecasting and Social Change, by Elsevier, presents several robust studies of the sort. These studies, however, are commonly focused on overly specific aspects of technologies. They cannot illustrate comprehensive, speculative scenarios that allow for a broad understanding of the impact of AVs, and other transportation technologies, on urban form and quality.

In order to investigate the systemic urban impact of new transportation technologies, a new comprehensive methodology is required. This paper will propose one such methodology based on existing future envisioning techniques for business decision making, precedent discussions on the impact of AVs, and on visionary traditions of architectural and urban design. We do not intend a precise method for future prediction, but rather a useful and robust tool that can be used by decision makers to make better informed decision on maximizing benefits and mitigating problems of new transportation technologies with regard to the quality of urban environments.

In the next section, a historical perspective is presented in order to illustrate the impacts of transportation technologies in our cities and to outline a trajectory which may be then analyzed and used for forecasting. Next, we present publications that discuss methodologies and the impact of AVs on our cities, highlighting how our methodology contests their approach or builds upon their contributions. Lastly, the methodology itself is introduced and discussed.

2 Looking into the Past: The Trajectory so Far

For the most part of human history, walking had been the foremost mode of transportation. As a result, since the first urban settlements until the Industrial Revolution, cities had maintained fundamental similarities among them.

Early cities were compact and typically located near a water source. Being compact assured that they were not only easier to defend, but also that there would be a reasonable walking distance between activities, dwellings, and the waterfront. This spatial constraint resulted very dense and congested cities, with a mix of functions and with the best addresses located closer to the centre (Jackson 1985). The scale of the street was also for the most part related to the human body.

With the Industrial Revolution, successive technological innovations related to transportation appeared throughout the 19th century, such as the steam ferry, the omnibus, the cable car and modern railroads. This allowed a large number of people to commute daily, easily covering larger distances than that allowed by walking alone. In the U.S., the first suburbs appeared, like Brooklyn Heights, connected to lower Manhattan by a regular steam ferry service inaugurated in 1814 (Frumkin et al. 2004).

However, even with mechanized transportation, cities remained compact. American rail cities in the early 1800s, where homes and business clustered around the rail lines, are good examples of this. The rail lines determined also the direction of suburbs development, "extending like fingers from the central city" along the lines (Frumkin et al. 2004).

By the end of the 19th century, urban mass transit provided urban mobility and links to suburban locations to an increasing number of people. Around this time, cities saw the emergence of specialized districts, given the ease of mobility between them. The residents with more financial flexibility started permanently setting residence outside the clustered city cores, which were dirty, overpopulated and prone to frequent epidemic bursts. Thus, given increased mobility, spatial segregation based on income and social status gained new means and proportions.

When the 20th century arrived, it witnessed an unprecedented revolution on personal mobility, with the availability of commercial flights, fast trains and—most importantly—the automobile.

Although forerunners of the automobile appeared during the 1860s, it is only after Model T's debut (1908–1927) that automobiles became affordable. Several reasons were responsible for the slow initial adoption of automobiles, including: laws restricting the use of cars, poorly surfaced roads, technical unreliability of early automobiles, and the difficulty to navigate poorly signalized roads. Yet, the automobile culture developed rapidly. Aspects that favoured the adoption of automobiles included the fact that road building became a publicly financed enterprise, pushed by the interests from the oil, automobile, road-building and land development industries (Frumkin et al. 2004).

The immediate consequences for the city were a business boom in downtown areas, followed by automobile congestion and parking issues; and the great development of suburban areas, mostly configuring automobile suburbs. Several aspects justify such expansion pattern, among them a strong rural/land tradition in North America and, perhaps most significantly, the enormously profitable enterprises of suburban development (Frumkin et al. 2004).

Automobile suburbs were different from previous suburbs. The settlement pattern was dispersed, in contrast with the proximity to trolley lines that configured previous suburban developments. Jobs and services also became more scattered, changing transportation patterns in the cities and metropolis. The scale of the street increased over this period to accommodate the scale of the automobile, and the road became highly segregated in functions.

It is also important to notice that automobile adoption coincided with a significant increase of urban population. Mechanization of rural areas, for instance, along with appealing opportunities arising in urban areas, caused the drastic decrease of farm population. Urbanization and cities' inflation became a main process in several parts of the world. However, the resulting urban patterns are not always consistent across different regions.

In Europe, the urban shaping process during the post-war occurred differently than in North America. European cities retained a more centralized and agglomerated spatial structure (Sommers 1983). The difference is explained by that fact that land was expensive due to its scarcity, and money for private enterprise development was insufficient. Also, there was strong governmental control over urban land development and a different culture regarding cities.

The contrast between urban growth patterns in North America and in Europe shows that transportation technologies are not the only determinant in the configuration of urban form. Socio-political context, available resources and stakeholder interests, all have a large role to play.

Another important observation is that succession of transportation technologies typically leaves a much more significant mark in the expanding urban areas than in pre-existing urban fabrics. A study compares transportation choices in two different kinds of urban settings: “older, more traditional neighbourhoods that at one time were served by a streetcar, and newer, post-World War suburbs that were designed principally for automobile circulation” (Cervero and Gorham 1995). Although being anterior to automobile introduction, the older neighbourhoods were not fundamentally rebuilt to serve automobile infrastructure; instead, adaptations were made to allow for circulation of automobiles, leaving the basic urban fabric moderately unchanged.

Therefore, contemporary cities are often composed of different urban fabrics established at different moments in time and designed around a different set of transportation modes. Older city forms remain, around which newer urban designs develop. Based on this understanding, we can anticipate that AVs will impact urban form in two different ways: (1) by producing its own optimum infrastructure and urban design in areas of urban expansions and (2) by adapting existing urban fabrics without fundamental changes to the way they have been established. Furthermore, it is expected that cities who undergo massive expansion in posterior decades to AV introduction will develop specific AV-oriented patterns and design, while cities whose expansion has been stabilized will keep a character much closer to what can be observed today.

This conspicuous characteristic of urban expansion has led authors like Peter Muller to focus analysis on the metropolitan space (Muller 1995). He notes that “the spatial extent of the continuously built-up urban area has, throughout history, exhibited a fairly constant time-distance radius of about 45 min’ travel from the center, each breakthrough in higher-speed transport technology extended that radius into a new outer zone of suburban residential opportunity” (Muller 1995). This observation has also been independently reached by several other researchers, e.g. Marchetti (1994) and Iacono et al. (2008).

AVs have the opportunity to increase cities’ limiting radius in two ways. First, by increasing speed and efficiency of the transportation system, therefore achieving longer distances in a same amount of time. Second, AVs might be able to increase people’s flexibility towards commuting time. AVs’ comfort and convenience might allow for longer trips by merging transportation time with time used for other activities, i.e. working.

The expectation of urban expansion, especially on the form of sprawl, is a topic expected to raise concern. Some authors have argued that the introduction of AVs will signify further stimulation of Automobile-oriented development (Fagnant and Kockelman 2014). Therefore, it is important to consider the effects of such model of development, the ways in which AVs might assist in the aggravation of its problems, and what can be done to mitigate any negative impact.

Currently, most urban planning advocacy is focused on promoting public transit. New Urbanism and similar movements that arose since the 1980s strongly condemn automobile dependency and push forward agendas of smart growth, density, mixed uses and transit orientation, in some ways recovering urban models anterior to the automobile.

The future of AVs and our cities will be the result not only of transportation technology, but also of the confluence of several stakeholders' interests, from smart growth advocates to AV-related business investors. Long term planning will give us the chance to put forward important agendas for the city, and ensure that AVs will engage responsibly with current urban issues.

3 Looking into the Future: The Tools Available

The previous section provided an unstructured critique of past transportation technologies' impact on urban form and quality. However, in order to construct valid future scenarios based on a multitude of known variables, a well-structured approach must be established. We begin this process by studying existing methodologies and predictions.

By the time of the writing of this paper, the only known attempt to build future scenarios of AV impact on urban environments, using established methodologies, is the work by Townsend (2014). Townsend uses the "alternative futures method", developed at the University of Hawaii. This method posits that any story about the future can be grouped into one of four archetypes: Growth, Collapse, Constraint, and Transformation. He then presents his considerations for each scenario regarding AVs, following each archetype's defining characteristics, and develops the story of each scenario around these.

While Townsend's paper is fascinating to read, we do not believe that this method is sufficiently robust to serve as a decision-making support for planners, politicians and the public. Instead, the method is static, not allowing for the weighting of different decisions on the outcome. It is also overly deterministic and focuses on a limited number of aspects.

Instead of the "alternative futures method", we chose to base our proposal on what Townsend refers to as the "Shell approach", a traditional method widely adopted in large companies as a support for decision-making.

In the book "Learning from the Future" Liam Fahey stresses that this method should not be considered as a hard prediction of the future, nor be used as an end in itself (Fahey 1998). Rather, the objective is to explore possible developments, acknowledge uncertainties and understand the way they might evolve. This information can then be used by people to manage the future strategically, for which reason the author adopts the term “scenario learning”.

The scenario learning methodology is fundamentally based on the identification of as many key factors and driving forces as possible that can have an influence on the development of future scenarios. Key factors of high impact and high uncertainty are then chosen to define scenarios to be explored, while the remaining factors are considered marginally.

The methodology we propose has its foundations on this scenario learning approach. However we specify a particular form of analysing and selecting key factors which is most relevant to the context of transportation technologies and urban impact. We also develop a unique approach for analysing and developing each scenario based on architectural and urban design traditions. The whole process in described in detail in the following section, precedented by an overview of the overall approach to the future scenario development problem.

4 Methodology for Studying AV Impact on the Urban Environment

4.1 Approach Overview

Despite prescribing the existence of unforeseeable consequences for technologies, McLuhan suggests that when we look back in history for new technologies and their developments, we can identify the seeds for these developments already present in the beginnings (McLuhan 1963).

Authors like McLuhan, Postman and others share a determinism that is, above all, complex (Vassão 2008). It accepts multiple variations and it happens in fields of constant negotiations. What exists is an ecology, a systemic environment where several conditionings are already at play. Each and every entity in such a system in connected to everything else, and every change propagates.

Because the system is overly complex, the number of variables is unmanageable, and unforeseen effects are bound to happen. Based on this understanding, the intention of the methodology here proposed is not to generate a precise portrait of a future that is still under construction. Instead, the objective is to provide support for informed intervention in such a system.

Each step of the methodology we propose is described in the sub-sections below. After each description, we provide a summary of the outcome for each step as developed by a team of researchers in the Transportation Infrastructure and Public Space Laboratory (TIPSLab) at the University of British Columbia. These outcomes must be treated as examples of the product expected for each step, rather than definitive findings. Given the limitation of space, this paper focuses on presenting the methodology in itself, and not on expanding on and grounding the scenario results.

4.2 Initial Instructions

Before beginning, it is important to have a clear view of the context which will be investigated, the appropriate time frame for the scenarios, the public and the questions of relevance which the scenarios will serve.

TIPSLab is concerned with AV impact in North American cities in the next 40 years. The objective is to create knowledge for planners and politicians who are tasked with making decisions concerning public policies for transportation.

4.3 Steps in Process

Step 1: *Identifying key factors and driving forces in the system*

Based on the methods described for scenario learning (Schwartz and Ogilvy 1988), the largest possible number of relevant factors and driving forces must be collected through collective brainstorming sections. The authors suggest using the SEPT formula (Fahey 1998) for a comprehensive exploration, which considers five general categories: social, technological, economic, environmental, and political forces, which can be broken down into more relevant and specific categories.

In TIPSLab, we found nearly 70 key factors that we judged pertinent to the problem of AVs and urban form, across several categories. These factors are presented in Table 1.

Step 2: *Classifying the key factors*

The next step begins at distinguishing pre-determined elements from uncertainties. All the key factors and driving forces are studied individually and a number from 1 to 3 is assigned to each. Three indicates high uncertainty, two indicates average uncertainty, and 1 indicates low uncertainty. If any factors are considered inevitable, these factors should be reflected implicitly or explicitly in each and all of the scenarios to be developed.

In TIPSLab, for instance, we assigned low uncertainty to the fact that the average age of North American population will increase in the next decades. High uncertainty was assigned to the fact that coming generations will be less attached to the ideal of owning a personal vehicle.

Every key factor must also be classified regarding how impactful they can be. The number 1 must be assigned for aspects of little impact, the number 2 for aspects of some impact, and the number 3 for aspects of high impact. These classifications

Table 1 Driving forces and uncertainty/impact scores

Category	Driving force	**U**	**I**
Demographic patterns	Population growth	1	2
	Aging population	1	1
	Continued Immigration	1	1
	Decline in the share of active workforce	1	2
	Increase in one-person households and other configurations	1	2
Social and lifestyle factors	Automation-induced unemployment	2	2
	Deterioration of automobile's image and desirability	3	3
	Conveniences of personal car ownership	1	3
	Attachment to driving	2	3
	Increase of flexible lifestyles	1	3
	Increase in work hours	2	2
	Increase in productivity	2	2
	Emergence of AV hacking and customization	3	2
	Attitudes towards new technology	2	2
	Emerging consumer demands	3	3
Natural resources	Availability and accessibility of conventional automobile fuels	1	2
	Availability and accessibility of alternative automobile fuels	1	2
	Makeup of electricity production	1	1
	Availability of land	1	3
	Availability and accessibility of raw materials for AVs	1	3
Physical environment/urban planning	Land use	2	3
	Urban movement patterns	2	3
	Type, size, age of urban fabric	1	3
	Scale of AV infrastructure implementation	1	3
	Existing transportation options and trends	2	3
	Connectivity between transportation modes	2	3
	Urban planning trends	3	3
	Relative importance of planning	2	3
	Consideration of AVs in planning	3	3
Political and regulatory forces	Pressure for climate change action	1	1
	Pressure to reduce accidents	2	2
	Political trend towards privatization and deregulation	3	2
	Government subsidizing power	2	2
	Resolutions on sustainability and energy efficiency	2	1
	Governmental agenda and development plans	2	2
	Subsidies for public/shared transportation	3	3
	Lobbying and Protectionism	2	3
	Regulations on AV implementation, use, driving standards and maintenance	3	2
	Regulations on personal and public safety	3	1

(continued)

Table 1 (continued)

Category	Driving force	**U**	**I**
Technological forces	Powering options of AVs	3	1
	Development of AI and possible limits of AV capability	3	2
	Digital connectivity between transportation platforms and users	2	3
	Development of technologies for stationary use inside AVs	3	1
	Development of other novel transportation technologies	3	3
	Ubiquity of EV charging infrastructure	1	2
	Fast development of EV/AV battery technology	1	2
	Organization of AV software and hardware upgrades	3	1
	Development of vehicle only intelligence	2	3
	Development of infrastructure only intelligence	2	3
	Development of AV technological standards	1	3
	Integration of AVs into "Internet of things"	2	3
	Speed and trajectory of AV uptake	3	3
Market forces	Stability of macro economy	2	2
	Configuration of stakeholder interests	1	3
	Cost of energy	2	2
	Cost of key raw materials	2	2
	Cost of key technologies	2	2
	Cost of skilled labour	2	2
	Cost of AV maintenance	2	2
	Local cost of land	2	3
	Monetization strategies for AVs	3	2
	Car manufacturers' interest in maximizing sales	1	3
	Service providers' interest in offering continued services	1	3
	Real estate market trends	2	3
	AV financing schemes	2	2
	Insurance risks	1	2
	Cost of AV purchase	2	2
	Effectiveness of publicity strategies	2	1

are also part of the original scenario learning methodology (Schwartz and Ogilvy 1988).

Table 1 below presents a summary (descriptions and details omitted) of all key factors found by the TIPSLab team, with the uncertainty (U) and impact (I) numbers assigned to each. These factors resulted from focal groups and an extensive literature review around AVs.

Step 3: *Connecting the system*

The next critical step is identifying which factors direct influence the outcomes of other factors. The purpose of this is to identify those factors that are dependent or related to other factors. We connected all factors in a network of influences. This step is not a standard technique in the scenario learning methodology we have adopted as a foundation but since the topic under discussion is highly complex and there are many interrelated factors, it becomes necessary. Similar approaches have been discussed in this field of study, e.g. Ward and Schriefer (1988).

Figure 1 presents the final network diagram defined by TIPSLab. All of the key factors listed in Table 1 are present in the network, inside circles, interconnected to the factors which they influence and by which they are influenced. They have been grouped into general categories—indicated by the colors of the circles. The direction of the arrow connecting the factors indicates the direction of influence. For clarity, the arrow has the same color as the factor from which it's being issued. The thickness of the circle's border indicates the factor's level of impact, while the grey shade of the fill color indicates the degree of uncertainty.

Step 4: *Defining the scenarios' structure*

Given the complex network presented in the previous step, it would be unfeasible to carefully consider every possibility generated by every single variation within the system. Consequently, the possible scenarios that could be constructed as a result of all factors' interaction are too numerous to be useful. This is why it is critical to identify the events that can be most impactful in the final outcomes, as well as to identify the factors whose certainty presents the greatest challenge.

Ideally the Shell methodology proposes focussing only on two key factors for structuring the scenarios' main variances. They are expected to be **very uncertain and very impactful** (i.e. the critical uncertainties). Because of their uncertainty, at least two opposite behaviours can be defined for each key factor. Finally, the combination of these variations would result in 4 scenarios, a reasonable number for in depth exploration (Fig. 3). All the remaining factors should be then considered in relation to the structuring variances in each scenario.

In the TIPSLab's process, a study of the key factors network allowed for the identification of crucial clusters. It was the clusters of factors which were interrelated and had high uncertainty and high impact, rather than individual factors, which were chosen to be the key factors. These **clusters** are recognizable by two aspects: (1) number of connections of core factors, and, importantly, (2) coherent cohesion of behaviour within group. By coherent cohesion of behaviour we refer to the tendency of a cluster of factors to vary together in a coherent direction, given they are very closely related.

Two main clusters were selected as structuring elements of scenarios. Each structuring cluster was articulated in two plausible outcomes—these are the extreme

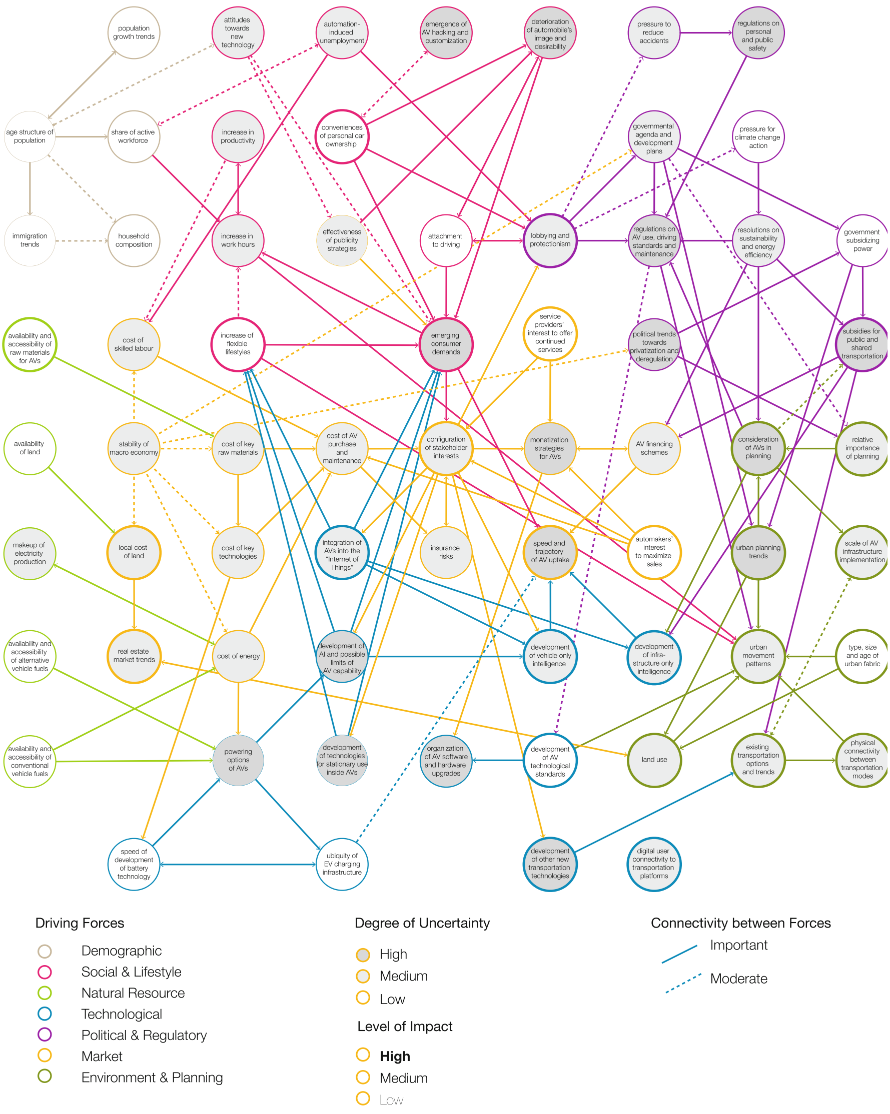

Fig. 1 Final network diagram developed by TIPSLab

outcomes of each cluster. The orthogonal combination of structuring clusters/ factors and their outcomes will create four scenarios, as described in the next paragraphs.

In the network composed by TIPSLab, it was observed that the factor named "emerging consumer demands" occupies an evident central role in the disposition. Its cluster, which we titled "lifestyle forces + market forces" is simplified in Fig. 2, cluster (a). The two opposite outcomes of the cluster were organized under the titles "conservative" and "progressive". As example, some characterizing aspects of the "conservative" outcome are:

- Consumers want to keep option of manual driving
- Consumers are heavily supportive of current ownership models

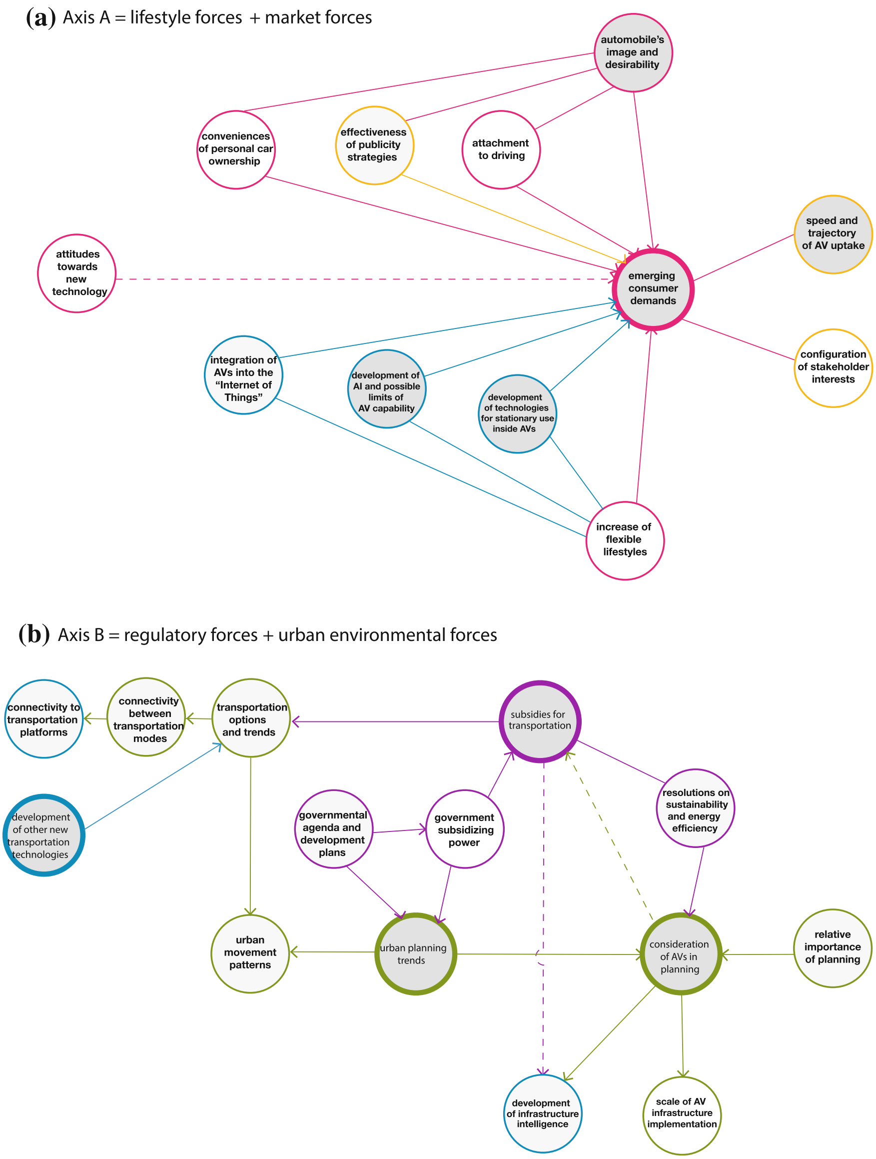

Fig. 2 Scenario defining clusters of factors

- Automaker companies control the market for automobiles
- Extended warranty bundles don't compete with insurance companies.

Comparatively, some examples of a progressive outcome could include aspects such as:

- Consumers support long-term ban of manual driving
- Consumers are open to different ownership models, such as car sharing
- A diverse landscape of software and hardware companies emerge and become main players in the automobile industry
- Insurance companies need to drastically adapt their business models to survive in the long term.

The second most relevant cluster identified was named "Regulatory forces + urban environmental forces". This cluster comprises factors that planners and decision makers can directly act on, and that are of great interest to the developers of this study. The core factors of the second cluster are "urban planning trends", "considerations of AVs in planning" and "subsidies for transportation"; its diagram is simplified in Fig. 2, cluster (b).

The two opposite outcomes of the cluster were organized under the titles "transit oriented investment" and "AV investment". As example, some characterizing aspects of the first outcome are:

- Neglect of AVs on main planning strategies
- Direct support for compact urban growth
- Limited infrastructure intelligence
- Advance in intermodal technologies and structures.

Comparatively, some examples of a "AV investment" outcome could include aspects such as:

- Faster implementation of favorable legislation on AV traffic
- Indirect support for sprawling growth
- Infrastructure intelligence as a main public enterprise
- Faster AV technology development.

Step 5: *Defining the scenarios' structure*

To define the decision making matrix, each of the factor groups becomes an axis. Each axis has two boxes—an extreme in one outcome and an extreme in the other outcome. The orthogonal combination of the outcomes discussed thus far form the basic structure of the scenarios to be developed. Figure 3 provides a brief description of the four scenarios and their fundamental contexts. The two factors which become the axes—'Regulatory & Urban Environment Forces' and 'Market and Lifestyle Forces'—create four scenarios which can then be used to play out various futures for planning and governmental agencies. In the case of the 'Regulatory and Urban Environment Forces', the choices are between a support for Public Transit or a support for AVs. Support is defined as government policy at any level which provides financing, disincentives, or incentives to push adoption in either one of these directions. Because the AV operates within a highly regulated framework of publically controlled roads and much legislation regarding safety, the government policy and funding can have a large influence on outcomes. On the other axis is 'Market and Lifestyle Forces' which is either a progressive and quick acceptance and uptake of technology by the public (labeled 'progressive') or a slow and resistive uptake of the technology by the public (labeled 'conservative'). This may vary highly even from district to district. This is the second highly influential and highly unpredictable group of factors.

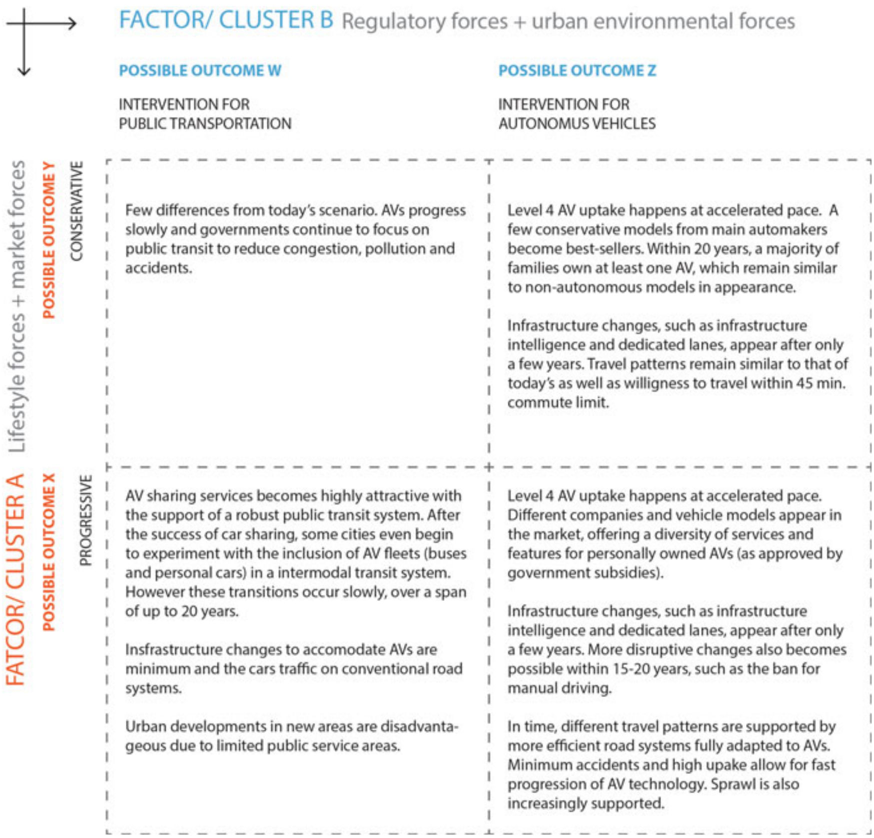

Fig. 3 Brief descriptions of the four scenarios and their fundamental contexts

5 Implementation: Running Scenarios

Figure 4 shows an example of what may be the outcome from running the four scenarios for a particular region. In this case we are demonstrating how one could predict effects of AVs on transportation mode share given the four scenarios. This type of analysis could be done for many of the aspects agencies are concerned with and brackets likely scenario outcomes.

Fig. 4 A theoretical example of scenario outcomes

It is worth noting at this point that one of these key factors has to do with the policies made by governmental agencies themselves. In our experience, there is often a wait and see attitude about the technology, however this analysis notes that the decisions made by regulatory agencies—incentives and rules—have a huge impact on the future outcome.

6 Developing Descriptive Visualization Scenarios

In order to engage with the public and other stakeholders in discussion, TIPSlab finds it useful to do scenarios that place the public or the individual audience members into the future with AVs. This really allows people to understand the implications and potentially radical different directions that may occur. Here we illustrate one of these scenarios for a suburban single family—this has been done for a series of demographic groups and in general we pick the most populous demographic groups in a region to use as examples. The scenarios are set up around the 'generic group' so are somewhat stereotypical but do reflect a large group within the region. In this case, for the sake of brevity we illustrate only the two 'Progressive' versions of the four scenarios.

Scenario Visioning: The Suburban Family

Profile Stats:

- Name: Alan and Alex ASTOR; children: Asher and Alice
- Location: Surrey
- Family-Type: Nuclear—2 adults; 2 dependents
- Ages: (adults) 32 and 36; (dependents) 12 and 14
- Professions (adults): Business administrator; creative development in start-up
- Interests: Outdoor and hiking enthusiasts.

Scenario: Public Transit Subsidy + Progressive (Box Lower Left)

Alan and Alex Astor are hard-working partners in a small-size Vancouver tech-start-up. Their investment in the company demands a great deal of time at the downtown Vancouver office—a commute they make daily. In 2040, the Metro Vancouver public transit system has expanded into an extensive network of regional Skytrain lines, arterial streetcars, electric buses and community or 'last mile' shuttles, all of which are automated on-demand vehicles controlled by the regional public transit service Translink. In Surrey, where the Astor family resides, a community-dedicated transit system links into the Skytrain. The family takes full advantage of this network by almost exclusively using transit, and only subscribing to the more expensive car-share services occasionally.

Alan and Alex commute to work by meeting an on-demand transit shuttle a short distance from their home. Alex calls a shuttle for herself and Alan—to leave after the automated dedicated school shuttle—and the trip is automatically booked through to the shuttle stop near their office. Since the system adjusts 'live' based on the number of passengers using it at any moment, they can always be assured to get seats on both the shuttle and Skytrain car involved in the trip. Alex then checks-in Asher and Alice to the community school bus and the whole family walks to the end of their residential street for pick-up.

By day's end, Alan had made a trip to a meeting cross town—once again using public transit. In this case he knows that one of the fixed route shuttles run every two minutes on this particular route during the day, and hails the next one at his stop. Apart from slowing down at stops, the AV shuttle maintains a constant speed along with the rest of traffic. At intersections, only the pedestrian crosswalk signals remain in place, since AVs carefully navigate their surroundings and communicate with transit control via information beacons, which guide and organize cross-traffic flow. The system is accessible and used by all—a completely de-stigmatized form of travel.

The last school bell rings and Alice makes her way to the school-dedicated shuttle to return home. Asher walks to a nearby field for soccer practice. Each are registered as minors in the transit system and have automated notifications sent out to their parents of their trip status and safe arrival each time they use the transit. Asher finishes his practice and hails the community shuttle to stop nearest to the field. His app says the wait for the shuttle will be seven minutes, so he plays for a few more minutes at the field. Meanwhile, a notification goes out to Alex that the request has been made, and in a short while she meets Asher at the shuttle stop near home.

Scenario: AV Subsidy and Progressive (Box Lower Right)

Alan and Alex Astor are hard-working partners in a small-size Vancouver tech start-up. Their investment in the company demands a great deal of time at the downtown office—a commute they make daily from their home in Surrey. The couple uses an AV-share program which they pay a monthly fee to use. It is a medium-price on-demand service that many of their peers subscribe to, with relatively short wait times and a sporty but family-oriented image. Alan and Alex use their smartphones to secure themselves a car in the mornings and again in the evenings to return home. The service is separate from and more expensive than the public transportation system, but it comes with alternative benefits that Alan and Alex value. For instance, it allows for the two to determine their own commute time and privacy during the travel—something Alan prefers so he can make private phone calls and start his workday on route to the office.

During the day, Alan often uses the on-demand car-share to drive him to meetings across town. When asked to describe the quality of the ride in the AV, Alex relates the experience to that of the rapid transit trains in Japan—the AVs ability to maintain a consistent speed makes the trip quick and efficient. Because of automation, highway interchanges have been reduced to adaptations of the cloverleaf, which allow AVs to enter the interchange at higher speeds while reducing the scale of infrastructure.

The family also currently owns an AV and depends on it for shuttling the children, running household errands, and weekend excursions out of the city. During the week, Alan and Alex depart early using the car-share service to beat the morning rush, leaving the personal AV to take Asher, 12, and Alice, 14, to school. They have set their car to send an automated message when it leaves the house and also once the children arrive at the school. Throughout the day, Alan and Alex can order household goods and groceries online, and remotely direct the family AV to a "Grocery Drive-Through" market where the order is loaded into the AV. This saves Alan and Alex the time of shopping, allowing them to spend more time with their children after their long work hours.

After classes at school end, the AV meets Asher and Alice at the school drop-off area. Asher has soccer practice nearby and walks to the field after picking up his soccer bag from the AV, while Alice is taken to piano lessons. During the children's activities, the AV waits at the nearest parking and charging station for the call from the two children to be picked up. The family reunites in the early evening at home and the AV retreats back into its compact garage for overnight charging.

7 Prioritizing Regulatory Directions

As can be seen from the analysis and set up of the methodology, what the regulatory authorities prioritize can have a large impact on the scenario outcomes. What this methodology creates is an ability to see four extreme outcomes for any particular region. Within that range, part of the question for any authority then is where do we want to be and what steps need to be taken along the way to get there? The answer to this question will "generate" a future and decisions taken by decision makers will help to bring that future into being. To design a future for an AV city, then, we need to clearly outline what aspects we would like to see manifest.

In TIPSLab's perspective, social equality, increased agency for the population and a positive environmental effect (no GHG emissions) are key criteria for authorities but each governmental agency will have their own priorities. As such, the next step for each agency is to identify what means and tools they have and what they see as an ideal future and inform decision-makers what is possible and necessary to reach these outcomes. This has been carried out in Metro Vancouver in order to create a plan for the implementation and direction of policy in the region.

8 Conclusion

This work proposed a new methodology for investigating the impact of transportation technologies on the urban environment. The methodology was put to test by TIPSLab, with a focus on AVs, and proved to be a helpful tool in generating rich and systematic scenarios for study. The scenario process has been outlined to municipalities, transit and provincial authorities in the BC Region and priorities for the region's transport goals and steps forward have been developed.

A main limitation of the methodology here proposed is the fact that it constructs a simplified model of the world. We acknowledge the impossibility of capturing all possible determinants of our futures. However, we believe that the strategies incorporated in the methodology allow for a more comprehensive examination of possibilities than would be otherwise achievable.

In the course of study for this process, it can be seen that regulatory authorities and government funding can highly influence the outcome of the future. As such it can be noted that regulatory authorities have a key opportunity to direct the future of transportation outcomes. This research highlights the importance of authorities to take a coordinated approach and defining priorities for their regions and then using the tools they have available to direct the future. The opportunity to 'design the future' for transportation is here. The risk in not doing so is that demographic groups become marginalized as public transit becomes eroded and private corporations take over the public transit role, servicing only areas they see as profitable.

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“AV-Ready” Cities or “City-Ready” AVs?

Siegfried Rupprecht, Stephen Buckley, Philippe Crist and Jane Lappin

Abstract The session “‘AV-Ready’ Cities or ‘City-Ready’ AVs” at the Automated Vehicles Symposium 2016 in San Francisco addressed key aspects of road automation from an urban policy perspective. The aim of the session was to raise the awareness of urban policy needs within the automation community, as well as enabling urban policy makers to understand better the opportunities and issues related to automated, connected vehicles when drafting their cities’ policies in the area of automated road transport.

Keywords Surban automation · Automated road transport · Sharing · Cities · Public transport · Transit · Autonomous vehicles · Automated vehicles · C-ITS · Urban planning · Urban mobility

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1 Introduction

While the focus of road automation is still on interurban transport, a major challenge of a full take-up of automated vehicles (AVs) is the complex conditions of inner-urban mobility. How can cities create an environment where automated road transport is likely to deliver the promised benefits of increased safety and accessibility, less space consumption, as well as better environmental and economic performance? How should AVs and AV-based services be designed to help create products and services that support key policy goals of cities and that allow cities to meet their multiple functions more effectively (rather than enhancing mainly the comfort of driving)? In other words, should cities aim to respond to the needs of vehicle automation by becoming "AV-ready" or should automated vehicles and services aim to help deliver policy goals by becoming "city-ready"? Or, more realistically, where is the right balance?

2 What Do Cities Need? Urban Mobility and Road Automation

Cities across the world are dealing with increasingly complex and interconnected problems. Growing transport demand due to urban and suburban growth, changing lifestyles and travel patterns, and increases in inner-city freight movements are common issues; closely connected with these are deteriorating environmental quality, lack of quality space and challenges of accessibility and social inclusion. In addition, many cities are under severe financial pressure which limits their ability to implement sustainable, long-term solutions. Road automation appears to solve several of these problems. The "automation promise" for cities includes improved safety, better mobility for all, innovative collective transport services, cost savings, freed public space, energy savings and environmental gains.

However, policy priority setting is a complex task, especially as there are also many market disrupting trends. As the example of London shows, attitudes towards driving are changing: reductions of vehicle kilometres are especially significant in the inner city (−20% points between 2000 and 2012) and sharing becomes attractive to many travelers (de Estevan Ubeda 2016). At the same time, the boundaries between traditional and new mobility providers are blurring and highly competitive offers are disrupting the transport market. In this situation of uncertainty, policy coordination and long-term planning become difficult tasks, and increasingly, simultaneous agendas need to be coordinated.

A major area of concern for highway authorities is the impacts of automation on infrastructure development: roadway and traffic signage, electronic vehicle to infrastructure communication, liability in case of infrastructure failure (e.g. due to hacking), and infrastructure maintenance impacts.

On the policy side, key uncertainties are the likely impacts of automation on transport demand, the likely speed of market uptake of automated vehicles and automation-based services, behavioural/lifestyle changes of customers influencing the choice of mobility options. Additional concerns include institutional technology readiness, especially competencies of staff, obsolescence, resilience and liability. A key issue for public transport authorities are automation impacts for public transport: will automation in the foreseeable future change cost structures significantly to facilitate the emergence of new business models for mainstream public transport services? How can automated shared services and feeder services become part of a new urban mobility concept? Can (or should) traditional public transport services and new automated collective mobility services become integrated?

Wider policy impacts require additional consideration: how can automated transport services contribute to mobility equity (Reynolds 2016)? As the example of the winner of the highly prestigious US Smart City Award shows, solutions for social challenges in an inner-city "mobility desert" in Columbus/Ohio, are a key requirement for the success of automated mobility solutions.

Transport authorities need to make strategic decisions in designing new mobility portfolios based on the "Mobility as a Service" paradigm and including, as in London, a wide range of topics, including the provision of on demand services, advanced journey planning, interoperable payment systems, shared mobility services, low emission/electric vehicles, connected infrastructure, and last not least, automated and connected vehicles (de Estevan Ubeda 2016).

Determining the impacts and relative contribution of high-level automation towards achieving policy goals and consequently, deciding the priority of automation-related investments is a complex choice to be made.

3 How Can Cities Plan for Automation?

There is a growing awareness among urban mobility decision-makers that a pro-active strategy is required: it is not only inevitable to consider the potentially disruptive impact of automation, but rather should try to anticipate the likely potential of road automation for transforming urban mobility fundamentally—and in a policy-supportive manner. This is becoming part of a wider discussion of the impact of transformational technologies, or "game changers", on how cities design, build and operate transport services, and, essentially, how cities are planned and governed.

3.1 Toronto's Automation Scenarios

A city that has started early in shaping the development of automated road transport is Toronto, Canada (Buckley 2016). In February 2015 a multi-stakeholder working group has analysed possible approaches to automation in order to determine how they could shape the direction of automation as a transport authority: at a minimum how to best protect public interest against negative unintended consequences and how to manage the transition. Three scenarios were analysed (David 2015):

- Ownership leads: private vehicles retain a large share of the mobility market despite shared and public vehicles becoming popular.
- Mixed leadership: shared and public vehicles are the dominant means of transport.
- Shared leads: private vehicles and shared/public vehicles are of similar importance.

The likely impacts of these automation scenarios are summarised in Fig. 1.

On the basis of this analysis Toronto has decided to follow an active strategy of harnessing the potential of automated vehicles "to help us create the city that we want" (David 2015). The preparation for the arrival of automated vehicles has become an official goal of the Toronto Transportation Services Work Plan. In addition, Toronto is cooperating with its province, Transport Canada and NACTO, as well as the International Transport Forum/OECD.

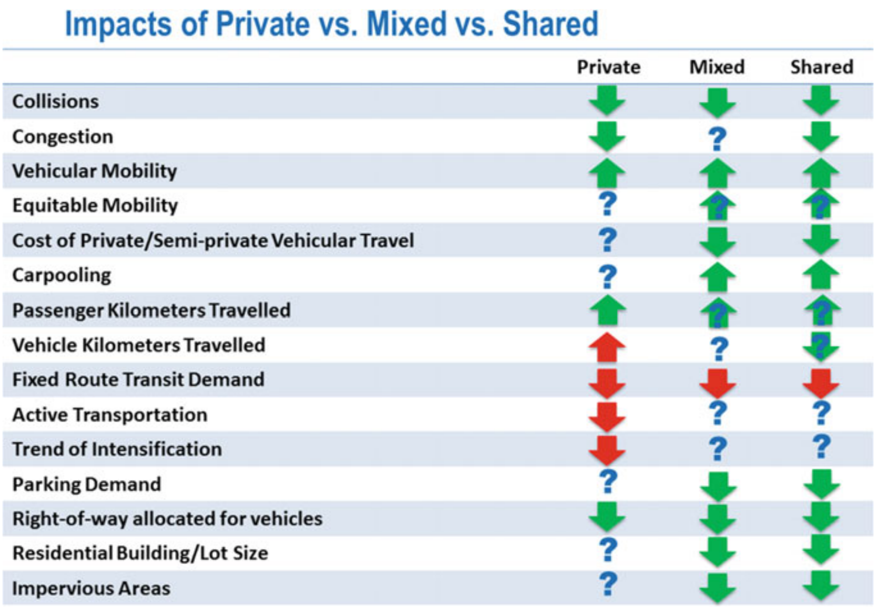

Fig. 1 Toronto's automation scenario analysis

3.2 ITF Automation Study for Lisbon

A complimentary perspective is provided by a study of the International Transport Forum at the OECD which analysed the impact of a shared and fully autonomous vehicle fleet in the city of Lisbon, based on an agent-based model simulating the behaviour of all actors in the mobility system (Crist 2015). The study models an upgrade of the urban mobility system with a fleet of (1) "Shared taxis", i.e. vehicles sharing simultaneous rides, or alternatively, (2) optimised on-demand "TaxiBuses", in addition to a high-capacity public transport system. It assumes that the same trips as today (in terms of origin, destination and timing) are made and all car and bus trips are replaced by one of the new modes. The results of the study provide a strong case for automation-based shared mobility solutions:

- In a 24-h scenario only 3% of the current number of cars are required to provide the same trips as before.
- 20% of the curb-to-curb street space are freed up, 80% of the off-street parking could be reused for other purposes.
- Total vehicle kilometres travelled are reduced by 23% (for a 24-h period), or 37% (for a peak hour period). CO_2 emissions are reduced by 34%.
- Access to jobs is significantly increased; in the "TaxiBus" scenario only the most peripheral parts of the city are not accessible within thirty minutes.
- The price for "Shared taxis" is reduced by 76%, the price for "TaxiBus" use is 57% lower (at a 72% cost reduction).

The study argues that shared mobility accelerates clean technology penetration and leads to additional resource and emission savings due to the intense use of vehicles, their shorter life cycles and, therefore, rapid fleet renewal, which eventually leads to fast-paced technology uptake.

The study concludes that highly automated vehicles can change "public transport as we currently know it" (Crist 2015), but their introduction process must be shaped by policy choices and deployment options. Active management of freed public space is essential to lock-in the benefits created by automation and urban transport governance needs to adapt as public transport and taxi operations will directly compete with automated fleets.

4 Addressing the Transition Challenge

When assuming a continued renewal of the vehicle fleet within a 20 year period, as for example in Europe, urban road automation is likely to be a lengthy process where conventional and automated vehicles (of different automation levels) will coexist on the same road network. The dynamics of the take-up of automated vehicles in cities and the effective policies facilitating or restricting their use are uncertain. Nonetheless, it is clear that different transport contexts and modes will have to deal with perhaps widely varying levels of "AV readiness". In addition, it is not clear which share of high-level automation will mark the "turning point" of creating a significant transport network impact.

Transition needs to be considered as part of the large transformative process of the digitalisation of the transport sector. Its outcome will in any case create major impacts for our cities, reaching much beyond mobility. There is widespread understanding among urban mobility stakeholders that a passive, or even a reactive approach to managing the transition to automation will create safety problems, reduce compliance with public policy goals and will increase the uncertainties associated with automation. Conversely, a well-managed transition process can be a key success factor for effective deployment of automated vehicles—overall, not only on cities.

The speed and characteristics of transition are determined by a wide range of factors, including user acceptance, business case development, legal frameworks, but also the impacts generated by synergies resulting from successful integration with Intelligent Transport Systems, with electrification and generally due to the availability of new service and business models in the transport sector. Beiker (2015) has suggested three models to characterise the dynamics of transition: (1) an evolutionary process, where the automobile industry would bring vehicles with gradually increasing levels of automation on the market, leading to a situation of "something everywhere". Alternatively, (2) a revolutionary process, as currently followed by the IT industry that is trying to introduce high automation levels rapidly ("everything somewhere"), while (3) transformative transition dynamics are characterised by mostly locally driven automated mobility on-demand services, often involving start-ups. As all three transition models are working simultaneously, mobility stakeholders representing a variety of transport actors are increasingly trying to shape the transition process by developing visions, strategies and policies.

The direction of urban transport policy is, therefore, likely to shape the speed and direction of urban road automation. This impact will be most significant in countries, where cities have strong regulatory powers to shape their transport policies, e.g. as in many European Union Member States.

5 What Are the Next Steps? Addressing the Transition Challenge

5.1 Policy Context of Road Automation

In order to understand the "automation challenge" in cities, it is important to consider the policy context from a local government perspective.

As Fig. 2 illustrates, there is a clear threat of automation leading to higher mobility demand (and more vehicle miles travelled; VMT) and an increase in urban

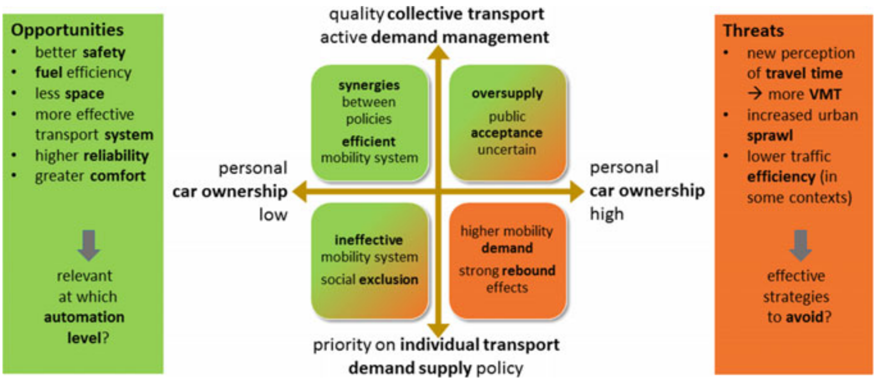

Fig. 2 Policy context of road automation (local government perspective) (Rupprecht 2016)

sprawl, if transport policies focus on demand supply and prioritise individual transport choices, with personal car ownership being the prevailing model.

Automated urban transport will be most effective when it becomes part of a collective quality transport system and when it is supported by an active demand management policy; low personal car ownership will be a major success factor of automation, from this perspective.

As urban transport planning needs to deal with many uncertainties, cities are eager to understand impacts and their options to effectively improve them. In order to prepare better for the transition period, cities should focus on the following actions (Rupprecht 2016):

- Plan "with automation in mind".
- Identify modifications to infrastructure that are "AV-enabling" as well as supportive of urban policy goals.
- Create institutional structures capable of supporting effective automation.

5.2 *Planning "with Automation in Mind"*

Planning "with automation in mind" is an attempt to deal with automation uncertainties in a pro-active and pragmatic manner; it includes:

(1) Developing scenarios for increasing shares of autonomous/automated and connected vehicles that are operated either as personal cars or as collectively shared vehicles. Scenarios should also include also potential impact of freight automation on urban delivery. An important question to consider is how mainstream public transport can benefit from automation and what the likely impact of automated, collective (shared) services may be for traditional public transport operations.

(2) Considering the impact of increasingly automated corridors in the urban road network, both from the perspective of automated as well as the non-automated modes; what is the traffic efficiency impact? How should automated vehicles interact with human road users, especially with pedestrians and cyclists? How could risks resulting from complex traffic situations be reduced?
(3) Avoiding to overestimate the predictive quality of formal transport models, as most modelling is not yet "AV ready"[1]: Are driving patterns of automated vehicles represented appropriately in micro simulation? Which assumptions can be safely made for value of time, car ownership, and modal choice in a period of significant changes in and personal value sets and mobility patterns? At which automation rate and in which traffic context will automated vehicle produce a significant network impact?

5.3 "AV-Enabling" Infrastructure Development

Transport infrastructure planning needs to take a long term perspective, changes to infrastructure take time and require significant investments.

Considering the uncertainties associated with automation especially in cities, it would be premature to propose a concrete course of action for "AV-enabling" infrastructure development on a large scale. However, automation pilot tests are increasingly seen by urban decision-makers as very useful to better understand future infrastructure needs of connected and automated, vehicles, e.g. for identifying IT requirements, financing needs, use of standards. A key aspect of pilot testing is to understand the users' response to automation-friendly infrastructure and its traffic impact.

In order to identify effective modifications to infrastructure that are "AV-enabling" as well as supportive of urban policy goals, especially when planning "automation corridors", it is important to consider their longer term dynamics. Will an automation-friendly major road develop into a road with "dedicated" (and soon "segregated") lanes for highly automated vehicles? How will pedestrians and cyclists, and in the long term also conventional vehicles move safely and effectively in highly automated areas?

Infrastructure requirements for automated "collective" transport are only beginning to be considered. While it is unclear which proportion of mass public transit will be taken over by new forms of collective (almost) door-to-door mobility services in the longer term, the need to rethink the concept of the "bus stop" is evident. A combination of automation and electrification of public transport in combination with general digitalisation trends will require to rethink collective interchange infrastructure.

[1]"AV readiness" of transport modelling and infrastructure planning is the focus of the CoEXist research project funded by the European Union's Horizon 2020 programme, starting in May 2017.

Freight distribution, increasingly based on automated delivery will require new storage functions and loading and unloading facilities. Should, for example, parking garages that loose customers due to increased use of shared services be converted into highly space-efficient (automatic) vehicle storage units? Should they become logistic centres storing goods for immediate delivery? Should 'parkings' be converted into 'parks'?

Whatever the future will bring, infrastructure development is a long-term activity and automation has the potential to become a trigger for redistributing space and reassigning urban functions in a manner that better meets the requirements of attractive cities.

5.4 "AV-Enabling" Institutional Structures

It is hard to imagine that the disruptions due to the technical and socio-economic opportunities of automation can be utilised for sustainable urban mobility policy without rethinking governance structures. Consequently, the discussion about the institutional side of urban road automation is increasingly part of a wider discussion about "mobility on demand" or "mobility as a service".

There are many use cases requiring cooperation models for last mile and low-density services, mobility solutions catering for travellers with special needs, as well as newly emerging demands. Societies will need to make choices how much autonomy should be left to competing private operators, or rather regulated by public authorities. However, from a traveller perspective, a "platform" coordinating the activities of new and traditional mobility providers may be a more attractive and overall a more effective solution.

Special attention is required to create effective regulatory environments for mainstream public transport and taxi operators. While automation is at present mostly perceived as a serious threat to the very foundation of these organisations, it is not unthinkable to provide them with a beneficial role in a new collective (mostly automated) transport system.

Automated freight delivery will remain a privately operated business. However, sharing vehicles and infrastructures may reward private-private, as well as private-public considerations in the future.

While newly emerging, and often very successful mobility services and business models have created a highly dynamic situation in many countries, regulation has prohibited change in other contexts. Any discussion of creating "AV-enabling" institutional structures, therefore, needs to consider very carefully the specific regulatory and policy environment. However, there is strong agreement that the potential impact of automation in supporting public policy goals is highest, when the transition phase is accompanied by an effective multi-stakeholder cooperation process. Many cities, like Toronto, San Francisco, or London that presented in this session are in the process of developing visions and action programmes in order to take a proactive role in the transition towards automated and sustainable urban mobility solutions.

5.5 Action Planning

There are many uncertainties about the dynamics of automated vehicle introduction and their resulting impacts, but many cities have started on an "Urban Automation Agenda"; some common elements include[2]:

(1) Develop visions of how automation can help "transform mobility as we know it"—considering the very specific context of your own city.
(2) Promote behaviour change through shared mobility services, quality public transport development, and demand management policies.
(3) Support local shared vehicle pilots. Identify their impacts, upscale when successful.
(4) Think about "increasingly AV enabled" corridors (in terms of both, policy and technology enhancements)—and how they develop over time ("AV only"?); how are they interacting with other modes.
(5) Develop scenarios for re-using parking space (e.g. as freight hubs, pick-up areas) and how transit infrastructure (e.g. interchanges) can develop.
(6) Consider also obsolescence, resilience, (new) liability issues, when planning for enabled infrastructure.
(7) Automation of freight and public transport deserve special attention; including new service models. Review impact of building regulations.
(8) Address public perception, involve stakeholders.
(9) Develop automation work plan with partners and stakeholders (and internal working group).
(10) Engage in exchanges with other cities and in dialogue with industry, academia and other government institutions.

6 Conclusions

Mobility planners should consider identifying corridors with gradually increasing automation support and/or pilot areas for shared automation trials, that are supported by infrastructure (as far as feasible), policies that maximise impacts that support public policy goals, and high-level political commitment.

There was strong agreement among session participants on the following points:

[2]This section has not been explicitly part of the session. It is based on the session summary presentation of Siegfried Rupprecht in the final planetary of AVS 2016.

(1) Automation is getting high on the urban policy agenda. However, city policies are not yet prominently on the automation agenda of industry, academia, and government—although urban automation will be a key success factor.
(2) From pro-active city perspective automation is one tool (of many) to implement policies (within a wider institutional, financial and policy context). Investment decisions need to consider which transport problems can automation help to solve more effectively than other technologies or policies (e.g. Mobility as a Service)—and how these various options could be integrated?
(3) It is important to understand well the automation dynamics from an urban policy point of view: What is the turning point at which automated vehicles are generating a significant transport impact in which kind of urban transport context (e.g. increased safety, congestion reduction), rather than being a mobility option that should be restricted.
(4) Major urban automation challenges are: Avoiding unintended impacts/disbenefits, while dealing with uncertainties. Lack of qualified staff in administrations and proper planning tools and assumptions. Need to make long-term infrastructure decisions and keeping pace with simultaneous changes.
(5) The co-existence of automated and conventional vehicles may be a long and challenging, but decisive period.
(6) In order to benefit from automation, cities should pro-actively support behaviour change and create an enabling policy framework in their areas of competence.

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Workshop presentation by Natalia de Estevan Ubeda: Transport for London (TfL) in Breakout Session 12, "AV-Ready" Cities or "City-Ready" AVs?' at AVS 2016

Workshop presentation by Seleta Reynolds: City of Los Angeles in Breakout Session 12, '"AV-Ready" Cities or "City-Ready" AVs?' at AVS 2016

Workshop presentation by Stephen Buckley in Breakout Session 12: '"AV-Ready" Cities or "City-Ready" AVs?' at AVS 2016

Workshop presentation by Siegfried Rupprecht in Breakout Session 12: '"AV-Ready" Cities or "City-Ready" AVs?' at AVS 2016

Traffic Flow of Connected and Automated Vehicles: Challenges and Opportunities

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Abstract Significant progress has been observed in recent years in the development of connected and automated vehicles (CAVs). Such progress has been publicized through the latest products/applications being released or announced by the industry. However, there is a limited knowledge on the impact of CAV technologies on surface transportation network performance. In particular, the technological specifications associated with CAVs and the response of drivers to such technologies are not well integrated into traffic flow models. These models are needed to assess and evaluate the safety and mobility impact on our roadway conditions. Accordingly, a more elaborate discussion is needed between three entities: (1) the industry partners leading the efforts in developing CAVs; (2) the academic traffic flow modeling community researching the impact of CAVs on traffic flow

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performance; and (3) the public/government agencies devising the standards and the rules to regulate the deployment of CAVs on our roadway network. This chapter summarizes the presentations of speakers from these three entities during the Automated Vehicles Symposium 2016 (AVS16) held in San Francisco, California on July 19–21, 2016. These speakers participated in the break-out session titled "Traffic Flow of Connected and Automated Vehicles". The corresponding discussion and recommendation are presented in terms of the lessons learned and the future research direction to be adopted. This session was organized by the AHB45 (3) Subcommittee on Traffic Flow Modeling for Connected and Automated Vehicles.

Keywords Traffic flow modeling · CAV · Deployment · CACC · Urban networks · Research needs

1 Introduction

As the deployment of connected and automated vehicles (CAVs) is being advocated for by different industry stakeholders, it is important to understand the implications of CAV technologies on the traffic flow dynamics at both the local link level and the network level. Such implications will not be understood without studying two dimensions: the technology dimension and the human dimension. In terms of the technology dimension, the communication, the vehicle dynamics and the sensing specification of CAVs should be identified and should be translated into traffic flow models. In terms of the human dimension, the responsiveness of drivers to CAV technologies should be measured and tested through elaborate experiments especially that CAVs have different types of connectivity and different levels of automation.

Towards studying the technological and human dimensions mentioned earlier, the Transportation Research Board (TRB) AHB45(3) subcommittee on "Traffic Flow Modeling for Connected and Automated Vehicles" organized a breakout

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session at the Automated Vehicles Symposium 2016 (AVS16)—held in San Francisco, California, on July 19–21, 2016. The breakout session titled "Traffic Flow of Connected and Automated Vehicles" brought together five scholars from academia, the industry and the public sector (Federal Highway Administration). These scholars presented their latest work in the CAV field. Following the presentations, a panel consisting of the five invited speakers had extensive discussions with the audience. This chapter summarizes 4 out of the 5 presentations made while identifying the key challenges in this research area and the corresponding efforts made to incorporate both the technological CAV specifications and the corresponding human behavioral response in traffic flow models.

The remaining sections of this chapter are organized as follows: Sect. 2 presents the summary of four out of the 5 invited presentations and Sect. 3 introduces the key results from the panel discussion.

2 Challenges and Research Opportunities on Connected and Automated Traffic Flow

This section presents a summary of four out of the five invited talks, which addressed the research challenges, opportunities and existing efforts in translating Connected and Automated Vehicles (CAVs) characteristics into traffic flow models. The summary includes the motivation and the contributions associated with the presented research, the main conclusions, and the future research directions.

2.1 Challenges of Automated Vehicles for Traffic Flow Modelling

The[1] development of automated vehicles (AVs) has been a long one that has been going on for many decades (Shladover 2007; Tsugawa 2008). The recent developments in the field are in response to a level of maturity in vehicle automation that has reached the stage that vehicles with lower level of automation [SAE L1 and L2 (SAE 2014)] are now present on roads and testing is in full flow for higher levels of automation (Ibañez-Guzman et al. 2012). At the same time, there are still many unknowns in relation to the physical performance of AVs in traffic and in interaction with other vehicles (Calvert et al. 2016). For a safe transition from the current state of affairs to the one where AVs are commonplace, much research is still required. This is the case for the deployment of these vehicles and therefore all the more for the modelling of the effects of the vehicles when deployed.

[1]By Simeon Calvert, Delft University of Technology (Netherlands).

Modelling AVs in traffic requires accurate models. Firstly, the movement of conventional vehicles needs to be more accurate than in regular traffic, as the interaction with AVs is subtler. Secondly, the different levels of AV's need to be considered and accurately captured, from vehicles with driving assistance (SAE L1), right up to fully autonomous vehicles (SAE L5). And thirdly, the interaction between conventional vehicles and the different levels of AV needs to be correct. These requirements are far from trivial, especially as we have not yet even considered the influence of vehicle cooperation and connectivity, and the fact that each automated system will perform differently, even for identical levels of automation. An SAE L2 vehicle from manufacturer A, will undoubtedly be programmed differently one from manufacturer B and therefore will drive differently.

Currently, traffic flow simulation for longitudinal driving generally performs well, however often lacks for the lateral modelling of conventional traffic (Schakel 2015). This is a major issue when it comes to simulation. Empirical research is already ongoing in relation to SAE L1 AVs, and some level 2 systems, which should give good insights into their dynamics and performance in traffic. However, ground truths for higher levels of automation and especially for the interaction between AVs and conventional traffic are scarce. There are a number of challenges that vehicle manufacturers need to consider that also need to be considered for AV simulation. Five of the main challenges relate to: anticipatory capabilities of AVs, situation and behaviour recognition, flexibility of (safety) protocols, consideration of other vehicles and the extent to which AVs are considered equal to conventional vehicles in traffic flow.

There is much to be done in understanding AV dynamics and being able to model these, however the outlook is not bleak. There is a need to focus on acquiring greater ground truths for the performance of AVs in real traffic, that goes beyond what can be achieved from theory. Furthermore, a solid reference with accurate conventional driving models is imperative. There must also be an awareness that AVs will also create new stochastic dynamics in traffic flow, stemming from the interaction with other vehicles and due to differences in vehicle and system design and capabilities. These aspects will need to be continuously addressed as the deployment of vehicle automation advances and should lead to greater capabilities to perform forecasting with the next generation of traffic simulation models.

2.2 Network Level Modeling and Applications of CAV Technologies: Strategic Level

This[2] summary is based on a recent survey article that examines the flow and operational considerations of autonomous and connected vehicles (Mahmassani 2016a); additional discussion of these issues can be found in that document.

[2]By Hani S. Mahmassani, Northwestern University, U.S.A.

The impacts of autonomous vehicles may be far-reaching on several levels. They entail changes on (1) the demand and behavior side, (2) the supply of mobility services, and (3) network and facility operational performance. For individuals and households, it becomes simpler to share the use of vehicles among household members, relieving the need for parents to chauffeur dependent household members, or to tightly synchronize joint travel. This may eventually provide households (and businesses) with the equivalent of a robotic assistant that could perform small errands and pick-up and delivery chores. These benefits, along with the perceptions of safety and reliability of the technology, will play a major role in the adoption equation for autonomous technologies (Mahmassani 2014). Autonomous capabilities may also reduce the need to own multiple vehicles, and some researchers have argued that it would preclude individual vehicle ownership altogether in favor of shared mobility fleets (Fagnant and Kockelman 2015).

The second point is that driverless vehicles will enable new forms of mobility supply. By eliminating the cost and performance limitations of human drivers, and increasing the ease of communicating instructions to both vehicles and travelers, autonomous vehicle fleets can be operated efficiently to deliver dynamically scheduled services to individuals riding privately or in shared vehicles. As such, new forms of car sharing with greater convenience may reduce the motivation for individual ownership. With driverless cars, vehicle availability in sharing services is not limited to fixed locations as vehicles can be repositioned dynamically (Hyland and Mahmassani 2017). Likewise, ride and car sharing marketplaces will likely expand with driverless vehicles, building on platforms developed by ride-hailing app companies like Uber and Lyft. This would contribute to reducing the cost and uncertainty of the sharing model by increasing the supply pool and enabling rapid dispatch of driverless vehicles. More generally, the realm between personal transportation and public mobility can widen considerably to include various hybrid forms. With transit companies adopting a broader portfolio of services, possibly in conjunction with third parties, one could envision disappearance of conventional fixed-route, fixed-schedule bus service in most lower-density communities, supplanted by driverless, personalized service at low density, and shared hybrid forms at medium densities; and greater focus on frequent rapid service along dedicated right of way (rail and/or BRT) in higher-density travel corridors (Mahmassani 2016b).

The potential changes in the supply of transportation and mobility at the urban scale are difficult to predict and characterize for the purpose of developing specific planning tools, and forecasting the demand for these services over time.

These changes in demand patterns, coupled with potentially far-reaching changes in the supply of mobility services, place considerably different loads on transportation networks than under the current situation. The net result is likely to be more, not less, travel, given the additional capacity, flexibility and convenience introduced by autonomous features and the mobility business models devised to leverage them. Actual performance at the network level will reflect these new patterns, and will be greatly affected by the specific routing and scheduling algorithms developed for both individual autonomous vehicles and for vehicle fleets.

These problems share many features of vehicle routing problem (VRP) variants, though coordination for network control purposes introduces features unique to the autonomous vehicle context. Several of the standard assumptions routinely made in predicting flows in networks, such as the prevalence of a user (Nash) equilibrium (UE) in how drivers route themselves through networks are likely to be challenged. For instance, repositioning or return trips, when driverless vehicles are not carrying any passengers (the equivalent of deadhead trips), could be routed on paths that are optimal for the system, i.e. that minimize marginal cost instead the vehicle's average cost. The formulation presented by Peeta and Mahmassani (1995) in the early days of advanced traveler information systems, for multiclass users that include UE, SO along with bounded rational users would be applicable in this case.

The most direct impact on network performance will result from the operational performance characteristics of the vehicles in the traffic stream, and the control algorithms enabled by and deployed with varying degrees of V2 V and V2I connectivity as vehicles navigate through the network's links and junctions. While greatly dependent on decisions made in the commercial marketplace and in the regulatory arena, understanding and modeling these impacts under a given set of assumptions about technological features, deployment scenarios and control measures is somewhat less speculative than the preceding two aspects (behavior, mobility supply models) because it lies mostly in the realm of traffic physics. Accordingly, there are already existing studies in the literature that have attempted to address some of these questions, particularly with regard to throughput and flow stability (Talebpour and Mahmassani 2014, 2016; Talebpour et al. 2016, 2017). A summary of these is found in Mahmassani (2016a).

2.3 CACC—V2X Solutions to ACC Challenges

The[3] CAMP V2I Consortium is a consortium of nine light-vehicle and one heavy-duty truck manufacturers, collaboratively working on Vehicle to Infrastructure applications. The consortium is conducting the CACC Small-Scale Test project that is aiming to understand the necessary technical steps and potential challenges to implement CACC in vehicles.

The project studied the behavior of conventional ACC systems when they are operated in strings of vehicles following each other. These tests were conducted by implementing a prototype ACC system into four vehicles from different manufacturers and then characterizing them on a test track. The test results showed that during deceleration maneuvers, the reaction time from vehicle to vehicle was 1.5 s. Around 0.8 s of those can be attributed to the detection of the previous vehicle's maneuver and the remaining 0.7 s can be attributed to the reaction of the host vehicle to the computed desired reaction. Due to these latencies, the vehicles would

[3]By Jan-Niklas Meier, CAMP V2I Consortium.

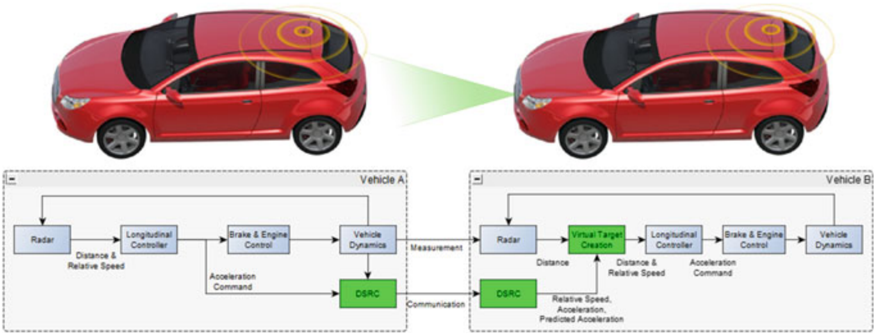

Fig. 1 CACC control diagram

operate in an undesired manner, amplifying decelerations from vehicle to vehicle which could lead to increased traffic perturbations or even so-called phantom traffic jams.

Since the reaction time of the host vehicle likely can't be improved without significant modifications in the vehicle's brake and engine control systems, they are assumed to stay. The project instead focused on implementing a CACC system that aims to reduce or remove the initial detection time. This is done by introducing Dedicated Short-Range Communications (DSRC) to the vehicles. Through this communication channel, the vehicles receive the current acceleration from the preceding vehicle. Most importantly, the vehicles also transmit and receive a predicted acceleration of the preceding vehicle, giving them an indication of how that vehicle will be acting in ~ 0.5 s into the future. This would effectively turn a 0.8 s detection disadvantage into a -0.5 s prediction advantage. Using this information, the project hopes to design a CACC system that can stabilize traffic flow instead of increasing perturbations. For the design of the system, the project team chose to keep most components of the existing ACC longitudinal control system unmodified but instead modifying the inputs to that system through the new module "virtual target creation". If successful, this would allow for a relatively simple modification to improve ACC systems or other longitudinal control systems (e.g. found in automated vehicles) using DSRC (Fig. 1).

The project team built a simulation environment including a traffic simulator, Radar and DSRC models, and a vehicle dynamics model to test out the developed system. This was necessary since the goal is to execute the same algorithms that would be executed in the vehicle in the simulation environment.

The project is still ongoing and will implement different algorithms for CACC and then characterize them using the built simulation environment to assess the potential benefits. Additionally, a functional safety analysis will be conducted, assessing necessary modifications when using DSRC data in addition to Radar data when computing vehicle control commands. When the project is completed, it will show, if CACC can be implemented as an extension to ACC and what the estimated benefits of mixed make and model CACC strings are.

2.4 *Connected Vehicles Can Increase Throughput and Decrease Delay on Urban Roads*

Intersections[4] are the bottlenecks of the urban road system because an intersection's capacity is only a fraction of the flows that the roads connecting to the intersection can carry. Consider an intersection with four approaches, each with one through and one left-turn lane, so these approaches can accommodate eight movements. But the intersection can only permit two non-conflicting movements at any time. So, the intersection's capacity is one-quarter that of the approaches.

Therefore, the throughput of the urban road system can be increased only if vehicles can cross the intersections in platoons rather than one by one as they do today. Platoon formation is enabled by connected vehicle technology. This talk assesses the potential mobility benefits of platooning. It argues that saturation flow rates, and hence intersection capacity, can be increased by a factor C in the range 1.7–2.0.

The queuing analysis and the simulations reveal that a signalized network with fixed time control will support an increase in demand by a factor C if all saturation flows are increased by the same factor, with no change in the control. Furthermore, despite the increased demand vehicles will experience the same delay and travel time. The same scaling improvement is achieved when the fixed time control is replaced by the max pressure adaptive control. However, the queue lengths will also increase by C, which may lead to saturation. But part of the capacity increase can alternatively be used to reduce queue lengths and the associated queuing delay by decreasing the cycle time. Impediments to the control of connected vehicles to achieve platooning at intersections appear to be small.

3 Discussion

The panel discussion (including audience interaction) identified the key challenges in traffic flow research in the connected-automated environment and outlined the future research needs, which not only help to advance research on traffic flow modeling of CAV, but also to promote the collaboration and coordination of the traffic flow research community with other communities from the industry and the public sector.

As a first step, the traffic flow modeling community can offer insights into the propagation of disturbances along different traffic steams with different types of vehicles involved. The resulting traffic dynamics are a function of the vehicle/driver behavior reaction latency and the technological specifications to be adopted and regulated by the industry stakeholders and the public agencies respectively.

[4]By Pravin Varaiya with J. Lioris, F. Yildiz, R. Pedarsani, D. Farias, A. Kurzhanski, A. Askari (UC Berkeley, USA).

The research findings from the traffic flow modeling community will pave the way to improved inter-vehicular interactions. Such contribution is essential since added CAV technologies is not synonymous to improved driving conditions.

In particular, researchers can analyze existing CAV applications including ACC and their role in reducing reaction time at signalized intersections. Additional methodological contributions may be through offering quantifiable traffic performance measures associated with the introduction of CAVs in a traffic stream. Such measures may include safety measures, throughput measures (capacity), stability measures (local versus global stability), reliability measures, emission and sustainability measures. Moreover, traffic flow simulation models may be seen as an economically feasible way to analyze the traffic worthiness of CAVs manufactured by the industry. Simulation models may create different congestion dynamics and may serve as a virtual environment to test if a vehicle with specific specifications will function properly. Although these simulation models require field experiments and ground truth data for calibration and validation purposes, they remain an essential feasibility medium before deploying vehicles in the real-world.

The second set of recommendations made in this break-out session is related to the technological specifications of CAVs. In particular, it is important at this stage to finalize the testing of CACC with the collaboration of the different entities mentioned in the abstract. Once the CACC research is deployed, the focus should be on the CAV applications associated with lateral movement. For example, lane-changing and merging CAV applications (for example: gap identification and lane usage per type of vehicle) need to be studied. Finally, the communication between vehicles remains the main feature to be analyzed in traffic simulation models. These models should recognize the potential errors in communication, the reliability dependence on the surrounding weather and infrastructure conditions, the cybersecurity related threats and the storage limitation given the amount of data transferred between vehicles.

In summary, the future research needs identified by the audience/presenters can be classified into three groups.

Data needs: even though the US Department of Transportation and the Federal Highway Administration are managing multiple CAV deployment testbeds, there is a lack of communication of the findings with the research community. Moreover, the data being collected/stored do not answer the research needs of the traffic flow modelers who need to calibrate/validate different assumptions when formulation/expanding on simulation modeling paradigms. On the other hand, the data produced by the industry is proprietary in nature and is not made public for further analysis. In response to such lack of data, researchers are attempting to conduct their own field (expensive) experiments in order to collect ground truth data.

Technological needs: the CAV market needs cheap and accurate positioning technology for implementing different CAV applications, including CACC. Such technology is not yet available especially given the lack of the full utilization of the DSRC channels, while having to rely on the more expensive but more reliable LiDAR technology. In addition, GPS resolution should be taken into consideration when modeling traffic in a connected driving environment.

Application needs: the objective of translating technological specifications and human behavioral responses in CAV-enabled traffic flow models is to devise improved CAV applications, including CACC. Accordingly, it might be useful to test variant CAV applications by: (1) studying scenarios when CACC platoons are broken by regular vehicles; (2) testing various combinations of CAV, CV, AV and regular vehicles; (3) investigating the impact of heterogeneous vehicles (e.g., trucks and passenger cars) on CAV-penetrated traffic flow; (4) capturing the impact of infrastructure and weather characteristics on the performance of different types of vehicles (including CAV, CV, AV and regular vehicles); (5) considering the role of electric cars in reducing congestion and emission/pollution in a connected and automated traffic environment.

It was agreed by the breakout session participants that traffic flow related research plays a critical role in advancing and implementing the CAV technologies, and that collaboration with other communities (if feasible) will be very beneficial.

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Potential Fleet Size of Private Autonomous Vehicles in Germany and the US

Stefan Trommer, Lars Kröger and Tobias Kuhnimhof

Abstract There are high expectations on autonomous vehicles promising a safer, more efficient and comfortable (auto)mobility experience. On the other hand it is important to discuss possible rebound effects going along with such a development. New user groups e.g. people who do not hold a driving license today, or are currently unable to drive because of physical and/or age-related constraints suddenly are enabled to “drive” a passenger car. In addition the past has shown that increasing efficiency and enhancing the comfort leads to a higher travel demand and subsequently more vehicle miles traveled. To support the research on the impact of autonomous vehicles on the transport system it is important to analyze the potential share of autonomous vehicles (AVs) on the passenger vehicle fleet in the future. The paper presents results from modelling private autonomous vehicle scenarios for the year 2035 for Germany and the US to estimate the number of vehicles within the fleet equipped with automation technologies Level 4 and higher (SAE in SAE International Standard J3016, 2014). A vehicle technology diffusion model has been developed to model an evolutionary and a rather revolutionary scenario which are distinguished by different market entry dates and AV technology take rates. Differentiating by passenger car segment, we introduce autonomous vehicles among new vehicles from 2022 resp. 2025 onward assuming an s-shaped market-take-up until 2035.

Keywords Vehicle automation · Autonomous vehicles · Diffusion rates of autonomous vehicles · Market penetration · Fleet evolution · New car sales · AV

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1 Introduction

Despite the technological challenges that need to be overcome before autonomous vehicles (AVs) become a reality on public roads, the degree of automation in road vehicles is expected to continuously rise. Advanced driver-assistance systems (ADAS), such as lane-keeping assistants and adaptive cruise control, are already available in currently produced vehicles, and this is moving the technology development forward. In the past, such advanced technologies have been available only in the higher vehicle segments, but today such systems are also available in medium-sized cars.

There are high expectations of automation technologies. Some experts envision autonomous driving as a comfort enhancing feature for drivers, as it would enable them to focus on other activities (Fraedrich et al. 2015; KPMG 2012). Other stakeholders, such as government officials involved in transport and traffic management, hope that the technology will reduce road fatalities since over 90% of road fatalities are caused by human error (Fraedrich et al. 2015; Fagnant and Kockelman 2015) and increase the efficiency of transport systems (Fagnant and Kockelman 2015). Autonomous driving could also provide mobility options for people who do not hold a driving license, or are currently unable to drive because of physical and/or age-related constraints. Automation technologies will provide these user groups with the means of independent mobility, will enable easier access to essential services, and will help reduce their social isolation (Anderson et al. 2014). Another much-discussed benefit of autonomous driving for the user is the decrease in the perceived time costs, since vehicle occupants are enabled to transfer their attention to other activities during the trip. Moreover, the increasing digitalization in vehicles, such as infotainment systems, can improve the overall travel experience and level of comfort (Fraedrich et al. 2015; KPMG 2012).

Especially the aspects of enhanced comfort, new mobility options for specific user groups and decreasing time costs are expected to have an impact on mode choice and subsequently vehicle miles travelled (VMT). Experts estimate the increase in VMT alone from new user groups such as people without a driver's license or people with medical conditions by 14% for the US (Harper et al. 2016). From the transport research perspective possible effects on mobility need to be discussed and quantified early to be able to help incorporating AVs in a sustainable way into the transport system.

When trying to analyze the impact on the transport system and specifically VMT estimations of the potential fleet size of autonomous vehicles are of high importance. Given the uncertainty of the timeframe for market introduction, availability in certain segments as well as the surcharge when buying a vehicle equipped with automation technologies, scenario based methods seem to be an appropriate possibility to approach the topic.

Several studies have been published until today addressing this topic. Litman (2014) suggested that the technology would reach the market by 2020 and grow to a market share (share of new car sold with AV technologies) of 20–40% and a fleet share of 10–20% in the US by 2030. Townsend (2014) found that depending on the regulatory and technological circumstances AVs could reach a fleet share of 25–35% in 2030 in the US. On a global level McKinsey and Company (2016) suggest that (depending on the scenario) 10–50% of new car sales could incorporate automation technologies. Within the high distribution scenario it is expected that up to 15% of the new car sales are vehicles that could operate fully autonomously. BCG (2015) expects about 20% of new vehicles sold in 2025 to have significant autonomous capabilities. This could lead to a share of 10–19% fully autonomous vehicles of new car sales in 2035.

This overview (covering the global perspective as well as the US market) suggests that there will be huge difference in share of AV of new car sales between the different markets. Also the information on new car sales is not sufficient when trying to investigate the impact to the transport system. The translation into fleet shares is also important to understand the timeframe that is necessary to reach significant numbers since several benefits such as positive impacts on transport efficiency cannot be realized until a certain share of AVs has been reached (Fagnant and Kockelman 2015).

The aim of this paper is to calculate scenario based shares of AVs of new car sales and the overall passenger car fleet for the US and Germany and to identify differences between these markets. This research is simplified in the sense that the scenarios do not take into account that autonomous vehicles could significantly affect car ownership by introducing new personal mobility services. This is subject to future research.

2 Methodology

In order to estimate the share of AVs within the national passenger car fleet, we used an AV diffusion model. This model consists of (a) a sub-model that estimates the share of AVs among new car registrations and (b) a simple stock-flow cohort model which was used to diffuse AVs throughout the entire car stock including vehicles of all ages.

The share of AVs among new cars is modelled by an S-shaped market-take-up. Four car segments are distinguished for each country. The German segmentation is an adapted version of the KBA classification (KBA 2016) and differentiates the following segments: small vehicles, compact class, medium-sized vehicles and large vehicles. The US classification is an adapted version of the vehicle type definition used in the NHTS (USDOT—U.S. Department of Transportation 2009) and differentiates small vehicles, pick-up-class, medium-sized vehicles and large vehicles.

The AV diffusion model distinguishes between Level 4 and Level 5 automation technologies. Level 5 can be seen as referring to fully autonomous vehicles (SAE 2014). An integrated curve with a change from Level 4 to Level 5 diffusion is used for simplification. It is assumed that if Level 5 technologies are available for a vehicle segment it replaces Level 4 systems in new car sales. There is no overlapping of Level 4 and Level 5 diffusion years within each segment in the model. Level 3 automation technologies have not been taken into account since the individual benefit is expected to be significantly lower when the driver is expected to take control over the car from time to time in certain situations.

Differences in the diffusion rates of different car segments arise from differing years of introduction, initial diffusion rates, and parameters defining the slope of the growth curve. The number of newly registered AVs P_t in year t is calculated as follows by using a Gompertz function:

$$P_t = P_\infty * a^{b^t}$$

P_∞ Maximum number of newly registered AVs (with the assumption of a maximum 95% rate of AVs)
a Quotient of the initial rate of newly registered AVs in the year of introduction
b Factor of growth
t Years since introduction

The forecast of years of introduction follows published road maps, e.g. those of vehicle manufacturers and automotive suppliers and information of associations of manufacturers (ERTRAC 2015; EPoSS—European Technology Platform on Smart Systems Integration 2015; PWC 2015).

The differences between the slope of the growth curve of the different vehicle segments are set by considering the historical diffusion of driving assistance systems (separately for Germany and the US). The delay, as well as the initial diffusion rate and market growth within the different segments, is adapted from the observed market take-up of automatic cruise control systems (ACC) and lane keeping assistants within Germany and the US. Internet automotive classifieds such as cars.com (for the US car market) and mobile.de (for the German market) have been analyzed to establish historic shares of vehicles equipped with ACC systems for each vehicle segment and model year within the last fifteen years. Interestingly, the share of vehicles equipped with ACC systems in the US is significantly lower than in Germany.

Reasons are the smaller share of luxury cars and longer vehicle lifetimes in the US resulting in a slower diffusion of such systems.

These forecasts about the proportion of AVs among new cars were combined with assumptions about the total number of newly registered cars per year (Germany 3 million; US 15 million) as well as about the average vehicle life span for each segment (Germany 14–17 years, US 16–22 years) in a stock-flow cohort model. As a result we obtained the proportion of AVs in the total car fleet per country per year.

Table 1 Year of introduction of automation technologies within the scenarios

	Scenario “Evolution”		Scenario “Revolution”	
Vehicle segment	Level 4	Level 5	Level 4	Level 5
Small	2029	2034	2024	2028
Compact/pick up	2027	2033	2024	2028
Medium	2026	2032	2022	2026
Large	2024	2030	2021	2025

3 Scenarios

Estimating and describing the impact on travel demand of introducing AVs into the private car fleet and comparing the results for the US and Germany is realized in two scenarios: scenario “Evolution” and a scenario “Revolution”.

The main differences between the two scenarios are:

- The time of introduction of AV technologies
- Growth rates reflecting the adoption of AVs
- Initial adoption rate when AVs are first introduced to the market

Within the model the diffusion of automation technologies follows a top down approach. It is assumed that automation technologies are first introduced in the luxury segment and later in the smaller vehicle segments. This follows the observation how new technologies found their way into the market in the past. The year of introduction of AV technologies is assumed to be the same for Germany and the US. Table 1 provides an overview of the assumed year of introduction of AV technologies into specific vehicle segments differentiated by scenario.

4 Results

In the following chapter the results of modelling the market introduction of AVs using a diffusion model are described separately for each scenario.

Scenario “Evolution”

Following the analysis of published roadmaps (see Fig. 1 and Table 1) it is expected today that the deployment of AVs with Level 4 automation technologies will start around 2024 within the luxury car segment in appreciable numbers; medium—and compact-sized vehicles follow in 2026 and 2027 respectively, and from 2029 on AVs are available in the small-car segment within the scenario “Evolution”. 2030 also marks the year in which fully automated systems (Level 5) are first introduced, subsequently replacing Level 4 systems in new cars of the luxury class (Fig. 2).

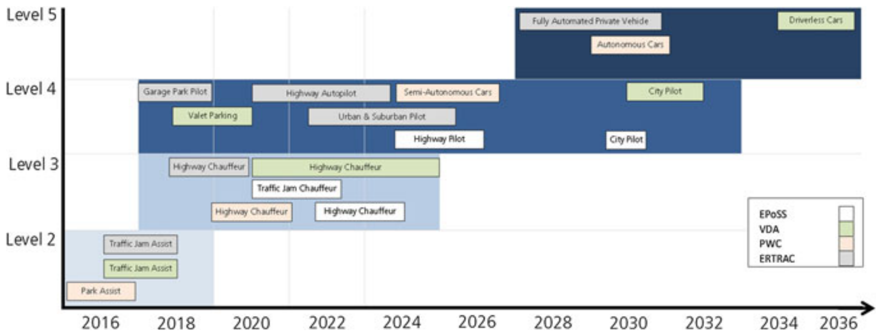

Fig. 1 Roadmaps for autonomous driving

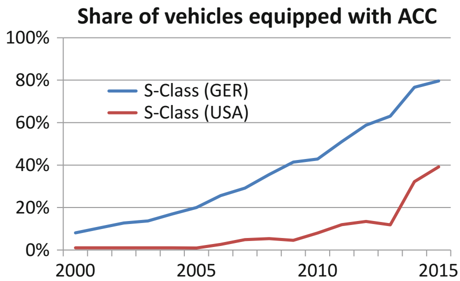

Fig. 2 Share of vehicles equipped with ACC systems per model year

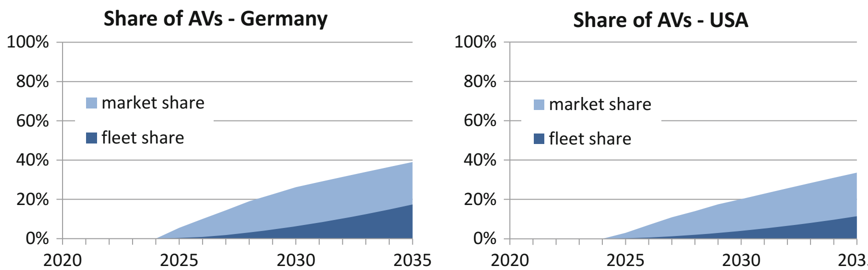

Fig. 3 Expected market share and fleet share of AVs in the scenario "Evolution"

In Germany AVs have largely entered the fleet as company cars and typically proceed to the private car market after 2–3 years. In 2035, Level 4 and level 5 AVs have reached a market share of 39% and account for 17% of the total vehicle fleet (see Fig. 3). In the US the introduction of AVs into the country's vehicle fleet is expected to happen somewhat slower compared to Germany: by 2035, about 11% of all passenger cars could be autonomous vehicles. The national fleet in general is rather old (see Chapter "Latest Development in SIP-adus and Related Activities

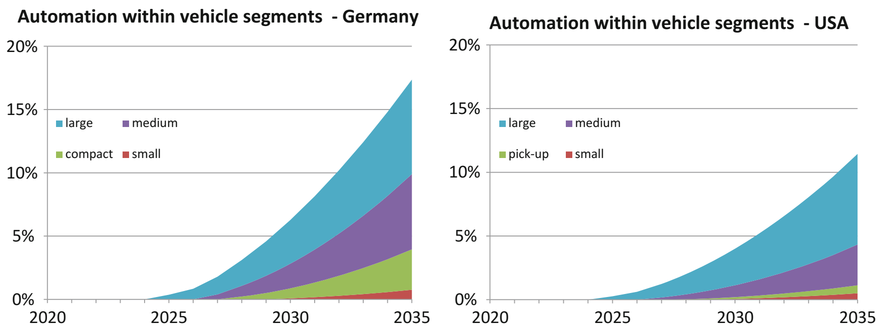

Fig. 4 Expected market share and fleet share of AVs in the scenario "Evolution"

in Japan"), making it harder for new vehicle technologies to break through. Another aspect is the lower share of luxury vehicles, which tend to be the bearers of new technologies into the rest of the market. The share of AVs of new car registrations is at about 34% in 2035.

Looking at the share of automated vehicles within the different vehicle segments it can be observed that large and medium sized vehicles make up for the largest part of automated vehicles within the fleets in both countries in the scenario "Evolution". Whereas almost 50% of the large vehicles within the fleet in Germany are already equipped with automation technologies (Level 4 + 5) only 4% of the small vehicles and just about 10% of all compacts are equipped with automation systems in the year 2035 (see Fig. 4). Against the background that the segments of small and compact vehicles combined make up for more than 50% of the passenger car fleet in Germany it becomes evident that it is crucial to reach these segments to achieve a higher diffusion of AVs. Within the framework of the scenario the driving vehicle segments are likewise large vehicles and medium sized vehicles making up for about 29% respectively 8% of the fleet being AVs in 2035.

Scenario "Revolution"

In the scenario "Revolution" autonomous technologies are introduced to the market earlier than in the scenario "Evolution", in combination with faster adoption of such systems. Within the scenario, technology has proven to be safe and beneficial, and the regulatory barriers—as well as liability issues—that autonomous systems face today have been overcome faster. Consequently, Level 4 vehicles had entered the market already by 2022 in the luxury class, and this was followed by a fast adoption down to the small-vehicle segment through to 2025. The year 2025 also marked the introduction of Level 5 technologies into the premium vehicles segment. This led to a widespread introduction of AVs into the transport system and compared to the scenario "Evolution" to a significantly higher share of AVs in the year 2035.

The earlier market introduction, higher adoption and specifically the earlier availability of the technology in the small and compact sized vehicle segments

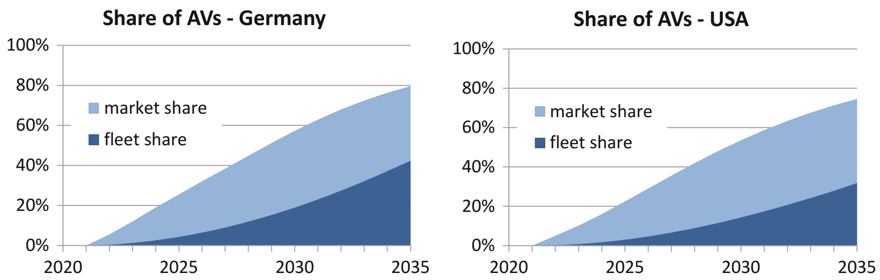

Fig. 5 Expected market share and fleet share of AVs in the scenario "Revolution"

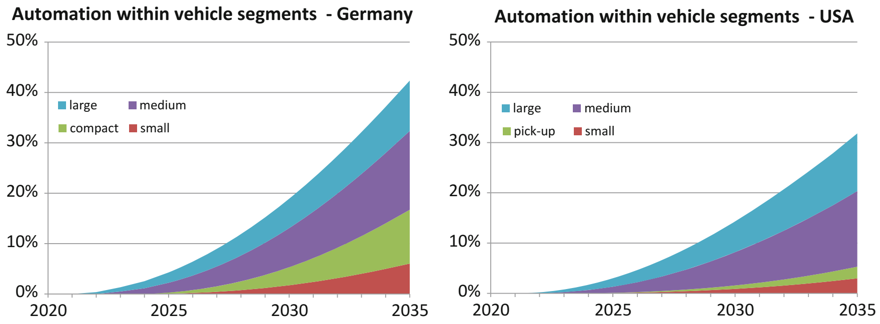

Fig. 6 Expected market share and fleet share of AVs in the scenario "Revolution"

results in a share of about 42% AVs in the overall fleet by 2035 in Germany (see Fig. 5). The share of AVs on new car sales totals to almost 80%, making purchasing a conventional vehicle the exception. In the US the development is similar due to the same framework conditions in terms of availability of AV technologies but again somewhat slower due to the lower market share of luxury vehicles and a lower fleet renewal rate due to the higher vehicle lifetime. This results in about 75% market share of AVs and a fleet share of 32% in 2035 in the US.

One of the most influential scenario assumptions has been the earlier availability of AV technologies within the segment of small and compact/pick-up vehicle segments in the scenario "Revolution". In combination with a generally higher adoption rate the share of AVs within the named segments is significantly higher. In Germany a share of 29% of the small vehicles respectively 33% of the compact sized vehicles within the fleet are equipped with AV technologies. In the US the share is somewhat lower at 19% within the small vehicle segment and 13% within the pick-up segment. The results are summarized in Fig. 6.

5 Conclusion

The aim of this study was to analyze potential shares of autonomous vehicles in new car sales within the passenger vehicle fleet for the US and Germany in two scenarios. A technology diffusion model has been used to quantify prospective numbers of vehicles. The following aspects can be concluded:

- The diffusion of new technologies into national vehicle fleets takes a long time due to the low renewal rates which depends on the number of vehicles entering and exiting the fleet every year. Long vehicle lifetimes as observed in the US slow down the process.
- Automation technologies are expected to enter the market about 2025 in large/luxury vehicles requiring a surcharge. If additional costs for these systems cannot be reduced significantly until 2030 the share of AVs in the pick-up/compact and small vehicle segment will be significantly lower than in the large/luxury and medium sized segment. Therefore potential positive effects such as efficiency gains of the transport network and the reduction of road fatalities are very limited due to the high share of compact and small vehicles within the fleet (about 50% in Germany).
- From today's perspective it seems rather unlikely that the necessary technological development and reduction of costs for automation technologies as pictured in the scenario "Revolution" could be realized. Nevertheless it is important to consider such a development to understand the dynamics behind. Consequently the results of the scenario "Revolution" suggest that measures might be necessary to boost sales of automation technologies in the pick-up/compact and small vehicle segment to reach a significant share of vehicles in these segments which are historically decades behind in adoption of new technologies such as driver assistance systems due to their high surcharge.

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Simulation-Based Traffic Management System for Connected and Autonomous Vehicles

Paweł Gora

Abstract The paper presents an idea for a simulation-based traffic management system, which may be especially successful in the era of connected and autonomous vehicles (CAVs). The most important aspect of the system is its ability to evaluate traffic conditions for different traffic control strategies (e.g., different traffic signal settings, different route assignments) using fast traffic simulations and neural networks. It also employs metaheuristics (e.g., genetic algorithms) to find (sub)optimal traffic control strategies. Results of initial experiments show that building such traffic management system might be technically feasible and it may be especially successful in the era of CAVs, for which it may be possible to collect required traffic data and make accurate traffic predictions.

Keywords Connected autonomous vehicles · Traffic management · Simulation

1 Introduction

The technology of connected and autonomous vehicles (CAVs) is developing rapidly, major car manufacturers and some information technology giants develop prototypes of such cars and announce their mass production in the near future (CB Insights 2016). Some companies have already started pilot self-driving taxi services (Davies and Marshall 2016), some countries and cities adjust law regulations and infrastructure to meet requirements for introducing autonomous technology (Hawkins 2016). The future with self-driving cars seems to be indispensable, especially that this disruptive technology may have a revolutionary impact on transportation and the whole society and the world economy. There might be even

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more benefits if autonomous vehicles could communicate with each other (V2V—vehicle-to-vehicles communication) and with a road infrastructure (V2I—vehicle-to-infrastructure communication) (Gielmo 2011). Generally, thanks to these innovative technologies, traffic might be much safer and efficient, but to achieve it, it is important to manage it wisely.

The paper presents an idea for a traffic management system which might be especially successful in the era of CAVs. The idea takes advantage of novel computer science concepts and technologies such as large-scale traffic simulation, deep neural networks, cloud computing, Big Data processing, computations using GPU. Many of these concepts made significant progress in the last couple of years. However, the major innovation comes from the theoretical concept that traffic can be predicted with a high accuracy using simulation and machine learning tools (such as neural networks) even in situations when traffic conditions significantly change (because of bad weather, car accidents, roadworks or other atypical cases). The behavior of a human-driver is usually hardly predictable (especially in a dynamically changing environment), but in case of autonomous cars, which know in details their future routes, algorithms of drive and interaction with the environment (reaction to external events) and can communicate such information to the traffic management system, the idea of good predictability of traffic might be fulfilled to a large degree. Thus, traffic management system may employ such information to evaluate different traffic management strategies and choose the optimal. Since the set of possible strategies is usually very large and the problem is considered as computationally difficult (e.g., traffic signal setting problem was proven to be NP-hard in some simple traffic models (Yang and Yeh 1996)), it is not easy to find (sub)optimal strategy. To solve this issue the proposed idea assumes applying metaheuristics (e.g., genetic algorithms) supported by traffic simulation and neural networks.

The rest of the paper is organized as follows: Sect. 2 presents state of the art in traffic management area including CAVs. Section 3 introduces the idea for an adaptive, real-time traffic management system, presenting its overall architecture and results of initial experiments. Section 4 concludes the paper and outlines future research directions.

2 State of the Art

The traffic management systems field emerged in the second half of the XX century as a consequence of growing number of cars on urban roads. We can distinguish the following approaches to managing traffic of conventional cars:

- Adaptive traffic signal control
- Traveler information systems
- Adaptive speed limits
- Adaptive directions of drive on lanes
- Adaptive tolling of roads/parking lots/usage of cars

Most of these approaches may exist also in the era of self-driving cars, however, the totally new approach will arise: direct control of a self-driving car by algorithm implemented in a car or commands sent from other cars or infrastructure (being part of the traffic management system).

Among existing professional traffic management systems the most common are traffic signal control systems, such as SCATS (Lowrie 1982), SCOOT (Hunt et al. 1981). In many cases (especially: typical, repeatable conditions, low travel demand) their quality is good and they are able to improve some traffic parameters. The problem usually arises in case of a high demand and atypical conditions, such as sudden road blockage (e.g., caused by car accident (Pan et al. 2013)), changes in traffic organization (e.g., mass events, roadworks), bad weather conditions. Then, existing traffic management systems might not be able to manage traffic in acceptable way, because of the following limitations:

- Reactivity, but not proactivity: reacting on past and present traffic conditions (which might be sufficient for a regular, smooth, recurrent traffic, but may not be sufficient when major changes happen—the reaction might be inappropriate or just too late to prevent occurrence of a large traffic jam), but not anticipating and preventing undesired traffic states
- Lack of accurate evaluation of changes
- Relatively small space of possible modifications to the traffic control system (often only slight changes are allowed)
- Lack of scalability, questionable efficiency in case of large road networks (most of existing traffic management systems focus on optimizing traffic on a corridor or relatively small areas, but not globally)

Also, existing systems don't take into account connected and autonomous vehicles, which bring new opportunities for traffic management systems. One of them is an opportunity to design roads and intersections without traffic signals, where cars can communicate with each other and synchronize trajectories of drive to make traffic as safe and efficient as possible. Investigations of this case consider a single intersection (Dresner and Stone 2008) and multiple intersections (Hausknecht et al. 2011). There are also works which consider a transition period, in which CAVs coexist on roads with conventional cars, also in such cases traffic delays might be reduced thanks to intelligent control and communication, without traffic signals (Au et al. 2015).

These works are important steps toward a holistic traffic management in the advent and era of CAVs. However, they focus mostly on assuring safety and traffic control based on reservation of time-space slots (which, of course, is a very important aspect, ensuring safety), but they do not focus on optimizing traffic characteristics in a city-scale. The control is decentralized and it doesn't take advantage of a full potential of traffic information which might be collected from CAVs. As a consequence, they don't consider making short-term traffic predictions (e.g., 5–10 min ahead) for a better traffic control. Also, it is not certain that traffic signals will be ever removed at all (even in times when all cars will be fully automated), because of pedestrians, who may need to cross the street. It is possible that keeping short time periods, in which pedestrians could cross a street, might be the most secure and efficient option (even if not, the transition period to removing traffic signals might be very long). That's why it is reasonable to consider traffic management methods including traffic signals and CAVs at the same time.

3 Simulation-Based Traffic Management System for Connected and Autonomous Vehicles

In comparison to existing approaches to traffic management, the proposed approach takes advantage of two important features of CAVs:

1. They can send information about their state (e.g., position, speed) and planned route to the traffic management system
2. Their short-term behavior and trajectory might be predicted with much better accuracy than in case of conventional cars

In the proposed approach, the process of a real-time traffic management consists of a few steps:

1. Acquiring traffic data
2. Building/updating a traffic model
3. Predicting traffic conditions in advance
4. Finding good traffic control settings (e.g., signal settings)
5. Applying best settings

3.1 Acquiring Traffic Data

Nowadays, traffic information is acquired mostly using inductive loops, cameras or other sensors which are external to cars. These methods are usually expensive, their accuracy may depend on many factors (e.g., visibility, weather) and they may collect only information about positions and speeds of cars, total congestion and travel times on some segments. They can't get information about a complete car's route (although, there exist approaches to predict future route based on a car's current trace and historical data, but they still require additional information (Krumm 2006)). Therefore, existing traffic management systems may base only on statistical data, such as current and past traffic congestion, traffic densities, travel times, factors of cars turning at a given crossroad etc.

Having additional information about car's trace and planned route may give new opportunities, e.g., it might be possible to estimate with a very good accuracy how many cars will be riding through each road segment and when (the estimation might be even better when it is supported by accurate traffic simulation). Thus, it might be very beneficial to have accurate data about car's trace and planned routes. Nowadays, this data is available in GNSS navigation systems, which are used by many drivers. In the future, passengers of CAVs will have to provide information about intended destination and route (the route may be computed by a car's onboard computer or a traffic management system, but still it might need to be confirmed by a driver). Then, such information might send to a traffic management system using a vehicle-to-infrastructure communication (V2I).

Car's location might be also detected using external sensors (traditional radars, cameras, drones or lidars/radars of other CAVs), while the car's route might be guessed by traffic management system, using a given trace, history of similar rides and origin-destination matrix (Krumm 2006).

All in all, it might be technically feasible to acquire (or estimate) information about positions, speeds and planned routes of all (or almost all) cars on a road. Also, analyzing traces of cars may give additional knowledge, which might be used to calibrate model of drive of a given driver. On the other hand, CAVs could just send some specific information about its settings. In both cases, drive of a car might be potentially simulated with a relatively good accuracy.

One of potential issues of that approach might be privacy of data. However, traffic management system does not have to collect any sensitive information about a specific driver, because it only needs locations and future routes, it is not important who exactly is sitting in a car. In the era of CAVs the idea of "mobility on demand" may even will lead to a situation in which almost all passengers just rent (and not own) a car, so it will not be possible to easily match cars with passengers.

3.2 Building a Traffic Model

Acquired data might be used to build virtual models of a real-time and typical traffic (both models might be useful in the process of a real-time traffic management). Model of a typical traffic should contain information about number of trips between any pair of communication regions (O-D matrix), divided with respect to different modes of transport and chosen routes. Such information should be available for each significant time period. Precise time periods should be determined by a careful analysis of available traffic information. Usually, duration of a single time period should be 1 h, but in some cases shorter time periods might be required. Since many trips are recurrent with a weekly period (e.g., people quite often travel to the same places in each Monday in a period 7:00–8:00), it might be sufficient to keep a separate model for each hour and each day of a week, which gives $7 \times 24 = 168$ different models. However, traffic is also influenced by holidays and some special events, so in practice it might be required to have much more different models. The exact number should be determined for each city/area separately, by analyzing available historic traffic data. The important thing is to determine all models of traffic which correspond to typical, average traffic conditions. In reality, these typical conditions may never occur, because usually they will be averaged by many different cases, and noise introduced by specific situations (e.g., roadworks, special events, new cars) may cause deviation from typical conditions. Thus, to manage the traffic properly, it is important to build also a real-time traffic model.

Real-time traffic model might be built based on data collected from cars in real-time, including positions, speeds, intended routes and models of drive. Real-time traffic model should be more accurate than a typical traffic model, i.e., it should contain information about number of trips between each pair of communication areas, with respect to different modes of transport and chosen routes, but also information about current positions, speeds and planned routes of all cars participating in the traffic. In Sect. 3.1 it was explained how (and why) such information might be available to the traffic management system. Also, a model of a typical traffic for a given period could be used to approximate missing data.

3.3 Predicting Traffic Conditions in Advance

Real-time traffic model might be used to run fast traffic predictions, e.g. based on traffic simulation or machine learning algorithms. Such predictions should be run once per some given time period (e.g., 1 min) to predict traffic state in advance, e.g., 10 min ahead. They could serve to detect undesired traffic conditions and make decisions whether to run traffic optimization algorithms and find better traffic control strategies.

3.4 Finding Good Traffic Control Settings

3.4.1 General Idea

The most important aspect of the proposed idea for a simulation-based traffic management system, is that the quality of different traffic control strategies might be evaluated using traffic simulation in which the input is constructed based on a real-time traffic model and parameters of the strategy (e.g., in case of a traffic signal control, these parameters may be signal offsets or durations of phases, in case of a route assignment (which is related to traveler information systems) it might be routes proposed to drivers/CAVs). The space of possible traffic control strategies is usually very large (e.g., in case of 120 traffic signal offsets for 800 crossroads with traffic signals in Warsaw, it is $\sim$120,800) and usually there is no easy method to find best possible strategy from a given set (in some cases it was proven that the problem is NP-hard). However, evaluating large number of different strategies using traffic simulation might give important insights on how to search for a good (suboptimal) strategy in a large set of possible strategies, e.g. it is possible to apply metaheuristics, such as genetic algorithms.

This approach might be used to find good traffic control strategies for a typical traffic situation (which brought very good results in case of finding good traffic signal offsets for Warsaw (Gora and Pardel 2015)). The optimization process required to evaluate large number of strategies (e.g., based on genetic algorithms) might be time consuming (it may require a lot of computational power), but it can be run offline, e.g., once per week/month/year, for each model.

For a real-time traffic management such approach may not be good, because each simulation evaluating quality of a traffic control strategy may need several minutes and the system has to check large number of possible strategies to find the one sufficiently good. However, the process can be accelerated in two ways:

- Speeding up running a single simulation
- Approximating outcomes of a simulation (e.g., using neural networks)

3.4.2 Speeding up Running a Single Simulation

The process of evaluating quality of a traffic signal setting can be done using any simulation model that is capable to compute values of a given objective function (e.g., the total travel time as a function of traffic signal settings). In the previous experiments, a microscopic traffic model based on a cellular automaton, implemented in the Traffic Simulation Framework software (Gora 2009) was applied. It is able to simulate realistic traffic on a large network of Warsaw with more than 100,000 agents in real-time. To achieve faster than real-time simulation, parallelization and additional computational power might be required. A cellular automaton underlying the simulation model can be parallelized and its evolution may be computed using GPU. Also, it might be possible to distribute computations on a cluster of machines, by splitting the whole road network into smaller parts, and running simulations of traffic on each region on a separate machine. If a single car travels between at least two different regions (and that case is typical—people usually use cars to travel long distances), it should be properly handled. The time of computation may depend on available computational power, which might be relatively large if the simulation has to be accelerated by a few orders of magnitude (e.g., from a few minutes to a few seconds). Since in the traffic management problem usually it is required to evaluate large number of different strategies (e.g., a few millions) and run multiple simulations with different settings, this approach may require very large computational power.

3.4.3 Approximating Outcomes of a Single Simulation

If the traffic management process requires running a large number of simulations (e.g. a few millions or billions) the method described in Sect. 3.4.2 might be too time consuming. Therefore, a better approach may be to make approximations of outcomes of simulation. This can be done with a good accuracy using neural networks and the process was described in (Gora and Kurach 2016). However, the system should first run some number of simulations to generate training set for a machine learning algorithm (experiments presented in (Gora and Kurach 2016) and their continuations show that the training set of a size 10,000–100,000 should be sufficient). After that, machine learning algorithms also need some time to train the approximation model, which may usually take a few minutes. Once the model is trained, its inference (i.e., approximating outcomes of a simulation for a given input—traffic control strategy) is very fast (it may take less than a second using GPU and TensorRT engine (2017)).

Hence, it is easy to see that the method can be applied for building neural networks approximating simulation outcomes offline, for a typical traffic model. For a real-time traffic management and real-time traffic models, the method might be still relatively difficult and time-consuming. Thus, the further research should go into at least three directions:

- Running traffic simulation as fast as possible (to generate training set for machine learning algorithms fast)
- Training machine learning algorithms as fast as possible and on as small training set as possible, ensuring satisfactory accuracy at the same time
- Developing metaheuristics (e.g., genetic algorithms) able to find acceptable traffic control strategies using small number of evaluations

It is likely that the best approach for a real-time traffic management will employ results from all these research directions. It is also possible that the best approach will take advantage of machine learning models (e.g., neural networks) built offline for a typical traffic conditions, which will be just adapted to a real-time conditions, and since real-time conditions will always have some similarities with typical conditions, the adaptation process should take less time (and will require smaller training set) than training model from a scratch.

3.5 Applying Best Settings

Best traffic control settings found during the process described in Sect. 3.4 might be applied by a traffic management system and sent back to vehicles (e.g., route assignments) or to the road infrastructure (e.g., traffic signal settings). An interesting question is: can it be assured that the traffic control strategy found by an algorithm based on a virtual traffic model will be also good in case of a real traffic? There answer is: no, because there might be some unexpected events (e.g. pedestrian crossing a road) which may disturb the traffic so that evaluation based on a virtual model will not be good. However, in case of such events, traffic management system may just run the traffic optimization procedure described in Sect. 3.4 again, to find a new strategy—that is one of advantages of a real-time traffic management. But even without such unexpected events, the compatibility between real-world traffic and a real-time traffic model is always up to some degree. Luckily, in case of CAVs, the traffic management system may know precisely the algorithm of drive, hence, it can include it in a real-time (or typical) traffic model and simulate drive of each CAV and its interaction with other CAVs, which may give sufficient accuracy of the simulation model. Again, in case of unexpected events having large impact on traffic and causing significant differences between real-world traffic data and real-time model outcomes, the traffic management system may decide to run a traffic optimization procedure again.

3.6 Results of Experiments

Experiments showed that it is possible to approximate outcomes of traffic simulations (e.g., the total waiting time of all cars) with a satisfactory accuracy (the average error was about 1.5%, the maximal error was about 9%, both results can be potentially reduced by using boosting—applying a few neural network models and averaging their results) (Gora and Kurach 2016). Similarly, experiments with a genetic algorithm showed that using a genetic algorithm it may be possible to find traffic signal setting better by more than 18% than best (random) configuration in the initial set (Gora and Pardel 2015). Results are very promising, but still some work should be done to make the idea work efficiently in a real-time traffic management.

3.7 Importance of Running Computations in a Cloud

The following reasons explain why the proposed traffic management system should operate in a cloud infrastructure:

- Reliability (the system may work even if some machines fail)
- Scalability (in most cases the system may not need a huge amount of resources, but in some critical cases, it may require a lot of resources)
- Location independence (traffic management as a service, the system may run independently on a location)

4 Conclusions and Future Work

The paper introduces an idea for a simulation-based traffic management system, which may be especially successful in the era of connected and autonomous vehicles, because of their ability to acquire and send information about current positions and planned routes, and predictability of their behavior using simulation.

The idea takes advantage of novel technologies such as deep neural networks, cloud computing, GPU, Big Data pressing. Initial results are promising and can be used for an offline traffic management, but to enable real-time traffic management, the future research should be directed to speeding up simulations, the process of learning and inferring neural networks, and improving efficiency of metaheuristics.

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