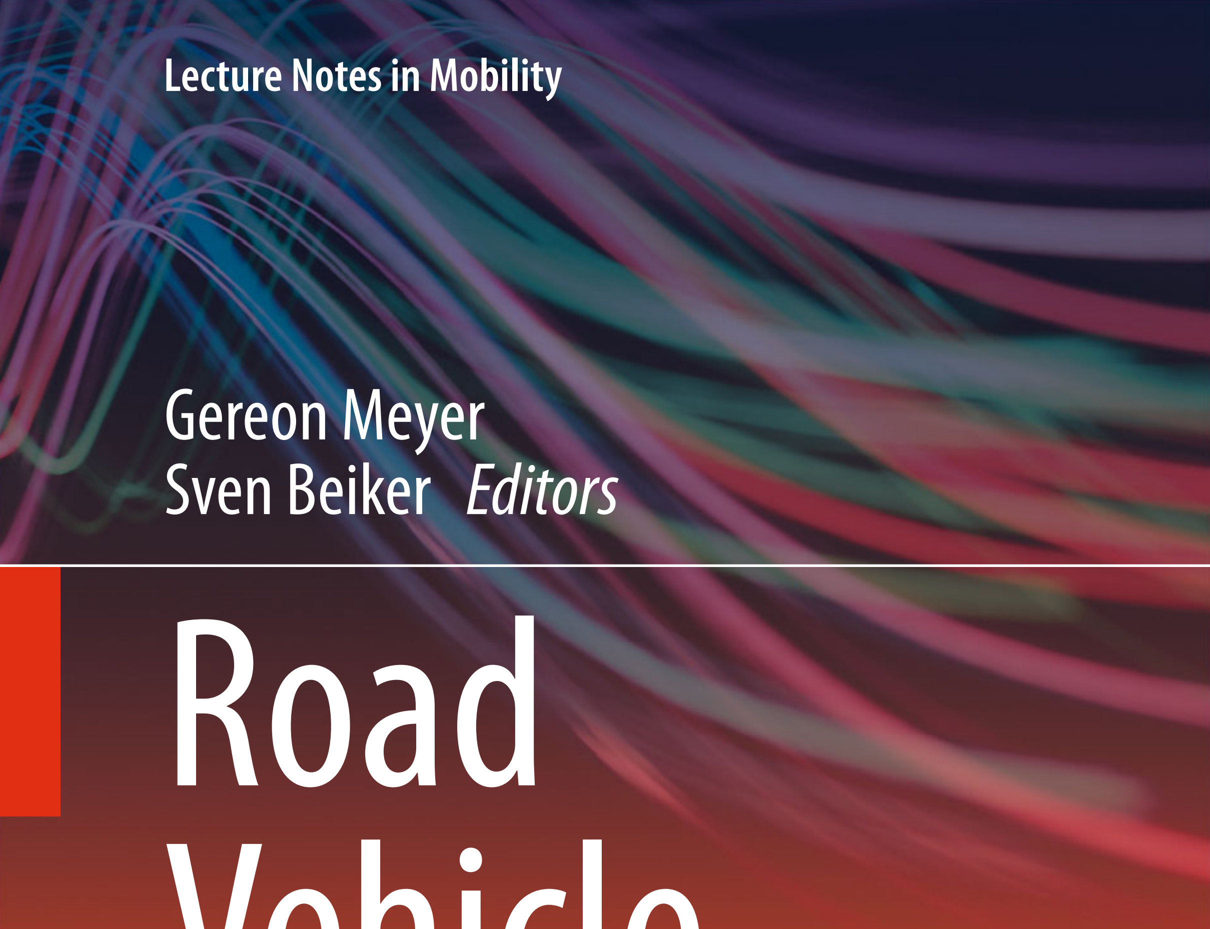

Lecture Notes in Mobility

Gereon Meyer
Sven Beiker *Editors*

Road Vehicle Automation

Springer

Lecture Notes in Mobility

Series editor

Gereon Meyer, Berlin, Germany

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ISSN 2196-5544 ISSN 2196-5552 (electronic)
ISBN 978-3-319-05989-1 ISBN 978-3-319-05990-7 (eBook)
DOI 10.1007/978-3-319-05990-7
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014941235

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As cars become intelligent, we now have
to act intelligent, not just be intelligent.

Clifford Nass (1958–2013)

Preface

2013 was an exceptional year for road vehicle automation: Public authorities around the world presented action plans to facilitate the development and introduction of automated vehicles. At the same time many announcements and demonstrations from automotive companies and research groups showed that the industry is moving closer to a scenario where the driving task will be gradually transferred from the human to the computer. In addition to these trends, several organizations proposed definitions for the different levels of such computer controlled vehicles and they all seemed to agree that the degree of "automation" is appropriate to describe what might otherwise be called "autonomous," "driverless," "self-driving" vehicles.

In July 2013, the U.S. Transportation Research Board (TRB), a private, nonprofit institution that is committed to "provide leadership in transportation innovation and progress through research and information exchange," hosted its second annual "Road Vehicle Automation Workshop" at Stanford University. The event was attended by over 200 participants from academia, industry, and public sector featuring talks by leading experts in the field and also offered breakout groups related to many different topics regarding vehicle automation. This very interdisciplinary setting did not only consider advancements in engineering but also covered legal, business, ethical, and administrative issues. The 2013 TRB Road Vehicle Automation Workshop at Stanford gave a great overview of the field that has the potential to transform road transportation as a whole and with that to redefine the way we drive.

The workshop also triggered this book project, which is to give a comprehensive overview of what is arguably—besides powertrain electrification—one of the most revolutionary trends in the automotive field at the moment. We are grateful that almost all presenters at the workshop volunteered to turn their presentations into technical papers for this book, which shows the commitment to bring this topic forward and to work together.

Collaboration is indeed needed in order to solve open questions regarding vehicle automation from various fields in a coherent manner, while also taking into account the different opportunities and challenges at regional level. In going forward, we hope that the field of vehicle communication will establish even closer ties with the vehicle automation field for safe, efficient, and convenient mobility in the future. We also expect that the combination of power train electrification and vehicle automation will lead to synergies.

At this point we would like to acknowledge the TRB committees' role in organizing the workshop, developing the program, and inviting the speakers. Coordinating all this was done in accordance with the charters of the Transportation Research Board (TRB) and National Research Council (NRC) and in accordance with TRB's scope "to provide a focus and forum for road vehicle automation and to promote a better understanding within the transportation profession of these systems including their research, deployment, and operation." It is explicitly pointed out that the papers contained in this book are not official reports of NRC or NAS, though.

We would like to thank especially the Workshop Chairs Jane Lappin, Bryant Walker Smith, Steven Shladover, and Bob Denaro for their dedication and for their enthusiasm that led to an incredible gathering of experts at the workshop, and which also provided strong support for the idea for this book. We would also like to thank everyone who helped making this book possible, particularly, Zakia Soomauroo and Sebastian Stagl at VDI/VDE-IT should be mentioned. And certainly we would like to express our deep gratitude to those who contributed with their papers to this publication, which to our knowledge is the first of its kind as a multidisciplinary discussion of vehicle automation in light of near-term deployment and future visions.

Finally, we would like to thank all of you who bought this book. We hope you will benefit from this comprehensive publication and that it will inspire you to seize the potential of vehicle automation for road safety, fuel economy, social inclusion, and productivity. We look forward to meeting, hopefully, many of you at the TRB Road Vehicle Automation Workshop 2014, or at another occasion to continue the exchange on such diverse topics regarding automated vehicles that this book is a great example for.

May 2014 Gereon Meyer
Sven Beiker

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Introduction: The Transportation Research Board's 2013 Workshop on Road Vehicle Automation

Steven E. Shladover, Jane Lappin, Robert P. Denaro and Bryant Walker Smith

Abstract This chapter introduces the TRB 2013 Workshop on Road Vehicle Automation, which was the original source for the papers that are included in this volume. The TRB organization and its functions are explained, providing the context for this workshop and its significance. The reasons for creating the workshop are explained, in the context of the history of road vehicle automation work in the U.S. The structure and organization of the meeting are explained, showing its mixture of plenary talks, breakout discussions, technical demonstrations and ancillary meetings. The chapter concludes with a discussion of future directions and thoughts about the future meetings in this series.

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_1,

1 Introduction

The Transportation Research Board (TRB) of the National Academies organized the Second Annual Workshop on Road Vehicle Automation, which was hosted by Stanford University on July 15–19, 2013. The workshop website, vehicleautomation.org, evidences the scale of this event. More than 60 people planned over 100 h of programming, much of it interactive, for 335 participants from 15 countries. Interest was so high that registration had to be closed nearly a month before the workshop due to capacity constraints.

Part of this interest was derived from the success of TRB's First Annual Workshop on Road Vehicle Automation, which was held at the Beckman Center of the National Academies at the University of California, Irvine, on July 24–26, 2012, and part was based on the growing interest in road vehicle automation both within and beyond the transportation profession. The 2012 Irvine workshop was organized to educate the transportation community about the recent progress in road vehicle automation, especially the activities outside the U.S., which were largely unknown to most of the U.S. participants, and to stimulate interest in new research on this subject in the U.S.

Although the U.S. DOT had sponsored a large and active program on road vehicle automation during the 1990s, it was terminated in 1998 and the topic was not given serious consideration by transportation agencies and professionals in the subsequent years. The level of public research activity dwindled to near zero in the U.S., but research on the subject picked up in Europe and Japan in the early 2010s. The Irvine workshop was an opportunity for U.S. stakeholders to learn about that work, as well as the new activities in the U.S. that arose from the DARPA Grand Challenge, DARPA Urban Challenge, and Google's announcement of their "self-driving cars". The response to the Irvine workshop by its 125 participants was very favorable, but that workshop did not make as much progress as hoped for on identifying the research that needs to be done to advance automation closer to deployment. This, plus the high level of organizer, presenter, and participant interest in another workshop, motivated the creation of the second workshop in 2013.

The 2013 workshop at Stanford focused on the challenges and opportunities for road vehicle automation. The goals were to enhance understanding of the current state of knowledge and to produce specific research needs statements that could become the seeds of new research projects. The workshop was organized by scores of volunteers representing multiple standing committees of TRB. It was important to have active participation from committees with widely varying backgrounds because of the multidisciplinary character of the topic.

The Center for Internet and Society (CIS) at Stanford Law School and the Center for Automotive Research at Stanford (CARS) hosted the workshop through their Legal Aspects of Automated Driving Program. This multidisciplinary initiative, led by Bryant Walker Smith, explores the legal, policy, and social aspects of increasing vehicle automation.

The 2013 plenary talks were organized more thematically to emphasize a wide range of issues that have to be considered before more advanced road vehicle automation can become a reality. (In contrast, the 2012 plenary presentations were organized along project lines to make people aware of the range of active projects.) These plenary talks were linked to breakout sessions focused on identifying specific research needs in ten distinct thematic topic areas.

These breakout sessions, which formed the “working” part of the workshop, followed a wide range of structures: Some set up as mini-conferences with multiple presenters, others as highly interactive workshop sessions for discussion of research needs, and others as conference/workshop hybrids. On the final morning of the main meeting, representatives of each breakout session presented their recommendations to the full plenary session.

An element that added considerable excitement to the meeting was the availability of vehicle demonstrations. Google and Bosch gave rides on a nearby freeway in their automated research vehicles, Autonomous Stuff demonstrated the capabilities of a variety of sensors that they retrofitted onto a rental car, and Stanford’s automotive researchers hosted an open house to display and discuss their research systems.

At the end of the conference, the attendees expressed overwhelmingly favorable interest in a follow-up meeting the next year, so TRB will continue to organize these annual workshops. The breakout discussions also yielded 46 research needs statements, which are being reviewed by the TRB standing committees for inclusion in TRB’s official database of research needs.

2 TRB Background and Significance

Although TRB has some resemblance to professional societies that organize conferences and publish technical journals of research results, it is quite different in several ways from most professional societies. TRB is one of six major divisions of the National Research Council—a private, nonprofit institution that is the principal operating agency of the National Academies (National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine). Its work cuts across many different professional disciplines and all modes of transportation, which makes it significantly different from societies that are discipline-oriented or modally-focused. It is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

TRB was established in 1920 as the National Advisory Board on Highway Research to provide a mechanism for the exchange of information and research results about highway technology. Renamed the Highway Research Board (HRB) in 1925, the organization accomplished its mission through standing committees, publications, and an annual meeting. In the decades that followed, HRB steadily increased in size. Information exchange remained its sole mission until the 1950s, when it began to undertake management of ad hoc research projects. During the 1960s, the Board’s activities became increasingly multimodal in outlook, so in 1974 it became the Transportation Research Board.

Since the early 1980s TRB's Studies and Special Programs Division has been conducting studies of national transportation policy issues, making formal policy recommendations to government agencies using a carefully managed process designed to produce authoritative and unbiased policy advice. For many years, TRB has also been managing cooperative research programs that are co-sponsored by the U.S. DOT and state departments of transportation, as well as special research programs mandated by the U.S. Congress.

The Technical Activities Division of TRB functions most like a traditional professional society, organizing conferences and publishing peer-reviewed technical papers in its *Transportation Research Record* series. This Division contains more than 200 standing committees that focus on a wide range of transportation topics, covering not only road vehicle transportation, but also pedestrian and bicycle transportation, aviation, marine, rail, and pipelines. These committees are organized in the following broad topic clusters:

- Design and construction (pavements, structures, materials, traditional civil engineering)
- Operations and preservation (traffic management, maintenance, security, and including the committees specifically devoted to intelligent transportation systems and vehicle-highway automation)
- Planning and environment (including energy, environment, economics, forecasting and societal issues)
- Policy and organization (including transportation finance, law, education and training, and data management)
- Safety, system components and users (including human factors and mode-specific committees in transit and non-road-oriented modes).

The standing committees are a critical resource to the transportation community. Their formal responsibilities include organizing meeting sessions, reviewing papers for publication or presentation, and formulating the research needs statements posted on TRB's website. The principal event for TRB—and for the entire transportation research and policy community—is the Annual Meeting, which attracts more than 12,000 attendees to Washington, DC each January. The 2014 Annual Meeting featured 450 lectern sessions, 195 poster sessions and 135 workshops, and it required committee peer review of some 5,200 papers. The committees select the best of these papers (22 % in 2014) for publication in the *Transportation Research Record*, the Journal of the Transportation Research Board.

The 2013 Workshop on Road Vehicle Automation was organized as the mid-year meeting of the standing committees on Vehicle-Highway Automation and Intelligent Transportation Systems, with cooperation and co-sponsorship from the committees on:

- Emerging Technology Law
- Major Activity Center Circulation Systems
- Emerging and Innovative Public Transportation and Technologies

- Vehicle User Characteristics
- Cyber Security
- Transportation Energy.

This shows the breadth of the topics that were covered and of the expertise that was assembled for the meeting.

The TRB Committee on Intelligent Transportation Systems, currently chaired by Jane Lappin, is concerned with ITS systems-level issues. Such issues include conceptual system planning and design, integration of information and communications technologies throughout the transportation network, facilitation of intermodal integration, and evaluation of the overall impacts of ITS on the developers, operators, and users of all parts of the ground transportation system. Activities focus on the broad planning, policy, economic, social, technological, and institutional aspects of the development and implementation of ITS. The Committee also facilitates coordination of ITS-related issues with other standing committees of TRB. It was established in 1992, as a spin-off from the Committee on New Transportation Systems and Technologies, when it was becoming evident that ITS would be an important new development in transportation.

The TRB Committee on Vehicle-Highway Automation, currently chaired by Steven Shladover, is concerned with the development, application, and operation of driver assistance and automated control to the vehicle and highway system. The scope includes all forms and levels of control ranging from driver assistance systems operating on existing streets and highways to full vehicle control systems operating on freeway type and/or dedicated lane facilities. It further includes systems that support specialized highway related functions including maintenance, fleet operations, and similar applications. The emphasis is on control systems that will enhance user safety, system efficiency, and operational performance while providing for increased convenience and trip quality to the highway user. The objectives of the committee are to provide a focus and forum within the TRB for vehicle-highway automation and to promote a better understanding within the transportation profession of these systems including their research, deployment, and operation. It was established in 1997 as a spin-off from the Committee on ITS, as the Committee on Automated Highway Systems, when the U.S. DOT was sponsoring the National Automated Highway Systems Consortium program and automated highways were expected to become the major new thrust in road transportation. When the Automated Highway System program was terminated, the Committee was re-named and its scope was adjusted to reflect more modest ambitions.

The TRB Joint Subcommittee on Challenges and Opportunities for Road Vehicle Automation (CORVA), currently chaired by Robert Denaro, was established as a subcommittee of the Committees on ITS and Vehicle-Highway Automation to provide a venue to bring together all the TRB standing committees having interests related to road vehicle automation so that they can participate in organizing meetings and other activities. The mission of CORVA is to identify, stimulate and disseminate research essential to the successful development and deployment of automated cars, trucks and transit vehicles operating on the road network and its associated infrastructure. CORVA is a forum for information exchange and definition of research needs across planning, policy, economic, social, technological, and institutional issues related to road vehicle automation. Through its meetings, conferences and workshops, CORVA attempts to maximize inclusion of the diverse organizational interest in road vehicle automation, creating dynamic interaction among government, academic and industrial leaders in the development of vehicle automation technology and products.

The TRB Emerging Technology Law Committee, currently chaired by Bryant Walker Smith, addresses both the legal implications of new transportation technologies and the practical implications of new legal technologies. It is highlighted here because it focuses at present on vehicle automation and connectivity, because its members were the principal organizers of three breakout sessions in the first two workshops, and because its chair invited TRB to Stanford.

3 Need for this Workshop in the Context of the History of Road Vehicle Automation Research

The 2013 Workshop on Road Vehicle Automation was important and timely for several reasons:

- Professionals in transportation and related fields have become increasingly interested in understanding road vehicle automation and what it means for them as managers, designers, facility operators, regulators, policymakers, lawyers, and planners, to name just a few. There have not been any sources of authoritative information to address these needs, and the large majority of the information that has been circulated in public is from sources that are less directly involved in the operating realities of the transportation world. This has led to a high level of uncertainty and anxiety about what automation portends for the future of the road transportation system.
- The information available from the general interest media, the trade press and the Internet has tended toward unrealistically optimistic views about the technical maturity of automation, the timing for its introduction, and its impacts. By its nature, the published work from these sources is not subjected to rigorous peer review processes, and is therefore largely unfiltered for accuracy and technical correctness. There was a need for discussion about what is achievable technically and economically, and on what timeline.
- There had not yet been a forum to bring together the diverse stakeholders who are interested in and likely to be affected by automation so that they can interact with and learn from each other. This requires people with expertise in vehicle, infrastructure, and information technology as well as legal, policy, human factors, business, and institutional issues. It also requires people who bring the different perspectives of private industry, government at all levels, academics, and consultants, representing both U.S. and international experiences.

- The state of the art is changing rapidly as more companies and research institutions get involved, so there is a need for frequent updates about what people have been learning. The first TRB workshop in 2012 provided an overview of the progress in the decade that immediately preceded it, but more updates were needed on the activities of the intervening year. As more people get involved in the topic, there is also a need to get them up the learning curve since many of them did not participate in the 2012 meeting.
- In the popular and trade press and throughout the Internet there has been a blurring of the distinction between full automation of vehicles in all road environments, and the partial automation that is emerging today with driver-monitored parking, traffic jam assist and adaptive cruise control systems. Experts agree that much more research and technology development work will be needed before the public can gain the benefits of fully automated driving. There has been a need for serious, in-depth discussion about the unknowns and the work that remains to be done to resolve them, so that both public and private sector organizations can invest their resources efficiently to address the important challenges that remain.

People who are getting involved with road vehicle automation for the first time now are not aware of the long history of prior efforts in this direction. There is a tendency for many to believe that road vehicle automation began with the DARPA Challenges of the mid-2000s, or maybe by the Google “self-driving” car activities that were inspired by the DARPA activities. In fact, these recent activities are only the most recent chapters in a story that began almost 75 years ago. That said, it is clear that both the DARPA Challenges and the aggressive promotion by Google have ignited a surge in research and development activity and may well have accelerated introduction of automation features on current automobiles.

The concept of road vehicle automation dates back to the late 1930s and the visionary ideas of Norman Bel Geddes, the industrial designer who inspired and developed the 1939 General Motors “Futurama” exhibit at the New York World’s Fair. At that time, automated highways were predicted to become reality in 25 years.

Serious technical work on automation of road vehicles began in the late 1940s at the RCA Sarnoff Laboratory and continued through the 1950s in partnership between RCA and GM. By the early 1960s GM had developed several generations of concept cars and research prototypes that were able to drive automatically (when the technology had to be implemented using analog vacuum tube circuitry). GM showed a more ambitious vision for highway automation in the “Futurama II” exhibit at the 1964–1965 New York World’s Fair, again predicting that it would be achieved in the next 25 years.

An extensive program of research led by Prof. Robert Fenton at the Ohio State University advanced the road vehicle automation technology further between 1965 and 1980, producing more advanced research prototypes. These were predicted to be on the road by 1990.

There was a hiatus in research on road vehicle automation for most of the 1980s until the University of California and Caltrans began extensive research on this subject in the PATH Program in the late 1980s. That work led to the creation of the federally-funded National Automated Highway Systems Consortium (NAHSC) program (1994–1998), which produced a large demonstration of a variety of road vehicle automation concepts in San Diego in August 1997. That Demo ’97 received extensive international media coverage and provided fully-automated vehicle demonstration rides to thousands of invited visitors, who were very favorably impressed by what they experienced.

However, the NAHSC program was terminated after the demonstration (the only milestone that was Congressionally mandated) and before it could develop the prototype system it was originally intended to develop. The prototype and a specification for a deployable system were scheduled to be completed in 2002, and those would have been the basis for a field operational test in the subsequent years. The U.S. government did not want to wait that long for the fruits of that effort to ripen, but wanted to focus on technologies that it thought would be less challenging and could be brought to market more quickly [1].

Throughout this history, the deployment of automated driving systems has always been over the horizon, just out of sight and reach. There have been manifold reasons for that, but it is important to understand this history in order to make accurate predictions about deployment timelines in the future. This longer perspective is also useful to bring to bear when thinking about the problems that still need to be solved before the multiple levels of road vehicle automation can be implemented widely. In short, thoughtful examination of the similarities and the differences between this past and the present is essential to a grounded discussion of the future of road vehicle automation.

Many organizations and individuals have become interested in the general topic of road vehicle automation in recent years, but without a clear view of what specific actions they could take to accelerate progress. This is where the identification of research needs becomes an important contribution of the workshop, particularly since such needs have not been widely considered or documented publicly for the past 15 years, since the final recommendations of the NAHSC for future work were presented. Bringing together experts with a wide range of experience and knowledge in the relevant subject matter enabled the development of a broad collection of research needs based on knowledge of what has already been done (to avoid duplication of prior work) and of the most important problems that have not yet been solved. These research needs are useful to a wide range of stakeholder interests:

- Public agencies that need to allocate their research resources to the subjects where they can have the most favorable impact
- Private companies looking for opportunities to develop new products that solve important problems to create good business opportunities
- Consultants seeking to understand where new contract opportunities are likely to arise
- Academic researchers seeking topics for graduate student theses or unsolicited proposals to funding agencies.

4 Workshop Organization and Structure

The workshop program was developed between January and June 2013, starting with the initial meeting of the TRB Joint Subcommittee on Challenges and Opportunities for Road Vehicle Automation, at the end of the TRB 2013 Annual Meeting. That meeting, a brainstorming session with about one hundred participants, was aimed at identifying the most important topics for breakout sessions on research needs. At the end of that meeting, breakout topics were chosen and volunteers signed up to work on the development and management of those breakout sessions. A chair was selected for each breakout, and those chairs worked with their subcommittees of volunteers to develop the breakout session programs, relying on conference calls and e-mail distribution lists.

The overall meeting planning was coordinated by an executive committee consisting of the authors of this article. These workshop co-chairs conducted frequent conference calls and e-mail exchanges and met approximately monthly with the broader planning committee, including the breakout session leaders and other volunteers in charge of vehicle demonstrations, the workshop's website, communications, and fundraising. Meanwhile, TRB and Stanford staff, in cooperation with the co-chairs, worked through numerous logistical issues related to the meeting's complexity and novelty.

The co-chairs not affiliated with Stanford selected the plenary speakers. This was difficult because the organizers wanted to include twice as many speakers as the schedule would accommodate and because multiple additional well-qualified people requested invitations to speak. The criteria for selecting speakers were multiple—they had to be thought leaders in the subject matter who were also effective at holding the attention of a large audience. As a group, the plenary speakers also needed to represent a balanced mix of the relevant stakeholder interests, nationalities, and types of organizations. Finally, topics were selected to match up with at least one of the breakout sessions so that there would be a logical linkage between the plenaries and breakouts. The plenary talks that were finally included in the program were:

- Bernard Soriano (California DMV): Autonomous Vehicles in California
- Bryant Walker Smith (Stanford University): Proximity-Driven Liability
- Steve Underwood (University of Michigan, Dearborn): Disruptive Innovation on the Path to Sustainable Mobility: Creating a Roadmap for Road Transportation in the United States
- Clifford Nass (Stanford University): Psychology of Automated Vehicles
- R. David Edelman (White House Office of Science and Technology Policy)
- Joe Peters [Federal Highway Administration (FHWA)]: Accelerating Road-Vehicle Automation
- Paul Rau [National Highway Traffic Safety Administration (NHTSA)]: Safety Through Automation Program
- Maxime Flament (ERTICO, representing the European Commission): Automated Driving from the European Perspective

- Yasuhiro Okumura (Japan’s Ministry of Land, Infrastructure, Transport and Tourism): Automated Driving Activities in Japan
- Jan Becker (Bosch): Toward Fully Automated Driving
- Arne Bartels (Volkswagen): High Automated Driving Functions
- Dirk Rossberger (BMW): Please Take Over
- Joakim Svensson [Volvo Group (trucks)]: Current Status and Future Opportunities
- Adriano Alessandrini [University of Rome La Sapienza (CityMobil2)]: Automated Road Transport Systems in European Cities
- Ron Medford (Google): Why Self-Driving.

Ten parallel breakout sessions were held for discussion of research needs in their respective topic areas. Some of these included extensive presentations by subject matter experts to set the scene for the rest of the participants, while others moved directly into discussion of their research needs. The breakout groups ranged from a minimum of about ten to a maximum of about 75 participants, depending on the level of interest and workshop attendance in their topic area. These breakout topics were:

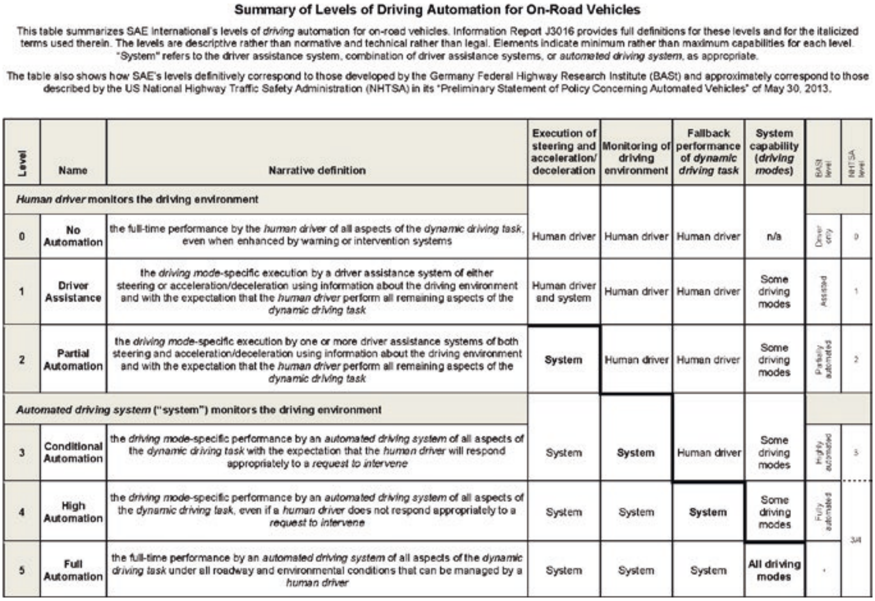
- Automated commercial vehicle operations
- Cybersecurity and resiliency
- Data ownership, access, protection, and discovery
- Energy and environment
- Human factors and human-machine interaction
- Infrastructure and operations
- Liability, risk, and insurance
- Shared mobility and transit
- Testing, certification, and licensing
- V2X communication and architecture.

These topics included a rich combination of mode-specific themes such as commercial vehicles and transit with cross-cutting themes on both technical and non-technical topics.

Additional topics were explored in 20 posters presented at the workshop and posted to the website. These posters were solicited less than 2 months before the workshop and were selected based on peer reviews of 200-word abstracts.

Because the TRB workshop brought together a large number of people from throughout the world who are interested in road vehicle automation, this made it an attractive opportunity for scheduling ancillary meetings related to automation:

- The SAE International On-Road Automated Vehicle Standards (ORAVS) committee held an open meeting to present and discuss the work that its members had been doing during the preceding 18 months. This included an extended discussion of the definitions and classifications that they have defined to help facilitate clearer communication about vehicle automation concepts. The accompanying figure [2] summarizes SAE’s levels of automation as discussed at this open meeting and subsequently published in SAE Information Report J3016.



Summary of Levels of Driving Automation for On-Road Vehicles

This table summarizes SAE International's levels of *driving* automation for on-road vehicles. Information Report J3016 provides full definitions for these levels and for the italicized terms used therein. The levels are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or *automated driving system*, as appropriate.

The table also shows how SAE's levels definitively correspond to those developed by the Germany Federal Highway Research Institute (BASt) and approximately correspond to those described by the US National Highway Traffic Safety Administration (NHTSA) in its "Preliminary Statement of Policy Concerning Automated Vehicles" of May 30, 2013.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
Human driver monitors the driving environment								
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system ("system") monitors the driving environment								
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

- The U.S. Department of Transportation held a Public Stakeholder Engagement Meeting to present its current thinking about the definition of its research plans related to road vehicle automation. This led to a lively exchange of questions and answers with the audience.
- The state of California organized a half-day meeting to discuss California-specific topics in road vehicle automation, specifically the industrial competitiveness issues associated with the cluster of automotive research laboratories in Silicon Valley, the implications of automation for the state's road infrastructure and public agencies, and the development of regulations to govern the testing and public operation of automated vehicles by its Department of Motor Vehicles.
- Two public transportation-oriented TRB committees, Major Activity Center Circulation Systems and Emerging and Innovative Public Transportation and Technologies, organized a "Strategy Day" to discuss the implications of automation for public transportation, energy, emissions and land use.
- The U.S. DOT hosted a day-long meeting of the trilateral Automation in Road Transportation Working Group, comprising representatives of the European Commission, Japan Ministry of Land, Infrastructure, Transportation, and Tourism, and U.S.DOT, which built from the content of the workshop to continue its consideration of automation research issues of shared significance.

5 Future Directions

The research needs statements developed by the 2013 breakout groups are being refined for ratification by the TRB standing committees for subsequent inclusion in TRB's online database of research needs statements. This database is publicly accessible at rns.trb.org.

The response of the 2013 workshop participants to the post-conference survey showed a high level of interest in participating in a similar meeting in 2014. The participants liked the mixture of high-level plenary presentations, detailed breakout discussions on focused topics, and live demonstrations of technology, so those elements will be retained. There was also strong support for returning to the San Francisco Bay Area, since it is a world high-technology capital and center for development of vehicle automation systems.

For this 2014 workshop, TRB plans to partner with the Association of Unmanned Vehicle Systems International (AUVSI). AUVSI has conducted its own Detroit-based "Driverless Car Summit" in 2012 and 2013. The organizers of both conferences felt that there was significant synergy in combining forces to offer a single venue for all interested communities in 2014. In common with TRB's 2013 workshop, the 2014 Road Vehicle Automation Symposium will feature informational and inspirational plenary speeches as well as breakout sessions to examine research needs and other important focused topics.

Breakout session topics and content under consideration for the 2014 workshop will be developed with the leadership of TRB committees, with new participation from committees in planning, operations, and human factors. The sessions will build on the current research needs statements, where applicable, and develop new statements or document the proceedings of the session with papers and session summaries. With the expectation that automation will continue to grow in significance, TRB is planning for a fourth workshop in 2015, location and theme still to be determined. It should be noted that participation in the TRB Joint Subcommittee on Road Vehicle Automation is open to the broad transportation community, enabling those with interest in automation, and willingness to volunteer their time, to become actively involved in planning and producing the workshop.

Road vehicle automation has emerged with new levels of interest in the past several years, fueled by a "perfect storm" of interest from the public consumer segment, increased research and development by research institutions as well as automotive manufacturers, and support by government at all levels, including NHTSA, due to the potential for greatly enhanced safety, efficiency and mobility. TRB has a responsibility to guide and support this activity to assure that the requisite research is conducted and information disseminated to maximize the benefits for all.

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Part I
Public Sector Activities

Autonomous Vehicles: A Perspective from the California Department of Motor Vehicles

Bernard C. Soriano, Stephanie L. Dougherty, Brian G. Soublet and Kristin J. Triepke

Abstract On September 25, 2012, California Governor Jerry Brown signed into law California Senate Bill 1298 (Chapter 570; Statutes of 2012) authorizing the California Department of Motor Vehicles (DMV or Department) to develop regulations for the testing and operation of autonomous vehicles on California's public roadways. This marked the first time that California regulations regarding automotive technologies were developed prior to federal regulations. After meeting with governmental, academic, and industry stakeholders in order to gain insights into the technology, the DMV embarked on the development of two separate regulatory actions. As the technology advances, the DMV will revise the regulations accordingly.

Keywords Autonomous vehicle · California · California Department of Motor Vehicles · DMV · Regulations

1 The California Department of Motor Vehicles

Just before the turn of the century, a new mode of transportation was seen and heard on the California landscape. Some referred to it as a "horseless carriage;" others called it an "automobile." It was to have a more profound impact upon

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_2,

the state than any other invention. Initially, the automobile was an instrument of adventure. However, the early day "motor wagon" was also considered a dangerous instrument. Several California counties passed ordinances requiring motorists to maneuver to the side of the road and remain standing when horse drawn vehicles approached. One court decision characterized the new contraptions as "highly dangerous" when used on county roads. Ordinances prohibited operations of the horseless carriage at night.

It was not long before restrictive legislation, designed to protect horse and mule traffic from the noisy horseless carriage, faded into the past. Speedy and convenient individual transit was welcomed as a benefit to society. California statutes of 1901 authorized cities and counties to license bicycles, tricycles, automobile carriages, carts, and similar wheeled vehicles. In 1913, the California Legislature approved legislation prohibiting the operation or driving of a motor vehicle without a license. In 1915, the first DMV was created with enactment of Senator F. S. Birdsell's "Vehicle Act of 1915."

1.1 The DMV of Today

Over the past 100 years, the DMV has grown in size and responsibility, reflecting the diverse landscape and population of California (37,826,000 residents in 2012) and the variety and complexity of the motor vehicle industry. At over 170 field offices, the DMV tests applicants and issues driver licenses to qualified drivers, provides identification services to the public, and verifies the identity of all licensed drivers and identification card holders. In 2013, the Department's database contained over 27 million driver license and identification cards. By monitoring the driving performance of licensed drivers, the DMV promotes traffic safety. Furthermore, the DMV evaluates high-risk drivers for driving competency and takes corrective actions against the driving privilege of drivers who demonstrate safety risks.

Additionally, the DMV issues titles and registers all automobiles, motorcycles, trailers, and vessels, as well as commercial vehicles used for both interstate and intrastate commerce. In 2013, almost 32 million total vehicles were registered with the Department.

To protect consumers, the DMV licenses and regulates occupations and businesses related to the manufacture, transport, sale, and disposal of vehicles, including: vehicle manufacturers, dealers, registration services, salespersons, transporters, and dismantlers. In addition, the DMV regulates all occupations and businesses related to driving and traffic schools. The purpose of the DMV's oversight in these areas is to ensure that consumers are dealing with reputable individuals and receiving the product that is represented to them.

Finally, the New Motor Vehicle Board, a program within the DMV, operates in a quasi-judicial capacity to resolve disputes between franchised dealers and manufacturers/distributors of new motor vehicles (including motorcycles and recreational vehicles) and attempts, through the Consumer Mediation Services Program, to resolve disputes between consumers and new motor vehicle dealers and/or manufacturers or distributors.

2 Autonomous Vehicles Regulations

The California Legislature has given the DMV an express statutory delegation of rulemaking authority to regulate the operation of autonomous vehicles on public roads. Senate Bill 1298 (SB 1298) enacted California Vehicle Code §38750, which requires the Department to adopt regulations by January 1, 2015, setting forth requirements for the submission of evidence of insurance, an application approval process for testing and the general operation of autonomous vehicles on public roads, as well as vehicle safety requirements.

2.1 California's Approach

Traditionally, motor vehicle safety standards have been set at the federal level, usually by the National Highway Traffic Safety Administration (NHTSA). Although NHTSA issued a preliminary statement of policy concerning automated vehicles in May 2013, Federal Motor Vehicle Safety Standards (FMVSS) specific to autonomous vehicles had not been developed by the time the DMV initiated its work on autonomous vehicles regulations. This marked the first time that California regulations regarding automotive technologies were developed prior to federal standards. As such, one of the Department's first actions was to establish relationships with governmental, academic, and industry stakeholders in order to gain insights into the capabilities, limitations, and viability of autonomous vehicle technology.

The DMV identified key federal and state stakeholders that needed to be engaged in the regulations development process and formed a statewide steering committee comprised of representatives from the: California State Transportation Agency; California Highway Patrol; California Department of Insurance; California Department of Transportation; California Office of Traffic Safety; DMV; and NHTSA. Meeting on a regular basis, the committee served as an advisory panel and provided input from their respective areas, ensuring that law enforcement, insurance, road infrastructure, and traffic safety-related issues be considered throughout the regulations development process. In addition, higher level autonomous vehicle risks were identified to be broader public policy issues. For example, what are the traffic safety implications for Driving Under the Influence (DUI) laws? What happens if an autonomous vehicle requires the driver to take control and the driver is impaired and unable to assume responsibility for the vehicle? These and other issues continue to be discussed and vetted through the committee.

The Department sought the expertise of researchers and academic institutions with specialized knowledge and expertise in autonomous technologies. One such entity is the Partners for Advanced Transportation TecHnology (PATH) administered by the Institute of Transportation Studies (ITS) at the University of California, Berkeley. PATH has over 25 years of research experience on large-scale technical innovations for transportation and was contracted by DMV to provide guidance to the Department on possible requirements to include in regulations, including testing, performance, and safety standards necessary to ensure public safety as autonomous vehicles are operated on California roads.

DMV also established relationships with automobile manufacturers, automotive component companies, and trade organizations. With research and development of many autonomous vehicle programs occurring in California's Silicon Valley, the Department met with entities directly engaged in the development of autonomous vehicle technology. These discussions provided the Department with insight into the capabilities, differences, and more importantly, limitations of the technology. In addition, the Department gained an understanding of the relative timeframe of the availability and viability of the technology to California consumers.

Through these conversations with governmental, academic, and industry stakeholders, the Department gained two key insights regarding the development and potential benefits of autonomous vehicles. First, DMV developed a broad-based understanding that autonomous vehicle technology is advancing quickly and constantly evolving. While ten years ago, the concept of a self-driving vehicle may have seemed like science fiction, autonomous vehicle technology is developing at a rapid pace. Several manufacturers are offering NHTSA Level 2 (combined function automation) autonomous vehicle technology in model year 2014 vehicles. Most manufacturers have publicly announced their plans to develop and deploy a NHTSA Level 3 (limited self-driving automation) vehicle within the next three to seven years. Other manufacturers have indicated an end goal of producing a NHTSA Level 4 (full self-driving automation) vehicle within the next decade.[1] With this perspective that manufacturers may produce autonomous vehicles with varying capabilities and on different timelines, DMV understood the need for regulations that could encompass a range of autonomous technology capabilities and limitations.

Secondly, the DMV gained a more refined perspective on the potential traffic safety benefits that could result from the deployment of autonomous vehicles. In 2011, there were an estimated 5,338,000 police-reported traffic crashes, in which 32,367 people were killed and 2,217,000 people were injured [2]. Distracted drivers were involved in 10 % of fatal crashes, and 17 % of injury crashes were reported as distraction-affected crashes [3]. Having a vehicle on the road that

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[1] NHTSA's preliminary policy statement on automated vehicles defines Level 2 as involving the automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Level 3 enables the driver to cede full control of all safety-critical functions under certain conditions, but the driver is expected to be available for occasional control. Level 4 is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip [1].

drives as well, or even better, than a human operator presents an opportunity to prevent a significant number of collisions and ultimately enhance the safety of the motoring public. With a keen understanding of the possible safety, mobility, and environmental benefits of autonomous vehicles, the Department is focused on developing regulations that will both support continued innovations in autonomous vehicle technology, while at the same time ensuring public safety.

2.2 California Rulemaking Process

All regulatory, or rulemaking, proceedings must comply with the requirements of the California Administrative Procedures Act (APA).[2] The APA requires that any rulemaking that involves complex proposals shall include public discussions with parties who would be subject to the regulations prior to the start of the formal rulemaking process[3]; consequently, the Department held several public workshops soliciting input from interested parties prior to initiating the formal rulemaking proceedings. Those workshops allowed representatives from the automobile, insurance, and computer software industries, as well as consumer representatives, to provide input to the Department prior to the notice of a formal regulatory proposal.

When a set of regulations has been drafted, the Department is required to: give the public notice of the proposed regulatory action[4]; issue the complete text of the proposed regulation with an initial statement of reasons for the proposal[5]; give interested parties an opportunity to comment on the proposal and respond to the comments in writing[6]; and, to submit the summary and response with the proposed regulatory text to the California Office of Administrative Law (OAL).[7] OAL is charged with reviewing all rulemaking packages for compliance with the requirements of the APA.[8] Upon a determination that a proposed regulation complies with the standards of the APA,[9] OAL is required to approve the adoption of the proposal.[10] OAL's primary task in reviewing a regulatory proposal is to determine that the proposal does not alter, amend, enlarge, or impair the scope of the enabling statute.[11]

The adoption of a regulation necessarily involves an interpretation of the enabling statute by the agency proposing the regulation. The California Supreme Court has

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[2] Calif. Gov. Code §§11340 *et seq.*

[3] Calif. Gov. Code §11346.5.

[4] Calif. Gov. Code §11346.4.

[5] Calif. Gov. Code §11346.2.

[6] Calif. Gov. Code §11346.8.

[7] Calif. Gov. Code §11347.3.

[8] Calif. Gov. Code §11349.1.

[9] The standards listed in Calif. Gov. Code §11349.1 are: necessity, authority, clarity, consistency, reference, and nonduplication.

[10] Calif. Gov. Code §11349.3.

[11] Calif. Gov. Code §11342.2.

stated that the fundamental principle of statutory interpretation is "the ascertainment of legislative intent so that the purpose of the law may be effectuated …." [*People* ex rel. *Younger* v. *Superior Court* (1976) 16 Cal.3d 30, 40 (127 Cal.Rptr. 122, 544 P.2d 1322).] SB 1298 includes uncodified Legislative findings which provide reliable insight on the intent of the Legislature. "Although such statements in an uncodified section do not confer power, determine rights, or enlarge the scope of a measure, they properly may be utilized as an aid in construing a statute." [*Carter v. California Department of Veterans Affairs* (2006) 38 Cal.4th 914, 925; 44 Cal.Rptr.3d 223].

The Legislative findings in the uncodified portion of SB 1298 supporting the enactment of California Vehicle Code §38750 states:

(c) The State of California, which presently does not prohibit or specifically regulate the operation of autonomous vehicles, desires to encourage the current and future development, testing, and operation of autonomous vehicles on the public roads of the state. The state seeks to avoid interrupting these activities while at the same time creating appropriate rules intended to ensure that the testing and operation of autonomous vehicles in the state are conducted in a safe manner.
(d) Toward that end, the Legislature finds it appropriate to authorize the establishment of specific safety requirements for the testing and operation of autonomous vehicles, and to require that future testing and operation of autonomous vehicles in the state comply with those requirements.

In drafting the regulations required by California Vehicle Code §38750, the Department has been guided by the expressed Legislative intent that the Department promulgate regulations that avoid interfering with the testing of autonomous vehicle on public roads, while at the same time ensuring that testing and post-testing deployment do not endanger public safety.

2.3 Regulatory Actions

California Vehicle Code §38750 established two phases of deployment of autonomous vehicles: first, testing by the manufacturer; and, second, non-testing operation. The Department implemented the autonomous vehicle regulations in two separate regulatory actions in the order specified in §38750. The first regulatory action addressed the requirements for the testing of vehicles by autonomous vehicle manufacturers[12]; including the financial responsibility requirements, the manufacturer application and permit process, accident reporting, autonomous vehicle test driver qualifications, vehicle identification and registration requirements, and disposal of prior test vehicles. The second regulatory action will implement the requirements for the operation of autonomous vehicles in a non-testing environment.

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[12] Calif. Veh. Code §38750 (a)(5) defines the manufacturer of autonomous vehicles as the original vehicle manufacturer that produces a completed vehicle with autonomous technology or a person who converts an originally manufactured vehicle by installing autonomous technology.

2.3.1 Testing Regulations

In the first phase of deployment, the testing phase, an autonomous vehicle can be operated on public roads by a driver holding the proper class of license if: it is being operated solely by employees, contractors, or designees of the manufacturer; a test driver is seated in the driver's seat ready to take immediate control of the vehicle; and, before the start of testing, the manufacturer submitted evidence of insurance in the amount of $5 million in a form and manner required by the Department pursuant to regulations that the Department has been given authority to adopt.[13] The Department's first set of regulations established a permit application process which requires that manufacturers: submit evidence of insurance, describe the training program required for autonomous vehicle test drivers, identify the employees, contractors and designees who will be designated test drivers, require a list of the vehicles that will be tested on public roads, and require that accident or collision reports be submitted to that Department.

One of the prominent legal issues in discussions about the operation of autonomous vehicles on public roads centers on the determination of fault and liability when an autonomous vehicle is involved in an accident. The California Legislature determined that instead of California's mandatory minimum limits of financial responsibility as specified in California Vehicle Code §16056 ($15,000 for injury or death of any one person in any one accident, $30,000 for injury or death of two or more people, and $5,000 for damage to property),[14] a manufacturer must be able to establish proof of financial responsibility in the amount of $5 million.

The Department's regulations will not be able to resolve the liability issues as its authority is limited by the language of California Vehicle Code §38750 to specifying the manner in which manufacturers can demonstrate they have the requisite amount of insurance. The Department is not given authority to regulate at-fault determinations. In fact, authority to promulgate regulations for the determination of fault in motor vehicle accidents is vested in the California Insurance Commissioner.[15] Once the testing phase is complete and autonomous vehicles can be operated by people not employed by the manufacturer,[16] California Vehicle Code §38750 (c)(3) still requires the manufacturer to maintain the $5 million

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[13] Calif. Veh. Code §38750 (b).

[14] The minimum liability insurance limits specified in §16056 is applicable only to private passenger vehicles.

[15] California Insurance Code §1861.025 sets forth the eligibility criteria for the purchase of a good driver discount automobile insurance policy and specifies that a person who in the past 3 years was "principally at fault" in a motor vehicle accident is not eligible for such a policy. Subdivision(b)(3) of that section states, "The commissioner shall adopt regulations setting guidelines to be used by insurers for the determination of fault" for accidents involving damage to property, personal injury or death.

[16] The requirement that the vehicle be operated solely by employees or designees of the manufacturer only apply to the testing phase [see §38750 (b)(1)].

proof of insurance. In addition to this manufacturers' insurance requirement, existing law requires that the owner/driver of the vehicle maintain the statutory minimum limits of financial responsibility coverage.

2.3.2 Non-testing Deployment

The second regulatory action will implement the requirements for the operation of autonomous vehicles in a non-testing environment, including an additional application containing certifications by the manufacturer that: the vehicle can be easily engaged or disengaged by the driver; the vehicle has a visual indication that the technology is engaged; the vehicle can alert the driver when there is a failure of the autonomous technology that either requires the driver to take control of the vehicle or enables the vehicle to come to a complete stop if the driver is unable to take control; the driver can take control of the vehicle in multiple manners; the autonomous technology meets FMVSS or other safety standards required by state and federal law and regulations; the technology does not make inoperative any FMVSS or applicable state or federal safety requirements; the vehicle is capable of storing sensor data at least 30 seconds before a collision, in a read only format; the vehicle has been tested in compliance with the regulations adopted by the Department; and, the manufacturer will maintain proof of financial responsibility in the amount of $5 million.[17]

The certifications required for the non-testing deployment of autonomous vehicles on public roads include a certification that the "autonomous vehicles' autonomous technology meets FMVSS for the vehicle's model year….".[18] This requirement could be read to prohibit the operation of vehicles outside of testing because a manufacturer cannot certify that the "autonomous technology" meets FMVSS. Currently there are no FMVSS for "autonomous technology." The NHTSA policy statement issued in May 2013, states "NHTSA is responsible for developing, setting, and enforcing Federal Motor Vehicle Safety Standards and regulations for motor vehicles and motor vehicle equipment… As NHTSA's research and experience develop, NHTSA will determine whether it should encourage and/or require application of the most promising crash avoidance technologies…" (National Highway Traffic Safety Administration, *Preliminary Statement of Policy Concerning Automated Vehicles,* May 2013, page 2.)[19] The policy statement clearly points out that NHTSA is responsible for developing

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[17] Calif. Veh. Code §38750 (c).

[18] Calif. Veh. Code §38750 (c)(1)(E).

[19] NHTSA cautions that states should refrain from establishing safety standards stating that it "does not recommend that states attempt to establish safety standards for self-driving vehicle technologies… in light of the rapid evolution and wide variations in self-driving technologies, we do not believe that detailed regulation of these technologies is feasible at this time at the federal or state level… until NHTSA has developed vehicle safety standards pertinent to self-driving technologies, states may want to ensure that self-driving test vehicles in their state adhere to certain basic principles." (Id at page 12–13, emphasis added.).

safety standards for autonomous technology and that NHTSA does not believe that it is feasible to develop regulations for that technology at this time; consequently NHTSA has yet to develop FMVSS for "autonomous technology."

Absent federal regulations establishing the safety standards for autonomous technology, the Department's ability to require a certification that the autonomous technology itself meets safety standards will have to rest on its statutory authority to require a certification that the technology meets "all other applicable safety and performance standards set forth in state and federal law and the regulations promulgated pursuant to those laws,"[20] consequently the Department will have to rely on any state laws establishing safety standards for such technology.

2.3.3 Fully Autonomous Operation

California Vehicle Code §38750 (e)(2) requires the Department to notify the California Legislature if it receives an application from a manufacturer seeking to deploy autonomous vehicles capable of operating without the presence of a driver in the vehicle. This requirement is necessary as there are many current California state laws that are drafted to require a driver be present in the vehicle. For example: California Vehicle Code §16025 requires drivers involved in accidents exchange information; California Vehicle Code §16028 specifies that on demand of a police officer, the driver of a vehicle must produce evidence of financial responsibility; California Vehicle Code §§20001 and 20003 require the driver of any vehicle involved in an accident, resulting in injury to a person or damage to property, to stop and provide their name and residence address to the owner of the property, the person injured, or a police officer; California Vehicle Code §15620 prohibits a parent, legal guardian, or other responsible person from leaving a child under 6 years of age in a vehicle without supervision, when the engine is running or the keys are in the ignition, or both; California Vehicle Code §23123 prohibits talking on a cell phone while driving a vehicle; and, California Vehicle Code §23123.5 prohibits texting or using an electronic wireless communication device while driving. While this list is not exhaustive, it is an example of the law changes that must occur before the concept of a fully autonomous vehicle operating on public roads without a situationally aware driver can become reality.

3 Conclusions

From the "horseless carriage" of one hundred years ago to the future where a car drives itself, motor vehicles' capabilities and technology have developed and continue to develop at an increasingly rapid pace. Input from governmental, academic,

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[20] Calif. Veh. Code §38759 (c)(1)(E).

industry, and consumer advocacy stakeholders will be critical as the California DMV develops regulations for autonomous vehicles by January 1, 2015. In addition, the Department will continue to monitor advancements in the technology and revise the regulations accordingly.

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Accelerating Road Vehicle Automation

Joseph I. Peters

Abstract This article addresses the roles that transportation infrastructure and government can have in accelerating the deployment of increasingly automated vehicles into society. Current intelligent transportation systems technologies deployed as part of the infrastructure can provide information that automated vehicles alone otherwise will not have (e.g., status of a traffic signal's phase and timing). Results from the Federal Highway Administration's connected vehicle research and development efforts demonstrate the potential benefits that can be achieved by connecting vehicles to infrastructure at any level of automation: reducing congestion, increasing roadway capacity, providing fuel savings, and sustaining the environment. These benefits can be achieved while maintaining safety as the highest priority. Ongoing and future research projects are also described.

Keywords Connected vehicles · Automated vehicles · Connected infrastructure · Speed harmonization

1 The Reality of Transportation Today

The reality of transportation in the United States today is that as congestion increases, agencies lack the resources and room to expand capacity of the roadway system through capital improvement projects. The transportation industry, which includes both public and private sectors, increasingly looks to innovative technologies and strategies that allow agencies to extend the capacity of the existing roadway, including the use of automated and connected vehicle technologies.

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_3,

Fig. 1 A congested corridor in the San Francisco region. A connected, automated transportation system could transform this scene of gridlock to one where all vehicles are traveling smoothly at a constant speed. *Source* Marcello Brivio, all rights reserved

Automated vehicle technologies are here today. The National Highway Traffic Safety Administration (NHTSA), in coordination with the Federal Highway Administration (FHWA) and other transportation modes, has defined five levels of vehicle automation, from no automation (Level 0) to full self-driving automation (Level 4) [1]. There is still ample opportunity to advance Level 1 and 2 technologies, which include safety-related applications for speed control and merging and weaving. These technologies still cede primary control to the driver, so consumers may be more willing to accept them in the near future. They also provide an opportunity for incremental benefits to be realized through partial automation while full automation continues to grow in the marketplace.

In addition to offering great promise for increasing safety through “crashless vehicles,” automation-enabling technologies have shown the potential to improve mobility through connected vehicle communications. Connected communications can be from vehicle-to-vehicle (V2V) or from vehicle-to-infrastructure (V2I). Fully realizing the potential of these technologies to mitigate congestion (such as shown in Fig. 1) requires exploring not just how automated vehicles can communicate with each other, but how they can communicate with infrastructure within a connected, automated transportation system. Connecting automated vehicles with road infrastructure will help to accelerate the introduction of increasingly automated vehicles into the marketplace.

2 The Role of Connected Infrastructure in Accelerating Vehicle Automation

The economic productivity of the United States can be increased by having fully automated vehicles on its roads; however, this can only be achieved if people are willing to buy the vehicles. Equipping a fully automated vehicle with information about the infrastructure will make the vehicle more attractive to a buyer.

Despite the significant potential for automation to improve the transportation system's performance, some of the greatest frustrations travelers face cannot be overcome through automation that is not connected. The nearly 360-degree field of view enabled by vehicle sensors has a rather limited range. For example, an automated vehicle will not be able to see stopped traffic around a curve a half-mile ahead. It will not know the status of stop-and-go traffic on the road ahead. Likewise, an automated vehicle will not be able to prevent the experience of waiting at a red light. However, an automated vehicle *equipped with both real-time and near real-time information* can overcome some of these challenges by making more informed decisions about potentially avoiding crashes and congested routes. Examples of the types of information that infrastructure can provide to an automated vehicle include:

- Traveler Information—Many agencies deploy dynamic signs that alert drivers of the travel times along different routes. With connected infrastructure, this information could be sent directly to an automated vehicle even earlier.
- Work Zone Information—With V2I communication, automated vehicles could receive information from a traffic management center on work zone locations and conditions and make route diversions as needed.
- Road Weather Information—Road weather sensors alert transportation agencies to weather conditions on the roadway. In a connected environment, this information could be broadcast to an automated vehicle, and an automated vehicle could communicate its weather environment back to a traffic management center.
- Pavement Markings and Infrastructure Asset Information—Pavement markings (e.g., lane striping) and infrastructure assets (e.g., stop signs) provide obvious assistance to sensors on automated vehicles. Sensors with information (e.g., lane marking type and location) might be coded in the pavement. Roadside equipment could also potentially alert automated vehicles to the position of lane markings when snow or other conditions make them difficult to detect.
- Incident Management Information—Infrastructure can broadcast incident location, time, queue length, presence of emergency vehicles, and other information to connected and automated vehicles more quickly and across a broader region than can one automated vehicle to another.
- Traffic Signal Information—By communicating with infrastructure, automated vehicles can know the signal timing along their route. Consequently, an

eco-glide path, which is the ideal speed at which vehicles should approach an intersection in order to minimize time spent idling at a red light, can be communicated to automated vehicles. This may be especially useful in an urban canyon environment, where human and sensor vision is occluded by buildings, and automated vehicles may not be aware of traffic signal phase and timing ahead. Intersections equipped with advanced sensors and dedicated short-range communications (DSRC) in roadside equipment can play a dramatic role in helping automated vehicles avoid fatal intersection crashes due to red-light running, for example.

- Operational Restrictions Information—Infrastructure can convey information to automated vehicles about both static and dynamic operations restrictions such as vehicle height and weight limits, vehicle occupancy requirements, time-of-day accessibility, truck-only and no-truck accessibility, reversible lane status, and dynamic toll prices.

2.1 The Benefits of Infrastructure-Provided Information to Automated Vehicles

There is a wide range of information that the infrastructure can provide to connected and automated vehicles. By providing useful information about what is happening on the highways, infrastructure improves the functionality of automated vehicles and offers numerous benefits to the transportation system, including mobility, safety, and environmental benefits. These three areas are inextricably intertwined, and improvements in one area may result in benefits to the others. Congestion increases the risk of an incident occurring, which in turn leads to more congestion and fuel emissions. Similarly, where incidents occur, queues build up and may cause vehicles to stop suddenly, contributing to secondary crashes.

As noted above, connected infrastructure can provide information about impending congestion to an automated vehicle that can be used to make better route choices, dispersing traffic more efficiently across a network and improving mobility. Infrastructure can also support automation capabilities by providing managed lanes for truck platooning, which can improve the mobility of freight, thereby increasing national productivity.

In addition to enriching the information environment, infrastructure may be a critical fail-safe when all other sources of information are unavailable. Connected infrastructure can contribute to safety by providing a redundant source of information that can be fused with sensors to increase the reliability of an automated vehicle. Any environment that relies upon highly sophisticated technology needs this redundancy so that if the primary system shuts down, backup systems are in place to ensure continuing functionality.

Environmental benefits can also be realized through connected infrastructure. For example, the delivery of signal phase and timing information from traffic signals to automated vehicles can contribute to improved throughput and fuel savings by limiting the number of vehicles that idle at intersections waiting for lights to turn green.

Timely infrastructure-provided information will enable new applications that are expected to be highly appealing to the buying public, thus benefitting all users of the transportation system. As intelligent infrastructure becomes increasingly deployed, automated vehicle purchases are expected to increase. The installation of connected infrastructure may ultimately be the tipping point for revolutionary adoption of automated vehicles.

Deployment of V2V technology has great potential; however, it requires at least two equipped vehicles to communicate via DSRC, which is line-of-sight and not ubiquitous. A transportation and communications infrastructure that broadcasts information to vehicles through a ubiquitous, currently available communications platform [e.g., a fourth generation (4G) wireless system] provides advantages to connected automated vehicles without them having to interact with other equipped vehicles. This would significantly increase market penetration of connected functionality. Drivers will realize the benefits of automated vehicles sooner through their connectivity to infrastructure than they will if they rely solely on V2V connectivity.

Moreover, consumers will seek out the advantages of V2I communications. In addition to automated vehicles providing safety warnings or keeping the car in a lane, consumers will like the fact that the vehicles can control the infrastructure to serve their purposes. For example, an automated vehicle could use V2I communications to alert a traffic signal to its presence at an intersection and cause the light to turn green sooner. This will appeal to consumers both for convenience and fuel savings resulting from reduced idling at the intersection. These types of capabilities will become selling points for automobile manufacturers, and automated vehicles that can communicate successfully with infrastructure will have a competitive advantage over those that cannot.

3 The Federal Government's Role

The FHWA recognizes the potential benefits of automation and full connectivity and seeks to accelerate deployment of both. When looking to the future of connected automated vehicles, FHWA does not consider just vehicles, but a connected, comprehensive transportation system that includes vehicles (passenger cars, trains, buses, trucks, etc.) along with travelers, goods, roadway infrastructure, parking facilities, major employment centers, special event venues, and more (Fig. 2). All of these pieces must communicate seamlessly with each other to maximize the effectiveness of transportation within a region as a whole.

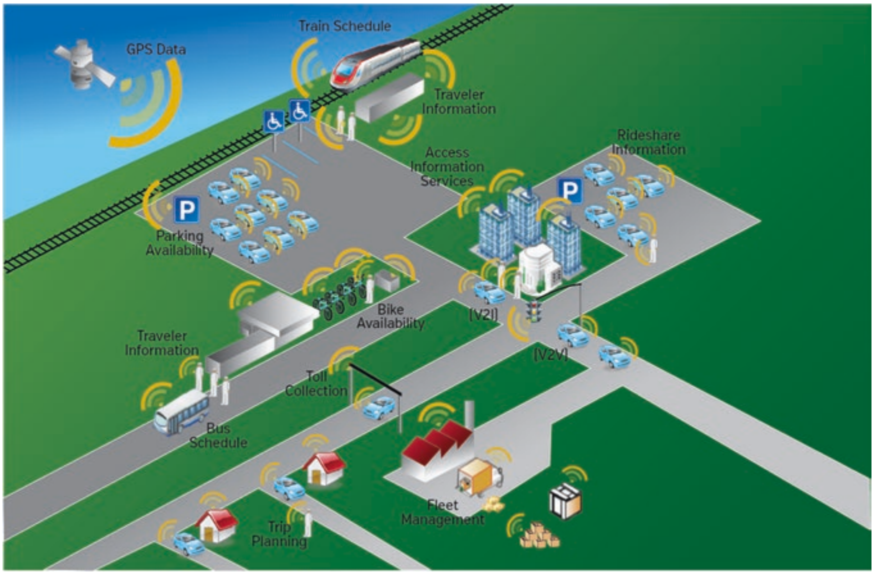

Fig. 2 An example of a fully connected transportation system. *Source* FHWA

Seeking to transform this vision of a connected transportation system into a reality, FHWA will provide states with guidance on how to prepare their roadway infrastructure to accommodate emerging connected vehicle technologies. In order for connected infrastructure technologies to work, they must have the same key functionality across all 50 states as well as in local governments and federally owned lands. The FHWA serves the nation in a way that a single state or municipality cannot because it is uniquely postured to pull the nation together to achieve a vision with a solution that works everywhere. The FHWA works with other U.S. Department of Transportation (USDOT) modal administrations to engage stakeholders such as the American Association of State Highway and Transportation Officials (AASHTO) in this process.

The FHWA will also work with industry to develop standards for connected technologies. For example, these standards will help ensure that traffic signal manufacturers develop equipment that communicates signal phase and timing information successfully to all vehicles, while still retaining a manufacturer's competitive advantage. Efforts will also include providing international standards so that American automobile manufacturers can sell automated vehicles that function properly with infrastructure overseas, and vice versa, bolstering the international marketplace for vehicle automation.

The FHWA also helps accelerate the development of connected automation through engaging in partnerships and conducting research and development of technologies to enable new information markets that serve not only the United States, but the world. Through research, FHWA seeks to understand how emerging

Fig. 3 Screenshot of a VisSim simulation of I-66 showing variable speed advisories implemented with 20 % compliance (*top*) compared to normal traffic flow at 55 mph (*bottom*). *Source* FHWA

technologies work—including what the potential benefits, costs, and challenges are—and to disseminate this information to transportation agencies, universities, and other organizations so that they can be prepared for what is coming and build upon federal research to advance the state of the practice.

3.1 FHWA's Connected Automation Research to Date

The FHWA has sponsored and led research projects focused on numerous applications of connected infrastructure and vehicle technologies, including speed harmonization and eco-driving.

3.1.1 Speed Harmonization

The FHWA partnered with the Virginia Department of Transportation (VDOT) to study the effects of increasing automation by using V2I to assist in smoothing traffic flow on Interstate 66 (I-66) in Northern Virginia. Through FHWA's Saxton Transportation Operations Laboratory, located at the Turner-Fairbank Highway Research Center, the project team developed a simulation of a stretch of I-66 where a bottleneck rapidly forms, accompanied by rapid merging and weaving. In the top simulation scenario, shown in Fig. 3, approximately 20 % of drivers chose

Table 1 AERIS demonstration results [2]

Speed (mph)	Average fuel savings (ml)	SD	Average % improvement
20	13.0	–	2.5
25	111	10.9	18.1
30	76.0	15.7	11.2
35	73.8	19.6	6.3
49	107	14.6	9.5

to activate cooperative adaptive cruise control (CACC), allowing a traffic management center to remotely control their own vehicles' speeds and headways based upon speeds and levels of congestion on the road ahead.

This speed harmonization strategy is intended to smooth traffic flow, decreasing the probability that cars will have to stop suddenly for a queue. Even with only 20 % of the vehicles in the scenario having this instrumentation, results showed a noticeable difference in queue buildup when compared to a control scenario without speed harmonization. In the control scenario, speeds ranged from approximately 0 to 45 mph, while in the speed harmonization scenario, speeds ranged from approximately 32 to 64 mph. The results would potentially be even more dramatic if more than 20 % of the vehicles were so equipped and if more drivers opted into using external speed control.

3.1.2 Eco-Driving

The U.S. Department of Transportation Intelligent Transportation Systems Joint Program Office sponsored a University of California, Riverside project called Applications for the Environment: Real-Time Information Synthesis (AERIS). This project explored the ability of an in-vehicle algorithm to collect signal phase and timing information from an equipped traffic signal and provide an advisory speed to drivers to ensure that they reach the signal along a glide path that makes the intersection approach and departure profile as fuel efficient as possible. The AERIS project team demonstrated this technology at FHWA's Saxton Transportation Operations Laboratory's Intelligent Intersection. As the equipped vehicle approached the intersection when the light was red, the application guided the driver to slow down to an eco-glide path speed to pass the intersection when the light turned green, without having to come to a full stop.

The AERIS demonstration showed fuel savings at all tested speeds, including an 18.1 % improvement in fuel savings at 25 mph (Table 1). Even if results in reality were as low as 5 % savings, the application would still contribute not only to environmental efficiency, but also to cost savings, particularly for the freight industry.

3.2 FHWA's Ongoing and Upcoming Connected Automation Research

3.2.1 National Connected Vehicle Field Infrastructure Footprint Analysis

The FHWA is working with AASHTO on a National Connected Vehicle Field Infrastructure Footprint Analysis that focuses on how the transportation infrastructure can support basic V2I applications. Specifically, the Footprint Analysis will:

- Describe the justification for and value of deploying connected infrastructure.
- Assess the infrastructure, communication, and data needs of priority connected vehicle applications.
- Generate a set of generic, high-level deployment concepts (i.e., settings in which an agency might want to deploy connected vehicle applications).
- Identify scenarios leading to a preliminary national connected vehicle field infrastructure footprint.
- Provide cost estimates and funding options.
- Identify workforce, training, policy, and guidance needs.
- Identify implementation and institutional challenges and timing.

The FHWA and AASHTO team has begun to identify scenarios for connected vehicle deployments on the transportation infrastructure (e.g., rural deployment, multistate corridor deployment, statewide integrated system with legacy intelligent transportation systems) and will move into building these scenarios into a national footprint. The analysis will help FHWA understand the types of connected vehicle applications that are currently, or will soon be, implemented by states so that they can better tailor guidance to be issued in 2015. With this guidance, states will be able to modify their infrastructure to provide V2I functionality. In the future, this functionality could be extended to support vehicle automation as well.

3.2.2 Speed Harmonization Development and Field Test

To field test the speed harmonization concept described above, FHWA recently acquired five test vehicles and equipped them with V2I CACC. Initially, these vehicles will be inserted into live traffic on I-66 in Northern Virginia. Traffic sensors will provide speed, volume, and occupancy data as inputs to an algorithm that calculates the optimal speed for traffic upstream of a bottleneck. This speed will then be transmitted to the vehicles' adaptive cruise control settings from a remote server maintained at FHWA's Saxton Transportation Operations Laboratory, and the vehicles will automatically adjust their speeds accordingly.

As the research proceeds and more equipped vehicles are introduced into traffic, FHWA anticipates that the equipped vehicles will substantially influence the speed of surrounding vehicles by causing drivers to reduce their speeds slightly and achieve the benefits of avoiding stop-and-go traffic downstream. The speed harmonization technique will be tested to see if it will provide smooth operation of the traffic stream to reduce the effects of bottlenecks, thereby increasing reliability, offering environmental benefits, improving safety, and providing travelers additional comfort and convenience.

3.2.3 FHWA Research Projects

In fall 2013, FHWA awarded new automation-related projects through its Exploratory Advanced Research Program. These new projects will continue to study the potential for connected and automated applications to benefit the transportation system. Some of these research topics include [3]:

- High-Performance Vehicle Streams—This project will explore the potential benefits of vehicle streams of CACC-equipped vehicles through development of operational scenarios, limited laboratory and/or field testing of prototype vehicle stream systems, and evaluation of operational strategies through microsimulation or similar tools to gauge the feasibility and performance of high-performance vehicle streams for managed lanes.
- New Approaches for Testing Connected Highway and Vehicle Systems—This project will involve developing, validating, and applying a tool to facilitate simulations that are hybrids, where alternative traffic control algorithms are connected to real hardware (e.g., connected vehicle technologies, including CACC).
- Innovative Applications for Emerging Real-Time Data—This project will conceive, develop prototypes for, and test infrastructure-based systems that can recognize individual vehicle passages and provide and broadcast these data frequently. It will develop a standardized database of information provided by connected vehicles, which researchers will be able to use for their projects.
- Partial Automation for Truck Platooning—This project aims to develop new operating concepts for truck platooning through CACC and will involve an analysis of needs and opportunities for platooning, vehicle dynamics and control strategies; assessments of possible operating strategies and safety performance; traffic simulation studies of specific operational concepts; and potentially a limited test track or living laboratory test.

4 Looking Ahead

There is no doubt that the number of automation technologies offered in vehicles has dramatically increased. Automobile manufacturers increasingly advertise driverless car technologies with the potential to achieve near zero fatalities as early as

2020. Prototypes of fully automated vehicles are here today; some have successfully completed entire trips from parking lot to parking lot. It is also clear that such advancements in vehicle automation are happening in the absence of any infrastructure support systems, other than existing signs and road markings.

The development and application of V2I communications has the potential to increase the functionality of automated vehicles, thereby accelerating their adoption even further. For example, when drivers have the ability to set their cars on an automated glide path that is fully coordinated with traffic signals at intersections, the demand for such capabilities will dramatically increase and generally help to accelerate the emergence of fully automated vehicles within the next decade.

Even though automated vehicles may very well be a reality in the not-so-distant future, they will initially be sharing the road with vehicles that are mostly not automated or with vehicles that have varying degrees of automated capabilities. Therefore, it is critical that connected and automated technologies are introduced through an evolutionary process. As part of this evolution, NHTSA announced in February 2014 that it will begin taking steps to enable V2V communication technology for light vehicles [4].

In order to lay a framework for how to move forward with connected automation research that will help accelerate deployment, FHWA is partnering with other USDOT modal administrations to develop a Multimodal Plan on Automation. The plan will define key road vehicle automation research challenges and produce a research and development plan for safe and connected vehicle automation that complements, leverages, and enhances industry activities. The plan will identify enabling technologies and applications for future research, such as speed harmonization; CACC; platooning; lane change, merge, and diverge; intersection management; and more. Implementation of this plan has already begun and recognizes the valuable role that infrastructure can play in helping to accelerate the deployment of automated vehicles into society.

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Activities, Findings and Perspectives in the Field of Road Vehicle Automation in Japan

Yasuhiro Okumura

Abstract In Japan, collaboration between industry, government, and academia have been developing a variety of initiatives to create automated driving technologies since the past few decades. In recent years, the major automobile makers have been actively developing vehicles equipped with automated driving technologies. They carried out demonstration runs using these vehicles at CEATEC Japan 2013 and the ITS World Congress 2013, held in October 2013. At the same time, the Ministry of Land, Infrastructure, Transport and Tourism established the Autopilot System Council which, from June 2012 until August 2013, organized and studied both the challenges and successes of automated driving on expressways and prepared the autopilot achievement road map. It presented the results of its studies in an interim report released on October 8, 2013. In the future, the public and private sectors will cooperatively promote and realize the early achievement from both the vehicle side and road side matters studied based on the process established by the road map.

Keywords Automated driving ・ Auto-pilot system

1 Past Initiatives Taken in Japan

In Japan, industry, government, and academia have cooperatively undertaken various initiatives to create automated driving technologies. This chapter introduces two projects demonstrative of these efforts: Advanced Cruise Assist Highway Systems (AHS: 1994–2010) and Energy ITS (Development of Energy-saving ITS Technologies; 2008–2012).

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_4,

Fig. 1 View of verifying test of AHS platooning

1.1 Advanced Cruise Assist Highway Systems

The Advanced Cruise Assist Highway Systems (AHS) are systems intended to link roads and vehicles by providing drivers with real-time information, thereby improving the safety of vehicle travel and increasing traffic volume, while ultimately aiming for the achievement of automated driving.

In 1994, the former Public Works Research Institute (now National Institute for Land and Infrastructure Management) started development and testing of the systems. In 1996, magnetic markers were installed at intervals of 2 m in the center of traffic lanes and a test of automated driving was carried out on a public road: the continuous operation of a platoon of 11 vehicles for about 11 km at a top speed of 80 km/h (Fig. 1).

1.2 Energy ITS Project

The Energy ITS Project is a project undertaken with the participation of 15 organizations from industry, academia, and the public sector under the leadership of New Energy and Industrial Technology Development Organization (NEDO) and subsidized by the Ministry of Economy, Trade and Industry for a five year research period extending from 2008 until 2012. The project has constructed an experimental system consisting of millimeter wave radar, laser radar, cameras, and steering control systems etc. intended to be used to achieve very safe and reliable platooning that can be performed on expressways. It also included research and development of prototype vehicles which have achieved platoon formation functions, lane-keeping control functions, inter-vehicle distance control functions, and so on.

At the end of 2010, a test in which 3 large trucks traveled 10 m apart in a platoon for a distance of 80 km was successfully carried out. And at the end of 2012,

Fig. 2 View of an energy ITS project platoon

4 large and small trucks successfully performed a test platoon traveling at intervals of 4 m [1] (Fig. 2).

2 Initiatives by Japanese Auto Makers

Japan's major automobile makers have been taking initiatives to develop automated driving vehicles. At the Fourteenth Combined Exhibition of Advanced Technologies (CEATEC) JAPAN 2013 (October 1–5) and the 20th ITS World Congress Tokyo 2013 (October 14–18) held in October 2013, the manufacturers conducted demonstration runs of automated driving vehicles.

2.1 Nissan Motor Co. Ltd.

Nissan Motor Co. Ltd. conducted a public demonstration at CEATEC Japan 2013 of a vehicle equipped with autonomous drive technology on a course especially set at the event site to simulate a city street in Japan.

The vehicle used for the demonstration run was equipped with autonomous drive technology developed for driving on city streets: five laser scanners and five cameras that can constantly confirm conditions over a full 360° around the vehicle. This vehicle uses artificial intelligence to predict the movement of other vehicles that it encounters while traveling and selects the action most appropriate to the situation through accumulated knowledge.

Using this system, an autonomous drive vehicle can correctly judge the situation and drive safely even in a complicated driving environment such as when entering an intersection without traffic lights or overtaking a parked car [2].

2.2 Toyota Motor Corporation

Toyota Motor Corporation has developed the next-generation Automated Highway Driving Assist (AHDA) for expressways, which is a system combining Cooperative-adaptive Cruise Control that follows other vehicles as it wirelessly communicates (700 MHz band) with the preceding vehicles, with Lane Trace Control, which is equipped with sensors that detect the white line etc. on the road in the entire vehicle speed range to aid steering to keep the vehicle on the optimum driving line.

At the ITS World Congress Tokyo 2013, Toyota demonstrated automated driving by AHDA on the Metropolitan Expressway [3].

2.3 Honda Motor Co. Ltd.

Honda Motor Co. Ltd. demonstrated Cooperative Autonomous Driving and Automatic Valet Parking at ITS World Congress Tokyo 2013.

The Cooperative Autonomous Driving demonstration used an automobile equipped with autonomous environment recognition technology to demonstrate—self driving on a narrow road and automatic stop and start based on the recognition of pedestrians by on-vehicle cameras. The demonstration proved the effectiveness of its safe driving assisting function based on communication between pedestrians and a car and coordinated communication among motorcycles, automobiles and electric carts, and the effectiveness of its technology intended to automatically support lane changes after its on-board camera detect vehicles parked on the road and the system confirm backward safety.

This demonstration also introduced the Automatic Valet Parking system. Drivers will be able to park their cars in the drop-off area of the parking lot of a supermarket etc., then the system will obtain information about available spaces in the parking facility, drive the vehicle to an available space, and park it in the space. It will be unnecessary to fit a special sensor to a vehicle, because the system will perform wireless communication between the vehicle and monitor cameras in the four corners of the parking area [4].

3 Auto-pilot System Council

In response to the rising expectations of next-generation ITS, which has sharply improved driver convenience and safety thanks to the advance of IT technologies, the Ministry of Land, Infrastructure, Transport and Tourism kicked off the Next-generation ITS Workshop in May 2011. The Workshop analyzed the need for next-generation ITS and technological and systemic challenges, performed necessary studies of the new concept, demonstrated automated driving on expressways, and summarized the results on March 2012.

As a result of this study, it is considered necessary to determine the concepts and challenges of automated driving so as to overcome them and thus achieve the set goals. Therefore, the Ministry of Land, Infrastructure, Transport, and Tourism also established the Auto-pilot System Council in June 2012, and organized and studied challenges facing auto-pilot system intended to perform automated driving on expressways.

3.1 Goals of the Auto-pilot System Council

ITS, an area in which research and development and commercialization of systems have been carried out in the road and automobile fields, has contributed to the reduction of traffic accidents and to the elimination or mitigation of congestion. Yet, in order to presume the final solution of these problems, the achievement of systems linking the infrastructure and vehicles is counted on to introduce next-generation ITS, that will advance and integrate conventional ITS technologies.

The Council was established to focus on automated driving, which is a new concept, to organize and study challenges to be overcome to make it a reality.

3.2 Contents of Studies by the Auto-pilot System Council

The Auto-pilot System Council held six meetings between June 27, 2012 and August 28, 2013. The results were summarized as an interim report released on October 8, 2013 by the Auto-pilot System Council.

3.2.1 Objects of Studies by the Council

There are various concepts of automobile driving, ranging from the driver performing all driving operations, partially automated driving in which the automobile's driving support system performs part of the driving operations, and unmanned driving.

The Council has organized different forms of automobile driving according to the degree of how the automobile contributes to the driving process, and has defined automated driving as one in which many or all of the operations—accelerating, steering, and braking—are performed by the automobile.

Among the types of automated driving, fullself-driving automation (driving with the vehicle performing all operations) faces a wide range of challenges including the revision of legal and other existing systems, clarification of the allocations of responsibility, the social acceptability of automated driving vehicles, and technology development. Since these factors will hinder the early stages in achieving full automation, the automated driving as aimed by the Council has been defined as one which includes a driver within the framework of the existing system.

Also on ordinary roads, traffic conditions are complex because bicycles, pedestrians, and many other factors require consideration, while on expressways, the traffic conditions are relatively simple; with the entrance and exit of vehicles from ordinary roads restricted to interchanges, and their alignments suited to high speed travel. Therefore, the Council has studied automated driving on expressways, where its actualization is more feasible.

A system that realizes automated driving on such expressways will be called an auto-pilot system [5].

3.2.2 Effects of Automated Driving

The execution of automated driving will presumably have six direct effects:

Eliminating or Mitigating Congestion

On inter-city expressways in Japan, major locations of congestion are sags (changes in longitudinal grades), rising slopes, interchange convergences, and tunnel portals. Achieving automated driving can be counted on to smooth the traffic flow and sharply mitigate congestion at major congested locations. And based on a computer simulation, it was trial calculated that when 30 % of vehicles are equipped with ACC (Adaptive Cruise Control: device that automatically controls speed and distance between vehicles), congestion caused by sags will be reduced by 50 %.

Reducing Traffic Accidents

More than 90 % of all accidents on Japan's expressways are caused by human factors: delayed discoveries, errors of judgment, and operating errors. The achievement of automated driving can be counted on to improve safety and reduce traffic accidents caused by human errors or a lack of information about the road ahead, for example.

Abating Environmental Load

Approximately 20 % of all carbon dioxide emitted in Japan is emitted by transportation, and about 88.1 % of the transport sector emissions are emitted by automobiles (17.1 % of all emissions in Japan). Achieving automated driving can be counted on to reduce unnecessary acceleration and deceleration, lower air resistance, and mitigate congestion, effectively improving fuel consumption and lowering carbon dioxide emissions.

Supporting the Movement of Elderly People etc.

The percentage of elderly people among traffic accident fatalities in Japan is rising and errors characteristically made by the elderly have occurred. The achievement of automated driving is counted on to sharply lower their driving load to resolve traffic problems characteristic of elderly people.

Making Driving More Pleasant

Driving tends to be stressful, and the most common complaint people give about traveling by car is that driving is tiring. The achievement of automated driving is counted on sharply reducing the driving load so drivers can drive even long distances suffering only minimal fatigue.

Strengthening International Competitiveness

The achievement of automated driving in Japan is counted on to give Japan a leading role in international cooperation in the automated driving field and a storehouse of related manufacturing technology and know-how, contributing to the strengthening of Japan's automobile related manufacturing competitiveness and more efficient logistics systems by applying automated driving.

3.2.3 Range of Driving by an Auto-pilot System

The range of driving by an auto-pilot system extends from entering the main lanes of an expressway from merges such as interchanges, service areas, or parking areas, to divergences where vehicles enter an interchange from the main line of the expressway through a junction etc. Inside service areas and parking areas, complex control is necessary so these are not included in the studies performed by the committee (Fig. 3).

3.2.4 Steps to the Achievement of an Auto-pilot System

To realize an auto-pilot system, it will be necessary to efficiently and effectively advance driving support. It is necessary to set development stages based on the level of commercialization of the technologies in order that users will genuinely sense the effects of automated driving. So three steps have been set:

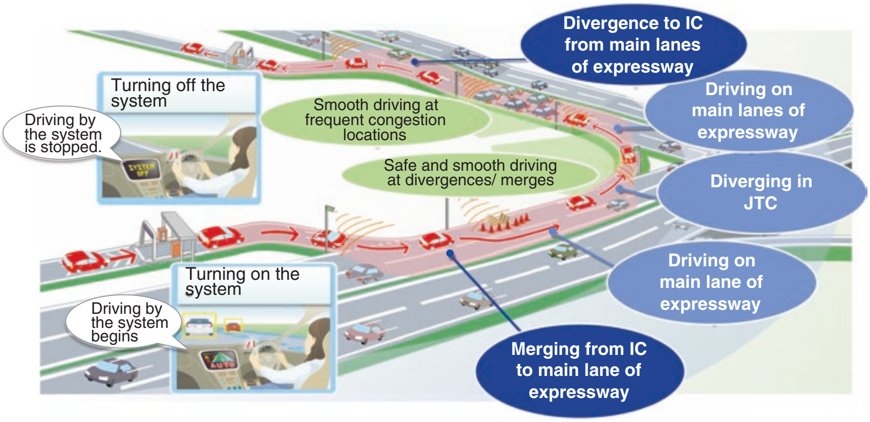

Fig. 3 Outline of the auto-pilot system that is the intended goal (image)

Continuous Driving on a Single Lane

Present driving support systems that have been commercialized include ACC, lane keeping assist, for example. In sections where the driving environment is relatively stable, these can support driving in a single lane. But in some cases, driving support cannot be sustained stably on sharp curves or in diverging and converging sections for example.

Therefore, support from the road side, such as road structure data which are forms of detailed road data or positioning information etc., will be studied to permit driving support being provided stably, even in harsh road environments.

Continuous Driving Including Lane Changes

In order to change lanes safely, automobiles must obtain advance information about traffic restrictions or traffic accidents, among others, on the road ahead.

So, it is necessary to study methods of providing detailed and dynamic information such as traffic closures or accidents ahead at appropriate times so that automobile of vehicles can change lanes or adjust their speed with time to spare.

During at Divergence/Convergence Locations and Optimum Driving During Congestion at Frequent Congestion Locations

In order to permit driving in the most suitable way at divergence/convergence locations and at frequent congestion locations, it is necessary to develop a system able to regulate distances between vehicles and permit driving adjusted to the surrounding environment even during at divergence/convergence locations and frequent congestion locations.

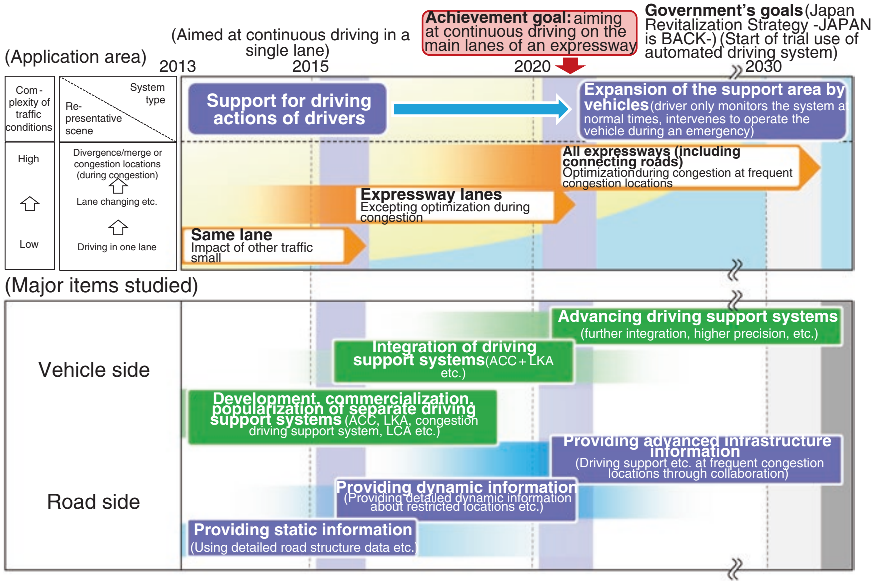

Fig. 4 Road map to the achievement of the auto-pilot system

Therefore, it is necessary to study ways to provide warnings of the approach of converging vehicles and information about lane changing and speed adjustment, which will contribute to smoothing the traffic flow at frequent congestion locations, from the road side.

3.2.5 Achievement Goals

The aim is to achieve automated driving using an advanced driving support system on expressways (excluding optimum driving during congestion) by the early 2020s.

After that is accomplished, efforts that will contribute to the government goal (Japan Revitalization Strategy—JAPAN is BACK—), which calls for the beginning of trial use of an automated driving system, will continue in order to quickly achieve automated driving based on advanced driving support systems on expressways and on connecting road, which includes optimum driving during congestion at divergence/convergence locations and at frequent congestion locations.

3.2.6 Road Map

The road map to the achievement of the auto-pilot system reveals specific achievement goals at the same time as it refers to matters which must be studied to achieve the goals while considering the ease or difficulty of achievement, research and development, testing periods (Fig. 4).

3.3 Future Progress Based on the Road Map

In the future, following a work procedure grounded on the road map and based on public-private sector collaboration, matters studied concerning both the road and vehicle side will be quickly and thoroughly implemented.

And in recent years, research and development by private companies, universities, research institutes etc. has been extensive, even on ordinary roads, so these research and development activities can also be mutually interrelated as they are studied.

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Part II
Industrial Research and Innovation

Bosch’s Vision and Roadmap Toward Fully Autonomous Driving

Jan Becker, Maria-Belen Aranda Colas, Stefan Nordbruch and Michael Fausten

Abstract High-performance driver assistance systems are already helping drivers reach their destinations more safely and comfortably. In the future, these systems will be able to analyze ever more complex traffic situations and act either independently or by supporting the driver. With each innovation, we move a step closer to the goal of accident-free and fully-automated driving. Future systems will evolve from “driver assistance” to fully automated driving, completely piloting a vehicle through highways and urban environments. With an increasing level of automation, automated functions will reduce the driver’s burden more and more, thereby creating space for productivity, communication or entertainment while driving. Bosch is developing technologies for an intelligent forward thinking vehicle—making the vision of injury and accident-free driving a reality. Automated driving will synchronize traffic flow, reducing travel times and fuel consumption. It reduces the driver’s burden by taking over dedicated driving tasks—in line with each individual’s needs—allowing all age ranges to be mobile and safe. Automated driving will allow the vehicle to become a part of the driver’s interconnected home and work life, making time spent on the road more productive and eventful. Bosch is developing holistic mobility concepts and services, paving the way for personalized environmentally friendly travel.

Keywords Automated driving • Driver assistance • Autonomous driving • Radar • Video • Bosch

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_5, © Springer International Publishing Switzerland 2014

1 Introduction

Capable driver assistance systems are already helping drivers to reach their destination more safely and comfortably. In the future, these systems will be able to recognize ever more complex traffic situations and to help drivers even more—or act independently. Bosch is developing a variety of pioneering driver assistance systems, and each innovation is bringing accident-free, automated driving a step closer. Reaching this goal will change the very nature of mobility itself. There will be fewer traffic jams, lower emissions, and fewer accidents. Instead of steering the vehicle ourselves, we will be able to relax and flip through a newspaper, prepare for a meeting, or read our emails. The dream of the driverless car is soon set to become a reality—the technical basis for it is very much in place.

1.1 Distinction Between Driver Assistance and Automated Driving

Automated driving is distinguished from driver assistance primarily through the role of the driver, and more specifically, through the involvement of the driver. Driver assistance systems including partially automated systems require the driver to constantly monitor the environment and to be instantaneously available to take back control from the vehicle. Automated driving systems will allow the driver to be completely out of the loop. If the driver is out of the loop, a significant amount of time may be required to return vehicle control to the driver. This challenge leads to relevant implications on the design of the automated driving system: the automated system has to make decisions *in all situations* and cannot rely on the driver to take back responsibility instantly. The shift from minimizing false interventions (i.e. false positives) to optimizing overall system performance, redundancy and reliability, constitutes a paradigm change for vehicle systems development.

1.2 The History of Automated Driving

The idea of self-driving cars is almost as old as the car itself. GM's vision for the future of transportation at the 1939 World's Fair in New York already included driverless cars. The idea remained popular in research, media, fiction and advertisement. Arguably, the first real automated vehicle was built in 1977 by Tsukuba Mechanical Engineering Lab in Japan, which was able to track white street markers and maintain velocity to achieve speeds up to 30 kph. In the 1980s, Prof. Dickmanns's group at the UniBW Munich developed one of the first automated vehicles travelling at highway speeds by controlling steering wheel, throttle, and brakes through computer commands based on real-time evaluation of image sequences. The Eureka PROMETHEUS Project (PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety, 1987–1995) was the largest R&D project so far in the field of driverless cars and several cars demonstrated automated driving during the final presentation in October 1994 on Autoroute 1 near the Charles-de-Gaulle airport in Paris. Since 1984, Carnegie Mellon University's Navlab program developed a total of eleven automated research vehicles, with a highlight of the program being the "No Hands Across America" drive in 1995, in which two researchers drove 3,000 miles across the US with the vehicle steering itself 98 % of the time. In 1991, the United States Congress passed the ISTEA Transportation Authorization bill, which instructed USDOT to "demonstrate an automated vehicle and highway system by 1997." The research culminated in a final demonstration in 1997 on I-15 in San Diego, California, in which about 20 automated vehicles, including cars, buses, and trucks, were demonstrated to thousands of onlookers, attracting extensive media coverage. In the 2000s, DARPA organized a total of 3 challenges for autonomous and completely driverless vehicles. While no vehicles finished the first race in 2004, Stanford University's Stanley won the 2005 DARPA Grand Challenge, which lasted 212 km across the Nevada desert. The 2007 DARPA Urban Challenge moved the competition into an urban environment with intersections and other moving vehicles, and was won by Carnegie Mellon University's autonomous vehicle. The series of challenges was able to show that advances in enabling technologies such as computing, sensing, networking and connectivity finally enabled automated street vehicles. This marked a milestone at which the focus moved from academic research to industrial research. Bosch, as the leading automotive supplier, is at the spearhead of this development.

1.3 Forecasts

Recently a number of technology and market forecast have dealt with the topic of automated driving. KPMG [6] expects reduction of crashes, reduced need for new road infrastructure, productivity improvement and improved energy efficiency, new business models as well as vehicle ownership models. IEEE members have selected autonomous vehicles as the most promising form of intelligent transportation, anticipating that they will account for up to 75 % of cars on the road by the year 2040 [3]. ABI Research [1] predicts that fully autonomous, self-driving, robotic vehicles will start appearing between 10 and 15 years from now and that 10 million such new cars would be rolling out on to United States' public highways every year by 2032. Wired Magazine forecasts that driver's licenses will not be required anymore after 2040 [7]. PricewaterhouseCoopers forecasts a reduction of traffic accidents by a factor of 10, a reduction of wasted time/fuel in congestion also by a factor of 10, and it concludes that the fleet of vehicles in the US would collapse from 245 to 2.4 million with the complete introduction of autonomous vehicles [4].

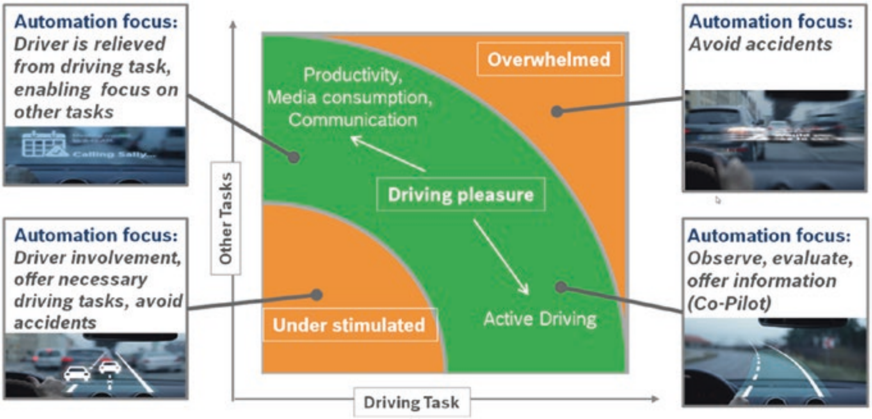

Fig. 1 Focus of vehicle automation during different driving tasks

2 Bosch's Vision for Automated Driving

Bosch has been active in the research programs for automated driving since the 1990s and has participated with Stanford University's team in the 2007 DARPA Urban Challenge. Since 2011, Bosch is developing technologies specifically for fully automated vehicles, and has since then showcased the technology at the 2013 IAA (Frankfurt Motor Show), the 2013 Transportation Research Board Workshop on Road Vehicle Automation at Stanford University, and in a video [8].

Bosch's vision is an intelligent forward thinking vehicle—making the vision of injury and accident-free driving reality. Automated driving of the future will synchronize traffic flow to reduce travel times and fuel consumption. It diminishes the load on the driver by taking over dedicated driving tasks—in line with each individual's needs—allowing all age ranges to be mobile and safe. Automated driving allows the vehicle to become a part of the driver's interconnected home and work life, making time spent on the road more productive and eventful. Bosch is set to develop holistic mobility concepts and services, paving the way for personalized environmentally friendly travel.

3 Motivation

Automated Driving is a key enabling technology for increased efficiency, comfort and safety. More than 90 % of all accidents are at least partly caused by human error. The Texas Transportation Institute estimates that in 2011, congestion in 498 metropolitan areas caused urban Americans to travel 5.5 billion hours more and to purchase an extra 2.9 billion gallons of fuel for a total congestion cost of $121 billion [5].

Increased vehicle automation still leaves plenty of room for driving pleasure. Figure 1 shows situations where automation can assist overwhelmed or understimulated drivers through accident avoidance or assistance functions. In situations

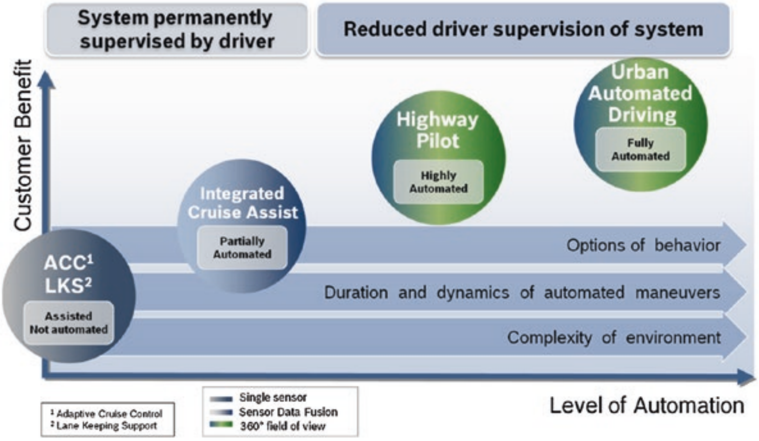

Fig. 2 Bosch's roadmap for automated driving

where the driver enjoys active driving, systems may offer information to the driver. In situations where the driver would much rather sit back and be productive, communicate or relax and consume media, vehicle automation can relieve the driver of tedious driving tasks and take over control.

4 Roadmap for Automated Driving

4.1 From Driver Assistance to Automated Driving

The introduction of automated driving will happen in several steps (Fig. 2). Adaptive Cruise Control (ACC) has been on the market for over a decade. Advanced assistance functions such as Predictive Emergency Braking Systems, Lane Departure Warning and Lane Keeping Support (LKS) help to prevent accidents or reduce their consequences. However, these well-used assistance systems require permanent driver supervision. The architecture of today's vehicle relies on the driver as a backup in case of system failure.

4.2 Partially Automated Driving

As a next step in driver assistance, Adaptive Cruise Control and Lane Keeping Support will be combined into Integrated Cruise Assist providing longitudinal and lateral guidance within one assistance system, see Fig. 3. This system will be based

Integrated Cruise Assist

- Automatic longitudinal & lateral guidance
- 0 – 130 km/h (on highways & major roads)
- In case of missing lane markings, lateral guidance provided via dynamic radar objects

Extensions with driver confirmation

- Automatic lane change
- Automatic speed adaptation based on road sign recognition

Fig. 3 Integrated cruise assist combining longitudinal and lateral assistance for partially automated driving

on a radar sensor for longitudinal guidance and a monocular video camera for lateral guidance. Automated lane changes with driver confirmation will require additional mid-range radar sensors for surround sensing. Speed may be adapted based on visual road sign recognition. Partially Automated Systems will still require permanent supervision by the driver and the availability of the driver as a backup.

4.3 Highly and Fully Automated Driving

The step from partially automated to highly automated driving will be significant. The driver will be enabled to focus on other tasks while driving, and will be able to communicate, watch a movie or spend the time in the vehicle productively. We envision the introduction of these systems initially on highways. The Highway Pilot (Fig. 4) will start on the highway upon driver request and system confirmation. The vehicle will center itself within the lane and will maintain complete awareness of the environment through a number of sensors for environmental perception. The vehicle will control its trajectory via automated steering interventions as well as automated longitudinal control. The vehicle may automatically change lanes when appropriate. The technical challenges and key technologies for highly automated driving vehicles are highlighted in the following section.

Fully automated vehicles will be able to assume the complete driving task including all the speed ranges and under all environmental conditions manageable by a human driver. This level of automation is currently seen more than 10 years in the future due to the significantly higher scene complexity to be encountered.

Highway Pilot

- Highly automated driving w/o driver in the loop
- Function starts upon driver request and system release
- Tracking the vehicle position within driving lane
- Lateral vehicle motion via steering wheel intervention or brake intervention
- Overtaking maneuver if convenient
- Reaction to construction zones

Fig. 4 Highway pilot

In the meantime, Bosch is developing additional functions to assist the driver also in low-speed situations such as parking and maneuvering. With Park Distance Control and Park Steering Control already being on the market, higher levels of parking automation will be introduced step by step. The highest level of parking automation will be automated valet parking.

5 Key Technologies for Automated Driving

Many key technologies for automated driving still require substantial research and development (Fig. 5). Without using the human driver as a fallback system, an automated vehicle has to decide on the best course of action in all situations encountered within the defined range of the function with highest reliability. Monitoring the driver and communicating vehicle intention will push HMI beyond the state of the art for existing driver assistance systems.

Surround sensing will require a combination of multiple sensors including radar and video sensors to generate a reliable and comprehensive 360° environment model of the vehicle environment. This will be supplemented by information from other vehicles (V2V communication), infrastructure (V2I communication) or a back-end server depending on availability. In addition the vehicle will get up-to-date map information from an online server.

Perception, also called sensor data fusion, is comprised of the processing of data from all sensors to a common sensor-independent description of the vehicle environment. Bosch is developing a probabilistic grid representation, where the vehicle environment is modeled as a grid of cells. Sensor measurements estimate the probability that each cell is unknown, blocked or traversable. This "occupancy grid" technology was developed for indoor robots, and Bosch has extended this technology to automotive applications by incorporating object velocity measurements and additional contextual information.

Localization is defined as estimating the position and orientation of the ego-vehicle for positioning in the lane and on the roadway. Localization requirements for automated driving depend on the respective use case: highway driving requires accurate lateral localization within the lane, while accuracy requirements are relieved longitudinally due to larger curve radii on highways. Requirements in urban environments are equally high laterally and longitudinally due to small curve radii encountered. Global Navigation Satellite Systems (GPS, etc.) are used for absolute positioning on the earth with an accuracy of several meters, and are therefore not yet accurate enough to determine the lane in which the vehicle is positioned. Improvement to centimeter-level precision is achieved by correlation of sensor data with prerecorded maps. These maps may be stored on an online server and transmitted to the vehicle.

An automated driving vehicle needs to handle all situations within its functional scope. Driver assistance systems are typically designed and optimized for certain scenarios and often use rules to makes decision based on the detected scenarios. Automated vehicles must make reliable decisions in all scenarios and Bosch therefore use continuous decision making to cover the complete continuous spectrum of possible situations in road traffic.

Automated vehicles require combined lateral and longitudinal motion control to also ensure the desired position over time. Unlike the current generation of driver assistance systems, our control algorithms use coupled lateral and longitudinal control for improved performance.

Another major change in automated driving systems will be in the ECU architecture. The E/E-architecture of automated vehicles will change from a fail-safe architecture as seen in current driver assistance systems (with the driver being available as a redundant backup), to a fail-operational architecture, which must maintain basic functionality in a failure situation and even without a driver in the loop. ECUs for automated driving will require significantly increased computational resources and connectivity while fulfilling highest automotive safety requirements.

Actuation systems for automated driving will be highly reliable, which may be achieved through redundancy. Bosch is in the unique position to have to alternative brake actuation systems with ESP and iBooster, which can be combined into one fail-operational system for automated driving.

The interaction of the human driver with the automated system will be most relevant when it comes to the "handover" between manual driving and automated driving. The vehicle must monitor the driver's position to take back control from the vehicle and must also ensure that the driver has taken back control. In case the driver fails to respond to a takeover request, the vehicle must be capable of bringing itself into a safe state. The execution of the safe state transition depends on the specific driving situation and may include changing to the emergency lane to come to a controlled stop or may result into a gradual slow down on the existing lane.

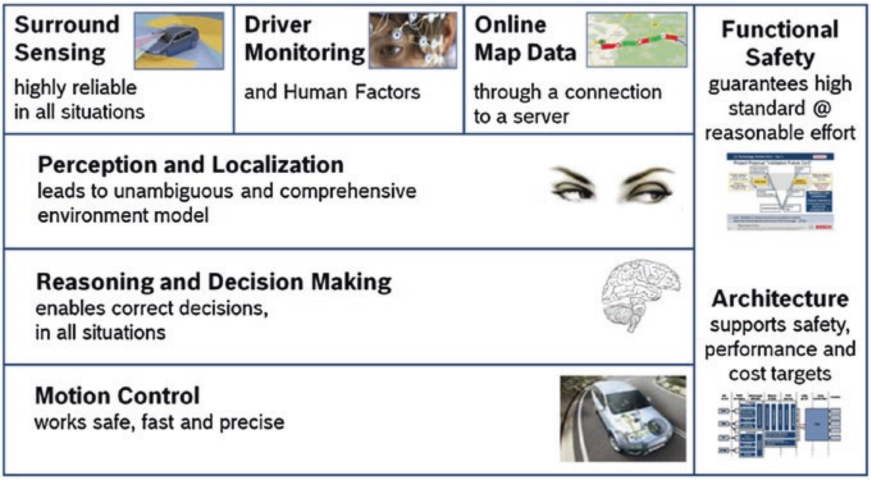

Fig. 5 Key technologies for automated driving

6 Test and Application

Bosch is testing automated driving on roads in Germany and in the USA [2, 8], see Figs 6 and 7. The goal is to use everyday driving situations to put the cars to the test and to improve them. In order to ensure safety during the development process, Bosch's safety concept was reviewed and confirmed by the German certification organization TÜV Süd.

In total, over 5,000 engineers work at Bosch to develop safety and assistance systems which form the foundation for automated driving. A project team dedicated exclusively to automated driving is now working to safely integrate these future functions with a car's sensors, control units, and actuators to form a unified system. They are working toward this goal in two places: in Palo Alto, California, engineers are driving the development of functions, while systems integration is being done in Abstatt, near Stuttgart in Germany.

7 Conclusions

Bosch is convinced that Automated Driving is becoming a reality and will offer benefits for safe, relaxed and economical driving. We expect a stepwise introduction of automated driving starting with increased levels of automation on the highway. The first highly automated driving function will be a Highway Pilot. The trend towards Automated Driving is generating new technical challenges for the sensors, algorithms, actuators as well as the E/E-architecture of future vehicles. Bosch is developing automated highway driving functions in dedicated project

Fig. 6 Bosch test vehicle brings highly automated driving to the Autobahn

Fig. 7 A Bosch engineer supervising an automated vehicle test drive. The safety concept worked up for the test campaign was tested and approved by TÜV Süd. [2]

teams in Abstatt, Germany and Palo Alto, USA. These teams are continuously testing automated vehicles on the German Autobahn as well as on highways in California and Michigan.

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History and Status of Automated Driving in the United States

Sven Beiker

Abstract Research in the field of automated driving has a long history in the United States. From the very early efforts in the 1930s and 1940s when automated highway systems were proposed and which were researched intensively from the 1950s to 1990s, the field gained new momentum and direction in the early 2000s when the military called for the DARPA Grand Challenge, which showcased what was possible in the field of infrastructure independent automated vehicles. These initiatives were the starting point for the recent push towards automated vehicles in the interest of road traffic safety and efficiency. This article reviews the history of automated driving research in the U.S. and discusses where the field is headed with players from industry and academia, as it also points out the role of the government in setting rules and driving innovation.

Keywords Automated vehicle • Automated driving • Automated highway • Autonomous vehicle • Autonomous driving • Stanford University • U.S. automotive industry

1 History of Automated Driving in the United States

1.1 Early Stages of Vehicle Automation

Figure 1 gives an overview of the history of automated driving research in the United States. What is widely considered the first concept of automobiles that don't require constant driver input or monitoring was the automated highway concept in

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
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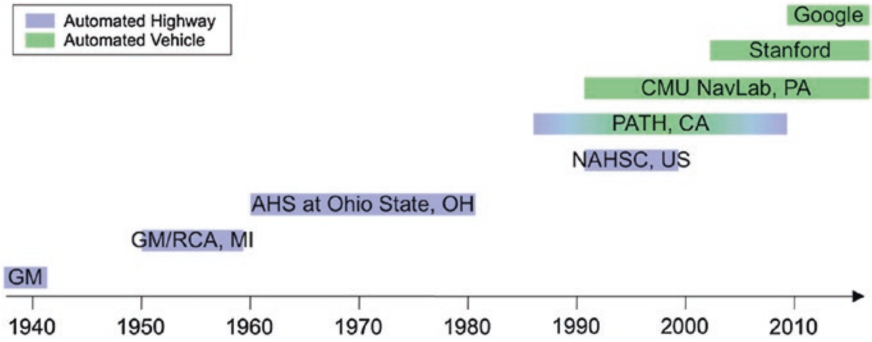

Fig. 1 Overview of automated driving research in the United States (author's depiction)

General Motors' Futurama vision that was shown at the 1939 World Fair in New York City [1]. That concept, created by Norman Bel Geddes, envisioned what the world would look like in 1960, about 20 years into the future from the date of the fair. For ground transportation, the vision comprised what about 15–20 years later became reality with the U.S. Interstate System and also some automated vehicle control, which was described as radio controls to maintain proper distance between vehicles—basically what became reality as adaptive cruise control about 60 years after the fair. In the book "Magic Motorways" [2], that Geddes published in 1940, he explained in more detail, how many of the systems that were used already in aircraft at that time, could help automobiles to stay in the lane and keep proper distance. An integral part of that was radio communication that was supposed to connect vehicles with one another as well as with a central infrastructure that would control the overall traffic flow.

While not much activity was spent on automating civilian vehicles during World War II, General Motors (GM) and Radio Corporation of America (RCA) collaborated through the 1950s, which yielded scale models of automated highways. Those concepts, probably mostly due to the involvement of RCA, a radio communication expert, built strongly on the use of radio communication for longitudinal and lateral vehicle control. Besides on-board control of the vehicle, the concept also included centralized traffic control towers that would manage overall traffic flow. The on-board technology used among other components magnetic coils in the front and rear of the vehicle, which would sense the magnetic field of counterparts in the road surface and therefore enable automatic steering for lateral control, what today would be called "lane keeping assist". In a 1958 press release, GM describes the accomplishments of this automated vehicle control: "An automatically guided automobile cruised along a one-mile check road at General Motors Technical Center today, steered by an electric cable beneath the concrete surface. It was the first demonstration of its kind with a full-size passenger car, indicating the possibility of a built-in guidance system for tomorrow's highways" [3]. Through these and other activities in the 1950, the term "Automated Highway System", or "AHS" was coined, which indicated that, different from today's efforts to integrate as much of the automation and control technology on-board the vehicle, back then a sizeable part of the technology consisted of roadside infrastructure and control architecture.

1.2 Automated Highway Systems

Automated Highway Systems also became a very important research topic at the Ohio State University, when in the 1960s much work was pursued in that field. The work, significantly funded by the U.S. Federal Highway Administration, started with automated steering, braking, and acceleration control for vehicles and went on for about 20 years. The basic concept was similar to the one that GM and RCA had worked on, that means magnetic sensors in the front and rear of the car, picking up magnetic signals from wires in the road surface. Especially during the 1970s, much work was done at Ohio State University in platooning vehicles on such automated highways, until federal funding ceased in the early 1980s. Also during the 1960s and 1970s, Bendix, which later merged with several other corporations such as Raytheon and Allied Signal, worked on similar concepts that aimed for automated vehicles by using cables in the road surface and radio communication.

In 1986, California Partners for Advanced Transit and Highways (PATH) was formed, a collaborative of academia, public and private sectors, which was administered by the Institute of Transportation Studies (ITS) at the University of California at Berkeley in collaboration with the California Department of Transportation (Caltrans). In its mission to increase highway capacity and safety, PATH put from the beginning a strong focus on highway automation (besides highway electrification, another primary research direction for the program) [4].

In 1991, U.S. Congress directed the U.S. Department of Transportation (U.S. DOT) with the "Intermodal Surface Transportation Efficiency Act" (ISTEA) to "develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed […] by 1997" [5]. Thereafter, the U.S. Federal Highway Administration (FHWA) formed the National Automated Highway System Consortium (NAHSC). NAHSC was a consortium of a number of technology and construction companies, transit organizations, as well as universities, with General Motors and FHWA heading the collaboration and the California PATH collaborative being a core member. In 1994 the consortium aimed to deploy automated highway systems between 2002 and 2010 with demonstrations of prototypes in the second half of the 1990s [6]. The most significant demonstration project was conducted in 1997 on Interstate-15 outside San Diego, when about 20 vehicles (cars, trucks, busses) platooned with close following distance and lateral control showing gains in energy and traffic efficiency trough automated control and still allow for other vehicles to merge in and out of the platoon [7]. The longitudinal control of the vehicles was performed through radar sensing on each vehicle as well as vehicle-to-vehicle communication so that the vehicles could be kept at a proper distance [8]. In order to keep the vehicles in the lane, lateral control used magnets implemented in the road surface that could be detected by on-board sensors to minimize lateral tracking error. The activities at NAHSC were ceased in the late 1990s due to budget constraints at U.S. DOT.

1.3 Automated Vehicles and Public Competitions

In 1995, Carnegie Mellon University demonstrated in a 4,500 km drive from Pittsburgh to Los Angeles, that they were able to accomplish 98.2 % automated lateral control on that journey with camera and laser vision systems together with a neural network control concept. The demonstration, which was dubbed "No Hands Across America" [9] did not use any longitudinal vehicle control, but was an important step in what would lead to Carnegie Mellon's activities in the DARPA Grand and Urban Challenges in the 2000s.

In 2003, the U.S. Defense Advanced Research Projects Agency (DARPA) decided to use a prize budget, which had been authorized by U.S. Congress earlier, to respond to a Congressional mandate from 2001 formulated as "It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that … by 2015, one-third of the operational ground combat vehicles are unmanned" [10]. To reach that goal, DARPA invited technology firms and research institutions to participate in the 2004 Grand Challenge, a 240 km desert race for unmanned vehicles. While no contestant could finish that race, the sequel, the 2005 Grand Challenge, a 212 km race in the Mojave Desert was completed by 5 out of the 23 vehicles that took part in the final run. The vehicles, equipped with laser, radar, and camera systems but no outside communication link except for emergency stopping, set the direction for academic and industry research in vehicle automation throughout the 2010s and beyond.

The concepts in the 2005 Grand Challenge differed regarding how much rule-based versus machine learning capabilities were used and therefore revealed which approaches were beneficial for certain situations. Also, the Light Detection and Ranging (LIDAR) sensors became the de-facto standard for automated research vehicles. That technology used rotating or sweeping laser scanners that sent out laser pulses to measure the distance of objects with a time-of-flight calculation and also enabled object recognition algorithms to determine the contour and type of an object.

In 2007, DARPA invited contestants to the Urban Challenge, which was a 96 km competition in a former military base with traffic rules to follow, including stop signs, merging, yielding, and detours. Same as in the previous Challenges, the participating teams were given a set of Route Network Definition File (RNDF) and Mission Data File (MDF) just shortly before the competition, so that the vehicle concepts had to be ready to follow generic data as a general description of the driving task and use the on-board sensors to detect obstacles such as other vehicles, stationary objects, or road closures in real-time and respond to it with appropriate action. This requirement basically coined the term "autonomous" vehicles, because, besides satellite navigation technology, no other external real-time information was permitted and therefore the vehicle had to be independent from outside information, which had been essential in the automated highway programs of the previous century. In the early 2010s, DARPA shifted its attention from a specific focus on ground vehicles to robotic systems in more general terms, including humanoid robots. The competitions that were anticipated as successions to the Grand and Urban Challenge were three events of the DARPA Robotics Challenge scheduled from 2012 to 2014. In these competitions, the robotic systems needed to perform different tasks that troops would perform in combat, which also included driving a ground vehicle [11].

2 Status of Automated Driving in the United States

2.1 The Role of Silicon Valley

After and probably through the Grand and Urban Challenge competitions, one of the worldwide leading centers for automated driving research evolved in Silicon Valley. With Stanford University being one of the most successful participants in the Challenges (first in 2005, second after Carnegie Mellon University in 2007), many automotive companies, most notably from Germany and Japan, came to the university to collaborate on automated vehicle research. In addition, Velodyne, a technology company in the area, became a major supplier of LIDAR systems for many research vehicles. After five of the six finishers in the 2007 Urban Challenge had used Velodyne's laser technology [12], many subsequent research programs used the same or succeeding systems. Among these programs was Google's self-driving car project. The company disclosed in 2010 that it would work on automated vehicles with the goal "to help prevent traffic accidents, free up people's time and reduce carbon emissions by fundamentally changing car use" [13]. In summer 2012, Google had driven more than 500,000 km with its automated vehicles [14], which had grown to a fleet of more than 10 vehicles and at least two different models to perform any kind of technology development and user testing.

With Google becoming a major player in automated vehicle development, global research and development activities got accelerated and virtually all major vehicle manufacturer as well as major suppliers in the industry started or grew their efforts in the field, often seeking collaboration with Silicon Valley academic and industry partners. This movement also attracted the legislators' attention, sparking initiatives to regulate testing, operation, and sales of such vehicles.

2.2 Regulation and Government Initiatives

In spring 2011 a bill was introduced to the State of Nevada Assembly Committee on Transportation, which the State Governor subsequently signed into action and thereby requesting the Nevada Department of Motor Vehicles to implement regulation for "autonomous vehicles". The regulation, which became effective on March 1, 2012, and largely described how the testing of automated vehicles was to be performed on state highways and how the certification process for such vehicles as well as its test drivers had to be established [15]. Other states followed Nevada's initiative, most notably California and Florida, however with different scope and timelines.

In the meantime, the National Highway Traffic Safety Administration (NHTSA), the agency under the U.S. Department of Transportation that deals with road vehicles and traffic, had not taken a general position by late 2013. In a "Policy on Automated Vehicle Development" that NHTSA published in spring 2013, the agency aimed to "provide guidance to states permitting testing of emerging vehicle technology" [16], which also included a proposal for definitions of different levels of vehicle automation and put vehicle automation in context with other automobile safety technology including vehicle to vehicle communication.

At the same time, in summer 2013, the first results from another federal, until that point largely separate program were published, the Connected Vehicle Safety Pilot Program, that "supports the development of safety applications based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications systems, using dedicated short-range communications (DSRC) technology" [17]. That program had been pursued in various phases since the late 1990s with the goal to improve vehicle safety and efficiency through the exchange and use of information such as other vehicle's location, velocity, driver inputs, and more. In the 2013 Policy on Automated Vehicle Development, NHTSA pointed out, that this technology would also support automated vehicle technology [16], which eventually closed to the loop to the concepts that Geddes had envisioned already in 1940.

2.3 Definition and Standardization Activities

As many terms had been used to describe automated vehicles, with "autonomous", "driverless", "robotic", and "self-driving" being some of them, different initiatives came underway in the early 2010s to define different levels of automation and respective systems. SAE International organized the On-Road Automated Vehicle Standards Committee, which for instance had established standards for adaptive cruise control (ACC) and other driver assistance systems. In 2012 the committee issued Taxonomy and Definitions for Terms Related to On-Road Autonomous Vehicles [18] that set forth six descriptive levels of automation that defined which part of the driving task the human would perform and which the automated system would take over.

A year later, with the 2013 Policy on Automated Vehicle Development, NHTSA proposed a similar but not identical set of descriptive levels for vehicle automation, which consisted of five levels [16]. The primary difference between SAE's and NHTSA's definitions was that SAE distinguished in its highest levels between automation of all or some driving modes, which NHTSA combined into one category. However, both proposed the term "automated" to describe vehicle systems that take a driving task over from the driver at least in part.

2.4 The U.S. Automotive Industry in 2013

In the year 2013 the automotive industry in the United States was in a situation that seemed to be unprecedented. After the 2008–2010 economic recession, the American vehicle manufacturers and suppliers were recovering from what had arguably been the biggest crisis of the industry in its over 100-year long history. Now the manufacturers and suppliers were keeping up again with European and Asian competitors as the entire industry was getting more and more engaged in vehicle automation.

In the early 2010s, General Motors revealed its plan for "Super Cruise" [19] and showed also different concepts for the "EN-V" [20]. Super Cruise combined advanced versions of lane keeping assistance and adaptive cruise control, which were supposed to navigate the vehicle under mostly congested or mostly empty highway driving conditions. Because the driver's attention was still required, GM called the Super Cruise a "semi-autonomous" driving system. While a launch date was not known in 2013, Super Cruise was expected to come to market within a few years from then. The EN-V concept, the "electric, networked, vehicle" was first shown at the 2010 Shanghai World Expo and demonstrated what a vehicle for the city of the future could be like. Despite many other features, GM envisioned a combination of wireless communication and sensor systems that permitted fully automated driving, so that commuters would also be able to pursue their business or pleasure during the journey. A launch date for the concept was not stated as of 2013.

In 2012, the Ford Motor Company released its "Blueprint for Mobility" [21]. Herein the company envisioned a rapid deployment of information and warning systems coming to the mass market and therefore making a large partition of the fleet safer. Between 2017 and 2025 a massive deployment of vehicle-to-vehicle and vehicle-to-infrastructure communication technology was expected, which would also benefit the expected deployment of "semi-autonomous" driving technology such as platooning and autopilot in that timeframe. Beyond that "fully autonomous" vehicles were expected, which would include extended autopilot functions and automated valet parking.

In 2013, Tesla Motors announced that it would offer within 3 years a production concept that would "allow the driver to hand 90 % of the control of the car over to the vehicle's computer system" [22]. While details were not disclosed at this point, it was assumed that the referred concept would resemble those of other vehicle manufacturers that were projected for the same timeframe, such as the aforementioned GM Super Cruise.

On the automotive supplier side, Delphi for instance got more and more involved in components as well as entire systems for collision avoidance, longitudinal and lateral vehicle control. One example was an industry-first integrated radar and camera system that combined radar sensing, vision sensing, and data fusion in one module [23]. Such systems and components were expected to be key enablers for the immediate and later steps in vehicle automation while automotive suppliers would play an important role in offering innovation to vehicle manufacturers and realizing scaling effects by leveraging volumes across multiple customers.

2.5 The U.S. Universities in 2013

Since the 1960s, U.S. universities have been a significant contributor to and driver for automated driving. As mentioned before, especially Stanford University and Carnegie Mellon University were very successful in the DARPA Grand and Urban Challenges, which attracted many industry partners to collaborate for future vehicle systems.

Carnegie Mellon, the Massachusetts Institute for Technology (MIT), Virginia Polytechnic Institute (Virginia Tech), and other universities with a strong engineering focus mostly dedicated their efforts on technology development in computer science, electrical and mechanical engineering. For instance, at the General Motors-Carnegie Mellon Autonomous Driving Collaborative Research Lab, engineering researchers together with industry partners conducted their work on further improving computer vision and decision making for automated vehicles with the goal of deploying respective technology in the near future [24]. At MIT some similar activities could be observed, while also research projects addressed the field of automated on-demand mobility concepts, such as automated vehicles for the “last mile” problem, i.e. to close the gap between public transportation and personal mobility [25].

The Virginia Tech Transportation Institute (VTTI) in collaboration with Google and NHTSA conducted research regarding human aspects related to automated vehicles. The goal in this was to better understand how to handover control from the vehicle to the human when the automated mode would be suspended [26]. The University of Michigan Transportation Research Institute (UMTRI) pursued two main directions in the field. One thrust was to move closer to deployment of connected vehicles, which was much researched with the Safety Pilot program [27] involving almost 3,000 vehicles exchanging data for vehicle safety purposes via 802.11p communication, and another thrust to research automated, connected, and shared vehicles to transform how automobiles would be used by combining the benefits of personal mobility and public transportation [28].

The aforementioned accomplishments of Stanford University in the DARPA Challenges led to an unprecedented spike of industry interest at the Silicon Valley institution. In answering the requests that the university was receiving from vehicle manufacturers, suppliers, and service companies worldwide, it established in 2008 the Center for Automotive Research at Stanford (CARS) to form a community of industry and academia and address the challenges of personal mobility in the twenty first century. Automated driving was defined as one of the primary directions for the program and an interdisciplinary approach was proposed early on. That resulted in a vital community of engineering, humanities, law, policy, and environmental researchers as a multifaceted collaboration toward automated driving. Some of the research that the labs at Stanford pursued for vehicle automation covered computer vision and machine learning algorithms [29], vehicle control at the limits of handling [30], and the understanding of how professional drivers control the car to further improve control algorithms [31]. Other research intensively discussed legal aspects of automated vehicles [32], human factors and interface questions, as well as automated on-demand mobility and the influence automated driving would have on the mobility behavior and urban planning. The CARS program played a vital role in connecting the academic research with industry players, which included vehicle manufacturers, system suppliers, and service providers. With this interdisciplinary setting and industry-academia network, Stanford University had also become an important source for federal and state administrations alike to seek advice regarding future policies and regulation for automated vehicles.

3 Outlook and Summary

It was laid out that automated driving research has a long history in the United States and the industry as well as academic activities, very often in a collaborative effort, have experienced a renaissance since the mid 2010s. With many different players in the field, it is safe to assume that vehicle automation, through the different levels of the technology, will help the industry move closer to the proclaimed goals of lower accident numbers, increased traffic efficiency, extended mobility, and more convenient personal mobility. The timeline and scenarios for deployment are heavily debated, but it is expected that automated driving will eventually have a great impact on the transportation system of the United States, and that many concepts and benefits that were envisioned well over 50 years ago will play out in the near future. The U.S. industry and academia seem to be well positioned to play an important role in the global attempt to redefine the personal mobility experience with unprecedented safety and efficiency through automation driving.

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Research and Innovation for Automated Driving in Germany and Europe

Gereon Meyer and Stefan Deix

Abstract German and European vehicle manufacturers and automotive suppliers have been at the forefront of developing and commercializing advanced driver assistance systems in the past. They are thus well prepared to proceed towards increasing levels of road vehicle automation, and engage in a multitude of technology development and demonstration actions around the world, now. Nonetheless, serious steps in reliability, security and affordability of the key enabling technologies still need to be taken and solutions for the liability issues and legal requirements have to be found before a broad rollout of automated driving in Europe. Starting from the motivations of automated driving this chapter reviews recent achievements in driver assistance systems and highlights promising paths of future development of automated driving, pointing out the research and innovation needs in key enabling technologies and also considering solutions for non-technical issues. Furthermore, potential synergies between the automation and the electrification of the vehicle are analyzed.

Keywords Advanced diver assistance systems • Vehicle communication • Europe • Germany • Vienna convention • Electrification

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_7, © Springer International Publishing Switzerland 2014

1 Introduction

With striking demonstrations and successful field tests, vehicle manufacturers in Germany and Europe recently drew public attention to their research and innovation activities in highly automated and autonomous driving. In summer 2013 Daimler mastered the 100 km-long route from Mannheim to Pforzheim with a Mercedes-Benz S 500 prototype car equipped with production-based technologies for autonomous driving. It was the same route where Bertha Benz had set out on the first long-distance automobile journey 125 years ago [1]. Researchers at BMW are currently testing applications for autonomous driving in a prototype BMW 5 vehicle on highways between Munich and Nuremberg, giving a spectacular presentation of their achievements at the CES 2014 in Las Vegas in early 2014. The vehicle comprises radars, laser scanners, cameras and ultrasound sensors which are all unobtrusively incorporated in the car's body [2]. Already in 2012, a convoy of various Volvo vehicles including a truck was tried out in mixed traffic on a motorway outside Barcelona, Spain as part of a European Commission-funded research project on the feasibility of platooning [3]. Renault recently demonstrated its autonomous valet parking technology with a Fluence electric vehicle at the premises of their research center near Paris. It runs in auto-pilot mode without passengers from a dedicated drop-off area to a parking lot or wireless charging station and vice versa, and uses mainstream automotive sensor components [4]. At the same time, Valeo presented several solutions for the automation at slow speeds, like e.g. autonomous parking [5]. More and more car models of German and European manufacturers are now equipped with off-the-shelf driver assistance systems that, according to automotive supplier Bosch, will soon allow partially automated driving, e.g. adaptive cruise control and lane keeping assist [6]. Continental predicts that highly automated driving may be ready for the market by 2020, and fully automated driving by 2025 [7]. Despite these successes and announcements, it is questionable whether the regulatory frameworks allowing the driver to hand over the control of the car will be in place on time, and whether liability issues will be solved.

2 Motivations for Automated Driving

Road vehicle automation is expected to provide solutions for major societal, environmental and economic challenges, e.g.

- Emissions reduction through optimization of traffic flow management and reduction of fuel consumption
- Adaption to demographic change by supporting unconfident drivers and enhancing the mobility of the elderly
- Road safety enhancement by avoidance of human driving errors
- Congestion avoidance by traffic flow management and time efficient driving via automation

- Economic competitiveness based on unique selling propositions and technology leadership
- Exploitation of mature technologies by using approved and cost-effective sensors and series production actuators.

These solutions match the strategic objectives of major innovation and technology policies at German national and European levels. According to the High-Tech Strategy of the German Federal Government new forms of mobility are needed in order to transfer people and goods at high levels of speed, safety and comfort as well as efficiency and at low resource consumption in the future [8]. And, one of the major actions mentioned in the Transportation White Paper of the European Commission is a "vision zero" on road fatalities which shall be based on e.g. driver assistance systems, cooperative traffic systems and vehicle to vehicle communication as well as vehicle to infrastructure interfaces. However the topic of road vehicle automation is not explicitly mentioned in these high level strategies [9].

3 Achievements in Driver Assistance Systems

German national und European public research funding in microelectronics, embedded systems and smart systems integration have triggered innovation in sensor, actuator, control and communication technologies which lead to major achievements in driver assistance systems, recently [10]. European automotive suppliers firstly launched many of these levels 0 and 1 (according to SAE and VDA) road vehicle automation systems for lateral and longitudinal control on the market, or improved them significantly. Furthermore, systems for partial automation (level 2) are subject of current research and demonstration activities.

3.1 Research and Development Projects

In recent years, the European Commission has funded a couple projects for the development and demonstration of road vehicle automation and its base technologies:

The project "Highly Automated Vehicles for Intelligent Transport" (HAVEit, 2008–2011) showed that a higher level of automation is feasible on existing public roads in mixed traffic. As part of the project, three automation modes were developed and implemented in form of (a) an assisted mode by already-available standard driver assistance systems, such as lane keeping assistance or an emergency braking assistance (b) a partly or semi-automated mode where the vehicle drives with longitudinal automation (c) a high automation mode where lateral automation comes into play, meaning the driver no longer has to steer. Despite the level of automation selected, the driver was always fully responsible for maneuvering the vehicle, could take control in place of the system at any time, and had to monitor the vehicle's driving maneuvers. In the partly and highly automated modes, the system observes the driver with the help of a camera located inside the vehicle [11].

The project "Accident Avoidance by Active Intervention for Intelligent Vehicles" (Interactive, 2010–2013) aimed at taking the next step towards the goal of accident-free traffic and developed advanced driver assistance systems for safer and more efficient driving, e.g. driver warnings in dangerous situations, collision avoidance systems, and emergency intervention in the pre-crash phase [12].

The project "Automated Driving Applications and Technologies for Intelligent Vehicles" (AdaptIVe, since 2014) is a consortium of 29 European partners comprising OEMs, automotive suppliers, research institutes and SMEs who aim to make automated driving safer and more efficient [13].

Recently, the project "Interoperable GCDC (Grand Cooperative Driving Challenge) AutoMation Experience" (i-GAME, 2013–2016) started which shall speed up the real-time implementation and interoperability of wireless communication-based automated driving [14].

Moreover, a multitude of EU-funded projects dealt with the communication between vehicles and the road infrastructures, e.g. SAFESPOT, COOPERS, CVIS (Pre)DRIVE C2X, INTERSAFE (for cooperative intersections) and NEARCTIS (for traffic management). The project PReVENT contributed to road safety by developing and demonstrating preventive safety technologies. Advanced driver assistance systems were also subject of the EU-projects STARDUST, and isi-PADAS.

Also the German Federal Government funded a multitude of collaborative research and innovation projects in the field of road vehicle automation during the last 5–10 years.

One of the most prominent activities in Germany are the AutoNOMOS projects (since 2008) that are dealing with autonomous decision making, route planning based on digital maps, user interfaces including smartphone apps and neural signal detection. Two demonstrators have been presented and a multitude of test drives were conducted in city traffic [15].

The project "Forschungsinitiative Ko-FAS—Kooperative Sensorik und kooperative Perzeption für die Präventive Sicherheit im Straßenverkehr" (KO-FAS, 2009–2013) developed and demonstrated driver assistance systems based on cooperative technologies like vehicle-to-vehicle communication, as well as sensor data evaluation, data fusion and active safety systems [16].

Currently, the project UR:BAN is studying the opportunities of using driver assistance systems and car-to-x communication in the complex environments of city traffic such as intersections and narrowing roads, and in lane change maneuvers [17].

Previously, also the projects ACTIV and INVENT were focused on the development of driver assistance systems relevant for automated driving, and recent publicly funded projects on electric vehicles included aspects of automated driving as well, e.g. EFA 2014 II and VisioM.

3.2 Demonstration Activities

The European Union funded research and demonstration project CityMobil (2006–2011) addressed the integration of automated transport systems in the urban environment [18]. It dealt with guided buses in Castelleon, Spain, Cybernetic Transport Systems in the demonstration of Personal Rapid Transit (PRT) at the Heathrow airport of London, U.K., and Group Rapid Transit (GRT) at the exhibition centre of Rome, Italy. Its forerunner NETMOBIL (2003–2005) was a cluster of projects for innovative urban transport systems.

EuroFOT (2008–2012) was a series of Field Operational Tests with the aim of assessing the main Advanced Driver Assistance Systems (ADAS) that have recently appeared on the European market [19].

The project Safe Road Trains for the Environment (SARTRE, 2009–2012) developed and showcased strategies and technologies to allow vehicle platoons to operate on normal public highways where the following vehicles (cars and trucks) operate in dual-mode (fully autonomous within the platoon) with significant environmental and comfort benefits [20]. Its forerunner, Chauffeur, developed new electronic systems for coupling trucks at close following distances.

In Germany, a major demonstration activity for automated driving is the Stadtpilot project where two autonomous cars have been tested in regular traffic in the city of Braunschweig [21].

3.3 Product Developments

Driver assistance systems have greatly advanced in recent years: their two most relevant functionalities for highly automated driving, adaptive cruise control and lane departure warning, are commonplace in high-end automobiles today.

In an adaptive cruise control (ACC) system, the driver selects the desired speed and sets the distance to be maintained to the vehicle ahead. This gap can be set at several distances, adapting to the driving situation and individual driving style. Standard ACC can be activated from speeds of around 30 km/h (20 mph) upwards and can support the driver, primarily on interurban journeys and on highways or motorways.

An ACC Stop and Go system maintains a set distance to the receding vehicle even at very low speeds and can decelerate to a complete standstill. When the vehicle in front accelerates within a few seconds, the ACC vehicle follows automatically. Such system can support the driver in congested traffic at speeds below 30 km/h.

ACC and ACC for Stop-and-Go are provided e.g. by Bosch and Continental. BMW, e.g., is offering a ACC for stop and go situations for its series 5 and up vehicles.

Most German OEMs as well as Continental and Bosch develop Lane Departure Warning (LDW) systems which warn the driver in case the car moves to close to the edge of the lane. Lane keeping assist systems (LKA) actively steering the vehicle to keep it in the lane are offered by Daimler, Volkswagen, Audi and Bosch [22].

3.4 Communication Standards

Automated cars heavily rely on the data connection to other cars and to the infrastructure which cannot be developed without common technical requirements regarding, for example, frequencies used or data management. The European Commission's Action plan for the deployment of ITS in Europe thus aimed at the development of harmonised standards for ITS implementation, in particular regarding cooperative systems. Following a mandate by the European Commission, ETSI and CEN/ISO finalised a first standardisation package which was announced recently [23].

4 Future Development Paths

From a technological point of view, automated vehicles represent the evolution of today's driver assistance systems. It starts with the systematic combination of lateral and longitudinal control, and is further supported by C2X communication and environment perception. A networking with driver information and drive systems is gradually advancing the concept toward its goal. From 2016, partially automated systems may therefore be assisting drivers by combining lateral and longitudinal control in “stop and go” situations on the freeway at low speeds of up to 30 km/h. But this initial step toward automated driving does not relieve drivers of their responsibility to constantly pay attention to what is happening on the road. As well as covering higher speeds above 30 km/h on the freeway, highly automated driving will allow drivers to use the time they would spend driving on other activities. With both levels of automated driving, however, the driver must be able to regain control of the vehicle at all times. Fully automated road vehicles that require neither supervision nor takeover of control by a driver will be the most advanced system. It would have a significant impact on our mobility behavior, road safety and traffic efficiency in interurban (motorway/freeway) and urban applications as it could lead to radically new solutions such as robot taxis.

According to the ITS roadmaps of the European Association of Automotive Suppliers (CLEPA), highly automated driving will be launched into the market around 2020–2025 [24].

The German Association of the Automotive Industry (VDA) expects that partly automated driving (level 2) functions like parking assistant, lane changing assistant and construction site assistant will be available at the short term, whereas functions of conditional automation (level 3), e.g. overtaking chauffeur, traffic jam chauffeur and motorway chauffeur may be on the market on the mid term, and functions of high automation (level 4) will be either mid term (e.g. valet parking, emergency stop) or long term (motorway pilot) [25].

5 Key Enabling Technologies

According to a recent position paper by the eNOVA Strategy Board Electric Mobility and the ITS Roadmap of CLEPA, research and development on key enabling technologies is needed in the following domains.

5.1 Vehicle and Driver Systems Level

The driver engagement and driver re-engagement for various levels of automation in a safe and conclusive manner is important to ensure a safe system as well as user acceptance. In particular, transitions between human and automated vehicle control need to be managed. Therefore, human factors have to be considered as decisive design criteria. HMI (visual, haptic and acoustic) thus must take into account the role of the driver in highly automated vehicles and enable a safe interaction and usage. At the same time, the status of the driver has to be continuously controlled to make sure that he is able to take over control when needed. Furthermore, the user acceptance for partially and highly automated vehicle depends on human factors and the intuitive usability.

Based on environment perception through detection and modeling, driving strategies need to be calculated being fully aware of the dynamic behavior and the intentions of all traffic participants, particularly in complex situations like e.g. crossings and roundabouts. This also requires a use-case oriented fusion of sensor data. Simultaneously, the vehicle needs to be aware of its exact position at all times. Therefore, a passive and active real-time updating of map data is necessary, and needs to be complemented by the detection of physical markings in the road.

Generally, fallback options enabling a safe state in the case of failure or limited performance of the system need to be implemented in order to make drivers and users confident with automated driving and therefore accept it. Thus, a basic technical prerequisite for the implementation of automated driving is system reliability. This calls for fail-safe architecture at board net level that keeps the vehicle in a safe state in the event of a fault.

5.2 Components Development and Integration

In order to enable automated driving functions, the vehicle needs to be able to perceive the environment with very high precision and reliability. Environment sensors and cameras need to be further improved regarding energy efficiency, speed and affordability. Special focus is on false positive detection of sensors. Different sensor types need to be integrated and sensor fusion plays an important role as a main enabler for automation.

As vehicle automation is also based on robotic functionality, actuators are of increasing importance and need to be further optimized regarding their precision and cost.

Furthermore, automated driving requires additional information from other road users and from the infrastructure. Based on this information the vehicle/system can adapt the driving strategy and conclude on the best driving path according to the received information (e.g. upcoming congestion, traffic accident). Enabling this functionality requires the integration of validated communication devices into the vehicles. The security issues for this communication are of major interest for automated driving as unsecure communication may open the system for abuse, criminal or terroristic attacks. Date encryption will thus be needed.

5.3 Methods and Tools

In view of the legal and liability-related challenges to implement automated driving at a broader scale, reliability of all components in terms of functional safety, redundancy and fail-safe performance is required. In order to ensure these requirements, test and certification methodologies need to be adapted for these additional functions. The interaction between all involved automated components as well as the functions needs to be evaluated with focus on automation. In parallel to the use cases, automated driving functions need to be evaluated regarding miss usage/false usage by the driver, e.g. falling asleep or not taking back control functions after a take-over request.

Software methods that need to be further developed include methods for the highly dynamic modeling and simulation of the vehicle environment like e.g. electronic horizon, methods for sensor data fusion and for the communication and processing of big amounts of traffic and operation data, as well as for their fusion with sensor data. Furthermore, dynamic online maps, methods for prediction and decision finding will increasingly play a role as enabling technologies.

Also, criteria for the selection and proper combination of sensors are needed and design standards for software and hardware architectures have to be established.

6 Solutions for Non-technical Issues

The legal implications of automated driving have been analyzed in much detail recently. According to a study by the Federal Highway Research Institute (BASt) the use of high or full automation of road vehicles presently is not compatible with

German law, as the human driver would violate his obligations stipulated in the Road Traffic Code when fully relying on the degree of automation these systems would offer [26].

The underlying regulatory hurdle is the Vienna Convention of 1968, which is implemented in national road traffic regulations everywhere in Europe and in many other countries of the world—however not in the United States. It clearly states in its Article 8 that "Every moving vehicle or combination of vehicles shall have a driver", and "Every driver shall at all times be able to control his vehicle or to guide his animals" [27]. Assisted and partially automated driving (up to level 2) complies with this convention; conditional or highly automated driving (level 3 and higher), where the driver is not monitoring the system permanently, do not. The only exception is an automatic emergency stop system that steps in if the driver is not able to take control.

According to many stakeholders of the European automotive industry, the Vienna Convention of 1968 should be amended and clarified in the sense that the use of driver assistance systems including highly and fully automated systems does not contradict it, and the national road traffic regulations should be adapted. Furthermore, amendments of the vehicle regulations (e.g. of the UNECE) would be needed.

A comprehensive European study makes further suggestions for solving the non-technical challenges of automated driving [28]: In order to deploy the automated driving applications cost-effectively and at the right time, a short- to long-term plan for gradual introduction in certain categories should be established and supported by mandatory measures. According to that study, serious solutions at the legislative level would make it possible to break the chicken-and-egg problem of infrastructure creation and vehicle technology deployment. Beyond legislative measures, an appropriate standardization program would help the industry, the regulators, and the road infrastructure owners to take the right decisions in due time and avoid thereby undesired costs introduced by uncertainties in their business models. The technical in-vehicle environment that remains safe for the entire exploitation phase should be defined across company limits in order to avoid issues due to differences in innovation cycles in electronics compared to automotive industry.

7 Synergies of Automation and Electrification

According to a recent position paper by the eNOVA Strategy Board on Electric Mobility, automation can significantly benefit the energy efficiency, and thus increase the range of electric and plug-in hybrid vehicles [29]. Through sensors and IT-services, highly automated vehicles are able to collect data about their environment and autonomously choose routes and driving styles that minimize the energy and fuel consumption as well as ensure the best use of the battery capacity; resulting in an increased and better predictable range. These advantages are well applicable for conventional vehicles, yet for the electric vehicle even more so as they increase acceptance by counteracting the biggest shortcoming of its technology—the limited range.

At the system level, automation in combination with cooperative driving ensures that traffic flows are optimized in congestion areas both in the city, the primary area of electric vehicle usage, and on the highway where it can greatly increase the usefulness of electric vehicles for longer distances. Synergies can also be found even in slow traffic: highly automated electric vehicles can reduce time searching for a parking space and, in combination with inductive charging, simultaneously find the proper position on the charging-coil as well as charge automatically. An electric delivery van that slowly follows the driver when he walks from door to door was recently presented by Volkswagen [30]. Self-organizing fleets of electric vehicles could also coordinate their local availability and charging level with one another, thus increasing the reliability and efficiency in using car sharing services. Driverless electrified taxis, which represent the highest level of automation, play an important role as a long term vision.

From a technical perspective, the electric drive and the accompanying redesign of the electrical and electronic architecture enables the intelligent integration of electronic controls, communication modules and sensors that are the basis for the automation of vehicles. Higher levels of automation facilitate the synchronization of drive components and can thus, for example, improve the driving dynamics. Optimized decision-making processes and redundancies guarantee a safe and reliable operation of the vehicle, even if the automobile malfunctions. The cross-linking with the environment and the usage of maps and navigation data, which partly already can be found in electric mobility, can be further developed to implement automation. Simultaneously, the liberty with regard to the interior design that electric vehicles offer can be consequently used due to higher degrees of automation.

8 Outlook

Automated functionalities are on the agenda of German national and European Union's research and innovation funding programmes, e.g. in the context of the new Horizon 2020 framework and the Joint Technology Initiative on Electronics (JTI ECSEL) therein. It can thus be expected that European vehicle manufacturers and automotive suppliers will further strengthen their competitive advantages in developing and implementing the key technologies of automated driving in the next few years. The modification and renewed international harmonization of the regulatory frameworks as well as the establishment of solutions for reliability issues that would allow the deployment of highly automated driving in Europe will be a massive effort though, and require the involvement of many relevant stakeholders beyond vehicle manufacturers and car owners, e.g. insurance companies, and road authorities.

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Part III
Societal and Environmental Impacts

A Legal Perspective on Three Misconceptions in Vehicle Automation

Bryant Walker Smith

Abstract In this chapter I address three commonly misunderstood aspects of vehicle automation: capability, deployment, and connectivity. For each, I identify a myth pervading public discussion, provide a contradictory view common among experts, explain why that expert view is itself incomplete, and finally discuss the legal implications of this nuance. Although there are many more aspects that merit clarification, these three are linked because they suggest a shift in transportation from a product model to a service model, a point with which I conclude.

Keywords Vehicle automation • Automated driving • Autonomous driving • Self-driving • Driverless • Law · Regulation • Tort law • Levels of automation • DSRC • V2V • V2I • V2X • Telematics • NHTSA

1 Introduction

In my talks on vehicle automation, I often confront a specific preconception, fostered in part by casual media reports, of the "self-driving car." It is, many audiences assume, a car that is fully capable of driving itself on any road and in any weather

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_8,

while its occupants, should there even be any, are asleep in the back. It coordinates with other vehicles by exchanging electronic messages. And it is nearly ready to be sold to consumers—or it would be, if not for those darn lawyers.

I am not constructing a strawman (or strawcar): These assumptions seem to persist even as the public hears and learns more about vehicle automation. And because inaccurate perceptions can lead to imprudent policy, countering them is crucial.

To this end, automotive experts frequently emphasize incremental automation over full automation, contrast research platforms with production vehicles, and distinguish connected vehicles from automated vehicles. While these clarifications are correct in many ways, they also risk blinding automakers and regulators to transformative changes in transportation.

This chapter argues that some kinds of truly driverless vehicles are actually imminent; that the line between research and production will be blurred by novel deployments; and that connectivity, if properly defined, is integral to automation. The critical insight is that tomorrow's vehicles will belong to tomorrow's world, not today's [6]. As this chapter concludes, that world is likely to emphasize services over products—a shift with significant legal consequences.

2 Capability

In early 2012 Google released a video of Steve Mahan, who is legally blind, traveling around town in the driver's seat of one of the company's research vehicles. The video, which has been viewed more than five million times, reinforced the popular vision of the automated vehicle: A late-model car (in this case a Toyota Prius) retrofitted with electronics (most prominently a spinning laser system) that enable it to operate safely in any environment (including a Taco Bell parking lot) without assistance from the human user (who may even be blind).

This popular view—that fully driverless cars and trucks are imminent—is generally rejected by automotive experts, who instead speak of a gradual shift from human drivers to computer drivers. Influential taxonomies developed by the German Federal Highway Research Institute (BASt), SAE International,[1] and the US National Highway Traffic Safety Administration (NHTSA) all focus on intermediate levels of automation in which humans and computers consecutively or concurrently perform the driving task. An ongoing study initiated by NHTSA in partnership with General Motors and Google, among others, studies only this "mushy middle" of automation. And notwithstanding the headlines generated by their recent flurry of press releases, major automakers have in general promised at most to introduce cars over the next few years that can drive themselves in some environments.

By focusing on automobiles, however, this expert embrace of incrementalism tends to obscure alternative vehicle technologies that are more amenable to higher

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[1] I am involved in this work. Before changing its name to an unintelligible anachronitialism, SAE International was the Society of Automotive and Aerospace Engineers.

levels of automation. While a two-ton car might not drive itself unsupervised through a city at 30 miles per hour any time soon, some truly driverless systems that are low-speed, low-mass, geographically restricted, and centrally supervised are actually nearing commercialization. These simplifying constraints help reduce both the risk and the broader uncertainty inherent in deployment: For most irregular occurrences, the system might achieve a minimal risk condition simply by stopping the vehicle and requesting assistance.

These alternate systems hold promise for both passenger and freight applications. Automated passenger shuttles like those demonstrated in the European Union's CityMobil project could be particularly well suited for airports, city centers, business clusters, university campuses, convention centers, military bases, retirement communities, amusement parks, and last-mile transit applications. Small robotic trucklets could similarly facilitate on-demand and last-mile freight delivery.

Because of their unique promise and peril, these emerging concepts merit explicit attention from policymakers. Focusing exclusively on incremental automotive automation will result in laws, policies, and practices that are inapposite to these alternate concepts. This mismatch could either stymie these technologies or leave policymakers unprepared for their eventual debut.

With respect to existing law, there are at least two dimensions to this potential disconnect: These vehicles are driverless, and they are not carlike.

Driverless vehicles will face legal issues not present at lower levels of automation [3]. Cars that can drive themselves on freeways, for example, will generally fit well within existing vehicle codes: Although the legal obligations of the human operator are not entirely clear, at least this person will be physically present and readily identifiable. In contrast, the legal operator of a driverless shuttle may be a passenger, a remote supervisor, or no one at all. Recent state laws specifically regulating automated vehicles do not help: Who "causes the autonomous technology to engage" when a driverless shuttle is placed in service by an engineer, requested by and automatically dispatched to a passenger, and overseen by a technician in a remote facility?

Even if they are manually driven, special vehicles like shuttles face another legal issue: On the question of vehicles that don't quite look like a car (or quack like a truck), state and federal law are terrifically muddled [4]. Depending on how it is treated by NHTSA and by state governments, a low-speed shuttle might have to meet the full set of federal motor vehicle safety standards, a less demanding standard intended for low-speed vehicles, or none at all. Whether the shuttle must be registered, whether its operator (whoever she is) must be licensed, and if so what kind of license she must obtain will all depend on where and how the shuttle is deployed—and on how governments interpret their own ambiguous laws.

These questions are starting to get some attention. SAE International's taxonomy expressly contemplates driverless shuttles as an instance of "high automation." Thanks in large part to Adriano Alessandrini, one of the research needs statements to emerge from the workshop that inspired this book concerns the legal status of these vehicles. And California's ongoing rulemaking process for automated vehicles of all kinds provides a particularly important opportunity to meaningfully address the development and deployment of these driverless systems.

3 Deployment

Casual consumers of automated vehicle news—though not the many casual producers of this news—could be forgiven for concluding that driverless cars are ready to be sold to ordinary drivers. States are passing laws, companies are testing cars on public roads, and commentators are declaring that "the technology is here." The corollary of this belief is that, if such vehicles are not yet ready, then fault must lie elsewhere—with consumers for not accepting them, with governments for not "legalizing" them,[2] or with lawyers for outright blocking them.

A 2013 radio interview is illustrative: The first guest, a reporter, asserted that "the technology is here" and that "right here and now we can have driverless cars." I replied that the research vehicles under discussion were neither designed nor demonstrated to operate at a reasonable level of risk under a full range of unsupervised driving scenarios. After a short break, the host resumed the discussion by reminding listeners that "the technology for driverless cars is in fact available, and we're trying to figure out why we don't then have them."

Automotive experts recognize that the path from research to product is long—and that there is a tremendous difference between, on one hand, a research system that well-trained technicians carefully maintain, update, and operate exclusively on certain roads in certain conditions and, on the other hand, a production system that poorly trained consumers neglect and abuse for two decades in almost any conceivable driving scenario. For this reason, production vehicles take years to be developed, tested, and certified to a complex array of highly detailed public and private standards.

Recent state laws regarding automated driving embrace this important distinction between research-and-development testing and consumer operation: Nevada's infinity-styled "autonomous vehicle" license plates, for example, are red for test vehicles and, one day, will be green for all others.

However, a yellow license plate may, at least metaphorically, be most appropriate for a set of potential deployments that do not fit comfortably in either category. The first deployments of the low-speed shuttles described above are likely to be pilot projects. Volvo Cars intends to place 100 automated vehicles on public roads in the Swedish city of Gothenburg by 2017.[3] Internet companies that are comfortable with invitation-only beta rollouts of their software and hardware may adopt a similar approach for their updatable automotive products. And an individual who uses a vehicle that she herself has built or modified may likewise straddle the divide between testing and operating.

These hybrid deployments may push up against state and federal regimes that assume a more straightforward product path for research, development,

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[2] Referring to the "legalization" of automated vehicles is misleading [3].

[3] Similarly, as part of the US Department of Transportation's field study of dedicated short-range communications (DSRC)—a related but, as discussed below, distinguishable set of technologies—nearly three thousand ordinary vehicles in Ann Arbor, Michigan were retrofitted with DSRC equipment.

production, sale, resale, and disposal. For example, while automakers currently self-certify that their vehicles as originally manufactured meet federal safety standards, this date of original manufacture may be less determinative of the safety of vehicles subsequently modified. Similarly, while state tort law often looks to the date that a product is originally sold to a consumer, as a practical matter this date may become less clear or less relevant to alleged harms.

Indeed, automakers concerned about the post-sale modification of their vehicles by third parties have lobbied successfully in Florida and Michigan (and unsuccessfully in California) to expressly limit their liability for injuries caused by such modification. These statutory provisions, however, largely restate existing principles of tort law, which makes both the insistence on and the opposition to them rather striking.

The complete lifecycle of early automated vehicles does present significant concerns. The mechanical life of these vehicles may be much longer than the functional life of their automation systems. Consumers in the secondary market may face a hodgepodge of proprietary driver assistance systems with different capabilities and limitations that cannot be easily intuited. And vehicles may long outlive some of the companies—whether small startups or legacy behemoths—responsible for their design, sale, and ongoing support. For these reasons, what I have called "planning for the obsolescence of technologies not yet invented" should be a key consideration for automakers, regulators, and insurers [5].

4 Connectivity

The final element in my troika of popular misconceptions is the assumption that self-driving vehicles navigate by communicating in real time with each other or with some central computer. Media reports routinely refer to driverless cars talking to each other, and an (unsuccessful) ad in Florida bemoaned a state senator's interest in "legalizing driverless *remote-controlled* cars." This assumption encourages the belief that only when all vehicles on a given highway can drive themselves will any one vehicle be able to do so—an all-or-nothing view of automation more appropriate for the last century than for this one.

Contrary to the assumption, however, most of the automated vehicles to achieve celebrity status—Stanley, Boss, Shelley, and the Google fleet, to name a few—do not utilize information or instructions electronically transmitted either by other road users (V2V) or by local infrastructure (V2I). These vehicles typically lack the equipment for dedicated short-range communications (DSRC). With some exceptions, they rely less than commonly believed on satellite—and ground-based navigation systems like GPS. And, as research platforms, they generally do not engage in even the most basic forms of signaling, including honking the horn, engaging lights, and gesturing.

Automotive experts accordingly distinguish between "automated vehicles" and "connected vehicles." The research platforms of the previous paragraph are, or aspire to be, automated. The DSRC-capable vehicles involved in the US Department of

Transportation's Safety Pilot in Ann Arbor are connected. Some systems, like the platoons that have now been demonstrated on three continents, are actually both. As Steven Shladover explains, automation and what he calls "cooperation" may be symbiotic, but they are not synonymous [2].

The more common distinction between automation and "connectivity" has unfortunately abetted a casual conflation of the latter with DSRC. As the catchall term V2X suggests, vehicle connectivity is much more than just real-time communication with nearby vehicles and infrastructure. Today's vehicles already use cellular-based telematics for emergency assistance, vehicle monitoring, and the provision of entertainment and navigation services [1], and Tesla has been remotely updating critical systems in its vehicles since 2012. Consumer-ready automated vehicles will need to receive remote updates for their maps and their algorithms—updates that will likely depend on the real-world data that these vehicles collect and transmit. In other words, even if they never use DSRC, automated vehicles will be connected.

This broad connectivity, in turn, is just one aspect of what I call proximity: the information, access, and control that companies increasingly enjoy with respect to their products, product users, and product uses [6]. By making certain behaviors—such as warning a driver about newly discovered dangers, remotely updating vehicle software, or even restricting an owner's use of her vehicle—possible or practicable, this growing proximity may expand the legal obligations and liabilities of automotive companies toward people harmed by their products.

Consider, for example, an automaker that receives reports that a newly constructed bridge confuses a crash avoidance system on vehicles that it sold years earlier—vehicles that it has both the technical ability and contractual authority to remotely update. At this point the automaker faces a range of options: do nothing, warn consumers but do no more, release an update (voluntary or mandatory) as soon as possible, release an update (again voluntary or mandatory) only after it has been thoroughly tested, or disable the relevant system until this fully tested update has been released. Each of these choices might prevent some crashes but contribute to others. Should these crashes occur—and perhaps even if they do not—the automaker may need to defend its choice in court.

5 Conclusion

This chapter has addressed misconceptions regarding the capability, deployment, and connectivity of automated vehicles.

Despite the popular belief that cars will soon drive themselves anywhere and everywhere, the shift from human drivers to their computer counterparts will be more gradual—and yet driverless specialty vehicles are an exception that should be addressed proactively in law.

Despite the popular belief that research vehicles are consumer-ready, the path from research to production is long—and yet alternative deployment models will blur testing and operation in a way that merits more contextual regulation.

Despite the popular belief that all self-driving vehicles talk to each other, automation may not require this kind of real-time communication—and yet advanced automation will require some form of connectivity that could expand the tort obligations of automakers.

The key examples I have used for each of these—driverless shuttles, pilot deployments, and remote updates—collectively suggest that automation will accelerate the shift in transportation from products to services. Companies operate shuttles, manage pilot programs, and update software systems for which individual consumers are likely to pay, directly or indirectly, on an ongoing basis. In short, the automated vehicles of the future may be copiloted by companies as much as they are by computers.

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Machine Ethics and Automated Vehicles

Noah J. Goodall

Abstract Road vehicle travel at a reasonable speed involves some risk, even when using computer-controlled driving with failure-free hardware and perfect sensing. A fully-automated vehicle must continuously decide how to allocate this risk without a human driver's oversight. These are ethical decisions, particularly in instances where an automated vehicle cannot avoid crashing. In this chapter, I introduce the concept of moral behavior for an automated vehicle, argue the need for research in this area through responses to anticipated critiques, and discuss relevant applications from machine ethics and moral modeling research.

Keywords Automation • Autonomous • Ethics • Risk • Morality

1 Ethical Decision Making for Automated Vehicles

Vehicle automation has progressed rapidly this millennium, mirroring improvements in machine learning, sensing, and processing. Media coverage often focuses on the anticipated safety benefits from automation, as computers are expected to be more attentive, precise, and predictable than human drivers. Mentioned less often are the novel problems from automated vehicle crash. The first problem is liability, as it is currently unclear who would be at fault if a vehicle crashed while self-driving. The second problem is the ability of an automated vehicle to make ethically-complex decisions when driving, particularly prior to a crash. This chapter focuses on the second problem, and the application of machine ethics to vehicle automation.

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_9,

Driving at any significant speed can never be completely safe. A loaded tractor trailer at 100 km/h requires 8 s to come to a complete stop, and a passenger car requires 3 s [1]. Truly safe travel requires accurate predictions of other vehicle behavior over this time frame, something that is simply not possible given the close proximities of road vehicles.

To ensure its own safety, an automated vehicle must continually assess risk: the risk of traveling a certain speed on a certain curve, of crossing the centerline to pass a cyclist, of side-swiping an adjacent vehicle to avoid a runaway truck closing in from behind. The vehicle (or the programmer in advance) must decide how much risk to accept for itself and for the adjacent vehicles. If the risk is deemed acceptable, it must decide how to apportion this risk among affected parties. These are ethical questions that, due to time constraints during a crash, must be decided by the vehicle autonomously.

The remainder of the chapter is organized into the parts. In Sect. 2, responses are provided to nine criticisms of the need for ethics research in automated vehicle decision systems. Section 3 contains reviews of relevant ethical theories and moral modeling research. The chapter is summarized in Sect. 4.

2 Criticisms of the Need for Automated Vehicle Ethics Systems, and Responses

Future automated vehicles will encounter situations where the “right” action is morally or legally ambiguous. In these situations, vehicles need a method to determine an ethical action. However, there is disagreement among experts on both of these points. This section lists nine criticisms of the importance of ethics in vehicle automation, with responses to each.

Criticism 1: Automated vehicles will never (or rarely) crash. If an automated vehicle never crashes, then there is no need to assess or assign risk because driving no longer contains risk. Industry experts are mostly cautious regarding whether vehicle automation can ever ultimately eliminate all crashes. Claims of complete safety are often based on assumptions about the capabilities of automated vehicles and their interactions with their environments. These assumptions can be grouped into three scenarios: automated vehicles with imperfect systems, automated vehicles with perfect systems driving in mixed traffic with human drivers, and automated vehicles with perfect systems driving exclusively with other automated vehicles. Crashes are possible in each scenario, as described in the following paragraphs.

- **Imperfect systems.** Any system ever engineered has occasionally failed. In the realm of automated vehicles, Fraichard and Kuffner [2] list four reasons for a collision: hardware failures, software bugs, perceptual errors, and reasoning errors. While hardware failures may be somewhat predictable and often gradual, software failures are unexpected and sudden, and may prove riskier at high speeds. Perceptual errors may result in misclassifying an object on the roadway. Even if a pedestrian is correctly classified, an automated vehicle would need some way to perceive her intent, e.g. whether she is about to step into the road or is merely standing on the sidewalk. A mistake in this calculation could lead to a crash, especially considering the close proximity and high speed differentials on roadways.

- **Perfect systems with mixed human-driven traffic.** A perfectly automated vehicle with complete awareness of its surroundings should be able to safely avoid static objects. Dynamic objects with unpredictable behavior pose a greater challenge. The best way to avoid a collision is to avoid any place, time, and trajectory on the roadway (referred to as a state) which could possibly lead to a crash. In robotics, a state where all possible movement result in a crash is referred to as an inevitable collision state [3]. Researchers have acknowledged that with road vehicles, there is no way to completely avoid inevitable collision states [4], only to minimize the probability of entering one [5]. The only reasonable strategy is to construct a model of the expected behavior of nearby vehicles and try to avoid likely collisions-based on patent filings, this appears to be a component of Google's self-driving car [6]. Without a sophisticated model of expected vehicle behavior, a "safe" automated vehicle would be forced to overreact to perceived threats. For example, a "flying pass" maneuver, where a vehicle approaches a stopped queue at high speed only to move into a dedicated turn lane at the last moment, appears identical to a pre-crash rear-end collision [7, p. 140]. To guarantee safety, an automated vehicle would have to evade many similar maneuvers each day. This is both impractical and dangerous.
- **Perfect systems without human-driven traffic.** Perfect vehicles traveling on a freeway with other perfect vehicles should be able to safely predict each other's behavior and even communicate wirelessly to avoid collisions. Yet these vehicles would still face threats from wildlife (256,000 crashes in the U.S. in 2000), pedestrians (73,000 crashes), and bicyclists (51,000 crashes) [8]. Although a sophisticated automated vehicle would be safer than a human driver, some crashes may be unavoidable. Furthermore, the perfect systems described in this scenario are neither likely nor near-term.

Criticism 2: Crashes requiring complex ethical decisions are extremely unlikely. In order to demonstrate the difficulty of some ethical decisions, philosophers will use examples that seem unrealistic. The trolley problem [9], where a person must decide whether to switch the path of a trolley onto a track that will kill one person in order to spare five passengers, is a common example [10]. The trolley problem is popular because it is both a difficult problem and one where people's reactions are sensitive to context, e.g. pushing a person onto the track instead of throwing a switch produces different responses, even though the overall outcome is the same.

The use of hypothetical examples may suggest that ethics are only needed in incredibly rare circumstances. However, a recent profile of Google's self-driving car team suggests that ethics are already being considered in debris avoidance: "What if a cat runs into the road? A deer? A child? There were moral questions as well as mechanical ones, and engineers had never had to answer them before" [11]. Morally ambiguous situations can occur whenever there is risk, and risk is always present when driving.

One can argue that these are simple problems, e.g. avoid the child at all costs and avoid the cat if it is safe to do so. By comparison, however, the trolley problem is actually fairly straight-forward—it has only one decision, with known consequences for each alternative. This is highly unrealistic. A vehicle faces decisions with unknown consequences, uncertain probabilities of future actions, even uncertainty of its own environment. With these uncertainties, common ethical problems will become "complex" very quickly.

Criticism 3: Automated vehicles will never (or rarely) be responsible for a crash. This assumes that absence of liability is equivalent to ethical behavior. Regardless of fault, an automated vehicle should behave ethically to protect not only its own occupants, but also those at fault.

Criticism 4: Automated vehicles will never collide with another automated vehicle. This assumes that an automated vehicle's only interactions will be with other automated vehicles. This is unlikely to happen in the near future for two reasons. First, the vehicle fleet is slow to turn over. Even if every new vehicle sold in the U.S. was fully-automated, it would be 30 years before 90 % of vehicles were replaced [12]. Second, unless automated vehicle-only zones are established, every fully-automated vehicle will have to interact with human drivers, pedestrians, bicyclists, motorcyclists, and trains. Even an automated-only zone would encounter debris, wildlife, and inclement weather. These are all in addition to a vehicle's own hardware, software, perceptual, and reasoning failures. Any of these factors can contribute to or independently cause a crash.

Criticism 5: In level 2 and 3 vehicles, a human will always be available to take control, and therefore the human driver will be responsible for ethical decision making. Although the National Highway Traffic and Safety Administration (NHTSA) definitions require that a person be available to take control of a vehicle with no notice in a level 2 automated vehicle and within a reasonable amount of time in a level 3 automated vehicle [13], this may be an unrealistic expectation for most drivers.

In a level 2 vehicle, this would require a driver to pay constant attention to the roadway, similar to when using cruise control. Drivers in semi-autonomous vehicles with lane-keeping abilities on an empty test track exhibited significant increases in eccentric head turns and secondary tasks during automated driving, even in the presence of a researcher [14]. Twenty-five percent of test subjects were observed reading while the vehicle was in autonomous mode. Similar results have been found in simulator driving studies [15]. The effect of automation on a driver's attention level remains an open question, but early research suggests that a driver cannot immediately take over control of the vehicle safely. Most drivers will require some type of warning time.

Level 3 vehicles provide this warning time, but the precise amount of time needed is unknown. The NHTSA guidance does not specify an appropriate warning time [13], although some guidance can be found in highway design standards.

The American Association of State Highway and Transportation Officials (AASHTO) recommends highway designers allow 200–400 m for a driver to perceive and react to an unusual situation at 100 km/h [16]. This corresponds to 7–14 s, much of which is beyond the range of today's radar at 9 s [17]. In an emergency, a driver may be unable (or unwilling) to assess the situation and make an ethical decision within the available time frame. In these situations, the automated vehicle would maintain control of the vehicle, and by default be responsible for ethical decision making.

Criticism 6: Humans rarely make ethical decisions when driving or in crashes, and automated vehicles should not be held to the same standard. Drivers may not believe themselves to be making ethical decisions while driving, but they actually make these decisions often. The decision to speed or to cross a yellow line to provide a cyclist additional room are examples of ethical decisions. Any activity that transfers risk from one person to another involves ethics, and automated vehicles should be able to make acceptable decisions in similar environments. Considering that Americans drive 4.8 trillion kilometers each year [18], novel situations requiring ethics should emerge steadily.

Criticism 7: An automated vehicle can be programmed to follow the law, which will cover ethical situations. Existing laws are not nearly comprehensive or specific enough to produce reasonable actions in a computer. Lin provides an example of an automated vehicle coming across a tree branch in the road. If there was no oncoming traffic, a reasonable person would cross the double yellow line to get around the tree, but an automated vehicle programmed to follow the law would be forced to wait until the branch was cleared [19].

Of course, laws could be added for these types of situations. This can quickly become a massive undertaking—one would need computer-understandable definitions of terms like "obstruction" and "safe" for an automated vehicle whose perception system is never completely certain of anything. If enough laws were written to cover the vast majority of ethical situations, and they were written in such a way as to be understood by computers, then the automated vehicle ethics problem would be solved. Current law is not closed to these standards.

Criticism 8: An automated vehicle should simply try to minimize damage at all times. This proposes a utilitarian ethics system, which is addressed in Sect. 3.1 and in previous work [20]. Briefly, utilitarianism's main obstacle is that it does not recognize the rights of individuals. A utilitarian automated vehicle given the choice between colliding with two different vehicles would select the one with the higher safety rating. Although this would maximize overall safety, most would consider it unfair.

Criticism 9: Overall benefits outweigh any risks from an unethical vehicle. This is perhaps the strongest argument against automated vehicle ethics research, that any effort which may impede the progress of automation indirectly harms those who die in the interim between immediate and actual deployment.

While preliminary evidence does not prove automation is safer than human drivers [20], it seems likely that automation will eventually reduce the crash rate. Lin has argued, however, that a reduction in overall fatalities may be considered unethical [21], as improved safety for one group may come at the expense of another. If vehicle fatalities are reduced, but cyclist fatalities increase, even an overall safety improvement might be unacceptable to society.

Second, this assumption uses a purely utilitarian view that maximizing lives saved is the preferred option. Society, however, often uses a different value system considering the context of a given situation. For example, the risk of death from nuclear meltdown is often over-valued, while traffic fatalities are under-valued. Society may disagree that a net gain in safety is worth a particularly frightening risk. If, in fact, the ultimate goal is to improve safety, then ensuring that automated vehicles behave in acceptable ways is critical to earning the public's trust of these new technologies.

Finally, the safety benefits of automated vehicles are still speculative. To be considered safer than a human driver with 99 % confidence, an automated passenger vehicle would need to travel—without human intervention—1.1 million kilometers without crashing and 482 million kilometers without a fatal crash [20]. As of this writing, an automated vehicle has yet to safely reach these mileages.

3 Relevant Work in Machine Ethics and Moral Modeling

There are two main challenges when formulating an ethical response for an automated vehicle. The first is to articulate society's values across a range of scenarios. This is especially difficult given that most research into morality focuses on single choices with known outcomes (one person will always die if the trolley changes track), while in reality outcomes are uncertain and there are several layers of choices. The second challenge is to translate these morals into language that a computer can understand without a human's ability to discern and analogize.

The recent field of machine ethics addresses these challenges through the development of artificial autonomous agents which can behave morally. While much of machine ethics work is theoretical, a few practical applications include computer modeling of human ethics in areas such as medicine, defense, and engineering. This section provides background on ethical theories, and reviews examples of computational moral modeling.

3.1 Ethical Theories

Researchers have investigated the potential for various moral theories for use in machine ethics applications, including utilitarianism [22], Kantianism [23–25], Smithianism [26], and deontologicalism [27, 28]. Deontologicalism and utilitarianism have been discussed as potentials for automated vehicle ethics, with shortcomings found with both theories [20].

Deontological ethics consist of limits that are placed on a machine's behavior, or a set of rules that it cannot violate. Asimov's three laws of robotics are a well-known example of deontological ethics [29]. A shortcoming of deontological ethics appears when reducing complex human values into computer code. Similar to the traffic law example from this chapter's seventh criticism, rules generally require some common sense in their application, yet computers are only capable of literal interpretations. These misinterpretations can lead to unexpected behavior. In Asimov's laws, an automated vehicle might avoid braking before a collision because this action would first give its occupants whiplash, thereby violating the first law prohibiting harm to humans. Rules can be added or clarified to cover different situations, but it is unclear if any set of rules could encompass all situations. Developing rules also requires that someone articulate human morals, an exceptionally difficult task given that there has never been complete agreement on the question of what is right and wrong.

Another useful moral theory is utilitarianism. This dictates that an action is moral if the outcome of that an action—or in the case of automated vehicles, the expected outcome—maximizes some utility. The advantage of this method is that it is easily computable. However, it is difficult to define a metric for the outcome. Property damage estimates can produce unfair outcomes, as they would recommend colliding with a helmeted motorcyclist over a non-helmeted one, as the helmeted rider is less likely experience costly brain damage. This example illustrates another shortcoming of utilitarianism—it generally maximizes the collective benefit rather than individuals' benefits, and does not consider equity. One group may consistently benefit (un-helmeted riders) while another loses.

Hansson has noted that risk-taking in radiation exposure combines the three main ethical theories of virtue (referred to as justification), utilitarianism (optimization), and deontologicalism (individual dose limits) [30]. Automated vehicle ethics will also likely require a combination of two or more ethical theories.

3.2 Practical Applications

There have been several attempts to develop software that can provide guidance in situations requiring ethics. One of the first examples was a utilitarian software tool called *Jeremy* [31]. This program measured the utility of any action's outcome by using the straightforward product of the outcome's utility intensity, duration, and probability, each of which were estimated by the user. In an automated vehicle environment, utility could be defined as safety or the inverse of damage costs, with intensity, duration, and probability estimated from crash models. A major shortcoming of this model is its exclusive use of utilitarianism, an ethical theory which disregards context, virtues, and limits on individual harm.

The team behind Jeremy later introduced two other software tools. The first was *W.D.* [31], which used a duty-based ethical theory influenced by Ross [32] and Rawls [33]. This was followed by a similar program *MedEthEx* [34], a tool meant for medical applications and reflecting the duties identified in Principles of Biomedical Ethics [35]. Both of these program are deontological, and are trained using test cases that either violate or adhere to a formulated set of duties as indicated an integer score. The software uses machine learning to determine whether test cases of action are moral or immoral based on adherence to ethical principles, and calibrates these assessments using expert judgment. The output provides an absolute conclusion whether an action is right or wrong, and indicates which ethical principles were most important in the decision.

McLaren has developed two tools to aid in ethical decision making. The first tool is *Truth-Teller,* a program that analyzes two case studies where the subject must decide whether or not to tell the truth [36]. The program identifies similarities and differences between the cases, and lists reasons for or against telling the truth in each situation. This is an example of casuistic reasoning, where one reaches a conclusion by comparing a problem with similar situations instead of using rules learned from a set of test cases. Case studies are inputted using symbols rather than natural language processing to be more easily machine-readable. A similar program from McLaren, *SIROCCO* [36], uses casuistry to identify principles from the National Society of Professional Engineers code of ethics relevant to an engineering ethics problem. Like *Truth-Teller, SIROCCO* avoids moral judgments, and instead suggests ethically relevant information that can help a user make decisions.

The U.S. Army recently funded research into automated ethical decision making as a support tool for commanders and eventual use in robotic systems. The first step in this effort is a computer model which attempts to assess the relative morality of two competing actions in a battlefield environment. This model, referred to by its developers as the *Metric of Evil*, attempts to "provide results that resemble human reasoning about morality and evil" rather than replicate the process of human reasoning [37]. To calculate the *Metric of Evil*, the model sums the evil for each individual consequence of an action, taking into account high and low estimates of evil, confidence intervals, and intentionality. A panel of experts then rates a set of ethical test cases, and the weights of each type of consequence are adjusted so that the model output matches expert judgment. While the *Metric of Evil* provides decisions on which action is more ethical, it does not provide the user with evidence supporting its conclusion.

Computational moral modeling is in its infancy. The efforts described in this chapter, particularly *MedEthEx* and the *Metric of Evil*, show that it is possible to solve ethical problems automatically, although much work is needed, particularly in model calibration and incorporating uncertainty.

4 Summary

Automated vehicles, even sophisticated examples, will continue to crash. To minimize damage, the vehicle must continually assess risk to itself and others. Even simple maneuvers will require the vehicle to determine if the risk to itself and other is acceptable. These calculations, the acceptance and apportionment of risk, are ethical decisions, and human drivers will not be able to oversee these decisions. The vehicle must at times make ethical choices autonomously, either via explicit pre-programmed instructions, a machine learning approach, or some combination of the two. The fields of moral modeling and machine ethics have made some progress, but much work remains. This chapter is meant as a guide for those first encountering ethical systems as applied in automated vehicles to help frame the problem, convey core concepts, and provide directions for useful research in related fields.

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Vehicle Automation and Its Potential Impacts on Energy and Emissions

Matthew Barth, Kanok Boriboonsomsin and Guoyuan Wu

Abstract Interest in vehicle automation is at an all-time high, with many recent real-world demonstrations from a variety of companies and research groups. The key fundamental building blocks for automating vehicles have been in development for many years, making vehicle automation a near-term reality. Also in recent years, there have been significant efforts to make vehicles more energy efficient and less polluting, through the development of advanced powertrains and the development and promotion of alternative lower-carbon fuels, as well as traffic system operational improvements. With these two developing areas, one of the key questions is how will vehicle automation affect overall traffic energy efficiency and emissions. In this chapter, we briefly outline some of these potential impacts, examining issues such as vehicle design, vehicle and traffic operations, and even potential changes in activity patterns.

Keywords Vehicle automation • Energy • Environment • Platooning • Traffic smoothing • Traffic congestion

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_10,

1 Introduction

In the last few years, there has been a surge of interest in vehicle automation; there are now a number of workshops and conferences that are addressing a variety of important issues associated with vehicle automation that go beyond just the technical challenges (e.g., see [1, 2]). These issues include definitions, safety, mobility, environmental impacts, liability, privacy, security, reliability, insurance, cyber-security, human factors, human machine interfaces, certification, and licensing. As an example, one of the latest workshops has been the Transportation Research Board Workshop on Road Vehicle Automation in July 2013 which highlighted the state-of-the-art vehicle automation efforts by Google [3] and several automobile manufacturers, as well as addressing the different issues outlined above [1]. In addition to these conferences, there have also been a number of vehicle automation demonstrations taking place in a variety of environments. Even though these demonstrations have captured the general public's interest, it is important to realize that many automobiles today already have "partial automation" features such as anti-lock braking systems, electronic skid protection (i.e., positive traction control), adaptive cruise control, and lane keeping assistance, to name a few. As such, these automated vehicle efforts build on decades of vehicle advancements in safety, mobility, and driver conveniences.

In addition to vehicles becoming increasingly safe and convenient over the years, they have also become more fuel efficient and far less polluting. In the last decade, there has been a strong push to reduce greenhouse gas emissions from vehicles through a variety of means: (1) by introducing advanced powertrains (e.g., hybrid vehicles) and building vehicles with lighter (but stronger) materials; (2) by developing and introducing alternative lower-carbon fuels; (3) by implementing a variety of programs that aim to reduce overall vehicle miles traveled such as roadway pricing; and (4) by introducing better traffic operations, making traffic more efficient.

Given these two general areas of vehicle advances, it is important to consider the impact of vehicle automation on energy consumption and emissions (both greenhouse gases such as carbon dioxide, as well as pollutant emissions such as carbon monoxide, hydrocarbons, oxides of nitrogen, and particulate matter). There are several dimensions that must be considered, including vehicle design, vehicle and traffic operations, and even potential changes in activity patterns which may lead to additional travel. In this chapter, we primarily address vehicle and traffic operation issues associated with automation and the impacts it may have on energy and emissions.

2 Energy and Emissions Impacts of Traffic

In order to better understand transportation impacts on energy/emissions in general, it is useful to examine traffic as a function of average travel speed. In [4], the authors have developed a methodology that takes individual snippets of vehicle operation (i.e., vehicle velocity trajectories), applies them to a microscopic energy/emissions model, then uses the resulting values to characterize energy/emission effects as a

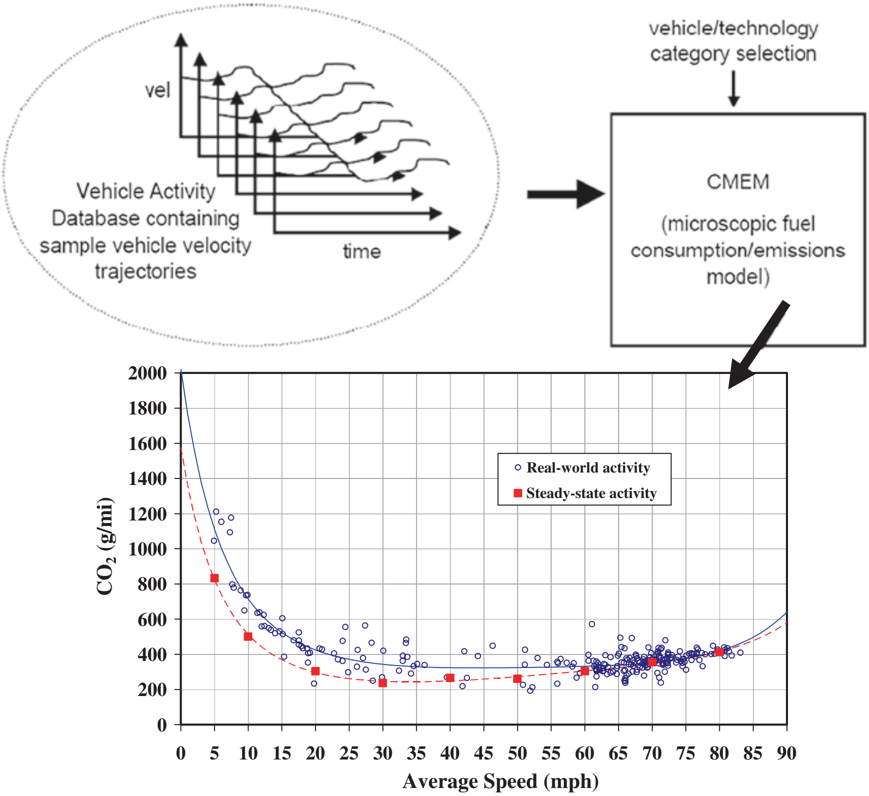


Fig. 1 Methodology of generating an energy/emissions curve as a function of average traffic speed (see [4])

function of average traffic speed. This general methodology is illustrated in Fig. 1. With enough snippets representing a wide variety of conditions and trips, a general curve emerges as shown in Fig. 1, relating energy or emissions (on a grams/mile basis) to average speed. This figure represents an average light duty vehicle type where the blue line represents carbon dioxide emissions as a function of average traffic speed. Also shown in this figure is a dashed red line, which represents the lowest energy or emissions that a vehicle can possibly achieve at any particular speed, made up of individual trips that have (unrealistic) constant speeds with no accelerations and decelerations. In addition to carbon dioxide shown in Fig. 1, other pollutant emissions are shown for this example average light duty vehicle type in Fig. 2.

These figures generally show that energy and emissions, normalized by distance traveled, are high at very low average speeds simply because the vehicles are on the road longer and therefore have higher energy and emissions for that particular type of driving. The energy and emissions then tend to flatten out at mid-range speeds (e.g., 35–55 mph), before increasing again at higher speeds (55 mph and above). This increase at higher speeds is due to increased aerodynamic drag forces; the vehicle's engine must work harder to maintain those higher speeds.

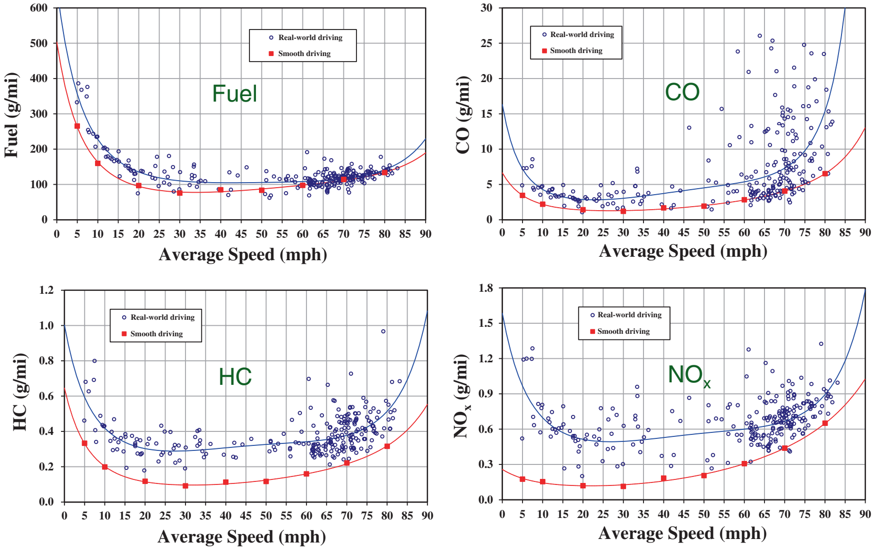


Fig. 2 Energy and emissions as a function of average traffic speed (see [4])

3 Vehicle Automation Impacts

Given these generalized energy/emission versus speed figures, it is now possible to identify the general areas where vehicle automation can potentially impact energy and emissions. Three general areas emerge, as shown in Fig. 3.

(1) The first area deals with reducing roadway congestion in general, which is an important mobility issue. Vehicle automation can potentially reduce roadway congestion in a number of ways, as described further in Sect. 3.1. When congestion is reduced, average traffic speeds increase, and average energy and emissions go down.

(2) Another way vehicle automation can reduce energy and emissions is by introducing platooning as part of the automation. Platooning effects are described in greater detail in Sect. 3.2.

(3) The third general area where vehicle automation can impact energy and emissions is through traffic smoothing effects. Vehicle automation has the potential to reduce the sharp stop-and-go characteristics of today's traffic, as outlined in Sect. 3.3.

3.1 Traffic Congestion Reduction

In the case of human manual driving, we can characterize driving behavior with car-following models and lane change logic. As part of this behavior we have to deal with reaction delays and different sensitivities on how closely drivers follow

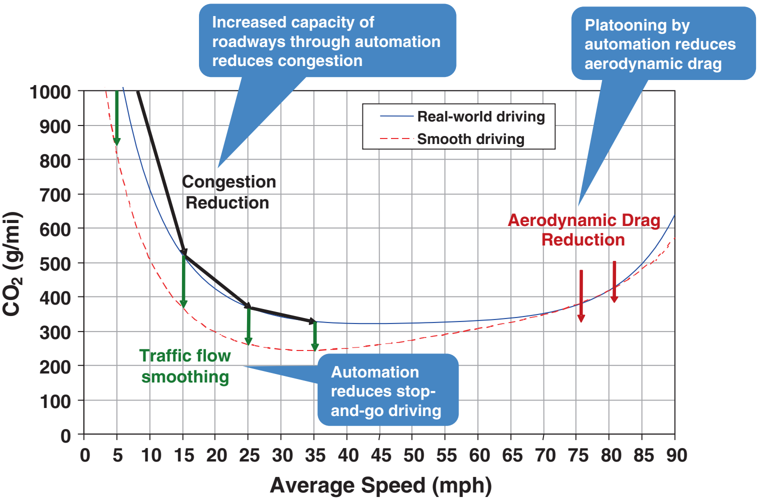


Fig. 3 General impacts of vehicle automation on energy and emissions, using data from Fig. 1

other vehicles. Under heavy traffic demand, the traffic flow often breaks down into a congested regime that limits the overall capacity of the roadway. Also with human driving behavior, we often get sharp stop-and-go effects in the traffic flow which is highly detrimental for fuel consumption and emissions.

In the case of vehicle automation, it is possible that vehicles can safely follow each other more closely with faster reaction times while in traffic, thereby increasing the net capacity of the roadway (in terms of vehicles/hour/lane). However, it is very important to distinguish between *autonomous* vehicles and *automated* vehicles in the analysis. These two terms are often used interchangeably, however there is a significant difference when considering how vehicles interact in traffic and with associated congestion. An autonomous vehicle typically relies almost entirely on its on-board sensors to make driving decisions, just as humans do. This is in contrast to automated vehicles, which in addition to on-board sensors, they can also take advantage of vehicle-to-vehicle communications, as well as infrastructure-to-vehicle communications. In the case of an autonomous vehicle, processing sensor information and making decisions solely on that information can sometimes take just as long as human drivers. Therefore, for autonomous vehicles, it is unlikely that there will be significant capacity improvements on the roadway due to vehicles not being able to follow each other very closely. For automated vehicles that can also communicate, much smaller gaps between vehicles are possible since communication can occur at a much higher rate. With these smaller gaps, there is the possibility for a net capacity increase.

In the case of automated vehicles with this increased capacity, roadway congestion can then be reduced, as long as the travel demand does not increase. This is illustrated in Fig. 3 where traffic moving at slower speeds would be able to now move at higher speeds due to less congestion, reducing energy consumption and emissions that are on the high left side of the energy/emission versus speed curve.

In addition to these capacity effects, there are many that have stated that with the advanced safety systems on automated vehicles, there will be fewer roadway accidents compared to human drivers. However, it is still unclear what the traffic accident rate will be with automated vehicles. On a mean-time-between-failure (MTBF) basis, today's traffic accidents are rather infrequent when counting up the total amount of vehicle-hours-traveled (VHT) or vehicle-miles-traveled (VMT). It will be a significant challenge for automated vehicles to reach that same level of safety. In any case, it is well known that traffic accidents cause significant delays and roadway congestion when they do occur. Any reduction in traffic incidents will result in less congestion, and therefore lower energy and emissions.

3.2 Vehicle Platooning

Vehicle platooning is generally defined as two or more vehicles following each other close enough to where there is reduction in the aerodynamic drag forces on the vehicles. Race car drivers are well aware of these drafting effects and they use them to their racing advantage. Over the last two decades, there have been a number of experiments that have been carried out to show that vehicle platooning can reduce energy consumption and emissions (see, e.g., [5–7]). Many of these experiments have focused on trucks, since they typically have such high aerodynamic loads. As an example, Fig. 4 illustrates the energy reductions due to truck platooning, based on both wind tunnel testing and actual field study experiments. This figure shows the increased fuel savings as the separation between the vehicles decreases. It is important to note that not only is there a benefit for the following vehicles, the leading vehicles also get an aerodynamic benefit. In general, operating at separations of around 4 m, 10–15 % energy savings can be achieved [5].

Vehicle platooning can be accomplished safely by introducing sensing, control, and communication systems in vehicles. Because the control cycle occurs at a much higher rate compared to human drivers, it is possible to adjust the vehicle's speed and acceleration so that the vehicles can safely follow each other at close spacings.

Although platooning has been demonstrated in a variety of experiments, there are still a significant amount of research that needs to take place before it can become commonplace, including the design of safe platoon maneuvers (e.g., getting in and out of platoons).

3.3 Traffic Smoothing

The third element where vehicle automation may have a significant impact on energy and emissions is due to smoothing traffic flow. In today's traffic, we often experience stop-and-go effects where vehicles speed up and slow down due to fluctuations in the traffic stream. As described in Sect. 3.1, the fluctuations

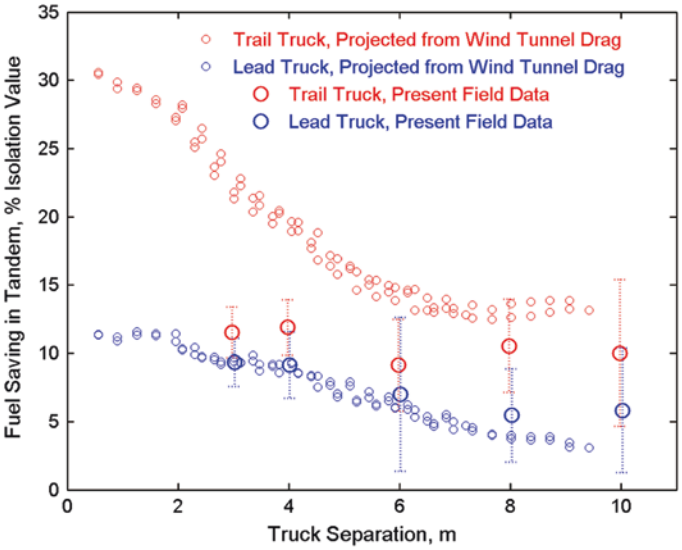


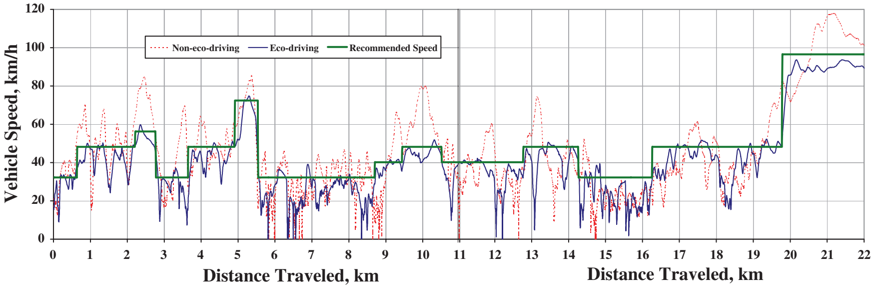
Fig. 4 Fuel Savings from Truck Platooning, as a function of vehicle separation, from [5]. In this figure fuel savings are shown for both wind tunnel tests (*smaller circles*) and real-world platooning experiments (*larger circles*). The *red data points* correspond to a following vehicle while the *blue data points* correspond to the lead vehicle

are often due to shockwaves in the traffic flow that are caused in many cases by human driving behavior. There are several system-level automation techniques that can be applied to smooth the traffic flow. In Fig. 3, traffic smoothing techniques would essentially lower the blue energy/emission versus speed curve to come closer to the theoretical minimum depicted by the red dashed line, representing traffic moving at constant speeds.

There are many examples of automation that can potentially smooth traffic. These traffic smoothing techniques often use similar approaches, but they often go by different names, such as speed harmonization, variable speed limits (see, e.g., [8]), intelligent speed adaptation (see, e.g., [9]), traffic jam assist, highway piloting, and connected eco-driving (see, e.g., [10]).

It is important to note that the concepts of speed harmonization and intelligent speed adaptation target primarily safety and mobility issues; however, many of the papers cite an energy and emissions benefit as well. In contrast, the concept of connected eco-driving is primarily targeted at environmental benefits, even though the general approach is similar to the others.

As an example of a connected eco-driving application, Fig. 5 (from [10]) illustrates the general concept. If a vehicle receives automated speed recommendations as it travels down the road, it can help eliminate the stop-and-go effects we experience today. Figure 5 depicts a real-world experiment on a congested highway in Southern California, where one vehicle (depicted by the blue speed versus distance plot) gets speed advice based on forward-looking local traffic conditions. In



Energy/Emissions	Non Eco-Driving	Eco-Driving	Difference
Fuel (g)	1766	1534	-13%
CO2 (g)	5439	4781	-12%
CO (g)	97.01	50.47	-48%
HC (g)	3.20	1.90	-41%
NOx (g)	6.28	3.97	-37%
Travel time (min)	38.9	41.2	+6%

Fig. 5 Connected eco-driving experiments showing traffic smoothing principles of automated driving (from [10])

contrast, a different vehicle (depicted by the red dashed line) doesn't get any speed advice and simply follows the traffic flow.

An algorithm is used to generate the dynamic speed advice, based on real-time inputs of traffic conditions on the roadway which is illustrated in Fig. 5 by the solid green line. The blue-line vehicle received this speed advice and followed it as closely as possible, naturally slowing down when necessary due to traffic. In this experiment, both the blue and red vehicles started at the same place and time, traveling for approximately 22 km through congestion. Both vehicles arrived at their destination approximately at the same time, however, the blue vehicle had significantly lower energy consumption and emissions, primarily by not having sharp accelerations then quickly having to decelerate once it hit a new pocket of congestion.

4 Other Automation Effects

In the analysis provided in Sect. 3, there are potentially significant energy and emissions savings that can be achieved, especially when all of these techniques can be implemented in parallel. If the different energy/emissions saving applications are truly independent, then the benefits cited can be additive. However, further research is needed to see if the different applications will be independent and if the savings can be additive.

Another area that can be considered part of the overall “automation” package is in the area of traveler information systems. A primary example of this is better route guidance that avoids areas of congestion and large changes in road grade. These so-called “eco-routing” applications have been in development for several years (see, e.g., [11]). A number of research efforts have shown that eco-routing can save as much as 20% energy and emissions, depending on the level of congestion in the roadway network. Some eco-routing algorithms are now being incorporated into on-board navigation systems. Another example of a traveler information system automation-related applications is smart-parking, where energy and emission savings are possible by reducing the amount of driving associated with searching for parking places in congested areas.

It is also important to note that vehicle automation is highly amenable to electric-drive vehicles. Electric-drive vehicles themselves have a large energy and emissions benefit; however greater synergies with automation are possible in terms of how automation can assist with providing electric energy to the vehicles (e.g., see [12]). Furthermore, the on-board energy management strategies of electric-drive vehicles (e.g., plug-in hybrid electric vehicles) can be specifically designed to take advantage of different automation regimes, including freeway driving, driving through automated arterial roadway infrastructure, and routing to known destinations [13]. It is highly likely that vehicle electrification and vehicle automation will go hand-in-hand in future developments.

Thus far, the majority of the discussion on energy and environmental impacts of vehicle automation has been citing potential benefits. However, there could potentially be a significant dis-benefit in terms of how travel demand could change, based on the introduction of vehicle automation. One of the key issues focuses on existing users of vehicles; if trips now become more convenient, reliable, and timely due to automation, will current users start making more trips and drive more? As such, it is unclear to what degree this “induced demand” or “rebound effect” will come about due to vehicle automation. Thus, further research is certainly warranted. Furthermore, it is also important to consider additional vehicle demand from *new* users that were not able to use vehicles until they become automated. Example users include youth, elderly, and disabled people. It may be necessary to couple the deployment of vehicle automation closely with more aggressive travel demand management schemes such that overall travel demand is kept in check.

5 Summary and Future Work

By using a generalized energy/emission versus speed curve for typical traffic, this chapter discusses the potential benefits of vehicle automation on reducing energy consumption and emissions, primarily from a vehicle and traffic operations point-of-view. Three general concepts were outlined, including the benefits of reducing congestion, taking advantage of vehicle platooning, and smoothing traffic flow. There are many specific examples of traffic congestion reduction mechanisms and traffic flow smoothing techniques through intelligent transportation system and automation deployment.

However, it is important to point out that vehicle automation also has the potential to fundamentally transform travel behavior in regards to trip profile, travel mode choices, vehicle ownership, activity location; all of these could lead to significant impacts on land use, energy consumption, and emissions. It is clear that more research is needed in this area, examining behavioral modifications of private, public, commercial and freight transportation resulting from automation.

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Human Factors of Highly Automated Driving: Results from the EASY and CityMobil Projects

Natasha Merat, Hamish A. Jamson, Frank Lai and Oliver Carsten

Abstract This chapter reports on a series of studies on driver behavior with a highly automated vehicle, conducted as part of the European project CityMobil and the UK project EASY. Using the University of Leeds Driving Simulator, a number of urban and highway scenarios were devised, where lateral and longitudinal control of the vehicle was managed by an automated controller. Drivers' uptake of non-driving related tasks, their response to critical events, and their ability to resume control of driving, were some of the factors studied. Results showed some differences in performance based on the road environment studied, and suggest that whilst resuming control from automation was manageable when attention was dedicated to the road, diversion of attention by secondary tasks impaired performance when manual control resumed.

Keywords Human factors of automation · Situation awareness · Visual attention · Eye tracking · Transfer of control · Highly automated driving

1 Introduction

The capabilities of 'driverless cars' and their positive contributions to road safety are cited in the media on an almost daily basis, with suggestions that they will eventually be safer than human-controlled vehicles [1]. Indeed, implementing a fully crash-proof

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_11,

driverless vehicle suggests that in the future, drivers can completely attend to other non-driving related tasks, such as reading their emails, whilst the vehicle is on the road, without worrying about the risk of a crash. Since research on naturalistic driving studies shows that 78 % of crashes and 65 % of near crashes are caused by driver inattention, removing the human element from driving is argued to lead to safer roads [2].

However, much of the effort in development of these vehicles has thus far been around ensuring the successful operation of the technology itself, for example, achieving successful detection of objects in the road by radars and sensors. The pace of research on other areas relevant to automated driving, such as the ethics and legal aspects of implementing such cars, how they might affect transport planning and what implications they will have on driver behavior and human factors has been much slower. For example, after a spate of research in the 1990s on the automated highways [3], most of the North American research in recent years regarding the influence of technology in vehicles has either been about driver distraction, or on the connected vehicles concept, with a more detailed program of research on automation currently planned for 2015–2019 [4]. Although European research has probably placed more resources in this area during the first decade of this century [5–8], the proportion of resources dedicated to human factors research in particular remains comparatively negligible.

Until recently, much of the work on the implications of automation on driver behavior has focused on their interaction with the Adaptive Cruise Control (ACC). Studies with ACC suggest changes in workload, although conclusions are conflicting, with both reduced [9, 10] and increased [11] workload reported, when ACC was compared to manual driving. Studies with ACC have also shown reductions in situation awareness (SA), and stress [10].

In the very recent years, research has progressed from studies on the ACC alone, to studying the implications of more advanced vehicles, for example when ACC is supplemented by a lane keeping assistance system (LKS)—see [12]. During such highly automated driving [13] also termed Level 3 ‘limited self-driving’ by NHTSA, the driver is expected to be “available for occasional control, but with sufficiently comfortable transition time” [14].

In this chapter, we summarize the main results from a number of studies, designed at the University of Leeds, to understand the human factors implications of driving a highly automated vehicle. Results compare performance in highly automated driving when both ACC and LKS were engaged, compared to manual driving and semi-automated driving, when only LKS OR ACC were operating. The implication of automation on driving performance and psychological factors such as situation awareness and visual attention are discussed, and in each case opportunities for further research are highlighted.

2 Studying Driver Response to Changes in Automation

The University of Leeds Driving Simulator (UoLDS) was used for all studies reported in this chapter. The vehicle cab for the simulator, based around a Jaguar S-type vehicle, has all driver controls fully operational and is housed within

Fig. 1 The eLane used in Experiment 1, showing lane markings (*left*) and sign (*right*)

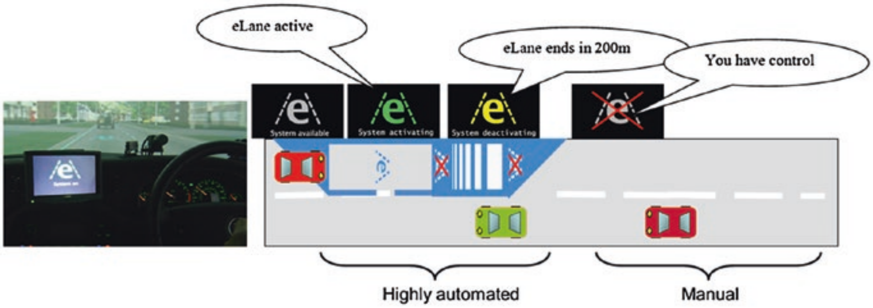

Fig. 2 The HMI used for Experiment 1—screen displaying the messages shown on the *left*. The order of visual messages displayed on the screen and their accompanying auditory stimuli (in *speech marks*) shown on the *right*

a 4-m diameter spherical projection dome. The front road scene encompasses a horizontal field of view of 250°, and three rear projectors display the scenes in the rear view and side mirrors. The simulator is also equipped with v4.5 of the Seeing Machines faceLAB eye-tracker, with its cameras mounted on the vehicle dashboard.

Two different road scenarios were designed to collect data for the reported experiments: In Experiment 1 (part of the CityMobil project), a single carriageway urban road was used, which was occasionally marked as an eLane [15, 16]. Blue road markings identified the eLane to drivers, notifying them that the automated system was available for use. As well as the road markings, shown in Fig. 1, a display was placed in the vehicle, which provided visual information via a screen in the vehicle and informed drivers about availability of the automated system as they approached the eLane. The same screen warned drivers as they approached the end of the eLane (Fig. 2). Drivers were therefore able to prepare for the transfer of control from highly automated to manual driving (and vice versa). The visual information was supplemented by auditory messages, as shown in the speech marks of Fig. 2. Thirty nine drivers (Mean age 41 years) completed Experiment 1.

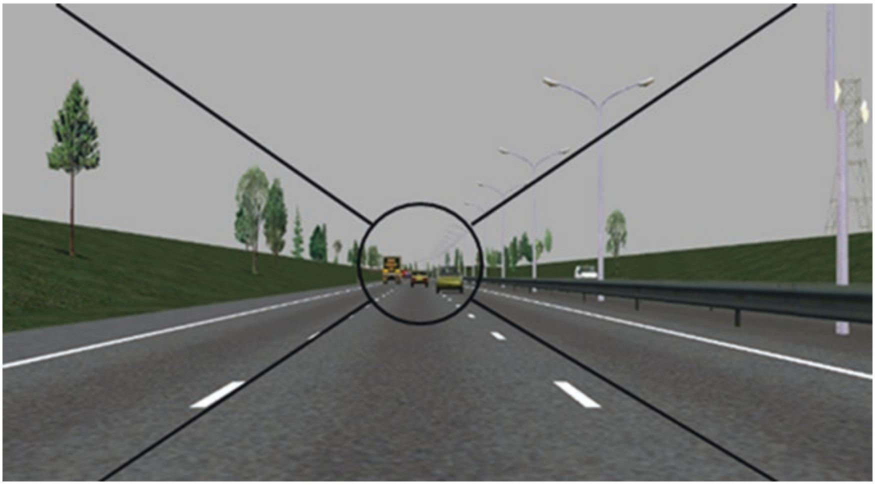

Fig. 3 The partitions used for observing scanning behavior. The central region (PRC) was a 6° radius circle around the mode of fixations within a 60-s moving window. The *left region* covered glances to the center console, left wing mirror/door/window, and passing traffic in the adjacent lane. The *right region* covered glances to the right wing mirror/road door/window, and passing traffic to the *right*. The *bottom region* covered the dashboard and the *top region*, the sky

In Experiments 2–4, a 3-lane motorway scenario was designed, which included varying levels of traffic flow (Low: 500 and High: 1,500 vehicles per lane per hour). The same forty nine drivers were recruited for Experiments 2–4 (Mean age: 47.8 years), but only 37 of the 49 participants completed Experiment 4 (Mean age: 47.4 years).

The aim of the above experiments was to study driver behavior in a highly automated vehicle, comparing performance in manual driving with highly automated driving (Experiment 1) and manual, semi-automated (lateral OR longitudinal) and highly automated driving in Experiments 2–4. For all experiments, an assessment of change in driver performance between manual and semi/highly automated driving was observed using lateral measures such as lane deviation (SDLP) and steering corrections (1° reversal rates), and longitudinal measures such as mean and minimum speed, time headway and time to contact. Driver visual attention was also observed across the different levels of automation in Experiments 2–4, using the faceLAB eye-tracker. The pattern of fixations towards the road centre (PRC, see [17]) with that in other sections of the vehicle and road (above, below, left and right of the PRC section) was compared for the three levels of automation (none, semi, highly). The aim here was to investigate whether drivers looked around the driving scene and the vehicle more frequently as automation increased (see Fig. 3).

For each experiment, we also studied the effect of the different levels of automation on other human factors concepts, such as drivers' situation awareness and propensity to engage in secondary tasks. For example, we examined how their ability to respond to sudden critical events in the road, or their capacity to comprehend changes in traffic volume changed at different levels of automation.

A summary of the scenarios used to study some of the human factors constructs assumed to be affected by automation is provided in Table 1.

3 Compared to Manual Control, How Do Drivers Behave in a Highly Automated Vehicle?

3.1 Driver Situation Awareness and Response to Critical Incidents

In the urban environment, drivers' interaction with the lead car was found to be more cautious when they were in control of the vehicle, compared to when lateral and longitudinal control was managed by the automated system. For example, drivers maintained a longer average headway than the automated system during normal car following, i.e. in the absence of an incident (2.8 s vs.1.8 s—(F (1, 38) = 60.47, $p < 0.001$). When the lead car decelerated due to a critical incident in the urban road (at a rate of 6 m/s^2), drivers' brake response was found to be much later when automation was in control, compared to when drivers themselves were operating the vehicle (0.4 s vs. 1.9 s, F (1, 38) = 212.83, $p < 0.0001$). In the absence of eye tracking data in this experiment, it is difficult to ascertain whether drivers were looking away from the road during automation. However, drivers were clearly relying on the automated system to brake in response to the decelerating lead car, as 70 % braked only after the auditory alarm warned of a potential collision. This over reliance on the system is a well-known consequence of automation [18] and can be problematic if collision avoidance by an automated system is not completely fail-safe.

Drivers showed an awareness of changes in traffic on the motorway when the vehicle was highly automated, because they assumed control of the vehicle and changed lane more often in heavy traffic in order to overtake slowing moving vehicles. However, they were generally happy to allow automation to control the vehicle, with most drivers staying in the middle lane throughout the drive, especially in light traffic.

When required to respond to critical incidents in the motorway, driver performance was actually the same in manual and highly automated driving, but only if drivers were not engaged in a distracting secondary task (the TQT). Here, drivers were instructed by the VMS to change lane, in order to avoid being stranded in their existing lane, due to an incident further ahead; such as a broken down truck. If not distracted, the same proportion of drivers (83 % vs. 81 %) moved to the correct lane, when driving manually or in the highly automated condition. Time taken to change lane after seeing the VMS was also equal in both conditions (around 30 s). However, if drivers were engaged in a secondary task, even though this task did not take their eyes off the road, they changed lane later when automation was in control, compared to when they were in control of the vehicle (64 % vs. 71 %, χ^2 (1, $N = 50$) = 21.37, $p < 0.0001$).

When driving on the motorway, drivers' average speed was higher when they were in control of the vehicle, compared to when the automation was operating

Table 1 Summary of constructs studied in Experiments 1–4

Experiment	Construct studied	Scenario	Dependent variable
1	Situation awareness	Lead car decelerates sharply (brake lights illuminated) in response to (1) traffic light changing to red (2) oncoming car turning right (3) car from side road joining main road in front of lead car[a]	Brake reaction time to lead car braking
2	Situation awareness in varying traffic levels	Changing traffic volume from low (500 vehicles per lane per hour) to high 1,500 cars per lane per hour)	Choice of lane occupancy Eye movements/scanning behavior
	Uptake of secondary tasks	Range of paraphernalia available for use in the vehicle, including DVDs, maps, sweets, puzzles etc.	Number of tasks engaged Time engaged in tasks
3	Driver distraction	Engagement in a Twenty Questions Task (TQT)	Accuracy in the TQT
		Incident in the road, requiring a lane change, prompted by a message on the VMS	Time to change lane
4	Transfer of control	Intermittent transformation from automated to manual driving (at a fixed or variable rate)	Time to resume control from automation Visual attention during transfer of control using gaze behavior

[a] Drivers heard an auditory alarm if the headway between the simulator and the lead car was less than 2 s

(70.46 mph vs. 67.62 mph, F (1, 49) = 24.16, $p < 0.001$). However, when engaged in the TQT, and faced with an impending incident, drivers were much more effective at reducing their speed when they were in manual control of the vehicle, compared to when they were required to slow down after resuming control from automation. Therefore, in terms of safety on the motorway, the automation clearly managed a safer travelling speed for the vehicle, compared to the drivers themselves, during normal (incident free) driving. However, better control of the vehicle was achieved by the drivers during critical incidents, as the requirement to regain control from automation seems to have had a deleterious effect on performance.

These results suggest that drivers need to be informed about the limitations of the system and need adequate warning about the possible failures of automation, including sufficient time to resume control, during emergencies. Our results also suggest that drivers' response to incidents is much worse if they are engaged in another task, unrelated to driving.

Taken together, our studies suggest better situation awareness with automation during motorway driving in our experiments, compared to the urban road. Clearly, the traffic conditions in the motorway and the brake reaction time required to respond to incidents are very different to that in an urban road [19, 20]. For example, drivers were able to change lane and had three lanes to choose from in the motorway. This provided more choice and therefore more time to respond to critical incidents, compared with the only response available in the urban road: braking. Further research is therefore warranted to study drivers' response to incidents when resuming control from automation in much more congested motorway scenarios.

3.2 Do Drivers Engage in Other Tasks When the Vehicle is Automated?

When provided with a range of paraphernalia in the vehicle, drivers were more likely to watch a DVD when high automation was engaged, compared to semi-automated (longitudinal OR lateral controller on) or manual driving. As shown in Fig. 4, drivers engaged in other tasks such as listening to the radio, which is not very demanding, and also read magazines and ate sweets. Although drivers did engage in more tasks when the vehicle was highly automated, they did not engage in as many tasks as expected. This is in contrast to finding from other studies [21], which showed a significant increase in secondary task uptake during highly automated driving. The main contrast between our study and that reported by [21] was that our drivers had no incentive to engage in the secondary tasks and were asked to act as they normally would in their own car. As this was a simulator study, drivers might have felt more comfortable in engaging in secondary tasks during automation as there was no risk of a real crash. However, the unfamiliarity of the simulator environment and the fact that they were being observed in an experimental setting may also suggest that drivers will engage in more tasks if their own vehicle was automated. A recent study in our laboratory showed that although young sensation seeking drivers admitted to engaging in

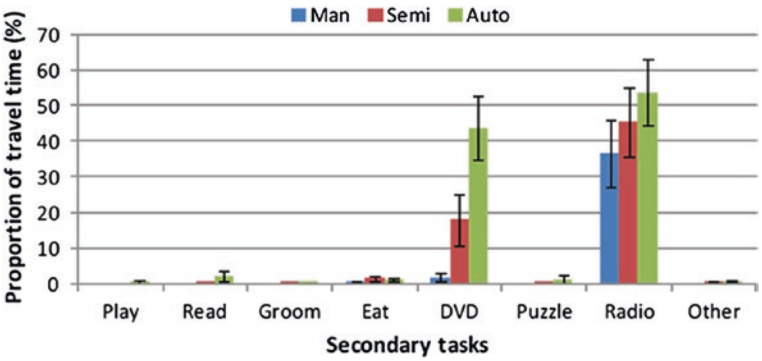

Fig. 4 Engagement in non-driving related secondary tasks

telephone conversations in their own car, they were less likely to talk or text when given the choice in our driving simulator [22]. Further research in this area, for example using naturalistic driving studies on automation is likely to provide more knowledge on the types of tasks drivers will undertake, when located in their own vehicles.

3.3 How Does Automation Affect Drivers' Eye Movements?

Drivers' gaze and blink patterns were observed in Experiments 2–4, to investigate changes in allocation of visual attention as a result of automation, as well as establishing whether automation can result in reduced physiological vigilance, as illustrated by blink patterns. Previous studies have shown an increase in driver fatigue with highly automated driving [23, 24]. We used the eye tracking measure of PERCLOS (PERcentage eyes ClOSed, [25] to compare driver arousal levels in manual and automated driving. PERCLOS measures extended periods of eye closure (75 % or more) in a moving time window of 180 s [26], and has been shown to be sensitive to fatigue [27, 28].

Drivers in Experiment 2 showed a significantly higher level of PERCLOS during highly automated driving, compared to manual driving (3.8 % vs. 1.8 %, F (1, 48) = 6.10, $p < 0.05$). Fatigue levels were particularly high when the motorway contained little traffic during the highly automated drive (Fig. 5). The use of automation in long monotonous roads with little traffic, known to be susceptible to fatigue-related accidents [29, 30], is therefore likely to be particularly detrimental to road safety, unless mitigation strategies for alleviating this fatigue are considered. Considering the attraction of automation in exactly this type of environment, further research is needed on effective methods for alleviating boredom and fatigue in drivers during automation.

Eye tracking results also showed that drivers look at the surrounding traffic and inside the vehicle at a significantly higher rate during high automation, compared to manual driving, although more time was spent looking at the road during high automation in heavy versus light traffic conditions. As shown in Fig. 6, drivers' attention to the road center was also quite low (61 %) when only the lateral controller

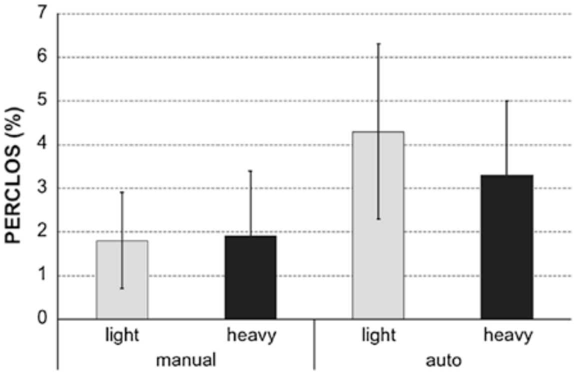

Fig. 5 Proportion of eye closure in light and heavy traffic for manual and highly automated driving (*error bars* show 95 % confidence intervals)

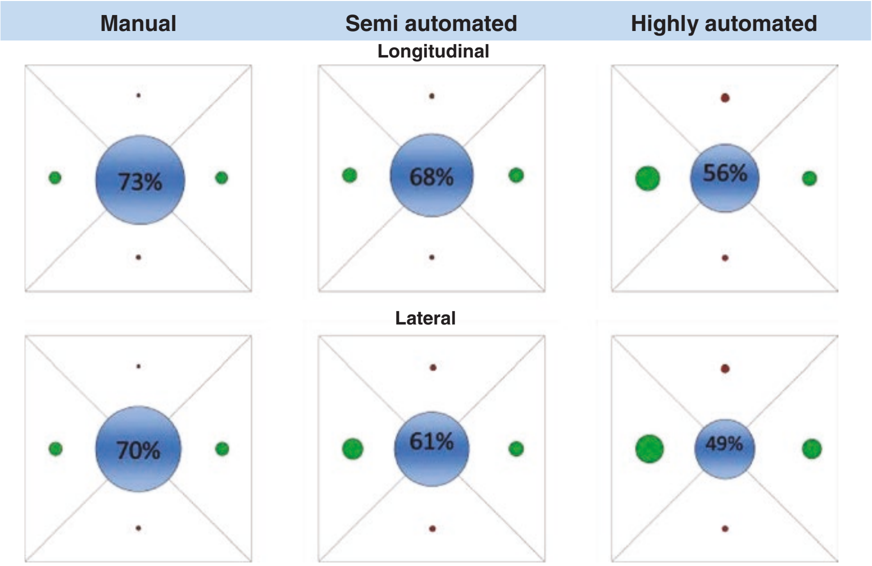

Fig. 6 Drivers' gaze concentration to different sections of the vehicle and road, during manual, semi and highly automated driving (see also Fig. 3)

was engaged. We argue that this propensity for drivers to move their attention away from the road center when only lateral support is provided (compared to when only longitudinal support is engaged) makes this condition more similar to highly automated driving [31]. Further research is required to understand why drivers feel more comfortable to look around when only a lateral controller is engaged, although it may be that in the absence of any traffic, drivers feel more confident to divert their attention elsewhere, as long as the vehicle is on a safe course.

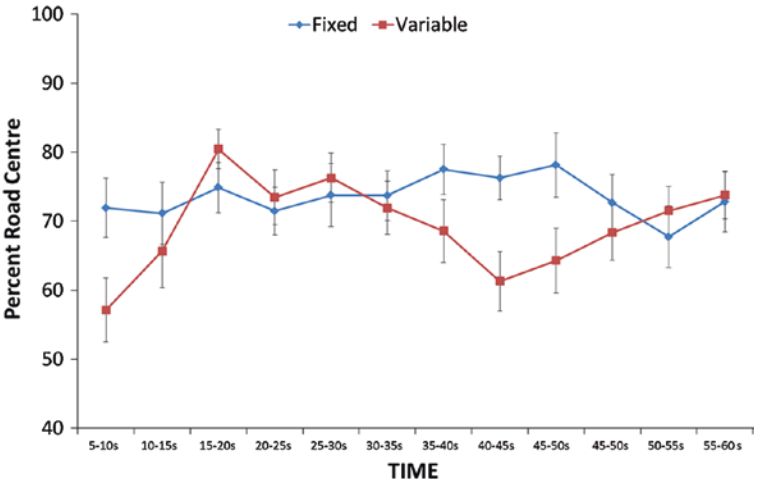

Fig. 7 Percent road centre values during the first minute after control was transferred back to drivers at a fixed (every 6 min) or variable (based on driver eye and head position) rate (*error bars* represent standard errors)

To assess how long drivers need to resume safe control of the vehicle and refocus visual attention back on the road, we used eye tracking data to observe drivers' allocation of visual attention when manual control was passed back to drivers at variable intervals. As shown in Fig. 7, when switching control between manual and automated driving was at regular intervals (every 6 min for 1 min), drivers' attention to the road center was not very variable. However, we also looked at disengaging automation only when drivers were looking away from the road center, by integrating faceLAB with the automated system and disengaging automation when drivers looked away from the road center for 10 s or more (see [32]). When automation was disengaged in the latter condition, drivers' eye fixations were much more variable during the 1 min intervals they were back in control of the vehicle (Fig. 7). Lateral control data (not shown here, but see [32]) also suggested that variable disengagement of automation resulted in a more erratic resumption of control by drivers. As it is not typical for the disengagement of automation to be predictable by drivers (unless it is initiated by the drivers themselves), these results highlight the importance of appropriate HMI for keeping drivers in the loop during automated driving, to ensure that drivers have adequate time to resume control of driving and can maintain their attention towards the road center, when required. Our data suggest that drivers require up to 40 s to stabilize their performance after resuming control from automation, which is clearly too long a time for avoiding a collision, considering that both simulator and real world data show brake reactions times to incidents be around 1–2 s [19, 20].

4 Conclusions

The studies reported in this chapter were designed to investigate how increasing vehicle automation at Level 3 (limited self-driving) affects driving performance, compared to manual and semi-automated driving. Results showed that when drivers were required to resume control from automation in an urban scenario, they demonstrated reduced situation awareness, braking later than when they were in manual control, in response to a critical event However, the effect of automation on performance was not as deleterious during less time critical incidents, for example when a lane change was required. Yet if drivers' attention was distracted by a demanding cognitive task, they found regaining control from automation to make a lane change more challenging, compared to when the secondary task was conducted in manual control.

Drivers' visual attention was found to be more dispersed as automation increased, with less attention to the road center during highly automated driving. Driver' fatigue levels were also seen to increase with level of automation, especially during quiet stretches of road, with low levels of traffic. Drivers were found to take around 40 s to stabilize their gaze fixations and vehicle handling after resuming control from automation, but were better at gaining control when transfer from automation was at a predictable and regular rate.

By far the biggest challenge for human factors researchers in vehicle automation at present is ensuring a successful path for the transfer of control between the human and the automation, creating suitable sensors which can predict the point at which drivers need to regain control of the vehicle, and providing HMI with the right information at the right time to allow a smooth and successful transfer of control. Understanding how to keep drivers alert, and allowing them to engage safely in other tasks is also an area requiring further insight.

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Key Factors Influencing Autonomous Vehicles' Energy and Environmental Outcome

William R. Morrow III, Jeffery B. Greenblatt, Andrew Sturges, Samveg Saxena, Anand Gopal, Dev Millstein, Nihar Shah and Elisabeth A. Gilmore

Abstract Autonomous vehicles (AVs)—vehicles that operate without real-time human input—are a potentially disruptive technology. If widely adopted, there is the potential for significant impacts on the energy and environmental characteristics of the transportation sector. This paper provides an outline of key drivers likely to influence the magnitude and direction of these impacts. We identify three broad categories: vehicle characteristics, transportation network, and consumer choice. Optimistically, AVs could facilitate unprecedented levels of efficiency and radically reduce transportation sector energy and environmental impacts; on the other hand, consumer choices could result in a net increase in energy consumption and environmental impacts. As the technology matures and approaches market penetration, improved models of AV usage, especially consumer preferences, will facilitate the development of policies that promote reductions in energy consumption.

Keywords Environmental impacts · Energy efficiency · Autonomous vehicles

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_12,

1 Introduction

The nature of the transportation sector is the manifestation of a continuous evolution in vehicle designs, transportation system infrastructure, and the built environment with complex interactions between consumers[1] vehicle manufacturers, energy markets, policy makers, and urban planners. Although there are some instances of rapid vehicle technology deployment (e.g., seatbelts for passenger safety), the transportation sector's evolution is often slow. In the least, consumers, auto manufactures, and infrastructure usefulness function on different relevant time scales. Historically, consumers retained their vehicles until end of life; increasingly, consumers are switching vehicles frequently. Manufacturers require many years of sales to recoup investments made in new vehicle models. Most transportation infrastructure (i.e., roads, highways, and fuel systems) has multidecadal life span. Thus, a transportation sector's energy[2] consumption profile reflects its mix of legacy and emerging technologies utilized to satisfy transportation services.[3] In the U.S., the transportation sector's evolution has led to continued increases in energy consumption, as transportation service demands—namely vehicle size and power as well as aggregate vehicle miles traveled—have historically outpaced vehicle efficiency gains [1].

Currently, vehicle automation technology is being developed with the promise of increasing transportation safety. This development has the potential to eventually offer affordable autonomous vehicles[4] (AV) to consumers. Although AVs are gaining attention, and a few are currently being tested as of 2014 (e.g., Google's AV cars), widespread AV adoption could still be decades away or prove too complex or socially unacceptable and always remain on the horizon. However, if successful and socially acceptable, it is possible that transportation sectors could become dominated by AVs one day. A hopeful co-benefit of AVs is to reduce transportation energy consumption. For example, reducing accidents could have a positive impact on energy consumption by lessening congestion. However, would AV dominance necessarily reduce vehicle energy consumption? Moreover, the transportation sector can influence other sector's energy consumption patterns (e.g., transportation enabled sprawl into larger footprint buildings can affect commercial and residential building sector energy consumption, and vehicle and road materials

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[1] For simplicity, we define consumers as the people demanding transportation services such as passenger mobility and the movement of goods.

[2] In all cases, energy consumption will have an environmental impact. Currently this impact is through the release of emissions resulting in poor air quality and climate change, water consumption and altered quality, etc. Even in an "all renewable" or "low GHG emissions" future, energy consumption will require infrastructure investments. An "environmental impact" is implied where energy is mentioned in this chapter.

[3] Transportation service includes the movement of both passengers and freight.

[4] Autonomous vehicles (AVs) are defined here as vehicles that provide transportation services without the need for a human driver manually operating the vehicle in real time.

have manufacturing and industrial sectors life-cycle energy implications). Would AV dominance have a significant impact on economy-wide energy consumption? Finally, how confident are we in anticipating AV's energy outcomes?

In this paper, we identify a set of broad categories that would influence the energy consumption of a fully AV transportation sector: vehicle characteristics, transportation network and consumer choice. Within each category, we then discuss several key factors that could influence AV's energy outcomes along these dimensions and discuss the variability inherent to these factors. For a simplified discussion, we imagine a future in which AVs are fully adopted for all transportation services (i.e., providing close to 100 % of road-miles traveled) with a focus on the U.S system. Assuming full AV adoption implies that a cost-effective and socially acceptable technology deployment pathway took place. It is not our focus to discuss pathways and timing, cost and policy/legal considerations. We also remain agnostic about the fuel types and drivetrains that are employed for AVs. Thus, we are evaluating the factors that are specific to AV usage and do not comment on potential interactions with fuel/drivetrain options.

While a specific forecast will certainly be wrong, early stage anticipation of outcomes can help facilitate debate, policy, research, and ultimately steer AV development and deployment. Our intent is to interject into a rapidly growing AV debate that AVs' energy outcome is far from certain. We argue that because of the scale of the influence AVs could have on energy and the environment, both research and policy communities should anticipate developments along these key factors, and, to the degree possible, address potential concerns at an early stage.

2 Key Factors

Here, we group the factors that will influence future energy outcomes from widespread AV adoption into three main categories: vehicle characteristics, transportation network, and consumer choice. In Table 1, we present these factors in terms of increasing complexity of the factor being evaluated, uncertainty in the range of values, and potential influence on the resulting energy consumption.

We develop our list by drawing from the existing discussions on AVs. For instance, the Economist recently provided its readers with an overview of the potential benefits (e.g., increased safety, elderly and disabled passenger mobility, and fuel economy) as well as challenges (e.g., will consumers, insurers, and courts inhibit or usher in AVs?) associated with an AV future [2]. Eno Center for Transportation's report titled "Preparing a Nation for Autonomous Vehicles—Opportunities, Barriers, and Policy Recommendations", considers a range of AV adoption rates and then estimates the effect on safety and vehicle miles traveled (VMTs) [3]. AVs have also sparked public interest. For example, Brad Templeton's "Robot Cars" blog provides essays on AV topics including potential automobile design concepts such as right-sizing, greater fuel switching flexibility, and potential shift in consumer preferences leading to better urban planning, to name a few [4].

Table 1 Key factors influencing the energy outcomes of widespread AV adoption

Category	Key factors	
Vehicles characteristics	Weight	*Increasing Complexity, Uncertainty & Influence* ↓
	Performance[a]	
	Right-sizing[b]	
Transportation network	Communication[c]	
	Roadways	
Consumer choice	Services (passengers and freight)	
	Vehicle miles traveled	
	Communities (the build environment)	

[a] Used here to describe vehicle's cruising speed and acceleration (how quickly a vehicle reaches the cruising speed)

[b] Right-Sizing describes a concept of vehicles designs that are appropriate for the service they provide. For example, a single-passenger commuter vehicle could be designed, or "sized", for a single occupant, versus four passenger vehicles common in current commutes

[c] Data transmission that facilitates an AVs' control

Table 1 is not intended to be an exhaustive list of factors but instead to group key factors together and discuss the potential influence they might have on AV and transportation sector's energy consumption. While many of these factor's are commonly thought to offer advancements towards the future sustainability of societies, counterpoints are possible for many of these ideas. We caution that a fully AV transportation future might not resemble today's transportation sector, and the rules that have helped sector analysts estimate the effects from some of the more uncertain factors, such as consumer choice, may no longer apply.

2.1 Vehicles – Weight, Performance, and Right-Sizing

Weight and performance fundamentally affect a vehicle's energy consumption. All else equal, a lighter vehicle gently accelerating to a slower speed will consume less energy than a heavier vehicle rapidly accelerating to higher speeds. Vehicle engineers continuously seek to maximize vehicle performance and fuel economy. In addition, efforts are currently underway to reduce vehicle weights without compromising passenger safety. Characteristics of AVs, such as accident avoidance, could reduce the frequency and severity of accidents by quickly responding to surrounding traffic conditions and removing driver error, producing an inherently safer transportation system. Importantly, AVs accident avoidance could enable lighter vehicles and thereby reduce fuel consumption. Theoretically, a fully AV transportation system could eliminate accidents entirely. As the probability of accidents approaches zero, the burden of passenger protection could migrate from vehicle chassis and shells to autonomous controls. This might allow for radically lighter vehicles than currently possible in today's relative risky transportation system.

AV-enabled performance optimization could reduce energy consumption independent of weight reductions. Replacing humans with autonomous controls could remove sporadic acceleration and breaking which tend to lower a vehicle's energy consumption. AV passengers could be content with overall slower accelerations and speeds if that enabled less congestion. Conceptually, AV's could also minimize energy consumption by selecting the least energy intensive pathway to deliver passengers and goods in a more efficient manner than present routing systems.

Finally, individual AVs could in theory be coupled using communication systems—e.g. multiple smaller modular vehicles could operate as one unit. This could facilitate savings from weight-reduction by vehicles that are right-sized for the services they provide. For example, AVs could allow passengers to use vehicles designed for specific transportation services such as commuting versus a family camping trip. Right-sized single-occupancy commuter vehicles could also be much smaller and efficient than today's sedans. Apart from passenger vehicles, there may be potentially larger efficiency gains for delivery systems. Right-sized AV delivery vehicles could be substantially smaller and lighter if safely delivering goods, but not protecting humans, became the dominant design objective.

2.2 Transportation Network – Communication and Roadways

Although it is theoretically possible for AVs to function without external communication, energy benefits could come from communication, either between AVs (i.e., "vehicle-to-vehicle"), a regional network, or both. Communicating vehicle positions, relative speeds, and destinations could reduce accidents and congestion by safely synchronize groups of vehicles to reduce cascading effects[5] . This communication could also accommodate merging and exiting AVs. Both of these will have the effect of reducing individual vehicle energy consumption. There could also be additional vehicle energy savings through higher-speed traffic "platooning". Platooning shortens safe traveling distances between vehicles reducing net drag resistance.

A vehicle-to-regional communication could enable benefits in localized zones as well as system-wide. For example, system-wide energy savings benefits could be realized if vehicle-to-regional communication enables predictive management at heavy commuter times. This could minimize the energy intensive vehicle starting and stopping of the majority traffic flow direction. Additional system-wide energy savings benefit could be realized through regional communication networks optimizing aggregate flows of passengers and goods and allocating AVs appropriately across all potential routes. Theoretically, a fully

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[5] Cascading effects are the subsequent vehicle responses to sudden braking and or accelerations in vehicles preceding them.

AV transportation system could satisfy all transportation service demands at all times while minimizing system-wide net service time and energy consumption. However, this could require system-wide regional communication networks that could be data intensive and require large computational resources.

While communication could enhance system-level performance with minimal infrastructure changes, roadway infrastructure adapted to a fully AV transportation sector could tap into even greater system-wide energy savings throughout the larger built environment. Presently, when the majority of vehicles are moving in the same direction, the counter-flow lanes are under-utilized. Thus, aggregate AV flows could determine road lane and direction allocations in a dynamic and safe manner. Also, a right-sized AV stock would present even greater flexibility in allocating traffic flows and roadway utilization. These changes to roadway patterns, however, may require new infrastructure designs. At the city level, we would need to consider how to accommodate pedestrians and bicycles. At the high-speed highway level, AVs might require roadway designs that facilitate entering and exiting AVs, directionally dynamic roadway lanes and other modifications that facilitate continuous AV flows.

2.3 Consumer Choice – Services, VMTs, and Communities

Consumer choice has the largest degree of uncertainty. This category may also have the largest influence on AV's energy outcome through changes in the total demand for transportation service demands. At the highest level, AVs could increase the total number of consumers if transportation services are opened to those currently excluded due to age, disabilities, or other reasons. Similarly, if AVs allow goods to flow more freely, a larger quantity of goods could be purchased and shipped. For example, a currently homebound person could become an AV user to travel across town and then order a single forgotten item (e.g., reading glasses) for immediate delivery, thereby introducing two new transportation service demands. In addition to increasing the size of the consumer pool, the choices those consumers make (e.g., vehicles chosen, VMTs, and life-style choices) in response to new flexibilities presented by AVs could be a radical departure from current choices. We highlight the range of possible outcomes through two scenarios.

Consumer choices could lead to an increase in energy consumption where individual energy usage and travel distances facilitated by AVs outpace any gains in efficiency – a resource dystopian outcome. Freeing passenger's attention from driving responsibilities could lead to increased "luxuries" designed into vehicles. This could include some elements that are presently in vehicles, such as entertainment systems. It could also extend to activities that we already to a lesser degree conduct in our vehicles, such as personal grooming and consuming food. For example, we could prepare food in our vehicle necessitating additional electronic equipment. If passengers communicate value from mobile luxury, then AV manufactures could respond by producing vehicles with increasingly larger sizes, weights, and ancillary energy requirements for electronics and climate control. Given these luxuries, consumers could have an increasing personal value derived from "living" in vehicles and choose to live further apart or away from employment resulting in increased VMTs and a sprawling built environment.

On the other hand, consumer choice could lead to decreasing energy intensity. Here, we emphasize the role that AVs can play in reducing the resources used for the transportation system as well as achieving more sustainable communities and built environments (i.e., buildings, roads, vehicles, utility distribution systems, etc.)—a resource utopian outcome. Conceptually, AVs could enable highly optimized and efficient transportation systems that deliver passenger safely and quickly, minimizing time spent in vehicles. Right-sized vehicles with minimal luxuries could become the least-cost and most demanded AVs. Moreover, AVs could arrive exactly when and where they are needed as well as transferred independently to the next service demand. This could make personal vehicle ownership unnecessary by providing right-sized vehicles "on demand". Future built environments could then emphasize living space over residential parking garages and productivity over commercial parking lots. Finally, an optimized network offering a highly efficient transportation system could draw people closer, supporting urban development, and reducing overall net energy consumption.

3 Anticipating Energy Outcomes – Complexity, Uncertain, and Influence

While our current understanding of the size and relative influence of these factors precludes a detailed model, we present "back of the envelope" estimates of potential AV energy outcomes for our two scenarios. Our approach is to estimate the change in fuel economy from vehicle and network improvements and VMT from consumer choice. In our utopian scenario, the resulting primary energy consumption could decrease by roughly 80 %, all else equal. Here, we envision radically improved vehicle and system efficiencies effectively tripling miles-per-gallons over anticipated average U.S. light-duty vehicle (LDV) performance [5], and shared vehicles and shorter distances decreasing VMTs by 40 %. In our dystopian scenario, if larger vehicles increase miles-per-gallons by 25 %, and privately owned vehicles and longer distances increase VMTs by 40 %, then transportation's energy consumption would more than double. The span of these estimates reflects the inherent uncertainty in predicting the future. However, as presented in Table 1, the factors that comprise our estimate range in complexity, uncertainty, and influence. Evaluating these factors qualitatively can inform future research and policy needs.

Engineers have well established methods and tools for predicting vehicle energy savings. While vehicles are complex machines, physics and engineering principles can be used to accurately estimate a vehicle's energy consumption and the relative energy savings potential from weight reductions and AV modified performance or drive-cycles. However, anticipating how much weight reductions or performance modifications autonomous controls will enable is much less certain. Although transportation researchers are currently working on energy savings estimates for measures such as platooning, energy savings estimates for other measures, such as "smoothing" entire highways, are speculative or rely on extrapolations from platooning. Estimating these savings is mostly theoretical in the current absence of AV traffic only highways for measurement and experiments.

Energy savings from transportation networks designed for AVs are far less certain than those derived purely from vehicles designs. Vehicle-to-vehicle communication will almost certainly be a component of an AV transportation network and will most likely offer some energy savings. There are, however, fewer established modeling approaches to quantify these energy savings. Additionally, we have assumed a regional communication network capable of system-wide optimization. This level of deployment may prove too difficult for implementation and its benefits speculative. For example, we did not explicitly address the practicalities of algorithms and computational needs of this system. We also did not consider social or economic constraints, such as public oversight and budgetary pressures, nor ethical, legal or liability concerns that may further limit the application and optimization of the networks. Improvements to roadway infrastructure, which has long construction times and life spans, could also prove too costly or impractical to accommodate a moving target of rapidly changing AV designs and needs. Thus, quantifying the network benefits may be bounded by optimization approaches, but the details of the final system and the interactions with the existing infrastructure over time may greatly reduce the observed benefits.

Estimating consumer preferences is even more challenging as we have little experience or analogs for AV options. Our scenarios for consumer choice, however, highlight the potentially large influence of consumers on the magnitude and direction of energy consumption. However, we limit our estimates to the potential response through variations in VMT and vehicle efficiencies. While these variables are clearly influenced by consumer behavior, they do not encompass the range of preferences that may influence AV energy consumption (e.g. private vehicle ownership versus vehicles "on demand"). Social scientists could address much deeper questions of consumer motivation and choice.

4 Conclusions

If the technology is successful and AVs become the primary mode of transportation, a number of key factors will likely influence the final energy consumption. AVs could be inherently safer compared to human operated vehicles (or even accident-free) enabling vehicle weight reductions and associated energy savings through vehicle efficiency gains. Further vehicle energy savings could be achieved if AVs are right-sized and their performance optimized. AVs operating in a dynamic transportation network could leverage additional system-wide energy savings and potentially alter roadway infrastructure to achieve even greater energy savings. Moreover, consumer choices could result in game-changing social efficiencies if urban densities emerge supported by highly efficient city transportation networks. However, the potential efficiencies that AVs offer should not obscure the possibility of a far-less optimistic outcome. Vehicle and system-wide energy savings could be negated by consumers choosing new luxuries and urban sprawl.

At this early stage of AV development, researchers and policy makers should be aware of the magnitude of influence that these factors could have on energy futures and prioritize an AV research agenda. Addressing these factors, however, will require new modeling approaches and multi-disciplinary collaborations. Policy makers may also want to anticipate the key drivers to facilitate the development of policies that promote reductions in energy consumption. While evaluating the social benefits compared to the costs is beyond the scope of this paper, a net benefit could provide motivation for policies that promote full AV adoption.

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An Analysis of Possible Energy Impacts of Automated Vehicles

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Abstract Automated vehicles (AVs) are increasingly recognized as having the potential to decrease carbon dioxide emissions and petroleum consumption through mechanisms such as improved efficiency, better routing, and lower traffic congestion, and by enabling advanced technologies. However, AVs also have the potential to increase fuel consumption through effects such as longer distances traveled, increased use of transportation by underserved groups, and increased travel speeds. Here we collect available estimates for many potential effects and use a modified Kaya Identity approach to estimate the overall range of possible effects. Depending on the specific effects that come to pass, widespread AV deployment can lead to dramatic fuel savings, but has the potential for unintended consequences.

Keywords Automation • Autonomous • Self-driving • Energy • Petroleum • Platooning • Smart routing • Electrification • Car sharing

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The original version of this chapter was revised: Chapter title has been updated. The erratum to this chapter is available at https://doi.org/10.1007/978-3-319-05990-7_22

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_13,

1 Introduction

Self-driving or fully "automated" vehicles (AVs) have rapidly moved from science fiction into the forefront of transportation technology news, with many automakers now demonstrating vehicles with some automation capability. Highly or fully automated vehicles are likely still years away from widespread commercial adoption [1], but this recent progress makes it worth considering the potential national impacts of widespread implementation. In addition to the expected safety and social benefits, widespread adoption of AVs has the potential for significant impacts on transportation energy use. This chapter makes an initial assessment of the energy impacts of AV adoption on a per-vehicle basis and the potential for AVs to change total personal vehicle fuel use. While AVs offer numerous potential advantages over conventional vehicles (CVs) in energy use, there are also significant factors that could decrease or even eliminate the energy benefits under some circumstances. This analysis attempts to describe, quantify, and combine many of the possible effects. The nature and magnitude of these effects remain highly uncertain, and further analysis in the coming years of each of these effects and the system as a whole will be needed to steer AV development in a way that captures the potential energy benefits.

2 Methods

National-scale modeling of the possible interactions with AVs and the transportation system of the future is not yet available. AVs have the potential to interact with each other, the transportation infrastructure, and the built environment in such complex ways that it is likely to take years of dedicated research to have a detailed assessment of the possible impacts of the future system.

For this effort, individual and combined impacts are assessed based on a modified Kaya Identity [2]. The Kaya Identity is an equation relating factors that determine the level of human impact on carbon dioxide (CO_2) emissions, which is often applied to specific sectors such as transportation. It divides emissions into "factors" of use intensity (UI), energy intensity (EI), and carbon intensity so that each can be examined in detail. For this analysis, we modify the identity in two ways. First, populations of AVs and CVs are separated by dividing the Kaya components into an AV and a CV term. This is so we can track the effect of different parameters as well as the impact of different fractions of AVs. Second, we use liquid fuel demand as the final output rather than CO_2 to isolate this issue from the CO_2 intensity of electricity or other fuels.

Fuel Demand

$$\begin{aligned} FuelDemand &= \#Vehicles \\ &\times \{\%AVs\frac{VMT}{AV} \times \frac{Energy_{AV}}{VMT} \times \frac{Liquids_{AV}}{Energy} + (1 - \%AVs) \times \frac{VMT}{CV} \times \frac{Liquids_{CV}}{VMT} \\ &\times \frac{Liquids_{CV}}{Energy}\} \end{aligned} \tag{1}$$

The product comprising the first term in the brackets represents fuel use by AVs and the second term by CVs. We refer to factors affecting vehicle miles traveled (VMT)/vehicle as "use intensity" (UI); factors affecting Energy/VMT as "energy intensity" (EI); and factors affecting Liquids/Energy (e.g., electric vehicles use no liquid fuels) as "fuel intensity" (FI). This method was implemented in an Excel spreadsheet.

Each potential impact examined in this analysis was translated into one or more effects on the terms in the equation above. Where possible, we adapt estimates from other sources as they might apply to AVs. Effects are generally assumed to be independent for this analysis, so impacts are chain multiplied to combine. In reality, system effects are likely to be significant but those interactions are beyond the scope of this analysis.

Note that a number of the impact estimates implemented in this analysis were identified and coopted from literature not necessarily describing AVs. For example, we use a study of eco-driving to estimate the possible benefits from smoothing starts and stops from AVs, assuming that they could be designed to capture those benefits at least as well as a human driver. In general, we collected and documented the maximum plausible impact identified, so the impacts here should be viewed as an estimate of the upper bound of each effect. Depending on implementation or other factors, each impact could be smaller.

This analysis uses 2030 as an example year for reference when determining the baseline. This is not intended to be predictive, only as a point for comparison. For the baseline, we assume 262 million vehicles, a 38.5-mpg on-road reference new light-duty vehicle, and 12,700 miles per vehicle per year [3]. CV values are left at baseline for this analysis for clarity; future analysis could examine the relative impacts of simultaneous improvements in CVs.

3 Effects Considered

We surveyed the developing literature on AVs to identify possible effects on energy use. Many possible impacts are mentioned in published papers and the popular press, but most are not rigorously quantified. Where possible, we have identified methods to quantify each potential effect. This set of effects is very unlikely to be exhaustive, but this analysis approach can serve as a basis for future estimates.

Recently, the US Department of Transportation released a policy statement on AVs that defined four levels of automation based on the degree of autonomy [4]. Most of the effects identified here require level 3: Limited Self-Driving Automation or level 4: Full Self-Driving Automation. Therefore, this study represents an assessment of the full potential of AVs, not the intermediate benefits of partial automation. Note also that AVs could become integrated into the broader vehicle population through a variety of approaches such as mixed-use operation with CVs on existing roadways or segregated operation on dedicated AV infrastructure. This high-level analysis does not endeavor to predict a specific implementation path, but consistent with the objective to estimate upper-bound effects, the analysis does draw assumptions from scenarios where the effects may be greatest. This is particularly true for system-level effects such as traffic flow smoothing where the impact would be greatest for AVs on dedicated infrastructure rather than AVs mixed in with CVs.

3.1 Individual Vehicle Effects

Some possible effects of AVs do not require strong system effects and could manifest themselves with only a few AVs on the road and where most AVs are owned by individuals. Table 1 summarizes the impacts and the sources used to support each assumption.

3.1.1 Platooning

Platooning is the proposed and demonstrated method of groups of vehicles travelling close together at high speed. This has the potential to reduce EI resulting from aerodynamic drag. Although platooning energy benefits would certainly be greatest on a dedicated infrastructure, there could also be ample opportunity for groups of two or more AVs to platoon together on mixed-use infrastructure. The exact impacts depend strongly on the shape of the vehicles, the number of vehicles, the fraction of time spent on the highway, the following distance between vehicles, and the particular algorithms used by the vehicles. AVs have the potential to allow safe following at close distances, and as long as there are enough AVs to find each other on highways, this could yield significant savings. This analysis surveyed three sources [5–7] that each produced similar estimates—approximately 10 % overall savings potential (or about 20 % savings during the roughly 50 % of travel occurring on the highway). Note that while the analysis in this chapter focuses on the energy implications for automation of light-duty passenger vehicles (the largest fuel-consuming road vehicle segment, accounting for 59 % of transportation fuel use in 2011 [8]), commercial vehicles would also be expected to achieve benefits, and in the case of Class 8 tractor-trailers (the largest heavy-duty vehicle fuel consumer) the energy savings due to platooning would be particularly significant given their high percentage of highway cruising miles.

3.1.2 Efficient Driving

This effect represents the energy savings from improved vehicle operation of AVs relative to the average human driver. It is well documented that smoother starts and stops can improve fuel economy of otherwise identical vehicles. To estimate the size

Table 1 Summary of vehicle effects

Effect	Approach	Effect estimate and reference source
(a) Platooning: close following at high speed to reduce drag	Use estimates of overall savings potential from literature	−10 % EI [5–8]
(b) Efficient driving: smooth start stop, some stop elimination	Use estimates of eco-driving potential	−15 % EI [9, 10]
(c) Efficient routing: traffic avoidance and most efficient route selection	Example cases from Buffalo, NY and from collaborative Chevy Volt project	−5 % EI [11, 12]
(d) Travel by underserved populations: (youth, disabled, and elderly)	Estimate the additional miles if all people over 16 had the VMT of the highest demographic	+40 % UI [13, 14]
(e) Efficient driving (additional): full stop elimination and trip smoothing	Use upper bound of efficiency improvement from smooth travel	−30 % EI (additional to previous estimate to give −40 % total) [9, 16]
(f) Faster travel: possible due to safe highway operation	Estimate impact on fuel economy from aerodynamic drag at 100 mph	+30 % EI [17, 18]
(g) More travel: due to faster travel and reduced traffic, people may live farther from destinations or travel more	Assume the current time spent travelling remains the same (so miles increase with speed)	+50 % UI [19]
(h) Lighter vehicles and powertrain/vehicle size optimization: Very few crashes and smoothed driving could enable light vehicles with small powertrains for many duty cycles	Assume weight could be reduced ~75 % and each 10 % reduction = 6–8 % EI reduction; Alternately compare average modern vehicle fuel economy to that of the 1994 Geo Metro	−50 % EI [20–25]
(i) Less time looking for parking: from fewer vehicles and self parking	Assume it cuts the wasted fuel in half	−4 % UI [26]
(j) Higher occupancy: facilitated by IT, automated carpooling	Use the upper bound estimates for “dynamic ridesharing”	−12 % UI [27]
(k) Electrification: deployed vehicle could be matched to user trip need	Estimate the share of vehicle trips that could be met with a 40 mi electrified range	−75 % FI (as a −100 % FI to 75 % of vehicles) [13, 28]

of this effect, we reference recent eco-driving analyses that identify potential fuel savings for aggressive drivers as high as 20–30 % [9, 10]. The fuel savings for drivers who are not at the most aggressive end of the spectrum would be significantly less, but considering AVs’ ability to constantly maintain eco-driving vigilance, we assume an upper bound of 15 % for the potential widespread improvement in EI (even absent specific traffic-smoothing assumptions).

3.1.3 Efficient Routing

Smart routing to the most energy efficient route has the potential to save energy in addition to efficient operation. This could be due to avoidance of traffic, use of a shorter but modestly slower route, or selection of a route with fewer stops. Of the few quantitative efficient routing impact estimates found in our literature review, one case study in the Buffalo, NY area estimated up to 20 % total reduction in EI as possible [11]. However, this estimate really represented a potential system-level impact of re-routing some vehicles in order to improve the operating efficiency for all vehicles on the traffic network. Another recent study of efficient routing for a plug-in electrified vehicle (PEV) identified up to 5 % overall energy savings [12], taking into account times when the default route already represented the most efficient route, and not taking into account traffic flow impacts from all vehicles simultaneously optimizing system-level routing efficiency. Because system-level traffic smoothing impacts will be separately considered, 5 % was taken as the widespread upper bound EI improvement for this analysis. Note that CVs using global positioning system (GPS)-connected navigation systems and real-time traffic information could also advise their drivers of the most efficient routing decisions; however, this by itself arguably represents one step down the vehicle automation and connectivity continuum. Widespread realization of the maximum efficient routing benefit for every trip would also most realistically be achieved by AVs.

3.1.4 Travel by Underserved Populations

The young, disabled, and elderly travel less per capita than other groups. AVs have the potential to serve these populations by allowing use of a vehicle without needing to provide direct operation. It is not known exactly how many people would choose to travel more if given the chance to do so without needing to operate the vehicle, and we did not identify any published estimates for use here. Instead, we examined data from the 2009 National Highway Transportation Survey [13] and the 2003 "Freedom to Travel" study [14]. As expected, travel varies significantly by age, with a peak at age 40 and is lowest during childhood and old age (Fig. 1). In principle, if all segments traveled as much as the 40-year-old segment then the miles of travel distribution would rise upward to align with the population distribution shown in Fig. 1. That method would yield an increase in miles of 70 %, but would seem to overstate extra travel even for this upper bound analysis. We instead estimate that increased travel under this effect could reach up to 40 %, which corresponds with each population segment from age 16 to 85 traveling as much as the top decile.

Additionally, the 19 % of Americans who are disabled individuals [15] leave the home less frequently, are less likely to travel by car, and take fewer long distance trips, resulting in fewer miles per person [14]. If AVs allow disabled individuals to make the same length and number of car trips, their per-capita VMT could increase by more than 50 %. Because we do not have the data to address interactions with

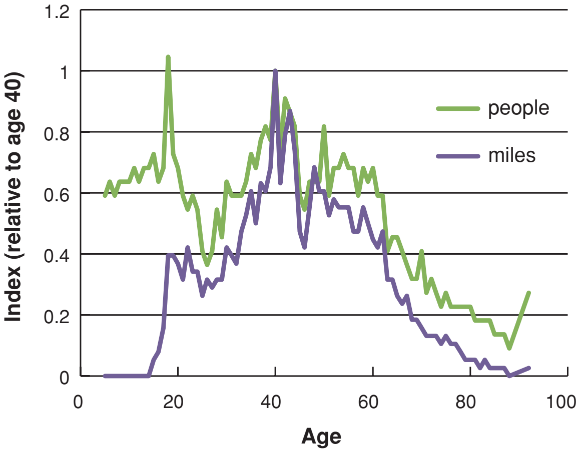

Fig. 1 Relative travel by segments of the population

the age-based approach discussed above, we do not include this as a separate factor and instead take the 40 % estimate to include increased travel by disabled individuals. It should be emphasized that providing better transportation services to these populations would yield significant social benefits, which should not be overlooked or ignored when considering energy impacts (see "Other Effects").

3.2 *System Effects*

Widespread AV use may make private ownership less necessary, with users instead summoning a shared-use vehicle for their immediate need. Widespread adoption without vehicle sharing is also possible and would represent a subset of these effects. The effects noted below become possible as penetrations increase so the majority of vehicles on the road are automated. The previously reviewed individual vehicle effects are also assumed to persist at high penetration levels.

3.2.1 Efficient Driving (Additional)

This category of impact is the additional efficient driving made possible by system effects if most or all vehicles are automated. This could manifest, for example, as no stopping required at intersections due to smart intersection control [16]. Savings here are assumed to be from complete elimination of traffic-related stopping and starting, which has been estimated to yield up to a 40 % reduction in EI [9]. This is not cumulative with the previous 15 % savings number identified above, so we reduce this effect to 30 % (to give a cumulative roughly 40 % reduction when chain multiplied). A question for future work is how much of the 5 % savings estimated for smart routing could still be counted separately as this estimate includes traffic avoidance as well as distance tradeoffs. This outer-bound impact assessment will continue to treat it as a separate effect.

3.2.2 Faster Travel

Due to increased safety of AVs, significantly faster travel may be viable on highways. Faster travel is known to increase air resistance energy loss with the square of velocity. Because of this, drag losses could become very significant at high speeds. To estimate the possible impact, we extrapolate from observations over multiple years on the speed-limitless German Autobahn [17] and assume 100-mph travel on highways becomes legal and routine due to automation. A study for fueleconomy.gov that measured the impact of speed increases in 10-mph increments to 80 mph reported that each 10-mph increase results in a 13.9 % increase in energy use [18]. In practice, precisely estimating the increased energy use out to 100 mph would require detailed assumptions about vehicle aerodynamic improvements that may occur in conjunction with such regular high-speed operation, as well as the efficiency profile for the evolved powertrain in the AV. For this high-level analysis, we take rough extrapolation of the results in [18] as sufficient, and assume the combination of increased highway energy use with the fraction of driving miles occurring on the highway (around half currently) could result in a 30 % aggregate increase in EI.

3.2.3 More Travel

There are several reasons travel per person might increase under an AV scenario. First, due to faster highway travel (above) and reduced traffic, time spent driving could decrease. Schaefer et al. observed that people on average are willing to spend a very consistent amount of time travelling across a wide variety of societies [19]. Therefore, if travel were faster overall, people might live farther from their destinations or travel to more. This is the method we use, estimating the increase in VMT per person that would keep the time travelling constant, an increase of approximately 50 %. Another consideration (not included as an additional factor here) is that travelers might not mind time in the vehicle as much because they could engage in other tasks due to automation. One subject for future study would be to see if this reduced "cost" for time while traveling in an AV might take away from other modes (such as long-distance rail or air travel) and therefore have a somewhat counteracting decrease in energy use for those sectors.

3.2.4 Lighter Vehicles and Powertrain/Vehicle Size Optimization

A fleet composed predominately of AVs could also allow vehicles to be dramatically lightweighted and have more efficiency-optimized powertrains. This is partially because collision safety features might be obviated and partially because, in a shared-use model, the vehicle used could be matched to the duty cycle required.

In a future fleet where vehicle collisions are virtually unknown, there would no longer be a need for large-framed vehicles for collision-safety purposes. This could allow a large portion of the weight of the vehicle to be reduced. It should be noted, however, that widespread lightweighting to this extreme would take a long time to occur due to the chicken-vs.-egg problem of reluctance to reduce AV size as long as they interact with heavier and less safe CVs on shared roadways.

As an example of vehicle size optimization for duty cycle matching, most driving could be served with a small, “Smart Car”-like vehicle, with larger vehicles being reserved for rarer trips with high cargo needs or more occupants. A shared use scenario with AVs summoned as needed could thus avoid inefficient commuting by a single passenger in large fuel consuming vehicles. Powertrain optimization/size reduction (and corresponding efficiency improvements) could also occur as an evolutionary response to drive profile smoothing from widespread AV use. CVs typically have power capabilities far in excess of their average power requirements to satisfy occasional high-power demands, such as from hard accelerations (needed for freeway passing of other CVs, and for viscerally satisfying the human driver/owner). AVs that permit passengers to devote their attention to other diversions may not need such excess power capability.

These two factors—safety-enabled lightweighting and smart rightsizing—will interact in complex ways. There are obviously limits to the total downsizing possible even if both of these effects are fully realized. The two could also have positive interactions, as when vehicles shed weight their power requirements would likewise diminish, and the smaller powertrain would itself weigh less, further reducing its power requirements.

Here we use two methods to estimate a potential energy impact. First, we take the Burns et al. reported possibility (primarily based on the safety effect) of a 75 % lighter fleet [20]. Several references cite a 6–8 % EI reduction for each 10 % reduction in weight [21–23], which would result in a roughly 50 % improvement overall. Recognizing the uncertainty from such an extended extrapolation we also consider an alternative method to estimate the relative efficiency improvement for AVs with low acceleration power requirements. For this method we observe that the sales-weighted average fuel economy of modern light-duty vehicles [24] is roughly half that of the 47-mpg 1994 Geo Metro [25], and therefore estimate that the significant energy savings impact of powertrain/vehicle size optimization could reach 50 %. Because the interactions between safety-enabled lightweighting and smart rightsizing are challenging to determine in advance, here we just use 50 % as an overall potential impact.

3.2.5 Less Time Looking for Parking

Americans use a significant amount of time and energy during city driving searching for parking. AVs could seamlessly integrate into a smart transportation system and either find open parking or drop off the occupants without the need to park. The Texas Transportation Institute reported that the fuel wasted is 19 gallons per person per year. If we assume that amount could be cut in half by AVs (which would still need to park somewhere, but would not need to search), that would be a 4 % reduction in UI.

3.2.6 Higher Occupancy

AVs have the potential to increase vehicle occupancy in some cases. In a shared-use model, multiple options could be available to a user, including a cheaper trip that involves sharing the vehicle with other users, similar to the airport shuttle model of transit. How many users would opt for this is highly uncertain. Here we assume AVs allow the higher end of potential impact of “dynamic ridesharing” as reviewed by the Transportation Energy Futures study, which includes accounting for trip characteristics [27]. That is a 12 % reduction in UI.

3.3 Vehicle Electrification

PEVs are inherently well suited for automation thanks to their drive-by-wire controls and electric actuation systems. Likewise, AVs may be more amenable to electrification than CVs, because a vehicle can be dispatched to meet a user’s specific need, only serving trips within range (consistent with the duty cycle matching discussion in the above section on powertrain/vehicle size optimization). AVs would also reduce or eliminate PEV infrastructure challenges since they would be aware of the availability and location of charging options. Lastly, because upfront cost is currently a barrier to PEVs, distributing that cost over many users can increase the relative competitiveness of PEVs as an option for many trips. While the potential more travel/on-demand AV system effects could cause range limitation issues to persist, it is conceivable that vehicle recharging could be coordinated in between scheduled trips. Having greater driving miles would also increase the importance of operating cost considerations, as well as the potential for lower cost fuels (such as electricity, even with occasional liquid fuel range extension) to pay back an initial vehicle purchase price premium.

While vehicle electrification could certainly happen anyway, the above arguments explain why AVs may make broad PEV penetration more likely. The key factor here is estimating the fraction of vehicles that could easily be electrified under an AV scenario. Absent a large number of additional assumptions, we generate our high-level estimate from an analysis based on NHTS data of the number of trips by length. We assume that vehicles satisfying trips of fewer than 40 miles could be replaced by electric vehicles. This would allow 75 % of the fleet to be electric vehicles, resulting in a 75 % decrease in FI. This is only the petroleum FI; the electricity would need to be produced and the method of production could affect the total energy and carbon intensity of the vehicle fleet. Those factors are beyond the scope of this chapter.

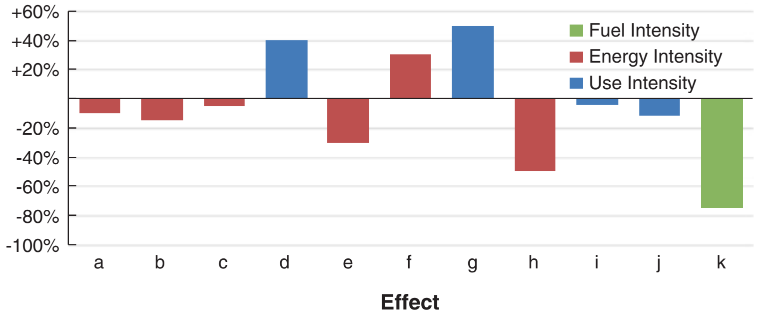

Fig. 2 Summary of effects

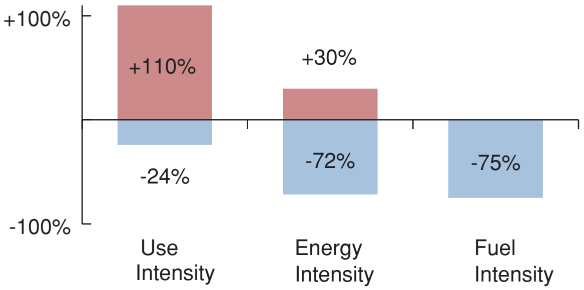

Fig. 3 Impacts by factor

3.4 Summary of Effects

Figure 2 highlights the potential for the above effects to vary from large increases in fuel use to large savings, depending on the scale and interaction of the various factors. Figure 3 illustrates the range of combined impacts when organized by intensity factor (UI, EI, and FI). Above the axis are the combined potential effects to increase energy use in that factor. Below the axis are the combined potential effects to decrease energy use. This illustration suggests that AVs would probably make us drive more miles but in a more efficient way and potentially on alternative fuels.

To further estimate the range of possible net impacts, we combined the effects above into several simple scenarios, summarized in Table 2 and illustrated in Fig. 4. There is a potential for fuel use increase of up to +173 % (more than doubling of energy use) if only service demand and speed increases occur. This could potentially happen if AVs expand access and increase safety and speed, but are not designed to operate more efficiently, be electrified, or to be lighter weight.

There is also a potential for a fuel use reduction of up to 96 % if all the possible savings are captured and there are no corresponding energy use increases. This could potentially happen if AVs are designed with energy-saving features as a central design parameter, but access to AVs does not for whatever reason lead

Table 2 Description of scenarios

Scenario number	Name	Active effects
1	All identified potential fuel use increases	d, f, g
2	All identified potential fuel savings	a, b, c, e, h, i, j, k
3	All effects	All

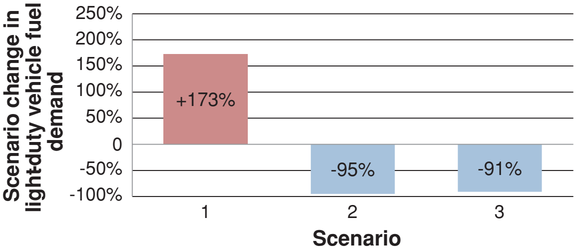

Fig. 4 Scenario impacts

to service demand increase or higher highway speeds. This might mean missing many of the non-energy social benefits (see below) that could accompany AVs.

If all effects are combined to the maximum potential identified in Table 1 and Fig. 2, we would still expect significant savings. This is because the service demand effects are overwhelmed by the decreases from efficiency and electrification. This scenario has the potential to yield large energy savings while also capturing many of the social benefits of increased transportation service and speed. However, it remains highly uncertain which of these effects will manifest themselves, and to what degree.

4 Other Effects

AVs would have many potential effects not covered here because they have non-energy impacts or the energy impacts cannot be reflected with the Kaya identity approach. Some include:

4.1 Faster Fleet Turnover

Even at the peak usage time, only 12 % of vehicles are on the road, so in a shared-use model with many AVs there could be many fewer total vehicles at a given time. Because these vehicles would be driven much more, manufacturing energy may not be significantly affected. However, with a faster vehicle turnover new technology could be rolled out faster.

4.2 Air Quality

More efficient use of fuel and the transition to electric vehicles could also improve air quality because less fuel combusted in the vehicle means fewer tailpipe emissions. A smart transportation system could also implement other air quality policies such as charging extra for pollution-causing trips on poor air quality days.

4.3 Economic Benefits

In shared-vehicle scenarios, a vehicle's capital cost would be spread over many users, resulting in lower transportation costs. Lower fuel use could also save drivers money spent at refueling stations. Shared AVs could also lower vehicle insurance, vehicle registration fees, parking permits, and other costs that coincide with private ownership. Reducing these necessary payments could be particularly attractive to portions of the populations that prefer carpooling to common destinations, live in apartments with inadequate available parking spaces, drive infrequently, or cannot currently afford transportation service.

4.4 Social Benefits of Transportation Access

In the energy impacts section, we report that addition of travelers could increase energy use. However, this would be as a result of significant expanded valuable transportation services and higher equity as transportation is available to more people. People of all ages and health conditions would have more convenient access to transportation than prior unprivileged options. Diverse benefits range from transporting children to school and extracurricular activities to transporting elderly citizens to health appointments and social engagements.

4.5 Land Use Benefits

With smaller and possibly fewer vehicles on the road, cities could repurpose land from parking and potentially in transportation corridors. Less use of land could minimize traffic congestion and therefore decrease travel time. More steady flows of traffic and less frequent instances of humans sitting in non-moving vehicles could also reduce fuel normally wasted from idling and lessen the concentration of tailpipe greenhouse emissions. Alternatively, parking or road space could be repurposed into private development or shared-use spaces such as parks.

4.6 Safety Benefits

Benefits would include less loss of life and injury as well as fewer vehicle replacements before the end of its usable life. Vehicle automation technology could consistently evade common vehicle accidents that are due to human error in judgment. The technology has the potential to be more reliable and would be less affected by distractions, including sleep deprivation, anxiety, consumption of alcohol, and uncooperative passengers. Communication between programmed autonomous vehicles ("V2V") could be a component of automation and can enhance the ability to avoid vehicle collisions because they would have consistent and precise spatial awareness, even beyond line-of-sight.

4.7 Interaction with Mass Transit

AVs could solve the "first and last mile" problem and lower labor costs for transit, but could also make transit less competitive. The "first and last mile" problem would be resolved by adding an additional paratransit mode of transportation to and from mass transit hubs that would have otherwise been inconvenient or required expensive parking. If automation could be expanded to buses and rail, lowering labor costs for transit would decrease costs in the transit sector and improve its competitiveness. However, the adoption of AVs may decrease the number of mass transit users since AVs could, if inexpensive, compete for transit users. Alternately, the lines between shared and individual transit could simply blur through implementation of an on-demand AV scenario with discounts offered for ride-sharing.

5 Future Analysis Needs

Additional analysis is needed to address several key remaining gaps. First, the literature would benefit from revisiting many of the factors described here with a specific look towards AVs. Second, the range of possible effects identified here highlights the critical importance of assessing system effects and interactions between effects to help distinguish the likelihood of various outcomes. Lastly, and potentially most importantly, there is a need for evaluation of the specific implementation decisions that will define where in this range of possible effects we end up. This may require ongoing analysis as AVs are deployed in test markets to measure effects. Each of these would require, or at least benefit from, the development of transportation system models that can incorporate AVs in various implementations and at many geographic scales.

6 Conclusion

The potential safety and social benefits of AVs are rapidly becoming widely recognized, but possible effects on energy use are often minimized or ignored. We find that AVs have the potential to make dramatic impacts on transportation energy use by individuals. Most possible effects on energy intensity may enable liquid fuel savings, but many effects on use intensity could counteract this or even lead to increases in fuel use, depending on the specific scenario. Our estimates of possible impacts range from more than 90 % fuel savings (if only energy benefits occur) to more than 150 % increase in energy use (if only energy increases are considered). At this very early stage, further investigation is recommended to improve understanding of the various effects identified in this chapter, but consideration of energy impacts will clearly be important when developing and implementing AV deployment strategies.

Acknowledgments We would like to thank Paul Leiby, Don Mackenzie, Zia Wadud, Bill Morrow, Andrew Sturges, Jake Ward, and Levi Tillemann for helpful feedback on earlier versions of this analysis.

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Part IV
Technical Progress

Disruptive Innovation on the Path to Sustainable Mobility: Creating a Roadmap for Road Transportation in the United States

Steven E. Underwood

Abstract An ongoing study sponsored by the Graham Environmental Sustainability Institute at the University of Michigan takes the position that the transportation system should enable individuals to meet their basic access needs safely and in a manner consistent with human health and ecosystem sustainability within and between generations. This chapter describes the history of road transportation in the United States and the legacy of infrastructure investments in an automobile-oriented culture. This history is the foundation for applications of forthcoming robotics and communications technologies that support vehicle automation. A research team is engaged in drafting a roadmap that includes the adoption of automated vehicles as a critical element on a path to sustainable mobility in the United States. Some of the conjectures and apparent conclusions in this chapter are intended to help pose questions for our panel of experts.

Keywords Sustainable · Mobility · Automation · Autonomous · Connected · Telematics · American · Transportation

1 Introduction

Surface transportation in the United States is a mixed blessing that connects and provides access to people and goods and services across the nation and comes with a legacy of road infrastructure that favors continued investment in automotive transportation. Much of the existing transportation infrastructure in the United States, and especially the interstate highway system, was developed with

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_14,

an emphasis on economic vitality and safety with less consideration given to long-term costs including social and environmental externalities. These developments focused more on expanding highway capacity than on improving operational efficiency, addressing demand management, or planning the integration of transportation with surrounding communities. This study takes the position that the transportation system should enable individuals to meet their basic access needs safely and in a manner consistent with human and ecosystem health within and between generations. It should be affordable; it should operate efficiently; and it should be agnostic to modal and technological preferences. This accessible, safe, and secure transportation system should also support economic vitality in an affordable and cost-effective manner that includes consideration of external costs like environmental and social impacts.

The Graham study calls for assembling a panel of experts on automated, connected, electric vehicle technology from both the engineering and policy communities. The study will look for solutions that maximize the efficient use of existing transportation infrastructure that optimize net individual and social benefits associated with alternative modes by improving inter-modal connections, sharing vehicles, and reducing crashes and delay associated with incidents. But fundamentally this study will focus on the redesign of the automobile to attain the vision of a transportation future characterized by intergenerational sustainability.

While this chapter focuses on the future of telematics, connected vehicles, and automated vehicles the Graham study includes a forecast of electric and hybrid electric vehicles. Another chapter included in this volume addresses the sustainability prospects of electric motors for propulsion and the storage of electricity.

Finally, this study will take into account the tragedy of the commons associated with the nonexclusive use road infrastructure, the externalities associated with emissions and travel demand management, the difficulties associated with balancing the current and future values of natural resources. More specifically, the goal of this Integrated Assessment (IA) is to investigate short, medium, and long-term technical and policy solutions that will support the design of automated, connected, and electric power automotive solutions that are injury free and accident free, healthy, relaxed, efficient, and productive, and do not discriminate with regard to age and health. Whenever the discussion addresses state and local considerations the states of Michigan and Washington will be used for case study. Our intent is to involve planners from Seattle, Washington to provide input on the local planning considerations addressed in the study.

The Integrated Assessment applies a modified version of the Delphi methodology for the purpose of bringing together several communities of experts on future technological developments in sustainable automotive transportation. The Delphi technique originated at the RAND Corporation in the late 1940s is a systematic method for eliciting expert opinion for technology forecasting. It is essentially a method for structuring communication among experts on a selected topic, in this case future innovations in automotive engineering related to sustainable transportation, and to facilitate structured group communication among the experts and ultimately present their concurrence on forecasts related to this topic. The three essential features of the Delphi forecasting process are anonymity of the panelists, statistical summaries of the response, and iterative polling of the panelists with feedback. The Delphi technique generally has the following characteristics: email and web-based questionnaire, questions about both quantitative and qualitative scales, easy to understand instructions for the panelists, statistical feedback with each iteration measuring central tendency, some verbal feedback with each iteration, anonymity of the expert panel, written justification for outliers, iteration of the process until panel reaches a "consensus," and the participants do not meet or discuss these issues face-to-face.

2 History of Automotive Transportation in the United States

The United States is a quiltwork of continental expanse stitched together through centuries of ambitious earthmoving and investment in infrastructure. From the earliest days of this nation the federal government encouraged the building of critical canals, railways, and roadways to connect the breadth and depth of cities and states. In the 19th century the United States Congress provided funding for the transcontinental railroad linking the East Coast to the West Coast. Then, from 1956 through 1992 the nation constructed the interstate system under the Federal Highway Act. At a direct cost of $128 billion, or $500 billion in 2008 dollars, the national system originally included over 46,000 miles of limited access highway and became the largest and most expensive public works project undertaken in the 20th century. The history of highway infrastructure in the United States is part of the transportation legacy that Americans experience today and must manage successfully in the future if sustainable mobility is going to be achieved in the United States.

Since 1992 the network of freeways has been extended, and as of 2010, it had a total length of 47,182 miles. As a symbol of American freedom and economic prosperity paved, limited-access highway provided the foundation for the automobile to become the dominant mode of passenger transportation in the United States. It was through construction of this National System of Interstate and Defense Highways that the automobile provided Americans with unprecedented levels of individual mobility and access to desired destinations across the United States. For the last 60 years the United States has employed highway construction as a coast-to-coast economic development policy with the purpose of improving access, location choice, and the movement of individuals, firms, and goods; and this has helped America's economy to remain one of the world's largest, and its citizens to be among the richest in the world.

The early 20th century in the United States saw critical advancements in technology. The US economy received a jolt by the spread of modern electricity, telephones, and the advent of the automobile, which evolved to provide point-to-point connections for people and goods across the nation. The automobile has been a major force in 20th century America serving as the backbone of the consumer goods oriented society in the 1920s and providing one out of every six jobs in the United States by the 1980s. Production line manufacturing of affordable automobiles started as America entered the 20th century and Henry Ford expanded this concept in 1914 with production of the Model T. By the 1920s the automakers were no longer experimenting with design. They placed the engine under the hood and installed cable brake systems, steering wheels, and combustion engines. The number of automobiles produced annually quadrupled between 1946 and 1955.

The growth of road transportation was a critical underpinning of economic growth in the United States in the later half of the century. The automobile has been the lifeblood of the petroleum and steel industries. Furthermore, the automobile ended rural isolation and provided the foundation for the modern American city with surrounding industrial and residential suburbs. Furthermore, urban Americans could take the car out of the city to escape the dirt, noise, and congestion of city life. Due to government encouragement after World War II, such as the Federal Housing Administration, many families migrated from cities to suburbs. These new middle-class families saw dramatic improvements in their quality of life. They married young, had many children, and adopted a suburban lifestyle. Central to this lifestyle was reliance on the automobile as the predominant means of transportation.

As the highway and road infrastructure of the nation flourished, the design of cities adjusted to requirements of automobiles for movement and space. Buildings were replaced by parking lots. Open-air shopping streets were replaced by enclosed shopping malls. Walk-in banks and fast food stores developed drive-in versions inconvenient for pedestrians. Single function business parks and entertainment complexes replaced mixed commercial town centers. Although the long-term historical trend in the United States is movement of populations from rural to urban areas, suburbanization has led to falling population density. In fact, in the US as a whole, the population-weighted density fell by 16 people per square mile between 2000 and 2010, while in metropolitan areas it fell by 405 people per square mile [1]. All of this favors automotive transportation over other modes. It also comes at a cost of maintaining the road infrastructure. As a consequence, all levels of government in the United States made highway funding a high priority at the expense of other modes of transportation.

3 Automotive Transportation Legacy

The outcome of the automotive culture and highway construction policy in the later 20th century and now in first decade of the 21st century has been mixed. While all cities and urban centers are connected across the nation with high-speed limited access travel corridors, the reliance on automobile transportation, and what some may argue as over-reliance on a single mode, has resulted the physical and political division of urban areas and in suburbanization and other low density land use patterns that produce long commutes and overuse of the highway commons with serious economic, environmental, and social costs. Automakers sold more than 14 million vehicles in the United States last year, accounting for around 30 % of domestic economic growth during the first six months of the year. The overall number of passenger vehicles has increased and surpasses the number of licensed drivers with a total of over 250 million registered passenger vehicles for close to 200 million licensed drivers in 2009 in the United States with a total population of over 300 million at that time. Accompanying this unrivaled expansion of investment automotive transportation was a parallel and related decrease in support for rail, private bus, and public transportation in general. Because of the reliance of automotive transportation the average American commuter spends approximately 250 h on the road, and although the total is decreasing, there are still approximately 15 traffic deaths per hundred thousand population in the United States, or roughly 6 million crashes, 2.5 million injuries, and over 30 thousand deaths per year.

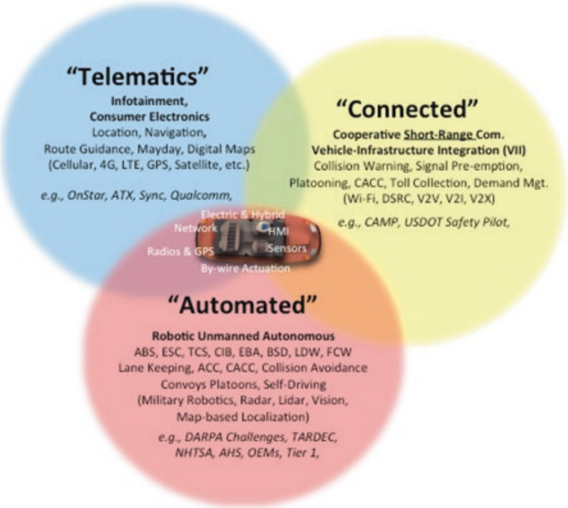
This is the leading cause of death for citizens between the ages of 4 and 34 years of age. According to the Texas Transportation Institute in 2011 Americans living in urban areas wasted about 5.5 billion hours sitting in traffic [2]. They also wasted 2.9 billion gallons of fuel with the total cost of congestion for the average commuter at a level of $818. Moreover, 68.8 % of adults in the United States are classified as overweight or obese with 35.7 % of them rating obese [3]. Many attribute the rise in obesity to the sedentary lifestyles associated with the automobile culture.

Road transportation is also largely dependent on petroleum as a fuel. The United States is a net importer of petroleum and subject to the fluctuations in the world market price of oil and political instabilities in the oil-rich regions of the world. Roughly 99 % of fuels used in road transportation are petroleum-based. Furthermore, the burning of fossil fuels in diesel and combustion engines has an adverse impact on local air quality and worldwide climate change. Nearly 30 % of all CO_2 emissions in the United States are caused by the transportation sectors.

Finally, if these costs of road transportation are not enough, the car-based transportation systems also have a direct impact on household finances and expenditures. Americans spend about 20 % of their household income on transportation and the largest share of this expenditure is associated with owning, operating, and maintaining automobiles. While the United States is still ranked number 12 out of 75 on the FedEx access index [4], indicating an ability to compete in world markets based on physical and information access including transportation, trade, and telecommunications, these important economic, environmental, and social consequences cited above bring into question the sustainability of automotive-centric transportation in the United States.

With regard to maintenance, total public spending on transportation infrastructure in the United States has decreased steadily since the 1960s and now stands around 2 1/2 % of gross domestic product. Funding for both capital investment and operations and maintenance the road infrastructure in the United States has dropped steadily for decades. The Congressional Budget Office estimates that America needs to spend at least $20 billion per year more just to maintain its infrastructure at the present levels. Up to $80 billion a year in additional spending

Fig. 1 Three communities



could be spent on projects that would show positive economic returns. The national surface transportation policy and review study commission in 2008 determined that America needs at least $255 billion per year in transportation spending over the next half-century to keep the system in good repair and make the needed upgrades current spending falls at least 60 % short of this amount.

4 Three Communities

Redesign of the automobile is part of the mobility solution. In recent years the field of automotive electronics has given rise to several independent and related prospects including telematics, connected vehicles, and automated vehicles. However, these three communities have advanced relatively independently in terms of innovations, professional practice, organizational boundaries, and dialogue with others outside their communities. Furthermore, the government community known as policy or public administration influences all three. So, for example, one could argue, "scientists and policy live in separate worlds with different and often conflicting values, different reward systems, and different languages." [5] While scientists and engineers are more concerned with pure science and esoteric issues, government policymakers are action-oriented, and practical people concerned with obvious and immediate issues.

A reason for describing the three communities in Fig. 1 at a high level of detail is to emphasize the need for systems integration in the future design of automotive electronic systems. The value of Integrated Assessment (IA) in this study is bringing together experts in the three automotive electronics engineering communities and the transportation policy community, creating bridges between these communities. This convergence of technologies and focus on integrated systems engineering is one of the critical paths on the roadmap to develop a fully automated or autonomous vehicle that address the sustainable mobility vision of this project. Envisioning an integrated technical and policy roadmap for the implementation of potentially disruptive innovation in the design of the automated and connected vehicle solution to sustainable mobility will only be fully enabled through bridging the three communities working on vehicle electronics, along with the power-train design community as well as the transportation policy and planning communities in the public sector. Our plan is to conduct an IA that will promote a unified vision of innovation of automotive electronics and communications technologies that will create new markets for automotive engineering solutions that will let the U.S establish and maintain a sustainable mobility system.

4.1 Telematics: Information and Digital Maps

The first of the three communities is what has come to be known as "Telematics" with a focus on infotainment and consumer electronics designed to communicate with the driver and to help in locating, navigating, and guiding the vehicle and the road transportation network. This is relatively mature area of automotive electronics engineering and product development that emerged in the 1990s with what may be more recognizable services and name brands including the likes of GM OnStar and Ford Sync. Telematics products are discussed, featured, and demonstrated at professional conferences like Telematics Update, the Consumer Electronic Show, and GENIVI.

The adoption of telematics poses a dilemma for the consumer because while it provides and number of conveniences like route guidance and traffic information it also potentially distracts the driver and poses a serious safety risk. Furthermore, not only does telematics distract but also should an accident occur telematics also offers mayday services that saves lives. However, perhaps the most important telematics product is the digital map that updates continuously for localization and wayfinding in automated driving systems.

4.2 Connected Vehicles: Safety and Much More

An outgrowth of vehicle communication is a somewhat later development came in the area of what is now known as "Connected Vehicles" that feature short range communication systems between vehicles, that is, vehicle-to-vehicle, or V2V, between vehicles and the infrastructure, or V2I, and between vehicles and others including pedestrians or the cloud, or V2X. Examples of these short-range communication systems include collision warning, signal preemption, platooning, cooperative adaptive cruise control, toll collection, demand management systems like road pricing. The most advanced demonstration of connected safety systems is the US DOT Safety Pilot in Ann Arbor, Michigan, where 3000 vehicles were outfitted with Dedicated Short-Range Communication (DSRC) to demonstrate safety applications including warnings of potential collisions.

Yet another connected feature that has market potential is cooperative adaptive cruise control (CACC) with initial applications for fleets and later in passenger vehicles. CACC not only promises to make driving easier while reducing potential crashes but at higher levels of market penetration it promises to smooth out the flow of traffic and increase overall energy efficiency.

One of the most recent issues concerning connected vehicles is the growing competition in the market of sensors for collision warning and collision avoidance. While the safety pilot in Ann Arbor demonstrated the real value of vehicle-to-vehicle communication with a large population of connected vehicles, it did not take into account the potential competition with radar and vision systems. That is, safety benefits of vehicle-to-vehicle communication are likely to be pinched by the growing demand for non-connected safety systems in new vehicles. While some make light of this market threat by pointing to the need for system redundancy, this risk comes to the forefront when taking into account the price and effectiveness of multiple sensor-based solutions, the need for other vehicles to have transceivers in order to communicate, and the years required for getting connected vehicles into the marketplace. It also doesn't help that the digital maps required for higher levels of automation are most likely to be updated by 4G cellular phone technology (i.e., telematics). If left only to the market the short-range communication systems are not likely to have a large role in automotive safety applications or transportation in general. However, should the government decide to mandate, to regulate, or even to provide incentives for connected vehicle technology then the long-term value of V2V as a redundant safety feature with other high-value applications possibilities will be assured.

It is critical to be aware of the potential non-safety applications of connected vehicles. Perhaps more important than safety is the role of vehicle-to-infrastructure (V2I) communication in facilitating the evolution toward the adoption of road pricing as a source of government finance for transportation. That is, the connected vehicle systems that have been tested most recently for vehicle-to-vehicle safety applications will also support V2I automated toll collection applications that can assist with congestion pricing and the collection of user fees that will have the potential to finance a sustainable transportation strategy.

Finally, some of the most promising automated systems from both productivity and environmental perspectives involve cooperative or vehicle-to-vehicle automation including cooperative adaptive cruise control and truck platooning. V2V communication enables platoons to coordinate multiple vehicles simultaneously and avoid issues of latency sequence delays with a result of shorter headways and greater benefits in terms of reduced emissions and greater fuel efficiency. Furthermore, V2V communication support platoon entrance, exit, merging, and other vehicle behaviors that requires two-way signaling between vehicles. It also supports coordination of vehicles with traffic signal timing and crossing traffic at intersections.

While much of the progress in these areas was made available through the conferences of the Intelligent Transportation Society of America, the Intelligent Transportation Systems World Congress, and the Transportation Research Board, much of the academic and engineering progress has been made available through conferences and publications of the Institute of Electrical and Electronics Engineers (IEEE).

4.3 Automated Vehicles: Crashless to Driverless

The next generation of active safety systems will prevent crashes by improving the driver's control of braking and steering, warning of potential crashes, and taking over control of the vehicle under certain circumstances to actively avoid a collision. Braking systems are now enhanced to improve steerability, hasten deceleration, and prevent skids and loss of traction. Soon a bubble of sensors and actuators will enclose the vehicle and protect it from crashes. The vehicle of the future will assist the driver with adaptive cruise control and lane keeping assist. The vehicle will warn the driver of potential crashes and intervene if for some reason the driver does not respond. Even when a crash is imminent the vehicle will take over to limit the impact. Many of these types of systems are on high-end or luxury vehicles today. However, as with most automotive electronics the cost is going down and in the not-too-distant future low-end vehicles will be equipped and some of these features may become standard.

The key point is that a crashless vehicle is not necessarily driverless. Systems are already and will continue to be designed to assist the driver and prevent crashes. The early active safety systems actually assist the driver and improve their control of the vehicle. On the other hand a self-driving vehicle must be designed with high assurance to not crash and these improvements in active safety and driver assist are steps in this direction. Over time as the population of crashless vehicles increases on the roadway it is likely to open the door to more widespread customer acceptance and adoption of self-driving vehicles. Furthermore, since the driver is the primary cause of vehicle crashes as automation technology develops and takes the driver even further out of the control loop, there are additional benefits to be had. For example, if over 40 % of fatal crashes involve alcohol, distraction, and drug involvement or fatigue, it then may help to find a source of control other than the driver. Looking far enough into the future, this trend toward crashless cars may also reduce the need for passive safety and crashworthiness. In other words, the crashless car can also be a lighter car with reduced vehicle mass and therefore more fuel-efficient.

More recent developments in the "automated" vehicle community have emerged primarily from projects sponsored by the Department of Defense (DOD) with an emphasis on robotic engineering associated with unmanned ground vehicles or what have become known as "autonomous" vehicles. While automation in the automobile can range from automatic door locks to higher levels of automation like the fully automated self-driving vehicle, more recently the Society of Automotive engineers (SAE), the National Highway Traffic Safety Administration (NHTSA), and the Germany Federal Highway Research Institute (BASt) have developed taxonomies of automated driving that define levels of vehicle automation ranging from no automation where the human driver performs all aspects the driving task, to full automation where the system executes steering, acceleration, and deceleration of the vehicle while monitoring the driving environment and providing failsafe control measures if needed [6].

For the purposes of this chapter an automated vehicle uses robotics to execute some or all of the driving tasks normally performed by the human driver. A fully automated, "autonomous," or "self-driving" vehicle, does all the essential things that an ideal human driver does to guide the vehicle to its destination. The vehicle knows where it is and where it is going; senses the road, other vehicles, pedestrians, and other objects in its environment; navigates and selects a path toward its destination; and then moves according to the path while avoiding objects by actuating steering, throttle, and braking. While a fully automated vehicle can assume and perform all the driving task of the human driver there are also lower levels of conditional or partial automation where vehicle control may be limited to specified conditions, e.g., highway traffic at low speeds, or isolated locations, e.g., campus shuttle. In conditional automation the human driver must take over control of the vehicle in situations outside the scope of the automated driving feature.

Examples of automated features include adaptive cruise control, lane keeping, collision avoidance, convoy and platooning, and all the way up to the fully automated self-driving vehicle, also known as an autonomous vehicle in the Department of Defense. In our Integrated Assessment, we find it useful to categorize developments in the automated vehicle community as driver assist, conditional or limited automation, and fully automated or self-driving.

As mentioned above the driver assist systems include features like antilock braking systems (ABS), electronic stability control (ESC), traction control system (TCS), crash imminent breaking (CIB), emergency braking assist (EBA), blind spot detection (BSD), lane departure warning (LDW), and forward collision warning (FCW). These function-specific systems are designed to assist the driver in controlling the vehicle and to improve overall safety. Other function specific driver assist systems include adaptive cruise control, lane keeping assist, and parking assist. However, these systems have already been introduced to the market and have widespread adoption and therefore are not a topic for this forecast. Likewise, more advanced combinations of these features like traffic jam assist and any simple coordination the adaptive cruise control and lane keeping features will not be addressed in this forecast.

Rather, the forecast will center on forms of conditional or limited automated vehicles some of which are legally and physically limited to specific geographic areas, for example, last-or-first-mile vehicles that use separate infrastructure or are bound to a gated area like a campus, or vehicles that have been designed for automated driving on the highway where the vehicle is self-driving from entrance to exit. The last-or-first-mile vehicles are distinct in that they offer mobility improvements like better access to transit for the mobility impaired. Similarly, the commuter

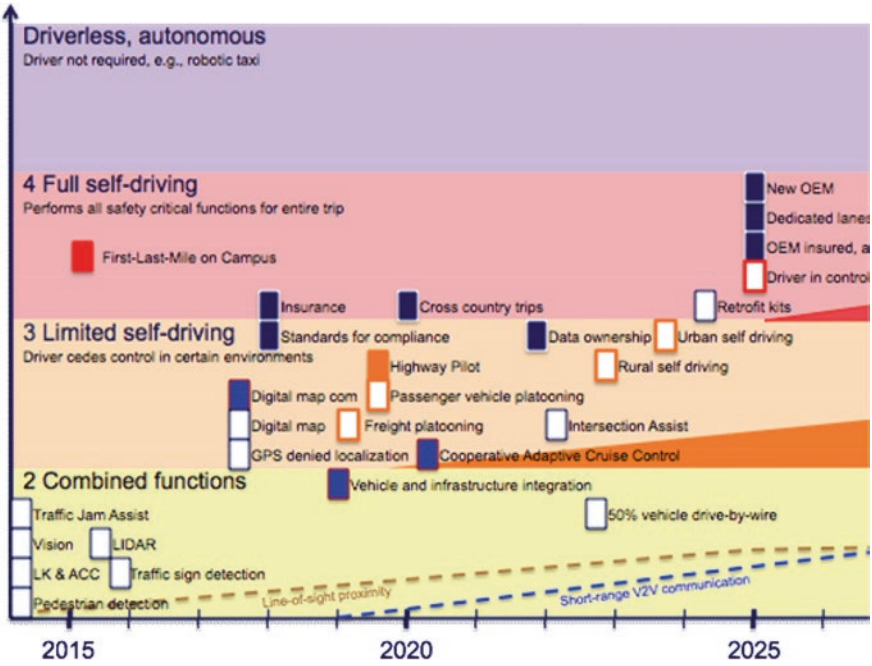


Fig. 2 Framework for delphi forecast

vehicle is distinct in that it offers unprecedented productivity or free time while the rider is on the highway. The forecast also addresses fully automated or self-driving vehicles that are designed to carry passengers from the beginning to the end of their trip whether the vehicle is owned by the passenger or whether it is shared like an automated taxi. Perhaps the key distinction of the fully automated vehicle is that it can provide single mode transportation, like a taxi, for the mobility impaired.

All of these vehicles at the higher levels of automation must also have high levels of functional safety. In addition, since the driver can attend to other activities it eliminates the concern of distracted driving and it creates a new market of former drivers who now want to be “distracted” whether it is by email or other office and productivity products or whether it is a new market for consumer electronics or digital entertainment.

A secondary impact of freeing these former drivers from the stress of traffic and offering more interesting alternatives is that their time in the vehicle, whether it is a commute or even a shorter ride, is less likely to be unpleasant or possibly even productive or entertaining, and this may increase travel demand. It is not difficult to imagine people being willing to locate their homes further away from work and other locations if their travel time is less stressful, more interesting, or actually productive. So, automation may increase traffic congestion. This concern brings us back to the connected vehicle and the opportunity it provides to manage travel demand through road pricing and market forces and essentially requiring the traveler to pay the marginal cost for their trip on the road network. Will the increased travel demand caused by automation technology be managed by connected or telematics technology?

Professional organizations that that have featured these types of automated systems in the conferences and workshops include, for example, the Association for Unmanned Vehicle Systems International (AUVSI) and the Ground Vehicle Systems Engineering and Technology Symposium (GVSETS).

The expert survey is designed to address the questions posed in this chapter. Figure 2 presents the conceptual framework for the technology forecast addressing three levels of automation (1) limited (2) conditions, and (3) full, over a period of years. The forecasts will address the market introduction of specific systems including automated commuter vehicles, automated first-and-last mile vehicles, full urban (and highway) vehicles that can take the rider to most places without a human driver, and the driverless taxi (or delivery vehicle) that can travel to most places without a human onboard.

5 Conclusion

This chapter explains the goals and objectives of our ongoing expert forecast on connected, automated, and electric vehicles and their potential for contributing to sustainable mobility in the United States. Vehicle solutions like first-and-last mile electric vehicles, self-driving commuter vehicles, and V2I demand management should augment and motivate creative use of the legacy infrastructure in ways that strengthen communities as well as increase worker productivity while improving safety and ultimately ensuring a sustainable mobility in United States. The purpose of this integrative assessment is to investigate these alternatives more completely and to forecast what features of the design will most likely become part of the mobility solution. The last phase of the project will explore how these solutions will influence urban and regional planning for sustainable transportation.

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CityMobil2: Challenges and Opportunities of Fully Automated Mobility

Adriano Alessandrini, Alessio Cattivera, Carlos Holguin and Daniele Stam

Abstract The main benefits of road automation will be obtained when cars will drive themselves with or without passengers on-board and on any kind of roads, especially in urban areas. This will allow the creation of new transport services—forms of shared mobility, which will enable seamless mobility from door to door without the need of owning a vehicle. To enable this vision, vehicles will not just need to become "autonomous" when automated; they will need to become part of an Automated Road Transport System (ARTS). The CityMobil2 EC project mission is progressing toward this vision defining and demonstrating the legal and technical frameworks necessary to enable ARTS on the roads. After a thorough revision of the literature which allows us to state that automation will perform its best when it will be full-automation and vehicles will be allowed to circulate in urban environments, the paper identifies where these transport systems perform their best, with medium size vehicle as on-demand transport services feeding conventional mass transits in the suburbs of large cities, on radial corridors as complementary mass transits with large busses and platoons of them and as main public transport for small cities with personal vehicles; then defines the infrastructural requirements to insert safely automated vehicles and transport systems in urban areas. Finally it defines the vehicle technical requirements to do so.

Keywords ARTS · Automated vehicle · Road users · Infrastructure · Safety

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_15,

1 Challenges and Opportunities of Fully Automated Mobility

CityMobil2 is a European project which deals with automating mobility. The CityMobil2 vision can somehow clash with others based on the automation of the single vehicle which is supposed to bring all kinds of benefits without requiring neither communication nor the involvement of the infrastructure. The first section of this chapter is dedicated to analysing the claims and quantifies the expected benefits of automation demonstrating that only driverless communicating vehicles which are capable of driving themselves out of the motorway can really provide the promised breakthrough.

Having established that automating mobility is much more than just automating vehicles, not all automation forms are useful whenever and wherever; each environment has a best performing system and sometimes, though sustainable in the long term, the implementation of automated road transport system might require legislative intervention to make possible and sustain the start-up of new transport concepts. Building on the results of its predecessor CityMobil project, CityMobil2 uses a geographical classification to identify the transport tasks better suitable to each transport system based on road vehicle automation. CityMobil2 has 12 cities studying how to best integrate (and where in the city) automated road transport systems. 7 of them will become real life demonstrators.

Where does this vehicle have to run then? How can they be safely (and legally) introduced on urban roads? CityMobil2 defined where these system should run and how to adapt roads to make them as safe as rail transport though as flexible as cars. Section 4 reports on these findings of the project.

Final section of the chapter, before the conclusions, reports on the development of a list of technical requirement for automated vehicles to be part of an automated road transport system.

2 Vehicle Automation Levels and Their Benefits

NHTSA and SAE have recently classified automated road vehicles in levels on the basis of how many and which ones of their functionalities are automated.

NHTSA has defined 5 levels of automation [1], from Level 0 (no automation) to level 4 (full self-driving automation) where *[…] the driver […] is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles*. SAE is currently defining 6 levels of automation (they will be reported in standard SAE J3016, currently work in progress) [2], from level 0 (non-automated) to level 5 (full automation) where the vehicle automatically manages *[…] all aspects of the dynamic driving task under all roadway and environmental conditions […]*.

The potential benefits of automating road vehicles are: increased road capacity, increased safety, lower environmental impact, opportunity for new business models.

However, different levels of automation bring to different levels of achievable benefits. In this section, the achievable benefits coming from different levels of automation will be discussed and analyzed.

Both SAE and NHTSA fail to include in their definitions of automation levels cooperative systems; V2V (vehicle to vehicle) and V2I (vehicle to infrastructure) communications can be crucial to claim some of the benefits.

2.1 Safety

Piao and McDonald argue in [3] that only cooperative systems allow the safety and efficiency benefits to be gained. For example ACC (Adaptive Cruise Control) allows maintaining a desired time gap from the preceding vehicle but for driving comfort convenience, the braking capacity is limited and the driver has to take over the control when a higher level of braking is needed. Such situations can bring to significant safety issues. Many studies addressed this topic; among them [4–7], agree that Advanced Driver Assistance Systems (ADAS) while increasing safety on one side might decrease it on several others:

- Some drivers might fail to intervene effectively in automation failure scenarios; ADAS seems to make drivers less likely to reclaim control in an emergency-braking; the measured brake time was 3 times higher and the brake reaction time 2 s higher than the corresponding ones in a fully manual scenarios;
- It is conceivable that newly qualified drivers with basic training could immediately use a vehicle equipped with ADAS; this may improve their performance in the short-term, but since novice drivers do not possess the knowledge or experience to react in a critical situation, there will be no experienced reactions to emergency situations and errors may occur.

Level 4 (according to NHTSA) and levels 4 and 5 (according to SAE) on the other hand will need to embed recovery strategies and fail-safe and safe-life protected failure modes because they do not have the possibility to rely on the driver presence in case of automation failure.

2.2 Capacity

Many studies have been carried out to investigate the effects of ADAS on road capacity. In short road, capacity is mainly a matter of time gap between 2 adjacent vehicles. In [8], the effects of both autonomous and cooperative ACC on highway capacity have been evaluated in a simulation of a single-lane highway. They represent the typical results that can be obtained in terms of road capacity using ACC. Setting an average time gap of 1.4 s, they found the greatest impact is from 20 to 60 % of ACC penetration in the flow but, even in this best case, the estimated capacity increase with ACC remain quite modest, at best less than 10 %. This means going from the 2,100 v/h of the reference scenario to the 2,250 v/h of the best scenario. Moreover, increasing ACC penetration to above 60 % leads to modest loss of capacity. The conclusion is that sensor-based (autonomous) ACC can only have little or no impact on highway capacity even under the most favourable conditions.

Time gap between vehicles can be reduced using communication-based (or cooperative) systems. Reducing the time gap under 1.4 s leads both to user acceptance and safety issues if driver intervention is still expected in emergency situations. These issues can be solved not contemplating driver intervention at all through CACC or platooning. According to [8] CACC set with a time gap of 0.5 s can potentially double the capacity of a highway lane at a high market penetration. In this chapter, it is worth to consider that such a result can be reached only with a 100 % market penetration: even a single vehicle not communicating with the other vehicles and/or with the infrastructure would create a non-negligible safety concerns.

Furthermore there is a legal issue to consider in this regard. Road code indicates the brick-wall-stop as the criterion to calculate the safety distance from the preceding vehicle. Setting an average deceleration of 5 m/s^2 and a reaction time of 1 s this criterion returns a maximum lane capacity of 1,500 v/h at 25 km/h that lowers when increasing the speed: 1,300 v/h at 50 km/h, 1,125 v/h at 70 km/h and so on. Basing on this criterion, a lane capacity of 2,100 v/h is already illegal and, in a certain way, the introduction of partial automation tends to force drivers to go against the law reducing even more the time gap between the vehicles. Platooning will only be possible if amendments to the road code are made as explained in appendix 1 to [9].

2.3 Environment

A recent study [10] comparing an automated highway system (AHS) and ADAS in terms of environmental impact, technical feasibility and economic affordability found that AHS are the most promising technology for increasing capacity and reducing CO_2 emissions.

An in-depth overview of many ICT-based solutions and their contribution to CO_2 reduction is reported in [11]. Among the most promising technologies of road automation platooning is the one guaranteeing the greatest CO_2 reduction, approximately between 5 and 7.5 %. At second place, there is ACC, with an addressed CO_2 reduction slightly above 2.5 %. Benefits of platooning in terms of CO_2 reductions are addressed in many other studies. Among those in [12] a 15 % reduction is reported for three trucks driving at 80 km/h with a gap of 4 m. In [13] a fuel reduction between 7 and 15 % is reported for three cars with a gap of 8 m following two heavy trucks at 85 km/h.

A vehicle consumes less energy in a smooth driving at constant speed rather than in stop and go conditions and it consumes less energy at high speed closely following another vehicle because it has less aerodynamic drag. Therefore from the environmental point of view, the major contributors of automation to fuel consumption is keeping the total driving mileage constant, reducing congestion and smoothing driving conditions and platooning to reduce aerodynamic drag at high speed.

As explained in Sect. 2.2 before full automation (and the necessary legal amendments), there is little contribution to be expected in reducing congestion and allowing platooning.

2.4 Lifestyle and Business Model

Automation, the full automation which allows sending empty vehicles to relocate them to where needed most, and therefore allows implementing shared mobility and transit systems. These are much more flexible and comfortable than conventional ones especially in those areas traditionally badly served by public transport.

The eventual increase of public transport (and shared mobility) segment that might result because of automation implies economic changes too, the greatest being represented by the overall business model of the road transportation system. There will be the real chance to substitute the one person-one vehicle business model with other business models. Such a topic deserves an in-depth argumentation that, however, goes beyond the aims of this section. On this regard, part of the work going on in the CityMobil2 project is focused on assessing the socio-economic impact of automated road transport systems. Findings from this work will help to define the economic scenario of the future and to set the proper path to make it real and convenient.

3 Which Automated Transport in Which Part of the City

A new mobility based on automated road vehicles providing door-to-door seamless mobility (on-demand and/or scheduled) with the aim of replacing private cars and, in some contexts, even traditional public transport is the subject of several subsequent research projects funded by the European Commission.

ARTS, Automated Road Transport Systems, as lately defined by the CityMobil2 project, range from large buses to be used on corridors to small individual vehicle to dual mode city cars and have been tested in several European Research Projects and some of them are now operating in different cities and contexts. Such ARTS can be summarized in the following four following categories.

- Personal Rapid Transit (PRT): automatic individual transport systems that use 4-place vehicles running in dedicated lanes.[1] PRTs work like taxis, carrying passengers from origin to destination without intermediate stops [14–17].

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[1] The traditional PRT concept is to keep the entire network dedicated and segregated to the point that most PRT networks are conceived on elevated monorails; however the same concept might apply using road lanes unnecessarily fully segregated and this concept has been exploited here.

- CyberCars (CC): automated road vehicles ranging from 4 to 20 passengers. Such vehicles work in a network as a collective taxi, in which the passengers can have different origins and destinations. The lane used by the network can be segregated or not [15–19].
- High Tech Buses (HTB): vehicles for mass transport using an infrastructure which can be either exclusive for the buses or shared with other road users. They can use various types of automated systems, either for guidance or for driver assistance or for full automation and platooning [15, 16].
- Dual-Mode Vehicles (DMV): city vehicles with zero or ultra-low emission and driver assistance systems, parking assistance, collision avoidance, also supporting full automated driving in certain circumstances (e.g. platooning for relocation, [16, 17].

According to the service required, the four ARTS perform best in different contexts inside and outside the cities.

An approach to evaluate where the ARTS perform best has been developed in the framework of the EU project CityMobil (2006–2011) [20], where the four ARTS were tested in 13 European cities through large scale demonstrators, showcases and city studies. They were evaluated by collecting indicators of social, environmental, economic, legal and technological impacts of the ARTS [20].

A Passenger Application Matrix (PAM), consisting of a two-dimension symmetrical matrix where the results of the evaluations of the ARTS are grouped according to their origins and destinations (respectively rows and columns of the PAM), was developed to consolidate and cross-compare results of different demonstration, study or simulation.

Ten possible origins and ten possible destinations are in the PAM.

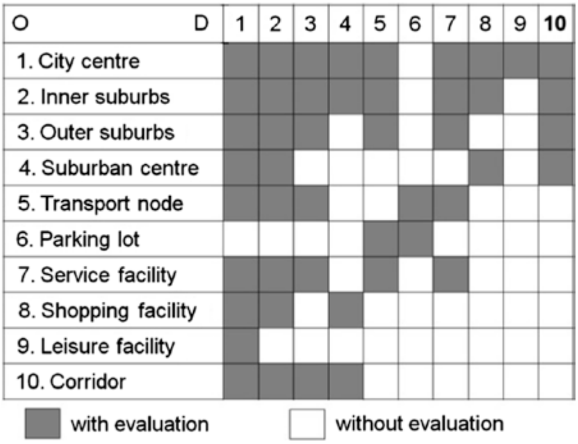
They are:

- City centre,
- Inner suburbs,
- Outer suburbs,
- Suburban centre,
- Major transport nodes (e.g. airport, central station),
- Major parking lots,
- Major educational or service facilities (e.g. university campus, hospital),
- Major shopping facilities,
- Major leisure facilities (e.g. amusement parks),
- Corridor.

The cells of the PAM represent all the possible OD pairs, as reported in Fig. 1, where the final PAM of the CityMobil project is reported, filled with the results of the evaluations made (the grey cells are those with evaluations available, whereas the white cells have no evaluations within CityMobil).

The PAM identifies which automated transport is best suitable to each cell and helps evaluate pros and cons of the implementation of the different technologies in each particular environment.

An example of the evaluations in the cells is reported in Fig. 2, where an extract of the CityMobil PAM, concerning the city centre and inner suburbs rows and columns, is shown.



O D	1	2	3	4	5	6	7	8	9	10
1. City centre	▨	▨	▨	▨	▨	□	▨	▨	▨	▨
2. Inner suburbs	▨	▨	▨	▨	▨	□	▨	▨	□	▨
3. Outer suburbs	▨	▨	▨	□	▨	□	▨	□	□	▨
4. Suburban centre	▨	▨	□	□	□	□	□	▨	□	▨
5. Transport node	▨	▨	▨	□	□	▨	▨	□	□	□
6. Parking lot	□	□	□	□	▨	▨	□	□	□	□
7. Service facility	▨	▨	▨	□	▨	□	▨	□	□	□
8. Shopping facility	▨	▨	□	▨	□	□	□	□	□	□
9. Leisure facility	▨	□	□	□	□	□	□	□	□	□
10. Corridor	▨	▨	▨	▨	□	□	□	□	□	□

▨ with evaluation □ without evaluation

Fig. 1 The passenger application matrix

D O	City centre	Inner suburbs
City centre	CC (Gateshead, Madrid, Trondheim, Wien) PRT (Gateshead, Madrid, Trondheim, Wien, Uppsala) DMV (La Rochelle, Orta San Giulio)	CC (Gateshead, Trondheim) PRT (Gateshead, Trondheim, Uppsala) HTB (Gateshead, Madrid, Trondheim, Wien)
Inner suburbs	CC (Gateshead, Trondheim) PRT (Gateshead, Trondheim, Uppsala) HTB (Gateshead, Madrid, Trondheim, Wien)	CC (Gateshead, Madrid, Trondheim, Wien) PRT (Gateshead, Trondheim, Daventry, Uppsala) HTB (Gateshead, Madrid, Trondheim, Wien)

Fig. 2 An extract of the passenger application matrix

Looking at the city centre to city centre cell, three ARTS were tested in seven European cities: Cybercars in four cities, Personal Rapid Transit in five cities, and Dual-Mode Vehicles in two cities. For each of them, different indicators were measured. The main outcomes on the ARTS after comparing the evaluations, extensively reported in [21, 22], are:

- The dual-mode vehicles are considered by the users as easy to use, useful and safe, in order to substitute the conventional cars.
- People are willing to pay more than conventional public transport to use the innovative service provided through the ARTS and well-disposed to substitute the private car with such new technology.
- PRT resulted to be more convenient than the other ARTSs in terms of performance and emissions reduction, but applicable only in small to medium size cities while conventional mass transits are the best option for the centres of large cities.
- As final result, in the city centre of small/medium cities both Dual-Mode vehicles and PRT can be applied, being well-accepted by the users and providing good improvement to the city mobility.

This is an example on how to use the PAM; the other main results which can be found in [21, 22], are:

- with medium size vehicle as on-demand transport services feeding conventional mass transits in the suburbs of large cities,
- on radial corridors as complementary mass transits with large busses and platoons of them and
- as main public transport for small cities with personal vehicles.

CityMobil2 [23] will contribute to populating the PAM with the results of its 12 ARTSs studies and 5 demonstrators in European cities.

4 How to Integrate Automated Road Transport Systems in Urban Areas

ARTS have the main purpose of providing passenger transportation services in urban areas, but deploying an ARTS in public urban roads must be done, first and foremost, safeguarding both the ARTS' users and the road users in the surrounding environment [24]. Of all road users, special attention must be given to Vulnerable Road Users (VRU). In fact, pedestrians' road fatality in urban areas is above 70 %, both in Europe and in the US [25, 26], with the elderly representing the highest fatality rates [27, 28]. Since elderly-related incidents have greater impact and likelihood of occurrence [29], safety regarding the elderly should define the baseline for the safe integration of ARTS in urban areas. Thus, the focus in the definition of the ARTS' safety requirements in CityMobil2 has been shifted, from a driver-vehicle-centric approach, to a comprehensive, road-safety approach. Other objectives, like the improvement of traffic conditions or users' comfort, were subordinated to safety. Though seemingly conservative, this approach aims might finally help to make road transport as safe as that of rail.

Up to date, the most relevant legal experience of an ARTS using at-grade infrastructure was the CityMobil Rome, Italy. In order to grant the construction and testing clearance[2] to the system, the Ministry of Infrastructure and Transport (MIT) demanded, besides an extensive series of tests of all the safety-related subsystems, that the ARTS' vehicle track be entirely segregated with physical barriers [30]. This approach creates a strong community severance effect in urban areas, CityMobil2's main target. To limit the community severance effect, CityMobil2 defined ARTS safety requirements with a two-fold approach: first, depending on the type of road users potentially present in each class of urban road.[3] Second, in a

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[2] This was among the first clearance valid on public areas in Europe, allowing the system to operate on the final site for test purposes without passengers.

[3] CityMobil2 concentrated on roads classified by TRB Highway capacity manual as (C) arterial road (D) urban street (E) collector street and (F) Walkway.

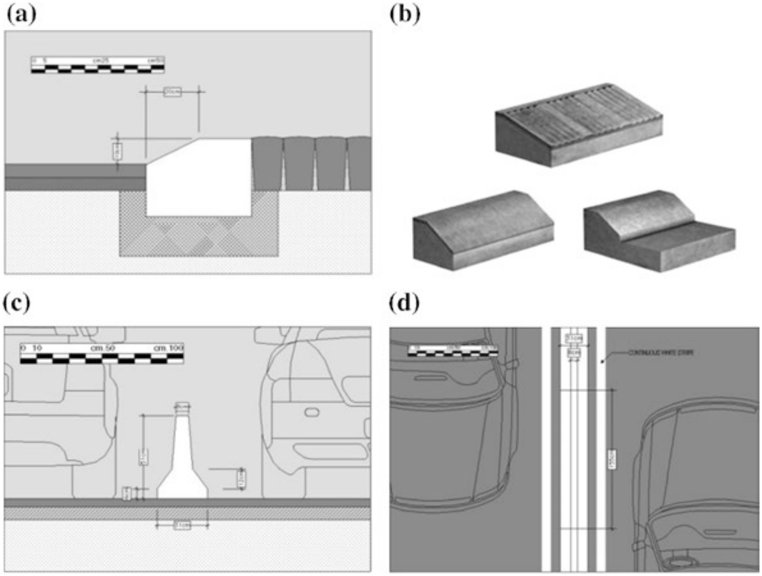

Fig. 3 ARTS infrastructure segregation elements

way that limited the use of physical barriers exclusively when no on-board, off-board or communication-based system could cope with the risks, just like existing, "manual driving" motorways are physically segregated from the surrounding environment.

A series of physical elements that can be used to separate the ARTS infrastructure from the other road users was identified. These elements, providing 13 levels of protection to the ARTS or to the road users, range from horizontal markings on the lowest level (level 1), to carriageway dividers on the strongest level of protection (level 13), plus an additional level on shared roads with no protection (level 0). Figure 3 shows a surmountable curb section view and examples (Fig. 3a, b respectively), corresponding to a level 5 protection, and a "New Jersey" carriageway divider (level 13) section and top view (Fig. 3c, d respectively), corresponding to a protection level 13 [24].

Based on the level of protection they provide and their impact on community severance, the elements were organized in five levels of protection for crossings, and in three levels of segregation for roads, [24]. The following are the three segregation levels defined for roads:

- Segregated: the infrastructure is dedicated solely to the circulation of ARTS vehicles, and it is protected with specific fittings (barriers) that physically prevent other road users from accessing it, even accidentally;
- Dedicated: the infrastructure is dedicated solely to the circulation of ARTS vehicles, and it has all the necessary markings and signals to make the restriction of

use obvious to other road users. The infrastructure may also be equipped with continuous or discontinuous fittings aimed at discouraging, but not physically prevent, other road users from accessing it. It can be accessed by other road users in case of emergency;
- Shared: the ARTS vehicles share the infrastructure space with other road users.

In order to provide recommendations on the segregation level required by ARTS in each road class, the ARTS road segregation matrix displayed in Table 1 was developed. The matrix helps defining the required level of ARTS segregation according to the potential road users present in the environment. Subsequently, a site-specific safety assessment allows selecting from the matrix the infrastructure segregation or crossing protection element (or set of elements), required in each risky location. A similar matrix was also developed for crossings.

As the demonstrations progress, all the involved parties (city and national authorities, transport operators, ARTS manufacturers, research bodies) will gain more experience on the use of the matrix and identify the best practices for the integration of ARTS in urban areas, with the perspective of integrating it into the legal framework.

The time horizon considered for the above delimitation recommendations is that of the demonstrations that will be carried out within the CityMobil2 project (2014–2016). As shown in the matrix in Table 1, no shared use of the infrastructure between the ARTS vehicles and other road users is recommended in the short term, in order to limit the safety risks, and to simplify the authorization process by the national authorities. Shared infrastructure is considered for a longer term horizon, and will be part of the legal framework that will be developed by the project.

These recommendations served as a baseline for the definition of the rest of the CityMobil2 ARTS requirements, and to provide integration examples to the partner cities. Figure 4 shows an example of a Collector street with one lane per direction before (left) and after (right) the integration of an ARTS dedicated lane. The posted speed considered in this example is 50 km/h. Horizontal markings are used to indicate the dedicated status of the lane, while sidewalks are used to separate the lane from the pedestrians and raised lane delimiters are used to separate the ARTS from other motor vehicles.

5 Requirements for ARTS

Section 4 above provides recommendations about the physical integration of Automated Road Transport Systems in urban areas, aiming to guarantee the safety of road users as well as that of the ARTS' users. As formerly mentioned, the use of physical barriers is advised exclusively when no other system, on-board, off-board or communication-based, could cope with the safety risks of a fully automated vehicle. This means that all these systems combined should guarantee a safety level equivalent to that of the physical barriers. The approach taken to reach the

Table 1 ARTS segregation level per type of road and road user

TRB HCM[a] road class	C				D				E				F	
	Arterial road				Urban street				Collector street				Walkway	
Road user	Pedestrians	Cyclists	Motorcyclists	Motor vehicle drivers	Pedestrians	Cyclists	Motorcyclists	Motor vehicle drivers	Pedestrians	Cyclists	Motorcyclists	Motor vehicle drivers	Pedestrians	Cyclists
0 Shared														
1 Dedicated					R	R			R	R	R	R	R	R
2 Segregated	R	R	R	R		R	R	R			R	R		

[a] Transportation Research Board Highway Capacity Manual

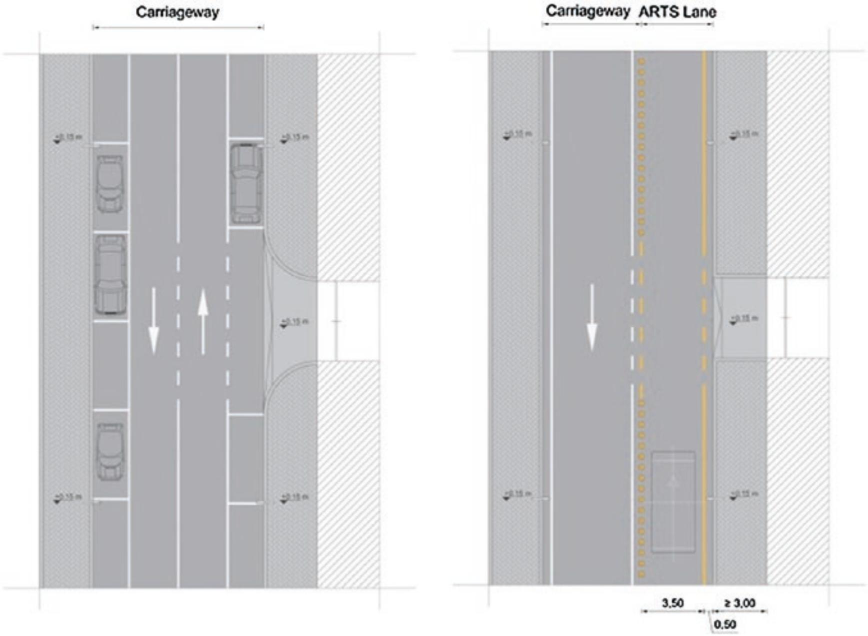

Fig. 4 Integration example of an ARTS dedicated lane in a collector street

mentioned goal was to require that off-board or communication-based sub-systems supplement the weaknesses of the on-board safety systems, which resulted in a set of safety requirements, explicitly independent from all other requirements.

An example of how this approach was applied is based on the limitations of on-board vulnerable road users' detection systems. In the evaluation of a remote (on-board) pedestrian sensor system, [31] determined through the incident analysis of the STRADA accident database[4] that almost half of car-pedestrian accident scenarios occurred in intersections, when a passenger car was going straight in an intersection and the pedestrian was crossing, either after the intersection (31 % of 2,199 accidents) or before the intersection (15.7 % of 2,199 accidents). This analysis determined that a remote (on-board) pedestrian sensor system should have an aperture angle of at least 30° in order to limit the occurrence of the identified scenarios, but if the pedestrian was obstructed to the sensor, this one would "fail to detect the pedestrian in time". When defining the requirements of a system to reduce car-to-vulnerable road users' crashes in urban intersections, [32] identified through the study of microscopic data, that in 48 out of 60 critical events studied, the contributing factor was *observation missed*. The factors contributing to *observation missed* were "reduced visibility" (29 of 48 drivers) due to "*Temporary*

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[4] Swedish Traffic Accident Data Acquisition database.

obstruction to view (8 drivers), *Permanent obstruction to view*[5] (3 drivers), and *Permanent sight obstruction* (1 driver)". Both [33] and [32] conclude that, despite the usefulness of vehicle-mounted VRU detection sensors, their limited visibility from the vehicle should be supplemented with infrastructure based sensors capable of sending to approaching vehicles data about dynamic objects detected in real-time.

This specifically led to three ARTS requirements in the CityMobil2 project. First, to limit the vehicle's speed in areas in which risk is high, the system *shall* have a full a priori knowledge of the physical environment in which the vehicles operate, including not only the road, but also the physical elements that surround it, such as sidewalks, urban furniture, and other elements that might occlude potential obstacles. This information helps in defining the speed profile of the automated vehicles, and can be stored in the vehicle, or sent by the infrastructure using V2I communication. Second, wherever a speed limitation does not guarantee the road users safety by itself, additionally, infrastructure-based obstacle detection sensors *shall* be installed in order to increase the vehicle's field of view. This could be the case in intersections in which other motor vehicles might approach at high speeds. Finally, it was required that the on-board obstacle detection sensors have a horizontal field of view of at least 180° from the front of the vehicle: Lateral obstacle detection was *recommended*,[6] to limit the risks of the ARTS' passengers at the stations.

Previous ARTS experiences have identified the role that other sub-systems play in the overall safety of an Automated Road Transport System. The parties involved in the Rome demonstrator in the CityMobil project defined that the only adapted legal framework under which the system could be certified was the EN 50126 [30] railway certification standard. This framework required that not only the vehicles, but the (fleet) control system, the user information system and the civil works (in particular the station doors) were certified as a whole. Heathrow airport's PRT system,[7] equally consisting on several on-board, infrastructure and communication-based subsystems, was also certified by HM Rail Inspectorate as a railway system [34]. These projects highlighted the need of a supervisory system capable of overseeing the complete fleet and intervene in case of need.

On this basis, the CityMobil2 project defined the ARTS subsystem architecture shown in Fig. 5.

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[5] Such as buildings, vegetation or containers.

[6] This actually means that it was agreed with the ARTS manufacturers not to make this requirement mandatory for the demonstration fleets of CityMobil2 and make it so in the draft legal framework the project is preparing for the EC future approval.

[7] This system runs on a segregated guide-way and therefore is only partially a reference for CityMobil2's on-the-road applications.

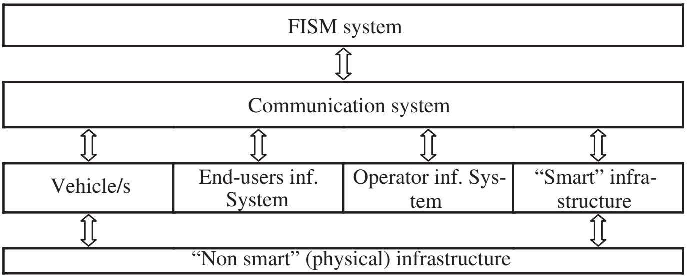

Fig. 5 CityMobil2 ARTS subsystem architecture

The ARTS components description and their role are the following:

- Automated vehicles, whose aim is to transport the passengers in a safe, secure and comfortable way from an origin station to a destination station;
- Fleet and Infrastructure Supervision and Management system (FISM), which automatically monitors all the other subsystems, manages the vehicle traffic and activates emergency procedures in case of malfunction;
- Infrastructure, whose role is to compensate the lack of performance on the on-board safety systems;
- End user information system, which allows end users to interact with the ARTS during normal and emergency operation;
- Operator Information system, which allows a (human) fleet operator to remotely supervise the system operation and to intervene in case of need;
- Communication system, which must allow all the components communicate at all times with, at least, the FISM.

Although standards on vehicle-to-vehicle and vehicle-to-infrastructure are currently under development, and ARTS should definitively comply to these points, CityMobil2 aims at demonstrating off-the-shelf, commercial systems, whose V2X systems are, for the time being, proprietary systems of the participating ARTS manufacturers. The system requirements developed by the project were made with this mid-term approach, but both selected manufacturers were required to cooperate to achieve interoperability between their systems.

6 Conclusions

After examining the quantification of potential benefits of partial automation available in literature, the paper highlighted how most of the promised benefits will be delivered by automation when it will be "full" and on urban roads. The new automated road transport systems, that can become extensively applicable, will make seamless mobility from door to door possible without the need of owning a vehicle and deeply impacting the economy and the society. The paper then reported the main findings of the CityMobil project, which highlighted how Automated Road Transport Systems is suitable for different trips which might range from individual to ridesharing to collective mobility depending on the city area. It finally showed how the infrastructure first and the vehicles and communication system then should be made to make ARTS fully safe, even in non-protected environments.

The main conclusions of this chapter are:

- a legal and public intervention is needed to understand that inserting automated transport on roads is much more than automating a vehicle, but requires revamping the law, the roads, and even the communication infrastructure; much less road and much more rail finally bring road safety to acceptable levels;
- automated vehicles would not need to be autonomous, they would need to be constantly connected and a supervising system (much like the air traffic control) should be established;
- further research and standardisation is needed in the communication field to allow large scale applications of these new transport systems.

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A Partial Reality Experimental System for Human-in-the-Loop Testing of Connected and Automated Vehicle Applications: Development, Validation and Applications

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Abstract This chapter describes a trans-disciplinary research initiative currently underway at the University at Buffalo, the State University of New York, which aims at developing next generation testing and evaluation platform for emerging Cyber Transportation Systems (CTS). Specifically, the work is developing an integrated traffic-driving-networking simulator (ITDNS), which allows for *human-in-the-loop* testing of Connected Vehicle (CV) and Automated Vehicle (AV) applications and their interactions. Following a brief discussion of ITDNS,

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_16,

its design rationale and unique advantages, the chapter proceeds to describe some of the on-going research designed to validate and extend ITDNS. The chapter also briefly describes our recent research which is taking advantage of the *human-in-the-loop* testing capabilities of ITDNS to evaluate a number of CV and AV applications such as eco-signals, Adaptive Cruise Control (ACC), and Co-operative, Integrated Vehicle Infrastructure Control (CIVIC).

Keywords Connected vehicles · Automated vehicles · Human factors · Integrated traffic driving network simulators · Advanced driving assistance systems · Eco-signals · Cooperative adaptive cruise control

1 Introduction

While highway transportation systems provide many indispensable functions to our society, several alarming statistics on road accidents, traffic congestion, fuel consumption and emissions have raised serious concerns over the sustainability of today's highway transportation systems. To address these challenges in next generation transportation systems, several approaches and programs have recently been proposed, among them is the Intelligent Transportation Systems (ITS) concept. Specifically, the latest ITS advances are promising to transform the system into a true Cyber Transportation System (CTS) with increased levels of connectivity among vehicles and the infrastructure (e.g., the Connected Vehicle (CV) initiative) and increased levels of vehicle automation (e.g., automated vehicles (AV) and ultimately self-driving cars).

CVs and AVs are expected to bring about transformative improvements in the highway transportation system's safety efficiency, and sustainability, and reduce long-term costs. However, like any emerging and future designs, technologies, infrastructures, and applications, such applications must be validated and evaluated before they can be implemented and deployed. The need for conducting extensive testing of CV and AV applications is especially prominent because: (1) human drivers or travelers will always constitute a major component of the system and as such, human lives are at stake; and (2) the development and deployment of applications will be evolutionary or incremental and accordingly, in the foreseeable future, vehicles will have a varying degrees of connectivity [with respect to communications between the vehicles (V2V communications), and between the vehicles and the infrastructure (V2I) communications] and automation (with respect to general autonomous driving capability).

While simulation-based studies are a flexible and economical way to evaluate emerging and future designs, technologies, infrastructures and applications of CV/AVs, they lack fidelity and realism. On the other hand, using multiple vehicles instrumented with yet-to-be-proven technologies on the road will not only be costly in terms of time and money, but also risky and inflexible. In either case, the human element also needs to be accounted for. It is therefore critical to have a versatile tool or platform for hybrid simulation and experimentation involving both Hardware-in-The-Loop (HaTL) and Human-in-the-Loop (HuTL) testing.

In particular, in order to enable research related to road safety, traffic congestion and sustainability in CV/AVs, as well as the interactions between human-drivers and automation, such a testing platform should be capable of (i) using a high fidelity and realistic driving environment with e.g., vehicles on real roads (as opposed to closed test tracks) as inputs, (ii) supporting large scale and high density experiments, in terms of the number of vehicles and the size of the geographical area involved; (iii) simulating not-yet-available technologies (such as advanced V2V and V2I (or more generally V2X) communications and networking protocols and applications), and/or rare events (e.g., an extreme event); and (iv) providing a safe, HaTL and HuTL environment for studying road-safety related CV/AV designs, technologies and applications and human-automation interactions.

To the best of our knowledge, there currently exists no instrument having the four main capabilities listed above in any governmental, industrial and academic organizations. For example, the US DOT's latest Naturalistic Driving experiment conducted under the auspices of the Second Strategic Highway Research Program (SHRP2) initiative [1], which represents the state-of-the-art effort in conducting experiments, can offer the capabilities in (i) and (ii) but not in (iii) or (iv). This is because the experiment is using today's vehicles and technologies, and cannot be used to evaluate emerging or unproven CHIVES and AV technologies, which may expose the drivers to risky or dangerous situations. This is also true of some of the latest USDOT's CV test-beds, such as the Safety Pilot experiment currently taking place in Ann Arbor, Michigan [2], and test-beds in New York, California, Virginia, and Florida [3]. While those tests are designed to evaluate the feasibility of wireless V2V and V2I communications, and for evaluating basic CHIVES applications, they are costly and, because they once again cannot expose drivers to undue risks, are limited to testing proven technologies that can be implemented today. In other words, they cannot be used to safely and economically test new, emerging and unproven designs and technologies. Finally, to date, we have not yet seen large-scale field tests of AVs and their interactions with regular traffic.

To address the aforementioned requirements, our research team at the University at Buffalo (UB), the State University of New York (SUNY) has been working on developing a unique integrated traffic-driving-networking simulator (ITDNS) for the design and evaluation of Cyber Transportation Systems (CTS) and Connected Vehicle (CV) applications. The ITDNS is architected to *allow a human driver to control a subject vehicle in a virtual environment* which is capable of communicating with other vehicles and infrastructure with *CTS messages* as well as sending warning messages to the driver. ITDNS combines the main features of a traffic simulator (TS), a networking simulator (NS) and a driving simulator (DS), and therefore may be referred to as an integrated 3-in-1 simulator. The key advantage of the ITDNS compared to previous efforts on the topic is its ability to take into account human responses to proposed CTS and CV applications in a *realistic* yet *safe* environment. Following a brief description of ITDNS, the integration challenges, and the unique advantages, the chapter proceeds to describe current efforts aimed at validating and extending the framework. The chapter then presents some of our on-going research which is taking advantage of the *human-in-the-loop* testing capabilities of ITDNS to evaluate a number of CV and AV applications such as eco-signals, Adaptive Cruise Control (ACC), and Co-operative, Integrated Vehicle Infrastructure Control (CIVIC).

2 Integrated Traffic-Driving-Networking Simulator

Historically, the transportation community has used several distinct simulators, but with no true integration. On one hand, traffic simulators (TS) were used to evaluate the operational efficiency of transportation networks. Driving Simulators (DS), on the other hand, were used to examine the behavior of individual human subjects within a virtual environment typically for driver behavior, human factors and traffic safety type studies. Finally, in recent years and with the interest in CV applications, transportation researchers have also begun to utilize communications network simulations (NS). Each simulator type, when used individually, has its own set of strengths and limitations as described next.

2.1 Rationale for an Integrated Simulator

While TS models are quite effective in simulating the evolution of traffic on large-scale transportation networks and in accurately capturing traffic dynamics, they suffer from a major limitation with respect to evaluating CV/AV applications. That limitation stems from the lack of *driver behavioral realism* in TS models because vehicle movements are idealistic and based on well-known car-following models. Drivers in TS, for example, do not run a red light or get too close to the vehicle in front so as to pose an accident risk. Moreover, the behavior of drivers in *state-of-the-art* TS does not consider their likely response to warning messages provided for example by an Advanced Driver Assistance System (ADAS).

DSs, on the other hand, are quite effective in studying driver behavior in a controlled environment. Their major limitation however, is that the majority of existing DSs lack *traffic network realism*. Background traffic in DSs is often non-intelligent and pre-programmed, and therefore does not respond to the actions of the human driver. This limits the application of DSs to scenarios that involve a single site (e.g., a particular intersection) without substantial neighboring traffic vehicles. Finally, because both TS and DS naturally lack the ability to model the performance of communication systems, Communications Network Simulators (NS) have been utilized in recent studies related to CV applications. NSs are capable of simulating wireless channels and exchange CTS messages among connected nodes. Unfortunately however, they are not designed to simulate the realistic motion of the vehicles themselves, a task which is best handled by a TS.

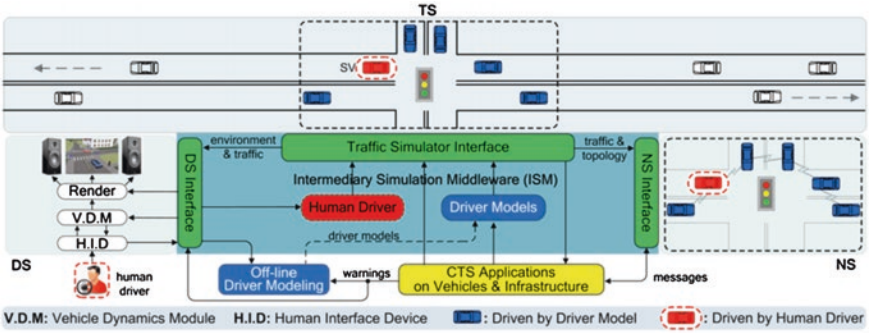

Fig. 1 Architecture of the ITDNS

2.2 UB 3-in-1 Integrated Traffic, Driving and Network Simulator

To address the limitations of the stand-alone simulators and to leverage the advantages unique to each type, our research team, with funding from the National Science Foundation (NSF) Cyber-Physical Program (CPS), has recently developed an integrated simulator which consists of: (1) PARAMICS [4], which serves as the traffic simulator; (2) NS-2 [5], to serve as the communications network simulator; and (3) the University at Buffalo's (UB) driving simulator.

Figure 1 shows the overall architecture of our ITDNS. The integration of PARAMICS and DS is implemented via a two-way data exchange, which allows the actions of the human subject in the DS to be reflected or mimicked by one chosen vehicle in PARAMICS (referred to herein as the subject vehicle). Specifically, the speed, position/orientation, acceleration or deceleration of that subject vehicle would be provided by the human driver in the DS. Overriding the default behavior of the TS is achieved using a plug-in written in C++ and which utilizes several of PARAMICS custom API's. At the same time, the positions, speeds and accelerations of the other vehicles in the vicinity of the subject vehicle are exported from PARAMICS to the DS, to represent the background traffic which the human driver observes and reacts to. Because the positions and speeds of the background traffic are determined by PARAMICS, background traffic in the DS is intelligent (i.e., because it follows PARAMICS car-following model) and reacts to the actions of the human driver.

Simultaneously, PARAMICS and NS-2 are integrated to allow them to run in parallel, by adapting the TraCI interface developed by the EPFL team [6]. In doing so, a complete feedback loop is implemented to send results from the NS back to the TS for further action. This will allow for eventually implementing new driver behavior models within the TS, which reflects how drivers are likely to react to warning messages coming from a CV application for example.

Naturally, integrating the three simulators together was not trivial and faced several challenges. These included: (1) incompatibilities among the coordinate systems used within the different simulators; (2) achieving an acceptable fluid motion of the subject vehicle; (3) rapid communication between the simulators; and (4) allowing NS-2 to handle a large number of fast moving nodes. The details of how those challenges were addressed can be found in one of our recent papers [7].

3 Current Work on Validating and Extending ITDNS

Following the development of the ITDNS described above, the researchers' efforts shifted toward validating and extending the framework, as well as on taking advantage of its unique capabilities to evaluate several CV/AV applications. In this section, we briefly describe some of our recent initiatives aimed at validating and extending ITDNS. The description of the use of ITDNS to evaluate CV/AV applications is the focus of Sect. 4.

3.1 ITDNS Validation

With respect to validation, our effort has focused so far on validating the integrated traffic-driving simulation component of the 3-in-1 integrated simulation environment. The basic premise behind the "validation" study was to compare drivers' performance data collected within the simulation environment to similar performance data collected when the same drivers drive an actual vehicle on the same (physical) roadways that have been modeled within the simulator. To do this, 15 participants were recruited, 11 males and 4 females, ranging in age from 21 to 39 years, with an average of 26.13 years. The validation experiment thus involved two parts: (1) Road Test; and (2) Simulator Test, as described below.

In the road test, participants were asked to drive their own vehicle along a 2.5 mile arterial segment, consisting of a total of 10 signalized intersections, once in the northbound direction and another in the southbound direction. The round trip was then repeated twice, resulting in data from a total of 4 trips/driver (two heading north and two heading south). Each test vehicle was equipped with a Car Chip Pro device [8], which recorded second-by-second vehicle data during the excursion. These included the time stamp, distance traveled, speed, instances of extreme acceleration and braking, and relevant engine parameters (e.g. engine load, fuel pressure, throttle position, and emissions status). As an auxiliary location tracker, a low-cost GPS receiver was also used, which furnished a timestamp, location information and GPS traces at 1 Hz; the location information helped complement the data collected from the Car Chip Pro units.

The same corridor driven by the drivers in the field test was then modeled in great detail in ITDNS. The same group of participants was then asked to drive the same path in the integrated simulator. In an effort to authenticate the driving environment, major structures and landmarks were modeled in great detail, along with road signs and vegetation. During the simulator tests, a variety of useful data (pertaining both to individual driver performance and to vehicle performance) were collected in real-time, and at a high frame rate (i.e., typically 60 Hz). The data channels included the following: elapsed time (seconds), longitudinal vehicle force (i.e., “throttle”) (lb.), vehicle velocity (ft./s), vehicle position (XYZ) (ft.), vehicle heading (degrees), longitudinal and lateral acceleration (ft./s2), front and rear tire slip angles (degrees), and a variety of other output channels.

So far, our validation has focused on comparing the following aspects of driver’s behavior between the real-world and the simulator: (1) the average corridor-level travel time for all 15 drivers; (2) the acceleration and deceleration profiles of individual drivers; (3) the number of lane changes for individual drivers while driving the course of the test segment; and (4) the trip’s energy consumption and vehicular emissions for individual drivers. In general, close agreement between the simulator and field observations can be discerned. We hope to report on the detailed results in a future paper.

3.2 Connecting Multiple Driving Simulators

One extension of ITDNS we are currently working on is the ability to have multiple human subjects, in multiple Driving Simulators, interact with the virtual environment of the TS and NS. The basic idea behind is to choose multiple subject vehicles, within the PARAMIS environment, and to override their behavior based on the actions of the human subjects in the different Driving Simulators. Specifically, the UB research team is currently integrating two driving simulators into the simulation framework, namely the six-degree-of-freedom UB Driving Simulator with motion-based platform and a more basic Driving Simulator hosted on PC. Both of the driving simulators takes the human driver inputs and convert the driver actions into the resulting vehicle dynamics measurements. The resulting vehicle movements are then transmitted to the traffic simulator, allowing the two subject vehicles to mimic the behavior of the human drivers in the simulators.

The aforementioned extension of ITDNS capabilities immediately opens the possibility to investigate the interaction among a number of human driven vehicles, either equipped or non-equipped vehicle. For example, considering the case of an Adaptive Cruise Control (ACC) system, one may investigate the interaction between two humanly-driven vehicles, one with ACC, being followed by a vehicle with no ACC, and how the headway distance between the two vehicles change over time, or what happens when the lead vehicle driver, for example, decides to disengage ACC. Another good candidate application for the extended ITDNS is the study of the interactions between vehicles with varying degrees of connectivity and automation, and issues related to the stability of the traffic stream, and overall system efficiency and safety.

4 ITDNS Applications

Since the development of the prototype ITDNS has been completed, we have been taking advantage of its unique capabilities, and in particular its *human-in-the-loop* simulation capability in several research studies related to CV/AV applications. In this section, we will briefly review two of those studies which focused on evaluating: (1) an eco-signal application; and (2) adaptive cruise control. The two studies are currently still in progress.

4.1 Eco-Signal Application

One of the first applications to which we applied ITDNS is an evaluation of the likely benefits of the eco-signal concept. Eco-signals are designed to provide vehicles approaching a signalized intersection with an advisory speed which allow them, if possible, to arrive at the intersection on green, thereby avoiding the need to stop at the intersection [9, 10]. The unique aspect of our study, however, was that, thanks to the *human-in-the-loop* capability of ITDNS, we were able to explicitly account for driver reaction to the advisory speed and to assess the likely fuel and emissions savings resulting from a humanly-controlled approach speed trajectory.

Based on experimenting with a rather small sample of drivers, the preliminary results indicate the potential of the eco-signal concept to result in tangible reductions in fuel consumption and emissions, even when manually implemented (i.e., when the approach speed is controlled by the human driver in response to the advisory speed provided by the application). Specifically, depending upon the aggressiveness level of each driver, our results indicated savings between 4 and 14 % in fuel consumption, between 6 and 35 % in Carbon Monoxide (CO) emissions, and between 6 and 42 % in Nitrogen Oxides (NOx) emissions. The average savings for the sample of drivers tested were 9 % for energy consumption, 18 % for CO and 25 % for NOx.

4.2 Adaptive Cruise Control

Traditional cruise control (CC) has been a standard driving assist package available on most modern automobiles for at least three or four decades. Recently, Adaptive Cruise Control (ACC) was proposed as a more advanced form of CC that utilizes dynamic control logic, rather than a static speed pre-set by the driver. In ACC, the speed control takes into consideration a desirable headway, which can be measured in terms of the distance or time from the host vehicle to the rear bumper of the leading vehicle (this can be measured using Radar/Lidar technology). Then, the ACC intelligence can dynamically adjust the cruising speed according to the trajectory of the vehicle in front, i.e. braking or accelerating. As a further advancement, Co-operative Adaptive Cruise Control (CACC) was most recently proposed. By taking advantage of vehicle connectivity (i.e. wireless communication among the vehicles), CACC can allow an equipped vehicle to "see" further downstream, and to base its acceleration and deceleration not only on information about only the vehicle right in front, but to take into account the vehicle trajectories of several vehicles ahead, resulting in a significantly improved string stability [11]. Despite the differences among CC, ACC and CACC, they all share one common feature, which is that the human drivers are kept in the driving loop by controlling the vehicle orientation via the steering wheel.

Besides the improved driving experience, comfort level and reduced work load of the driver, ACC and CACC have an additional benefit which stems from their potential to dramatically reduce the vehicle headway from an average of 2.0 to 0.5 s. This in turn could result in significant increases in roadway capacity, without additional infrastructure capital investment. However, the reduced following distance immediately raises the question of road safety, and whether drivers and passengers would feel comfortable with such low separation headway values. We have recently attempted to provide insight into that question by taking advantage of the unique capabilities of our ITDNS as explained below.

4.2.1 Experimental Design

As just mentioned, the objective of this research was to address the human factor issues in ACC and CACC deployment, including issues such as the comfort and confidence level of the driver, the workload, and safety concerns of having the car manage the longitudinal movement. Given the exploratory nature of the study, a simplified ACC module was coded with Paramics API to replicate ACC functionality in the ITDNS. The design works as follows:

1. If the time headway is less than the desirable headway, the target speed is set to the speed of the preceding vehicle plus a catching speed ΔV (bounded by the speed limit);
2. Based on (1), the next time step speed, V_{i+1}, is then set to the current speed V_i plus an acceleration rate (bounded by maximum rate for a comfortable operation) to achieve the target speed value.

The process stops if the headway falls into the range of desire headway ± acceptable margin. A similar procedure is applied to the decelerating scenario.

Our preliminary study proceeded in two phases. In the first phase, a total of nine headway and speed combinations were set up for evaluations; these combinations corresponded to three time headway levels (0.5, 1 and 1.5 s) and three speed categories representing rural and urban traffic (25, 45, and 65 mph). Thirty test participants were then asked to operate the driving simulator with ACC mode on for 2 min and then filled out a questionnaire afterwards regarding the workload, confidence, safety, comfortable and acceptance level for each speed and headway combination. Specifically, the questionnaire included questions on:

Table 1 Means (standard deviations) of driving variables on CACC and desire headways

Speed (mph)	25			45			65		
Headway (s)	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5
Workload	6.6 (3.0)	3.6 (2.7)	1.8 (2.0)	6.1 (2.5)	2.8 (2.3)	1.7 (2.3)	5.5 (3.0)	3.2 (2.4)	2.0 (2.1)
Confidence	3.9 (2.5)	6.9 (2.1)	8.6 (1.5)	4.1 (2.5)	7.4 (1.9)	8.9 (1.2)	4.4 (2.8)	7.1 (2.1)	8.6 (1.6)
Comfort	3.4 (2.7)	6.8 (2.2)	8.3 (1.6)	4.1 (2.6)	7.3 (1.9)	8.6 (1.0)	4.4 (2.9)	7.2 (2.1)	8.3 (1.5)
Safety	3.4 (2.7)	6.8 (2.3)	8.6 (1.6)	3.8 (2.6)	7.3 (2.0)	8.8 (1.2)	4.2 (2.8)	7.1 (2.0)	8.5 (1.4)
Acceptance	3.5 (3.1)	6.8 (2.4)	8.5 (1.6)	4.5 (3.2)	7.6 (2.1)	9.0 (1.0)	4.7 (2.9)	7.2 (2.3)	8.3 (1.7)
Headway (s)	1.26 (0.57)			1.12 (0.47)			1.17 (0.65)		
Distance (ft)	52 (21)			72 (31)			113 (61)		

1. Workload when the car was controlled by the intelligent speed-control;
2. Confidence in the intelligent speed-control not leading to a collision;
3. Comfortable level using the intelligent speed-control system;
4. Safety level with the intelligent speed-control system;
5. Overall acceptance of the intelligent speed-control system.

In the second phase of the experiment, the drivers had the freedom to set their own desirable headway under the same three speed setups (25, 45 and 65 mpg). The headway was made to be adjustable by pressing a button on the dashboard in a similar fashion as a general cruise control. The desirable headway values were then collected from the simulator trace file.

4.2.2 Preliminary Results

The results from the two phases of the experiment are summarized in Table 1 below. Specifically, the first or upper section of the table gives the mean and standard deviation (the number in parenthesis) of the responses solicited from the 30 subject drivers. For each question, the driver was asked to indicate the level of the workload, confidence, comfort, safety, and acceptance on a scale from 1 to 10, with 1 referring to very low and 10 referring to very high. The lower section of the table gives the average value for the desirable time and distance headway as set by the 30 drivers for the three speed levels of 25, 45, and 65 mph.

As can be seen, for all speed levels, the level of confidence, comfort, feeling of safety and acceptance increased with the increase in the headway value from 0.5 to 1.50 s. At the same time, the work load level decreased accordingly. Specifically, participants do not appear to be comfortable with the 0.50 s headway, where, as can be seen, was only in the 3–4 range. Headways of 1.0 and 1.5 s were generally associated with much higher comfort, confidence and acceptance levels.

With regards to desirable headway investigated in the second phase of the study, a consistent range of between 1.1 and 1.2 s were observed for all three speed settings (i.e. 1.26, 1.12 and 1.17 s); these corresponded to space headways of 52, 72, and 113 feet respectively for the cruise speeds of 25, 45 and 65 mph. This suggests that the test drivers tended to have a consistent desirable time headway, regardless of the speed. Moreover, it should be noted that the desirable headway of approximately 1.2 s is significantly higher than the 0.5 s headway assumed in some previous work related to CACC. This finding thus seems to indicate that it might take time for drivers to feel comfortable operating at such short headways.

5 Conclusions

This chapter has reviewed recent and on-going research at the University at Buffalo aimed at developing next generation research, development, testing and evaluation (RDT&E) platforms for CV and AV applications. Specifically, the chapter described the development and rationale behind an Integrated Traffic, Driving and Network Simulator, whose unique advantage stems from its ability to take into account human response to new and emerging applications, while at the same time ensuring a safe and secure environment. The chapter has also describes some of the researchers' recent efforts aimed at validating and extending the developed platform. Finally, a quick review of two research studies which utilized the integrated simulator was provided. The first study focused on assessing the likely environmental benefits of eco-signals where the speed of the approach vehicle is humanly controlled, and demonstrated the potential for such an application to yield tangible benefits. The second study, on the other hand, evaluated the comfort, confidence and acceptance level of users of ACC when operating at different time headways and at different speeds. The preliminary findings of that study seem to indicate that it may take time for drivers to get used to operating at the low headway values which may be possible with CACC.

Acknowledgements This work was supported in part by National Science Foundation of USA CPS Program (Grant No. NSF-CPS-1035733) and the Cisco University Research Program.

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Evaluation of Automated Road Vehicles

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Abstract In the past years various partially automated driving functions have been introduced on the market. More advanced functions are currently in research. By means of these functions partly automated driving in specific driving situations is already realized, e.g. a traffic jam assist performs longitudinal and lateral control at low speeds. Besides the technical challenges to realize automated driving in complex driving situations, e.g. intersection areas, new approaches to evaluate these functions under different driving conditions are necessary, in order to assess the benefits and identify potential weaknesses. In this context, this chapter describes a systematic approach to evaluate road vehicles with automated driving functions. The presented approach is divided into a technical, a user-related and an impact evaluation.

Keywords Evaluation · Technical assessment · User-related assessment · Safety impact assessment

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_17,

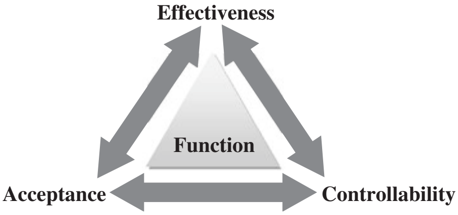

Fig. 1 Conflict of fundamental criteria for the evaluation of ADAS [8]

1 Motivation

Already in the early 20th century the idea of automated driving vehicles was developed. A first step towards vehicle automation was the introduction of cruise control in the Chrysler Imperial as the so called “auto pilot” in 1958 [1]. This mechanical system was able to keep a constant velocity, set by the driver, and therefore was able to partly take over the longitudinal vehicle control on a motorway. The focus of such early systems was clearly to increase driving comfort.

With the development of micro electronics and the introduction of computer controlled systems the possibilities to realize a further step towards automated driving was given in the last quarter of the 20th century. ADAS (advanced driver assistance systems) were introduced into the market in order to provide additional comfort and support the driver in the driving task. Besides, the improvement of passive safety the development of ADAS and active safety systems increased road safety. The first statistically significant proof of the high safety potential of the driver assistance system ESC (Electronic Stability Control) is based on German accident data [2]. Adaptive Cruise Control (ACC) and brake assistance also show an accident reduction potential of 20 % within a study of 800 vehicle collisions according to [3].

Besides ADAS, research on completely automated driving functions has been ongoing for many years. Within former research projects many prototype vehicles have already been built up and tested (e.g. VAMP [4], NavLab5 [5], ARGO [5] etc.). Most recently an increase of research activities in the field of automated driving is evident, mainly triggered by publications on the activities of Google and their so called Google Cars [6].

However, these advanced technologies require new approaches to evaluate the benefits and weaknesses. The evaluation of ADAS needs to consider the conflicts between the fundamental criteria acceptance, effectiveness and controllability, see Fig. 1 [8]. Additionally the requirements of functional safety defined in the ISO standard 26262 [10] need to be fulfilled.

The full evaluation process for these systems is complex and requires further research. So far research on the aspect of controllability has produced guidelines in terms of a Code of Practice [9]. The application of these guidelines is mainly driven by product safety.

An overall evaluation process for automated driving functions needs to provide an effective process, combining a defined number of interconnected evaluation methods, which are also in accordance with ISO 26262. The functional

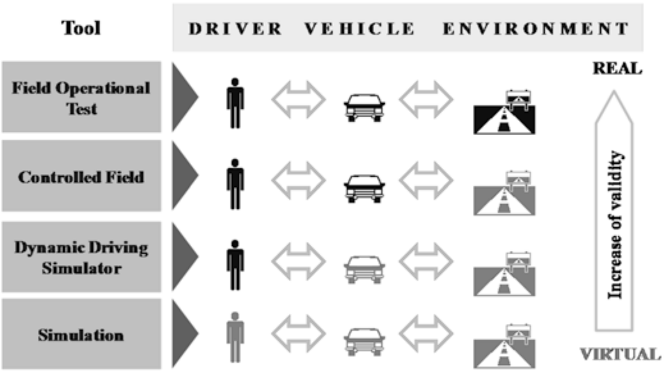

Fig. 2 Classification of evaluation methods (*grey* virtual elements; *black* real elements) [7]

safety requirements on automated driving need to be fulfilled by these methods. Especially the driver-vehicle interaction demands new methods and approaches.

Within this chapter an ideal evaluation approach for ADAS is presented in a first step. Since the final sign-off requires real world data today, this approach cannot be directly applied for higher degrees of vehicle automation. Taking this into account, the requirements for the technical and user related evaluation of automated driving functions are derived. An evaluation process for automated driving functions is proposed and discussed, which includes the systematic evaluation of acceptance, effectiveness and controllability. An additional focus is on the safety impact of such automated driving.

2 Evaluation Approach for ADAS

While ISO 26262 largely focuses on controllability as fundament for functional safety, Fig. 2 shows that the system's effectiveness and the resulting acceptance are equally important but conflicting with each other. An ACC functionality, for example, which maintains a rather large distance to the preceding vehicle, is easily controllable in case of a failure, but won't be well accepted due to other vehicles cutting in, which reduces system use and thus its effectiveness. An integrated and well accepted evaluation approach taking into account all three criteria for ADAS does not exist as of today. Guidelines and restrictions in form of single measures exist in order to ensure a certain safety standard in terms of functional safety and controllability.

The existing evaluation methods can be classified into four different levels with different validity. These levels range from complete virtual evaluation in traffic simulations to full real world evaluation in Field Operational Tests (see Fig. 2). The main elements of a traffic system, namely the driver (and all interactions between the driver and the ADAS), the vehicle (and especially the impact of the ADAS) and the environment (the interaction with other traffic participants in different driving situations) can either be simulated or represented in reality.

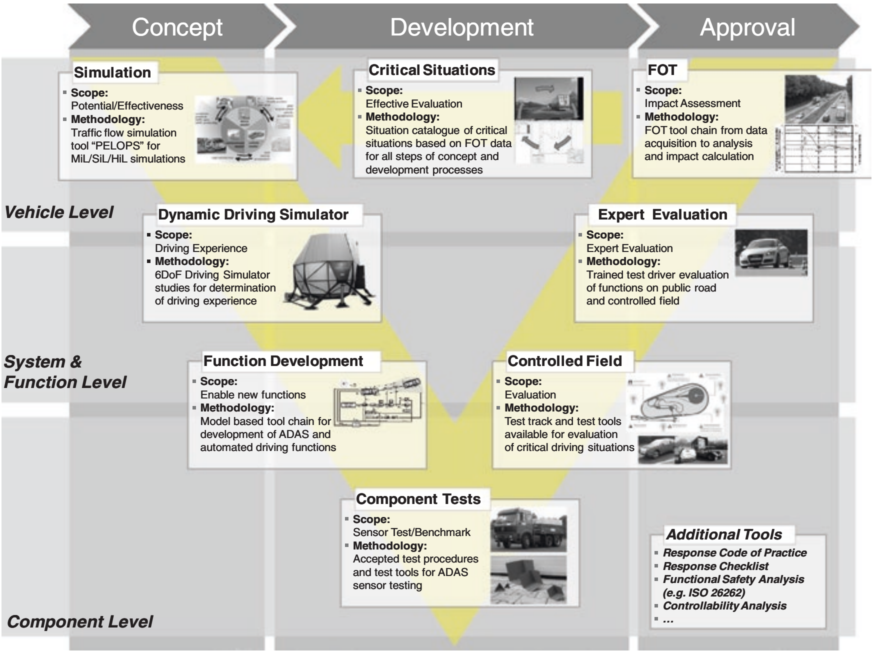

Fig. 3 A modular approach for ADAS development and evaluation methods over different stages of the product development cycle [11]

Figure 3 describes an ideal modular approach of these different methods for a consistent and modular evaluation approach for ADAS over different stages of the product development cycle.

Technical potentials as well as the analysis of accident statistics and upcoming market needs form the basis for new ideas for ADAS or other safety functions. Already in an early process stage traffic simulation tools allow a first effectiveness assessment of the tested function and can support the work of experts on the design. The driver vehicle interaction and especially the controllability are analyzed in driving simulator studies with naive subjects and focus groups. Based on the results the overall design may be specified and the necessary control algorithms are developed in detail. The requirements for the system architecture and the components are fixed on the basis of functionality, controllability and functional safety. The suppliers and their components are selected and integrated in prototypes. These are tested by expert drivers on test tracks under various conditions and in controlled field experiments with naive subjects in order to validate the results of the development process. Before system approval a significant amount of real world data may need to be collected in Field Operational Tests depending on the specific function. This driving data aims to prove the availability and reliability of the function and the effect of false positive and false negative system behavior.

Moreover the real driving data allows identifying a large spectrum of critical driving situations, which are crucial for a first safety assessment by traffic simulations. By providing catalogue of critical driving situations new evaluation possibilities within the concept and development steps are introduced. This catalogue allows a more detailed safety assessment of the tested function at an early stage.

3 Requirements on the Evaluation of Automated Driving

The available evaluation methods were developed primarily for the evaluation of ADAS functions, which considers mainly only a low degree of automation. Thus, it is necessary to adapt and extend the existing methods to the new requirements on the evaluation of automated driving functions.

According to NHTSA automated driving is divided into five different levels of automation [12]. Hence, the evaluation of automated driving needs to consider all requirements of the different automation levels. In the following the different levels of automation defined by NHTSA are presented.

Level 0 **No-Automation**: The driver controls the primary vehicle controls at all times.
Level 1 **Function-Specific Automation**: Automation at this level involves one or more specific functions. (e.g. ESC or ACC).
Level 2 **Combined Function Automation**: This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions (e.g. traffic jam assist with lateral and longitudinal control).
Level 3 **Limited Self-Driving Automation**: Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time (e.g. Google Cars [6]).
Level 4 **Full Self-Driving Automation**: The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. The driver might provide navigation input, but he or she is not expected to control the vehicle at any time during the trip.

As a first step the differences between the evaluation requirements for low level automation—considering mainly current available ADAS functions—and high level automation functions were identified. Based on the results necessary adaptations on the existing method as well as additional steps were derived. The differences between both evaluation methods for selected comparison criteria are shown in Table 1.

The main differences between both automation levels (low/high) results from the operation time the driver involvement as well as the description of single use cases. These differences will lead inevitably to a change in the focus of the evaluation method.

Table 1 Difference between different levels of automation

Criteria	Low level automated driving	High level automated driving
Automation level	Level 0–1 (considering today's ADAS functions)	Level 2–4
3 layer model [13]	Acting on the guidance and stabilization level	Acting on the guidance and stabilization level. (in level 4 also on navigation level)
Use cases	Clearly defined by either accidents cases or relevant driving situations (e.g. ACC—approaching slower vehicle)	Complete driving process. Certain situations are not clearly described. For lower automation level (level 2) only general restrictions of operation regime exist (e.g. traffic jam assist only on motorways and up to a certain velocity)
Operation time	Dependent on function: • long operation time (t > 10 s) for e.g. ACC • short operation time (t < 10 s) for e.g. Autonomous Emergency Braking systems (AEB)	Function operates over a longer time period (t > 10 s)
Control by driver	Driver needs to be in control	Depends on level of automation. The range goes from observation of the function (level 2 and 3) to no driver interactions needed (level 4)

The identification of the relevant driving situations to evaluate the tested function is a key research area for all evaluation areas. Limitations with respect to resources—time as well as budget—must be considered. It is questionable that all relevant driving situations can be determined by real world tests. According to [7] real world testing of automated driving function would require a total driving distance of 5.6 light minutes (=100.8 Million km) with costs over 100 Million EUR. One approach to overcome these issues is the "circuit of critical situations" approach as introduced in [8], by means of providing a situation catalogue of critical driving situations.

Figure 4 illustrates the principle idea of collecting hundreds of critical situations during field operational tests and the usage afterwards in traffic simulations and other methods.

Furthermore, the extended system operation time as well as interaction between different functionalities must be considered in the evaluation. Due to longer operation times especially tests related to "false positives" and "false negative" behaviour of the function will become a key aspect for evaluation, since it must be ensured that the function works properly.

In the user-related assessment acceptance and user behaviour (in particular controllability) will continue to play an important role. The interaction between driver and system will become less important while the system is active with increasing degree of automation. However, the transition phases, in which the driver releases the control to the system respectively vice versa, regain significant importance.

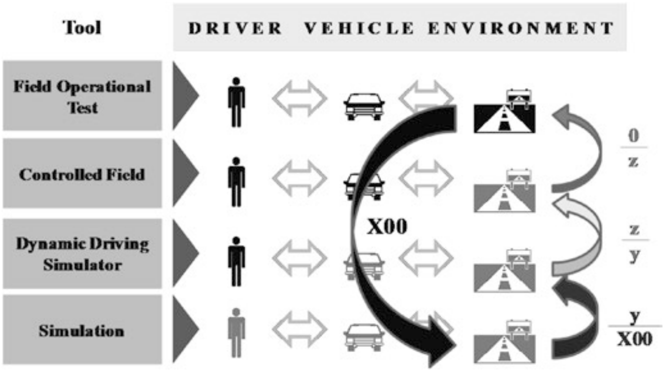

Fig. 4 Feedback of critical situations by the "ika-Circuit of critical situations" [7]

In the following the method for the evaluation of automated driving functions are described in detail.

4 Evaluation of Automated Driving Applications

The known methods for the evaluation need to be adapted to the new requirements on high automated driving. These adaptations are described for the main evaluation areas, which are:

- Technical evaluation
- User-related evaluation
- Impact Assessment

4.1 Technical Evaluation

The technical evaluation focuses on the analysis of the technical performance of the function under study or its components with respect to the defined requirements or use cases. For low level automation the technical tests are carried out on test tracks or public roads since the relevant situations are clearly defined.

High level automated driving functions do not fulfill this pre-condition. The test efforts need to be limited to an acceptable amount. This requires consideration of new evaluation concepts. Especially virtual evaluation with sophisticated simulation tools needs to be applied. The tests require simulation tools that can represent the real environment, at least up to a certain extend. This requires detailed simulation models vehicle (including e.g. actuators and sensors) as well as the environment (traffic, weather etc.) and to a certain extent the driver behavior. These models as well as the overall simulation chain need to be validated by means of real world tests, before it is applied.

These virtual tests drives can be used in two ways. The obvious approach would be to replace some of the real tests drives or even most of the tests by the virtual tests. In this case the same tests would be conducted in the virtual environment as in the real world. The second approach focuses on the identification of the most relevant situations for the tested function. These situations could be tested afterwards within the real world tests. In this sense the virtual tests are used to reduce the test amount within the real world tests. By this approach the requirements on the simulation models can be reduced, as a replacement of real world tests is not foreseen. Today, first prototype solutions such as the micro-simulation tool PELOPS [14] already exists, which take into account a high number of relevant driving situations.

4.2 User-Related Evaluation

The user-related evaluation of highly automated driving functions implies similar challenges as the evaluation of today's ADAS functions, e.g. acceptance of the systems' features and the usability of the interface design. However, special challenges regarding the user might be found in the drivers' reactions to mode transitions and in the long-term effects of fully automated driving (level 4).

Mode transitions are the only driver input available when evaluating an automated driving function. As was suggested for the observation of workload by [15], permanent surveillance of the drivers' state might be necessary to ensure the drivers' ability to react to a possible mode transition from automated mode to manual mode in critical situations. However, the most critical point regarding the driver in an automated vehicle is the successful mode transition in itself. Thus, higher efforts on the HMI are required, in order to inform and possibly warn the driver in due time in case of a system failure or a necessary mode transition.

A successful driver reaction to an announced mode transition needs to undergo different levels. These could be based on the levels differentiated in the decision making process as described by [16], i.e. situation awareness, decision and performance of actions. The first necessary step in mode transition might be described here as the orientation stage where the driver needs to perceive and process his current environment after an announced mode transition. The second level, following [16], might be called the decision level, in which the driver needs to decide which action is required to solve the situation, i.e. response selection in a very general sense, as well as which operator is to be used to interact with the vehicle. Finally, on the reaction level, the requirements to react are established, i.e. contact to the appropriate control element is made, and the decided reaction is executed. A system that reliably guides the driver through the, however unlikely, process of taking back control needs to consider the following aspects:

1. Due to taking the driver completely out of loop, drivers will need additional time to gain insight into the current driving situation, i.e. accomplish the orientation stage, which is necessary to conduct an adequate reaction. When giving only part

of the driving task away, for example longitudinal control, drivers will nonetheless be aware of the current situation as they still need to actively participate in the driving task in one way or the other. Thus, the orientation stage might be accomplished faster with such systems, leaving more time after the signal for the two following stages than when the driver is taken completely out of the loop.

2. To keep the time needed for a mode transition as short as possible, simple warning signals might not contain enough information to quickly lead the driver back into the driving task, particularly in situations that are more critical as the average driving situation and require an adequate and fast execution of a rather unpractised driving manoeuvre. Systems will thus need to find a trade-off between action preparation through information and avoidance of posing excessive cognitive demands on the driver, i.e. the system needs to simplify the decision process. Furthermore, the decision level might simultaneously be facilitated by priming the appropriate control element or action.
3. System failures should occur only at very low frequencies. Thus, expectation of a faultless system might occur. The drivers' awareness of possible mode transitions should therefore be enforced by the system and signals used by the system need to be fully understandable from first contact on.
4. The system should survey the drivers' state at all times ensuring that he is able to safely resume the driving task, e.g. when the driver is momentarily engaged in a non-driving related task [15]. Otherwise, the system should include precautions if the drivers' state is not fit for mode transitions. Thus, each system should be tested with use cases of different drive-length to include effects of prolonged driving time in automated mode into the evaluation.

The second challenge seen in automated driving is concerned with the long-term effects of automated driving. This is mostly true for systems taking over the driving task not only in specific situations, e.g. traffic jam assist, but for all or most situations. If drivers do not practice their driving skills on a regular basis and are only needed to challenge worst-case scenarios which the system is not able to handle, an insufficient decision- and reaction-basis for a successful mode transition may be the consequence. These long-term effects are difficult to test apart from in large field operational tests. However, as frequent use of automated driving systems increases, long-term effects need to be evaluated to ensure a safe functioning of systems.

4.3 Impact Assessment

Within the impact assessment the benefits of the systems on safety, traffic efficiency and environment are analyzed. For today's ADAS functions (low level automation) environmental effects are analyzed by means of traffic flow simulations in order to consider longer driving periods. The differences between ADAS and high level automated driving function in certain driving situations are less relevant for the analysis and similar approaches can be applied. Traffic flow simulations are used to identify how the traffic flow is influenced by the automated driving functions. Precondition is an appropriated modeling of the vehicle, automated system as well as environmental aspects. Furthermore, an important aspect is that different user groups will benefit in different manners. Hence, also the users as well as their usage frequency of the automated function must be defined and considered.

For the safety impact assessment different methods are known as of today [17]:

- Safety mechanisms [18, 19],
- Neural network [20],
- Accident reconstruction [21, 22], and
- FOT data analysis [23].

Most of the methods only consider certain accident scenarios in the safety impact assessment. The exception is the FOT data based approach that focuses on the analysis of the frequency of critical driving situations respectively accidents on public roads. However, the drawback of this approach is the need of high resources and that the approach is often not feasible at early stages of the development process—since several prototype vehicles are required it is usually performed only at the end of the development process. For the other methods, as they are applied today for ADAS functions, no impact on the overall traffic flow or the frequency of not explicitly by the functions addressed accidents is presumed, due to the short intervention time of the systems (e.g. collision mitigation system). Further research is needed whether this assumption is still valid for functions with a higher degree of automation. In particular the more frequent occurrence of certain accident types due to the combination of automated and manual traffic needs to be analyzed.

One possible approach to overcome the analysis is the utilization of traffic flow simulations also for determination of the effects of the function on traffic safety, as described in Fig. 5 and [24].

This approach analyzes the potential safety effects of a function on two levels, in a larger traffic scenario as well as in a certain relevant situation.

Therefore, first the function under study is simulated in a larger traffic scenario, which considers a higher number of vehicles in a road network. This traffic scenario needs to be validated with respect to the frequency of relevant situations. The frequency of the relevant situation should be the same or at least similar to the real world. Relevant situations in this context are accidents or critical situations close to an accident. The reason for considering critical situations as a surrogate measure results from the low number of accidents in real world tests. Changes in the frequency of the relevant situation can be detected considering the tested function in the simulated traffic scenario. The impact of a function in a certain situation still needs to be determined separately. Therefore, a comparable approach to the accident reconstruction method is used, as described in [21] or [22]. These situations can also be varied by means of e.g. Monte Carlo simulations [25] in order to take all possible variations into account.

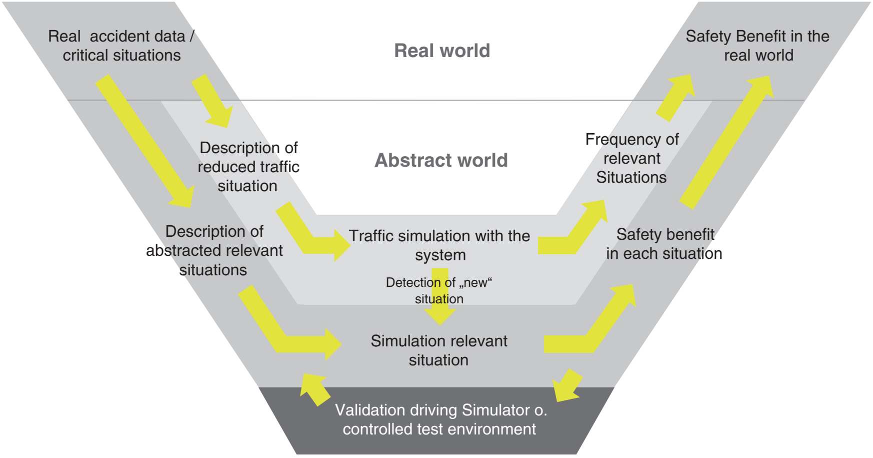

Fig. 5 Structure of the safety impact assessment process for ADAS with high degree of automation [24]

5 Summary and Outlook

This chapter describes the challenges as well as possible solutions for the evaluation of automated driving functions. Starting from the existing evaluation process for ADAS, requirements for the evaluation of automated driving functions have been derived based on the difference between the different automation levels (low/high). In the second step possible approaches for the technical, user-related and impact assessment were described, in order to fulfill the new requirements. Thereby, the main issue is to identify the relevant driving situation, since the high automated driving function will take over vehicle control for a longer time period.

As a next step the presented method will be applied for the evaluation of the developed automated driving functions in the European research project AdaptIVe. In this project automated driving functions for different speed ranges for parking, urban and highway situations are developed.

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Advanced Intersection Traffic Control Strategies Accommodating Autonomous Vehicles

Douglas Gettman, Jason Castillo and Lisa Burgess

Abstract The traffic management and control industry is about to undergo a major paradigm shift as autonomous vehicles start to enter the vehicle fleet. Autonomous vehicles will *revolutionize* the way we travel and will be a major, if not the major, contributor to driving the number of worldwide fatality crashes to zero. Traffic signal operations need to change to accommodate this, and priority operations can be developed that will improve service for autonomous vehicles. Priority service for autonomous vehicles can help facilitate their adoption. The time for this development is now; all the technologies are existing with only demonstration needed to transform vision to reality.

Keywords Infrastructure · V2X · Signal priority · Traffic management

1 Autonomous Vehicles and Traffic Signal Operations

The traffic management and control industry is about to undergo a major paradigm shift as autonomous vehicles start to enter the vehicle fleet. Autonomous vehicles will *revolutionize* the way we travel and will be a major, if not the major, contributor to driving the number of fatality crashes to zero worldwide. There are a variety of potential systems and technologies that may evolve as the technology matures, business models develop, and legal and liability issues are addressed.

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_18, © Springer International Publishing Switzerland 2014

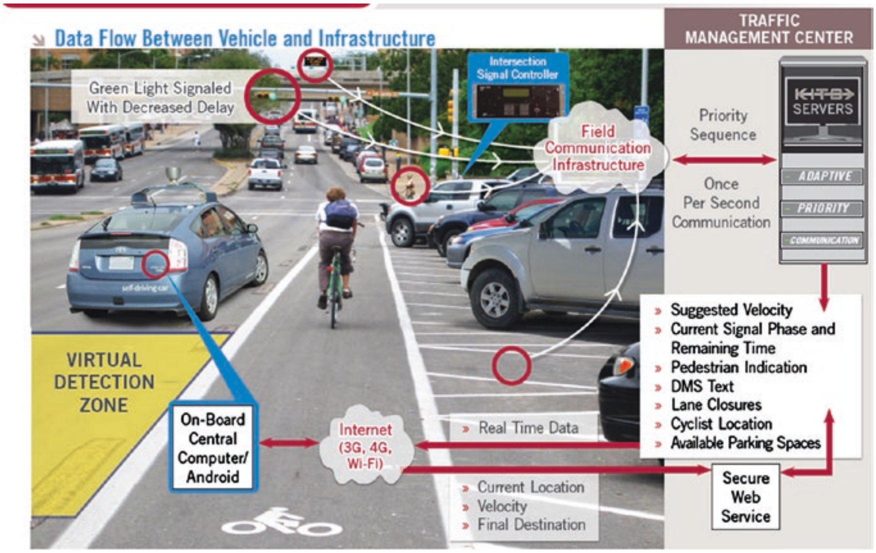

Fig. 1 Integration of autonomous vehicles with infrastructure

Each potential future reality may result in very different needs and requirements of control and management systems.

There are more than 350,000 signalized intersections in the United States. Existing controllers range from mechanical units to modern Advance Traffic Controllers (ATC). The majority of these devices have a deployment life of approximately 20 years. This means that about 17,500 controllers are replaced annually and about 2,500 new signals are added each year. To achieve the US DOT vision of safe and efficient transportation systems a new generation of traffic signal control algorithms and controllers need to be developed to support emerging technologies such as Autonomous vehicles. The progress of research in autonomous vehicles has been particularly accelerated in the last few years as evidenced by the recent laws passed in Nevada and California making autonomous driving legal on their State highway systems.

The USDOT Connected Vehicles program and associated V2X programs in Japan and Europe provide the foundation for interactions between traffic controllers and vehicles. Much of the underlying technology, messaging, and associated functionality will remain unchanged whether or not the vehicle is Automated or driven by a human. It can easily be envisioned, however, that autonomous vehicles provide additional opportunities for synergy as well as challenges to traffic control and system operation.

Figure 1 illustrates the concept of continuous, real-time connection from ATMS systems to autonomous vehicles.

There have been some re-examinations of how traffic signal control can operate with specific considerations for the information-rich environment provided by

Connected Vehicle capabilities, such as the TMC Pooled Fund Study MMITS [1], demonstration projects by USDOT at the UMTRI Safety Pilot [2], and a variety of research at leading Universities in the US and abroad [3, 4]. Very little of this research has made any distinctions between autonomous vehicles and human-driven vehicles. Autonomous vehicles may be able to provide better information to the signal controller. In particular, perhaps when multiple passengers share the same vehicle it will be less contentious to publish the vehicle's destination to the traffic management system.

1.1 What Could Traffic Control Systems Do with Data From Autonomous Vehicles?

With detailed data on traffic delays, vehicle trajectories, intended maneuvers, destinations, break-downs, and other information coming from connected autonomous vehicles, safety and operational efficiency improvements can be incorporated directly into the traffic control process. Autonomous vehicles rely on sensor systems of various types to provide the inputs that human drivers acquire through our eyes, ears, fingers, and bodies and synthesize into information. The human's ability to fuse information from multiple sources is unparalleled by computer systems to date. Take for example the challenge presented by four vehicles arriving virtually simultaneously at a four-way stop-controlled intersection. Human drivers negotiate the travel order using a combination of eye contact, hand signals, and vehicle movements (or lack thereof). Autonomous vehicles may be challenged to negotiate such situations. Interactions with pedestrians, cyclists, and permitted left turns offer similar challenges for autonomous vehicles that are negotiated by the human relatively easily by the human brain's sophisticated "sensor-fusion" wetware. There are likely many modifications to the built environment that can facilitate better autonomous vehicles performance in parking, searching for parking, negotiating signalized intersections, downtown areas, and so on.

1.2 What Could Autonomous Vehicles Do with Better Traffic Controls?

New traffic management strategies, intersection designs, striping, signalization, displays, communications, and other technological changes will be able to facilitate more rapid deployment of autonomous vehicles. With the enormous payoffs that autonomous vehicles present, it is in our national and worldwide interest to begin to prepare our traffic management systems and devices for autonomous vehicles rather than to react to their widespread deployment after the fact. The basic first steps for improved traffic operation are to provide autonomous vehicles with priority service at traffic signals. This could improve their adoption into the vehicle fleet and transform a city into an “autonomous vehicle friendly” city.

The time to undertake these efforts to develop advanced traffic control strategies is now, rather than later, to help shape the design and implementation of infrastructure, communications, and associated technologies to provide the maximum benefit to the motoring public as autonomous vehicles become a reality in the very short near-term. These new traffic signal control systems will achieve significant and substantial improvements in safety and efficiency at the intersection for both the autonomous vehicle and other system users.

Development of a new concept of operations for traffic control that considers the unique needs of autonomous vehicles as well as considering the unique information that autonomous vehicles can contribute:

- Route that the autonomous vehicle plans to take
- Vehicles obey all speed laws
- Vehicles obey all traffic signs.

2 Exploratory Research Should Consider Phased Implementation

It will be important to consider control strategies that take advantage of the fact that autonomous vehicles will be phased into the vehicle fleet over time. Perhaps early on it can be a premium service to get priority operation at a traffic signal. In the longer term, mileage-based user fees may replace gasoline taxes and similar “priority fees” could be charged to autonomous vehicle operators for improved traffic signal service. Similarly, since the infrastructure could know where the autonomous vehicle is headed and which route it is taking, operation algorithms for coordinated and grid systems of traffic controllers can be developed to provide priority on a route.

Advanced and exploratory research is needed to develop these traffic control strategies that consider Autonomous vehicles and infrastructure, now rather than later with field test beds and cooperative agency-operators, including on private campuses. The center to field infrastructure and field to autonomous vehicle infrastructure is easy to accomplish without huge investments in equipment—only software systems are needed and basic ubiquitous cellular coverage. Traffic control applications can be developed quickly that will make autonomous vehicles driving much more reliable, efficient, and safe. The developed algorithms, signal displays, and other control aspects can revolutionize the traffic control process, improving efficiency of operation by a “quantum leap” forward and enabling more rapid adoption of autonomous vehicle in the world-wide goal towards zero fatalities and order-of-magnitude reductions in injuries and other effects of traffic crashes.

3 Conclusion

We suggest the next transformative technology that will shape the future of transportation, and society in general, will be the autonomous vehicle. Many dreams of more efficient traffic management systems will be realized when it is possible to share data between the vehicles and the signal control system and the vehicles will respond as expected or directed. The reduction in fatality and injury crashes will facilitate smooth traffic flows that will reduce commute time reliability and increase productivity. Technologies exist today to begin to develop and test these schemes by integrate traffic management control systems with automated vehicles and preparing our infrastructure for the future of personal mobility.

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Synergies Between Vehicle Automation, Telematics Connectivity, and Electric Propulsion

Steve Marshall and John Niles

Abstract Vehicle automation is one of three broad categories of emerging and disruptive technologies that have the potential to fundamentally transform surface transportation. The other two are the emergence of practical and commercially viable electric vehicles, and the constellation of innovative ways to connect vehicles to the Internet, other vehicles, infrastructure, and data. Each of these new technologies taken alone represents an important advance in surface transportation. Taken and deployed together these three technologies can resolve the major objections to current vehicle technology and address the objections some have to individual components of each of the three main emerging transportation technologies.

Keywords Vehicle automation · Autonomous vehicles · Electric vehicles · Telematics · Vehicle safety · Demonstration project · Petroleum · Energy management

1 Introduction

One of the potential obstacles to large-scale and rapid deployment of self-driving vehicles in the United States is an underlying concern among policy makers that this technology will encourage more frequent use of single occupant cars, less use of alternatives and thus more urban pollution and greenhouse gas emissions.

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_19, © Springer International Publishing Switzerland 2014

Center for Advanced Transportation and Energy Solutions (CATES, based in Seattle) is working in partnership with the Connected Vehicle Proving Center at the University of Michigan—and with funding from the Graham Environmental Sustainability Institute—to conduct assessment research and develop policy options that would accelerate and integrate self-driving vehicle technology with other emerging technologies in ways that also enhance the goals of federal, state, and local government livable and sustainable community initiatives [1].

This task begins with recognition that personal automobile mobility is an important part of daily life in all communities, including those making progress on encouraging more pedestrian walkability, biking, and transit. The U.S. Census Bureau reports that 86 % of trips to work in 2011 were by private vehicles [2]. Personal automobile use is likely to continue to be high. For example, the U.S. Energy Information Administration forecasts that annual miles per driver will rise from 12,000 in 2014 to 13,000 in 2032 [3], even though U.S. DOT reports that miles of driving per capita have fallen since 2006 [4].

The challenge is how to minimize or eliminate the negative aspects of personal vehicle use while also making the alternative modes safer and better integrated. This should be an essential policy priority for livable, sustainable communities in addition to any public policy efforts to reduce solo driving via land use changes, financial incentives, regulations, and other means.

In a broad overview, there are four major problems with current surface transportation systems that can be significantly reduced with a combination of connected, autonomous and electric vehicles.

1.1 Problem 1: Oil Dependence in Transportation

Oil dependence in transportation harms the economy, national security and the environment. It is not sustainable because the cost of extracting oil is rising. Oil fuels 97 % of U.S. transportation, and the cost has risen sharply to over $100 a barrel today from $20 twelve years ago. Oil use in transportation is one of largest causes of anthropogenic greenhouse gas emissions and urban air and noise pollution. Tailpipe emissions of criteria pollutants, concentrated in urban areas, kill more people than collisions [5].

Imported oil in recent years has cost the U.S. economy over a billion dollars a day. New oil supplies from tight rock formations and deep off-shore sources are costly to exploit and are ultimately finite.

A significant percentage of world oil comes from unstable and undemocratic regions, harming world and national security. The annual U.S. military cost to protect world oil supply lines exceeds $80 billion, not counting direct war costs in the Persian Gulf region [6].

Replacing oil with electricity to power urban vehicles will dramatically reduce oil consumption, improve energy efficiency, help the economy, reduce greenhouse gas emissions and reduce other tailpipe emissions and urban pollution.

1.2 Problem 2: Fatalities and Injuries from Accidents

The ongoing carnage from U.S. road accidents—33,561 fatalities in 2012, 2.4 million people injured, and billions of dollars in medical costs and property damage [7]—could be reduced by as much as 80 % through road vehicle automation. New vehicles are now available with a growing array of automated driver assistance technologies, such as adaptive cruise control and lane keeping, to reduce driver errors leading to accidents. These technology applications are the precursors to a future of self-driving cars with and without a driver in the vehicle.

1.3 Problem 3: Congested Roadways

Traffic congestion wastes time and fuel, damaging the economy and the environment. Urban pollution and greenhouse gas emissions increase dramatically in stop-and-go traffic. The estimated cost of traffic congestion is $121 billion annually, not counting the costs of the adverse health consequences of traffic related vehicle pollution [8].

Information processing and wireless communications capabilities, collectively called telematics, can make travel safer and more efficient by providing real-time, hands-free information to drivers. Telematics today can calculate the most efficient travel route, provide hints on how to avoid traffic, assure that an emergency response comes quickly, identify and reserve the nearest available parking space, and provide increasingly sophisticated and detailed information on desired destinations. The era of big data and wireless communication for drivers and their cars is creating what some call the “mobility internet” [9].

Autonomous vehicles will also decrease urban congestion and reduce pollution caused by stop-and-go driving in part by providing more real-time information but also by increasing road capacity without the need to build more roads. Autonomous vehicles traveling safely at close intervals and in more narrow lanes can triple the capacity of existing highways. Autonomous vehicles will enable dynamically and temporarily dedicated road lanes that will aid public transit, emergency vehicles and other priority usage.

Finally, advanced telematics can enable future variable road pricing that will reduce peak congestion and provide a long-term sustainable and flexible method to pay for maintaining and operating urban road systems.

1.4 Problem 4: Underutilization of Public Transit

Due in part to changing work and family patterns—from one-wage earner households with set hourly schedules and one long-term employer, to two wage earners with variable hours at multiple employers—the percentage of daily work trips on public transit has declined from 6.4 % in 1980 to 5.0 % in 2011 [10]. Among other causes, commuters generally lack the flexible transit options and scheduling tools to meet their changing work patterns.

Transit applications of telematics can provide more flexible and accessible transit options into and around urban areas and help to intercept single occupant vehicles (SOVs) with easy-to-use transit options before SOVs enter core congested urban areas, increasing urban transit use and reducing pollution. This is part of what Zielinski terms the “New Mobility Grid” in which advanced telematics help make public transportation more affordable, more user friendly, and more often used than today [11]. These new technologies are beginning to enter applications that enable commuters to reserve parking places at transportation hubs, and then reserve seats on buses, car pools, van pools and company transit options.

1.5 Framework for Improvement

One goal of this chapter is to further outline the emerging and disruptive technologies that have the potential to help solve the four major problems and to advance urban livability and sustainability.

A second goal of this chapter is to provide more information to policy makers and suggestions on how to view these technologies in an integrated public policy framework. Many policy makers remain largely unaware of the pace and extent of the innovative and disruptive technologies that form the core attributes of smart, connected, autonomous electric vehicles and transportation hubs.

Unlike private sector advances in, for example, tablet computers, smart phones and their related applications, the public sector has a significant role in the application of new transportation technology through the public ownership of roads and transit systems, as well as through its broader and more compelling interests in public health, safety, national security and the environment.

Finally, we outline a proposal for a large-scale demonstration project in Western Washington State that will bring together and test a combined set of these emerging technologies in a real-time, real-world setting.

2 Electric Propulsion: Moving From Oil to Electricity in Surface Transportation

The near total dependence on oil to fuel U.S. transportation is a major and daunting challenge to the economy, national security, human health and the environment. Moving from oil to electricity in transportation is one of the most immediate and increasingly viable solutions. As former Assistant Secretary for Policy and International Affairs at the Department of Energy, David Sandalow, has said: “To reduce oil dependence, nothing would do more good more quickly that making cars that could connect to the electric grid." [12] "No technology has more promise to break the grip of oil on the U.S. transport sector than the plug-in electric vehicle" [13].

"Electrification of transportation is the best solution for dramatically reducing oil dependence. The electric power sector has substantial advantages over the current petroleum-based fuel system, and vehicles fueled by electricity are far more efficient than the conventional vehicles we drive today". Electric motors "can turn 90 % of the energy content of electricity into mechanical energy. In contrast, today's best internal combustion engines have efficiency of just 25–27 %" [14].

A study by the Pacific Northwest National Laboratory found that over 70 % of all the cars and light trucks in the United States could be powered by the existing power system by using off-peak power capacity accessible via smart charging computer applications that charged vehicles overnight [15, 16].

There are two power sources for electric vehicles: Batteries and hydrogen fuel cells. Batteries in gas-hybrid cars are charged by the gasoline engine, as in the original Toyota Prius. Plug-in electric vehicles (PHEVs), such as the Chevy Volt and the Ford C-Max Energi, have a plug for charging the battery from the electric grid and a back-up gasoline engine. In pure electric vehicles (EVs), such as the Nissan Leaf and the Tesla Model S, the batteries are charged only by a power cord connected to external electric power. Hydrogen fuel cells are seen by some as having a long-range potential to replace or augment batteries in electric vehicles [17].

The advantages of moving from oil to electricity are in five main areas: (1) Reduction of greenhouse gas emissions; (2) reduction of other criteria pollutants; (3) improvement to the national economy through greater efficiency and a reduced trade deficit; (4) national security improvements through reduced world oil dependence and less reliance on unstable regimes; and (5) reduction of water and noise pollution.

2.1 Reduction of Greenhouse Gas Emissions

Burning oil for transportation produces significant quantities of anthropogenic GHG emissions. In the Seattle area, for example, oil-based transportation causes over half of all such GHG emissions. A 2013 National Research Council study, *Transitions to Alternative Vehicles and Fuels*, found that EVs and other alternative fuel vehicles could reduce petroleum use and GHG emissions in light duty vehicles 80 % below 2005 levels by 2050 [17].

The *Transitions* report recommended keeping the price of petroleum-based fuels from dropping below a floor level in order to assure "a profitable market for alternative fuels, and encourage consumers to reduce their use of petroleum-based fuels" [17]. It also called for low-carbon generation of electricity—less coal and more solar, wind and nuclear power. Recent advances in nuclear power generation technology may lead to much safer and more affordable non-carbon power [18].

2.2 Reduction of Criteria Pollutants

There are six criteria emissions—particulate matter, ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead—which are regulated under the Clean Air Act [19]. Although catalytic convertors and more efficient engines have reduced these emissions, research now shows that tailpipe emissions are killing more people than car crashes, as noted earlier. Electric vehicles have no tailpipe emissions, and the electric power generating plants that provide EVs their electricity are increasingly clean or are located far from urban areas.

2.3 Improvement to the National Economy Through Greater Efficiency and a Reduced Trade Deficit

In recent years, the U.S. has spent over a billion dollars a day to buy foreign oil. Henry Kissinger has called this the greatest transfer of wealth in human history [20]. The cost to the U.S. economy from oil dependence over the last two decades is in the trillions of dollars [21]. As President Obama has said, paying for foreign oil "stifles innovation and sets back our ability to compete" [22].

In the last few years, the U.S. has reduced its oil imports from nearly two-thirds to just under half due to decreased demand and increased domestic production from new sources including hydraulic fracturing of tight rock formations and deeper and more remote off-shore oil drilling.

"Technology and high prices are opening up new oil resources, but this does not mean the world is on the verge of an era of oil abundance," according to the International Energy Agency [23]. The most troublesome long-term factor is increasing demand from emerging countries that threatens to exceed global oil production capability. The world is using oil at a pace that is hard to visualize: "The world produces nearly 1,000 barrels of oil every second. If those barrels were physically stacked up, the pile would grow taller at 2,000 miles per hour" [24].

2.4 National Security Improvements Through Reduced World Oil Dependence and Reliance on Unstable Regimes

As President Obama has said, "No single issue is as fundamental to our future as energy. America's dependence on oil is one of the most serious threats that our nation has faced. It bankrolls dictators, pays for nuclear proliferation, and funds both sides of our struggle against terrorism" [22]. The harm to national security from dependence on foreign oil is a major reason to accelerate the transition from oil to electricity and other alternatives in transportation. The added risk arises from the concentration of oil in the Middle East and the domination of those resources by OPEC countries—most of which are unstable, undemocratic or both; and some of which are openly hostile to our interests [25].

2.5 Reduction of Water and Noise Pollution

An underappreciated benefit of moving from oil to electricity is the reduction of water and noise pollution. Oil dripping from vehicles on roads and parking lots carried by storm water runoff is a significant non-point pollution source in many areas of the U.S., such as the Puget Sound region in Washington State [26]. Copper shavings from brake linings, which are sharply reduced by regenerative brake technology in EVs, are also becoming a significant threat to aquatic life [27]. Urban noise pollution is reduced as EVs run as quietly as bicycles—increasing the need for autonomous vehicles with their collision avoidance capabilities.

3 Synergies Between the Three Emerging Vehicle Technologies

There are significant synergies in combining autonomous vehicles, electric vehicles, and connected vehicle technology.

First, moving from oil to electricity in vehicles addresses the concern of policy makers and segments of the public that autonomous vehicle technology will result in more vehicle miles traveled and thus more greenhouse gas emissions and other pollution produced by conventional gasoline and diesel powered vehicles.

Second, autonomous vehicles support electric propulsion by better managing acceleration, cruising, slowing, and stopping. Automatic computation of driving profiles for power and brake application assists drivers to maximize efficiency and range. EVs are already software intensive; today's Chevrolet Volt extended range EV incorporates more computer code than the Boeing 787 [28].

Third, the need to make EVs as lightweight as possible to achieve more efficiency and longer range fits well with the capability of automated cars to avoid collisions. Smaller, electric urban vehicles are safer to the degree that they can be made more crash proof via automation. Automated cars over time may be able to substitute crash avoidance software for heavy structural elements that mitigate collision damage when crashes occur. Equally as important will be EVs that can avoid collisions with pedestrians, bike riders and other urban vehicles. The goal of livable, sustainable communities will be enhanced when walkers and bike riders are safer. Car companies are already working on this [29].

Fourth, wireless connectivity will provide data to vehicles connected to the cloud and to other vehicles. This helps EV drivers to know the shortest or most efficient path to a destination including the nearest charging station. Strong mapping and routing capabilities will be critical for increasingly automated vehicles.

Fifth, wireless connectivity is important for updating software and data in the car while in the owner's garage, and for the car reporting its status to maintenance providers.

Finally, wireless connectivity supports vehicle-to-vehicle and vehicle-to-roadside communications that is important for safety and smooth traffic flow. The reduction of stop-and-go traffic congestion allows EVs to go longer between recharging the battery or otherwise refueling. Wireless communications to and from points beyond the range of in-vehicle sensors are likely to be important in automated driving to avoid collisions at blind intersections. Furthermore, the efficient interaction of EVs with the charging or refueling infrastructure – finding where it is and getting there efficiently—is already a part of dashboard displays installed in the EVs being sold as of this writing. In the long-run, EVs in a driverless mode may be able to go to a charging/refueling point on their own.

4 The Interface of Cars with Livability and Smart Growth

Reducing the environmental, health and safety impacts of vehicles should be an essential policy priority for livable, sustainable communities.

Some predict and are concerned that automated driving will encourage more vehicle miles traveled (VMT). To mitigate the risk of adverse environmental impacts of more driving in and around cities, it is important that automated cars employ safe, low-emission, non-oil, energy-efficient, and quiet means of propulsion.

Turning the argument around, EVs with lower environment impacts and low operating costs may themselves encourage growth in VMT. In that case, higher levels of vehicle automation reducing collisions and allowing closer vehicle spacing can reduce congestion. Car parking without drivers at the wheel can also lower the space requirements of parking lots and will mitigate that growth in driving. These mitigation dynamics are important for livability and sustainability.

Parking and charging by automated, driverless access can also be done in less-prime, peripheral locations that do not impinge on walkable, pedestrian-friendly residential and commercial zones.

Furthermore, if public transit—a key element of livable communities—is to remain viable in competition with private autos and advanced taxis, then public transit will require innovative formats that are more energy efficient and more effective in attracting customers. Better transit is likely to require both electric motors for propulsion and information technologies for flexible, dynamic routing.

At the same time, road-vehicle automation could enhance the financial sustainability of transit by reducing the expenditures needed for professional vehicle operators. This cost component is about one dollar per passenger mile for buses, amounting to 45 % of direct operating costs in 2011. But with driver salaries not needed, that same cost for vanpools with eight paying passengers and one doing the driving is only 10 cents per passenger mile [30].

In the short run, starting with today's fixed-route van pools, organized ride sharing and car sharing, CATES envisions a step-by-step evolutionary potential for vastly expanded small-vehicle, electric transit, where in effect, passengers do the driving. Eventually they can travel door-to-door on driverless robotic vehicles.

Automation in the long run facilitates a step-by-step movement toward more sustainable public transit across all the dimensions of sustainability—environment, economics, and equity. By equity, we mean the ability to cover urban geography much more completely than fixed route buses can, and at an affordable cost.

As an immediate example of lowered environmental impact, small EVs with 50 % or greater load factors provide an opportunity to vastly reduce energy consumption and greenhouse gas emissions per passenger mile. In Seattle, for example, fixed route diesel buses average 44 passenger miles per gallon. At the same time, the transit agency has deployed four-passenger shared ride pool vehicles using Nissan Leaf EVs, with an efficiency rating of 396 passenger miles per gallon fuel equivalent [30].

To the degree that some bus and train services to urban centers carry high passenger loads and yield low fuel consumption and GHG generation as a result, there are opportunities in the long run for driverless, energy efficient electric shuttle vehicles in low-density environments to move customers from scattered residential locations to train stations and bus transit depots. Kornhauser has modeled such a future system for the entire State of New Jersey [31].

5 A Large-Scale Integrated Demonstration Project at Joint Base Lewis McChord

As this chapter has outlined, there are valuable synergies in combining the emerging technologies into smart, connected, autonomous, electric vehicles. There is a resulting need for large-scale, real-world testing to work out the integration of the technologies and to build public confidence. In seeking an environment to do this testing, CATES is inspired by the history of U.S. military involvement to date.

The U.S. Department of Defense (DOD) through its Defense Advanced Research Project Agency (DARPA) carried out a series of "Grand Challenge" autonomous vehicle competitions in order to develop driverless vehicles for use on battlefields. The DARPA competition produced successful prototypes which led to the more rapid development of autonomous vehicle technology for civilian use [32].

The DOD and the Department of Energy (DOE) have more recently signed a Memorandum of Understanding to use the purchasing power of the DOD (and its capability to do large-scale controlled experiments) in order to test technologies that hold the promise to save energy in both the military and civilian applications [33].

One of the largest military bases in the U.S. is Joint Base Lewis McChord (JBLM), located along both sides of Interstate 5 near Seattle, Tacoma and Olympia in Washington State. JBLM is the equivalent of a small city (it would rank 7th among Washington State cities) and ranks second in the number of employees in Washington State [34].

JBLM has unique and favorable attributes for testing the emerging vehicle technologies and associated systems:

(1) The power supplied to the base by Tacoma Power is over 95 % carbon-free hydroelectric, wind, solar and nuclear power;
(2) JBLM is adjacent to two project areas receiving livable community grants coordinated by the U.S. Department of Housing and Urban Development, Environmental Protection Agency, and Department of Transportation;
(3) The portion of the Interstate 5 highway running through the base is the most congested road segments on the West Coast and needs cost-effective solutions;
(4) JBLM has an existing vanpool program that can be expanded and used for experiments in smart, connected, increasingly autonomous, electric vehicles;
(5) JBLM is an award winning leader among U.S. military bases for its strong commitment to environmental sustainability as well as livable community design;
(6) It has strong civilian support at the local and state level through the South Sound Military & Communities Partnership and through new state level initiatives;
(7) Private sector companies located nearby are leaders in different aspects of the emerging technologies outlined in this chapter, including Google, Microsoft, INRIX, Airbiquty, VoiceBox, Amazon, PACCAR, and Boeing;
(8) Public officials frequently demonstrate leadership on technical and environmental issues;
(9) Residents of Western Washington have historically been early adopters of technology that improves the environment and the sustainability of communities.

The integrated, large-scale testing at JBLM would include the following elements:

(1) Incorporation of a new petroleum and CO_2 reduction goal into the existing Department of Defense program of Net Zero energy;
(2) Implementation of smart, connected electric vanpools for troops as well as contractors for commuting to and from the base—perhaps flexible versions of what Microsoft calls microtransit;
(3) Implementation of an on-base EV shuttle system to move transit commuters inside the base;
(4) Testing of driverless EV shuttles initially in limited numbers, then with expansion to all on-base shuttles;
(5) Testing of driverless and platooned vehicles along I-5 and I-90 from JBLM to the Yakima Firing Range in central Washington State;
(6) Testing of information protocols and standards in applications linking vehicles to infrastructure and data;
(7) Creation of connected transportation hubs north and south of the base to allow for reserved parking, flexible car pools and vanpools;
(8) Creation of incentives for military and civilian base employees to purchase EVs or to use transit;
(9) Testing of used vehicle batteries as back-up power sources for mission critical circuits;
(10) Testing of bi-directional power supplies for EVs that are capable of providing back up power and ancillary power services.

Planning effort is underway to detail the design of project components and muster resources for this large-scale demonstration of electric, automated mobility on and around Joint Base Lewis McChord.

6 Conclusion

Significant media and popular attention is focused on new technology applications in automobiles. Often stemming from a writer's informal understanding, problems and benefits are frequently mischaracterized. Based on research, we at CATES have now outlined an effective way to educate our region and nation about the benefits, costs, and barriers of these technologies applied in the integrated way we describe in this chapter. Our action plan is to facilitate a pilot implementation in a mixed military-civilian environment with careful measurement of resource inputs and performance outputs. We believe the result will be more accurate public perceptions of how a growing number of automated, connected, electric vehicles can support and influence sustainability and livability.

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Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore

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Abstract The objective of this work is to provide analytical guidelines and financial justification for the design of shared-vehicle mobility-on-demand systems. Specifically, we consider the fundamental issue of determining the appropriate number of vehicles to field in the fleet, and estimate the financial benefits of several models of car sharing. As a case study, we consider replacing all modes of personal transportation in a city such as Singapore with a fleet of shared automated vehicles, able to drive themselves, e.g., to move to a customer's location. Using actual transportation data, our analysis suggests a shared-vehicle mobility solution can meet the personal mobility needs of the entire

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_20,

population with a fleet whose size is approximately 1/3 of the total number of passenger vehicles currently in operation.

Keywords Autonomous vehicles · Self-driving cars · Car sharing · Mobility on demand

1 Introduction

In light of ongoing urbanization trends, cities face the challenge of maintaining the services and infrastructure necessary to keep pace with the transportation demands of a growing population. When the returns from investment in existing technologies, e.g., road expansion, added bus service, new subway lines, etc., begin to diminish, it is appropriate, perhaps even necessary, to consider new and potentially transformative transportation solutions. A responsible approach to address the merits of a proposed solution is to conduct a systematic analysis of its key operational components, thereby providing an informed foundation from which to gauge feasibility. It is in this spirit that this chapter examines a new solution to personal mobility; namely, that of replacing all modes of personal transport in a city with a fleet of shared autonomous vehicles, i.e., vehicles that are able to drive themselves in traffic, to safely and reliably pick up passengers and deliver them to their intended destination.

Research on autonomous vehicles is currently very active [1, 2]. Proponents of this technology typically point out as the main benefits (1) increased safety, as the automation reduces the effects of human errors, well known to be the leading cause of traffic accidents (2) increased convenience and productivity, as humans are absolved from the more burdensome aspects of driving (3) increased traffic efficiency and lower congestion, as automated vehicles can precisely monitor one another's position and coordinate their motion to an extent impossible for human drivers, and (4) reduced environmental impact, as velocity profiles can be carefully tuned to minimize emissions and noise.

For the sake of this article, though, we will concentrate on yet another potential major benefit, i.e. (5) autonomous vehicles as an enabling technology for widespread car sharing. It is well known that most private cars are used less than 10 % of the time [3], so car sharing is a clear path towards sustainability—especially if cars do not need a driver to move. Car-sharing services are growing worldwide, but typically do not offer one-way rental options, or if they do they often suffer from limited car availability. If shared cars were able to return to a parking or charging station, or drive to pick up the next customer by themselves, sharing would indeed provide a similar level of convenience as private cars, while providing the sustainability of public transport. Financially, car sharing distributes the cost of purchasing, maintaining, and insuring vehicles across a large user-base, leveraging economies of scale to reduce the cost of personal mobility.

While automated vehicle technology continues to surge forward, less attention has been devoted to the logistics of effectively managing a fleet of potentially thousands of such vehicles. Among those works that do exist, many are of a conceptual nature. Although they raise a number of interesting ideas and suggest novel operational paradigms, they frequently lack the rigor necessary to justify the feasibility of their claims. Those works that do take a design-oriented approach frequently rely heavily on simulations and unrealistic transportation demand models. Consequently, these techniques prove difficult to generalize and neglect salient features that have a fundamental impact on key performance metrics. Recognizing these shortcomings, this work provides some preliminary insights toward a systematic approach to size a fleet of shared vehicles given actual mobility patterns. These results are then applied, using actual transportation and traffic statistics, to the problem of fleet sizing for a shared-mobility system in Singapore. Financial estimates for a variety of car-sharing systems are provided to assess their financial feasibility.

While the main motivation of this chapter is provided by automated shared-vehicle systems, the results are applicable to more general cases, including, e.g., a fleet of shared vehicles, each with a human driver, coordinating with other drivers in such a way to maximize the quality of service provided to the customers (as opposed to their own interests, as is the case with current models of taxi services).

2 Shared-Mobility Systems

The efficiency gains that shared-vehicle systems can, in theory, offer to both the individual user and society as a whole have been well documented [3]. For select cities, including Singapore, lists of these advantages have even been specifically compiled [4]. To date, the majority of car-sharing programs feature a roundtrip vehicle rental model. In these systems, vehicles must be returned to the same station they were rented from. Zipcar's current rental service, for example, is based on this approach. Eager to capitalize on emerging markets and better serve existing ones, considerable effort has been devoted to characterizing the demand for shared-vehicle mobility in different markets [5]. Naturally, demographic factors, e.g., [5, 6], and geographic considerations, e.g., [7, 8], affect demand. However, researchers have also been quick to note the important role quality of service plays in establishing a clientele [9]. For example, by fielding larger vehicle fleets, companies make it easier for patrons to rent a vehicle from a nearby station. This, in turn, draws new members to the program [10]. As this effect takes hold, yet more vehicles are required to maintain the high level of service that initially attracted users.

Noting the limitations in the roundtrip rental model, one-way car-sharing services, such as car2go, have emerged. These services offer the added convenience of being able to return a vehicle to any one of multiple stations throughout the city [9]. However, left unchecked, asymmetries in travel patterns would, in general, create a surplus of vehicles at select stations, while leaving other stations underserved. Rebalancing mechanisms are therefore required to realign the supply of vehicles with the demand. Moreover, how effectively vehicles are shuffled between stations strongly affects vehicle availability, which, in turn, impacts demand for the service.

Simulation-based approaches have been used to infer the viability of various rebalancing schemes and, in turn, gauge consumer demand for one-way car-sharing, e.g., [11–15]. Initial findings suggest that one-way services are ideally suited for densely-populated urban centers. Unfortunately, the lack of insight in the presence of a large number of relevant but uncertain parameters has been noted as a limitation of predominantly simulation-driven methods [9]. A more theoretical direction has been pursued in a number of recent works aimed at understanding optimal rebalancing strategies, and the fundamental limits of stability and performance in car sharing systems, either considering automated or human-driven vehicles [16–18].

Each of the works referenced thus far focus on one or more important aspects of car-sharing systems. However, none of them tackle the more holistic problem of rigorously sizing the fleet for an Automated Mobility-on-Demand (AMoD) service to meet the transportation demand of an actual city. In this regard, [19], similar to this work, is noteworthy; it takes a design-oriented approach to fleet-sizing for hypothetical shared-vehicle systems at three sites across the United States (US). The approach used therein is heavily simulation-based and the spatial component of the demand model was not derived from real-world data. In contrast, we provide guidelines to size an AMoD system for Singapore based on measurable travel characteristics and, to the extent possible given the current technical literature, rigorous theoretical arguments.

3 Fleet Sizing for Automated Mobility-on-Demand Systems

In this section, we present the two key technical problems considered in the chapter. The problem statements are straightforward, but they are posed in terms of formal mathematical models of the physical environment and transportation demand.

3.1 Problem Formulation

Consider a compact planar region (environment) $Q \subset \mathbb{R}^2$. The i-th transportation demand in a random sequence $\{(t_i, o_i, d_i)\}_{i\in\mathbb{N}}$ poses the requirement to travel from an origin point $o_i \in Q$ to a destination point $d_i \in Q$. The demand, however, is only *revealed* after time t_i. Trip requests are to be serviced by vehicles that may transport at most one demand at a time. The average speed of the vehicles v is assumed to be periodically time-varying. A significant challenge to trip scheduling stems from uncertainty in the travel demand, which we will model probabilistically. Transportation demands arrive according to a non-stationary (separably) spatio-temporal Poisson process (λ, f), where λ is the arrival rate function, and f is a probability distribution function called the *demand distribution*; both are periodically time-varying. The individual trip data are all statistically independent, and the i-th O–D pair (o_i, d_i) is conditionally distributed according to $f(\cdot\,; t_i)$. The expected number of demands revealed within a time interval $[t_1, t_2]$, and with $o_i \in Q_1$ and $d_i \in Q_2$, for any time t and regions $Q_1, Q_2 \subset Q$, is $\int_{t_1}^{t_2} \int_{Q_2} \int_{Q_1} \lambda(t) f(p,q,t)\, dp\, dq\, dt$. The problems of interest are the following:

1. **Minimum fleet sizing**: What is the minimum number of vehicles, m_{min}, necessary to keep the number of outstanding demands uniformly bounded?
2. **Performance-driven fleet sizing**: How many vehicles, m_{per}, should be used to ensure that the quality of the service provided to the customer (e.g., vehicle availability, or waiting time) is no less than a given threshold?

The second problem acknowledges an intuitive trade-off between the fleet size and the user experience (beyond the bare minimum).

In the following, we provide techniques to address the fleet sizing problems in the case of Singapore. Interested readers may refer to, e.g., [17, 18] for similar problems defined with regard to a system of stations embedded in a road network, instead of a compact region in the Euclidean plane.

3.2 *Minimum Fleet Sizing*

As mentioned in Sect. 3.1, the problems of interest pertain to fleet sizing for a pickup-and-delivery system. A detailed theoretical treatment stressing the stochastic and queue-theoretic nature of the problem can be found in [16].

A fleet of m vehicles is said to *stabilize* the workload if there exists a service (routing) policy $\pi(m)$ that ensures the expected number of outstanding demands is uniformly bounded. Stability therefore implies that the fleet, as a whole, must be able to cover distance at least as quickly on average as the rate at which service distance accumulates.

Given a sequence of points $p_1, \ldots, p_n \in Q$, let $\mathscr{D}(p_1, \ldots, p_n)$ denote the length of the shortest path through each point in the order specified by the sequence. The average distance that a vehicle must travel in service *per demand* is $d^{\text{trip}} := \limsup_{i \to +\infty} \mathbb{E}\{\mathscr{D}(d_{\text{pre}(i)}, o_i, d_i)\}$, where $\text{pre}(i)$ is the index of the demand served immediately before the demand i. If the temporal variation of travel demand is discretized into, e.g., hourly temporal bins, the rate at which work enters the system is $\sum_k (\lambda_k \cdot d_k^{\text{trip}})$, where the subscript k indicates the bin index, and $d_k^{\text{trip}} := \limsup_{i \to +\infty} \mathbb{E}\{\mathscr{D}(d_{\text{pre}(i)}, o_i, d_i) : t_i \text{ in bin } k\}$. A fleet of m vehicles, each capable of traveling at average speed v_k during the k-th bin, is able to cover distance at a daily rate of $m \sum_k v_k$. Therefore, a necessary condition for system stability is

$$m > \sum_k \left(\lambda_k \cdot d_k^{\text{trip}}\right) / \sum_k v_k. \tag{1}$$

Dropping the subscript k for simplicity, the average trip length can be decomposed as $d^{\mathrm{trip}} = d^{\mathrm{OD}} + d^{\mathrm{E}}$, where $d^{\mathrm{OD}} = \mathbb{E}[\mathscr{D}(o_i, d_i)]$, and d^{E} depends on the ordering of demands served, and clearly depends on the routing policy $\pi(m)$. In [16], rigorous arguments are used to prove that d^{E} is bounded below by a computable quantity that depends on the mobility demand, and that the bound is approachable in practice. Letting f^{o} and f^{d} denote the first and second factors of f—i.e., the marginal distributions associated with origins and destinations, respectively—then $d^E \geq \mathrm{EMD}(f^d,f^o)$, where EMD is a function often called the *Earth mover's distance*, and will be defined shortly. Given the above, condition (1) becomes

$$m > \sum_k \Big(\lambda_k (d_k^{\mathrm{OD}} + \mathrm{EMD}(f_k^d, f_k^o))\Big) / \sum_k v_k. \tag{2}$$

Formally, the Earth mover's distance $\mathrm{EMD}(f^{\mathrm{o}},f^{\mathrm{d}})$ is a measure of distance between distributions f^{o} and f^{d}; in mathematical terms, given the *ground metric* $(Q, \mathscr{D})$, the EMD is the first Wasserstein distance [20], usually written as

$$\mathrm{EMD}(f_1,f_2) = \inf_{\gamma \in \Gamma(f_1,f_2)} \int_{Q\times Q} \mathscr{D}(p_1,p_2)d\gamma(p_1,p_2), \tag{3}$$

where $\Gamma(f_1, f_2)$ is the set of all measures with marginals f_1 and f_2 on the first and second factor, respectively. If distributions f_1 and f_2 are imagined as describing two piles each consisting of a unit of "dirt" (i.e., earth), then $\mathrm{EMD}(f_1,f_2)$ is intuitively the minimum work (dirt × distance) required to reshape f_1 into f_2.

Although some existing works are keen to emphasize the relationship between d^{OD} and $m_{\min}$, they often fail to recognize the contribution of $d^{\mathrm{E}} \geq \mathrm{EMD}(f^{\mathrm{o}},f^{\mathrm{d}})$. This is an unfortunate omission as $\mathrm{EMD}(f^{\mathrm{o}},f^{\mathrm{d}})$ represents the minimum distance, on average, a vehicle must travel to realign itself with an asymmetrical travel demand, and is a fundamental contributor to system workload. It is justifiable to ignore $\mathrm{EMD}(f^{\mathrm{o}},f^{\mathrm{d}})$ only when $f^{\mathrm{o}} = f^{\mathrm{d}}$, because in this case $\mathrm{EMD} = 0$. However, in most real cases, including Singapore, f^{o} and f^{d} are different on the time scales over which trips must be completed.

3.3 Performance-Driven Fleet Sizing

The analysis in the previous section provides crucial information about absolute minimum fleet sizes to ensure user demand can (in principle) be met. These results help to answer whether a particular fleet size is "large enough." However, another important question which is left unanswered is how the size of the fleet impacts the user experience, e.g., by decreasing user wait times or by increasing vehicle availability. It is worthwhile to quantify more accurately such trade-offs.

In this work, we study performance in terms of vehicle availability. To this purpose, we model an autonomous MOD system as a closed queueing network of m vehicles and N disjoint *regions* Q_1, Q_2, …, $Q_N \subset Q$. Idle vehicles are parked at the median of each region. When a customer arrives in region Q_i, destined for Q_j, a free vehicle in Q_i is sent to pick up and drop off the customer before parking at the median of Q_j. Customers arrive in each region $Q_i \subset Q$ according to a Poisson process with rate λ_i and take vehicles to region Q_j with probability p_{ij}. To maintain tractability for analytical results, we consider a simple model where if a region is empty of available vehicles, the customer immediately leaves the system (this model is usually referred to as *loss model*, which models well customer impatience). The performance criterion is then the availability of vehicles in each region, or the probability that a customer will be able to book a vehicle in his/her region.

This model of a MOD system can be analyzed as a closed Jackson network with respect to the vehicles. Jackson networks are a special case of a class of queueing networks known as BCMP networks [21], which, remarkably, admit stationary probability distributions in product form. In our case, regions are mapped into single-server nodes, while routes between each pair of regions are mapped into infinite-server nodes (note that we are not modeling congestion effects). Thanks to the product form of the probability distributions, the availability of vehicles in each region can be efficiently computed using mean value analysis (see, e.g., [22]). Previous work such as [22] used this model to generate guidelines for system design and perform profit-based fleet sizing. However, their analysis shows that without rebalancing the majority of regions can only achieve an availability strictly less than one *even* if m tends to infinity. To take into account the possibility of vehicle rebalancing offered by autonomous vehicles, we model the rebalancing process as an arrival process of “virtual passengers” with Poisson rate ψ_i and routing probability α_{ij}, independent of the real passenger arrival process. As with real passengers, the virtual passengers are lost if no vehicles are available in the booking region upon arrival. We can then optimize the availability with respect to ψ_i and α_{ij} to achieve a balanced system so that availability approaches one as m tends to infinity, for all regions. The approach is similar to that developed in [17], and allows us to determine performance curves in terms of m and vehicle availability. Also, it provides *baseline* policies that would guide the development of real-time closed-loop vehicle routing policies as in [17].

4 Data Sources

In order to apply our analytical results to estimate fleet size for a real-world scenario, we chose to consider Singapore as a case study. Singapore is a fitting venue for at least two reasons: First, we have access to a rich collection of data pertaining to the country, from which to gather the statistics that drive our analytics. Second, despite Singapore’s sophisticated and well-subsidized public transportation system, the rate of private vehicle ownership, and correspondingly traffic congestion, continues to increase. Given the island’s diminutive size and high population density, officials are limited in the extent to which traditional measures, e.g., roadway expansion, can alleviate rising congestion. In this regard, Singapore is a promising candidate for replacing existing modes of land transport with shared vehicles for personal mobility, i.e., an AMoD system. To support the analysis of such scenario, three complementary data sources are used, as described below.

The Household Interview Travel Survey—The Household Interview Travel Survey, or simply HITS, is a comprehensive survey conducted periodically by the Land Transport Authority (LTA) for the purpose of gathering an overview of high-level transportation patterns within Singapore [23]. This work employed the 2008 HITS survey in which 10,840 of the then 1,144,400 households in Singapore were selected to participate in the survey. The HITS database, which summarizes the survey, is structured as follows. For each household surveyed, each resident reported specific details of each trip taken on a recent weekday of interest. In general, each trip is comprised of several stages with a new stage introduced each time the participant switched their mode of transport, e.g., transferred from the subway to bus as part of the same trip. For each trip, the resident reported the trip's origin point, destination point, start time, end time, and the mode of transport, e.g., car, bus, subway, etc., used in each substage.

Singapore Taxi Data—To gather ground truth traffic characteristics, we rely on a database of taxi records collected over the course of a week in Singapore in 2012. The data chronicles the movement and activities of approximately 60 % of all active taxis by recording each vehicle's GPS coordinates, speed, and passenger status, e.g., "passenger-on-board," "vacant," "responding to call," etc. Owing to the high rate at which recordings are taken, approximately every 30 s to 1 min per vehicle, and the large number of taxis contributing to the database (more than 10,000), the fleet, collectively, serves as a distributed, mobile, embedded traffic sensor which may be queried to provide an estimate of traffic conditions throughout the city.

Singapore Road Network—A graph-based representation of Singapore's road network is used to determine the most efficient routes automated vehicles should take from point to point in Singapore (whether carrying a passenger or moving to fetch one). When the analysis method required simpler distance evaluations, the average ratio of trip length over Euclidean distance was estimated from the taxi data as a factor $\beta = 1.38$.

5 Sizing an AMoD Solution for Singapore

Having acquired both the necessary analytical tools, and the transportation data, we are now able to compute estimates for the AMoD fleet sizing problem in Singapore.

5.1 Minimum Fleet Sizing

This section describes the methodology used to estimate the quantities appearing in (2). Results are summarized in Fig. 1.

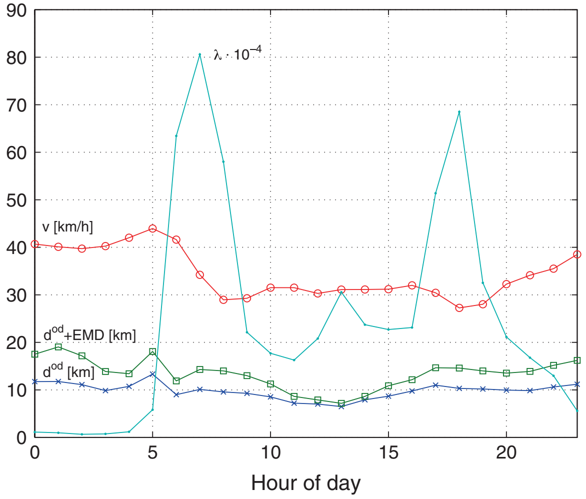

Fig. 1 Summary of the data necessary for the evaluation of the minimum fleet size. According to Eq. (2) the minimum fleet size to serve all of Singapore's mobility demand is 92,693 shared vehicles.

Arrival Rate (λ)—Let λ_k^{HITS} represent the average rate at which trips in hour $k \in \{0, 1, \ldots, 23\}$ arrive based solely on the HITS survey. The overall arrival rate, in hour k, is evaluated as $\lambda_k = \alpha \lambda_k^{\text{HITS}}$, where $\alpha = 1{,}144{,}400/10, 840 \approx 105.57$ is the scaling factor that, inversely, reflects the fraction of the households that took part in the HITS survey. From the HITS data, 56,839 trips were extracted. After eliminating trips for which the GPS coordinates of o, d, or both were unavailable, 56,673 trips remained.

Average O-D Distance (**d^{OD}**)—For each O–D pair in the HITS database, we assume the trip takes place on the shortest path (as measured by distance) connecting o and d. Shortest path algorithms, e.g., Dijkstra's algorithm, are computationally efficient, allowing calculations to be run on a detailed roadmap of Singapore. On an hourly basis, d_k^{OD} ranges from a minimum of 6.47 km to a maximum of 13.31 km.

Mobility Demand Distribution (f)—The road network of Singapore was divided into road segments, each of length no greater than 6 km. Each pair of such segments was treated as a bin, and a trip was assigned to bin (a, b) if its origin was on segment a and its destination was on segment b. The demand distribution estimate f is taken as the distribution whose sampling procedure is: (1) choose a bin (a, b) with probability proportional to the number of trips, then (2) produce O–D pair (o, d), with o and d independent and uniformly distributed, over a and b, respectively.

Earth Mover's Distance—To estimate EMD, Singapore was partitioned into regions R_1, …, R_N. Origin and destination points of trips were assigned to the corresponding regions, thus defining pick-up and drop-off bins. The EMD is computed using a linear program that minimizes the amount of work, i.e., the cumulative distance traveled by all points in the pick-up bins, required to transform the distribution of origin points into the distribution of destination points.

The distances involved in this calculation are inherently Euclidean; the previously described scaling factor $\beta = 1.38$ was used to approximate the distance on the underlying road network. See also [24] for a more accurate method to estimate EMD on road networks.

Average Velocity (*v*)—Taxi data was used to determine a conservative estimate of the average speed at which occupied taxis move about the city in the *current* traffic conditions. This value is then used as an estimate for v in (2). Note that this does not take into account potential changes in congestion due to vehicle sharing. To determine how fast, on average, an individual taxi travels, the total distance traveled by the taxi, with a passenger on board, was divided by the total associated time during each hour of the day over the course of a typical week in Singapore.

Minimum fleet size—Given the aforementioned quantities (2) yields that at least 92,693 automated vehicles are required to ensure the transportation demand remains uniformly bounded. Note however, that this should only be seen as a lower bound on the fleet size, since customer waiting times would be unacceptably high.

5.2 Performance-Driven Fleet Sizing

Finally, we consider how much the fleet size should be increased in order to reduce the waiting times of customers to acceptable levels. We use the technique described in Sect. 3.3. To apply the approach to Singapore, the HITS data is first used to partition the city's road network into $N = 100$ regions using k-means clustering. This number of regions corresponds to an average driving time from booking to pickup of 2.3 min. The system parameters λ_i, p_{ij}, and T_{ij} are estimated using trip data between regions.

Vehicle availability was analyzed in two representative cases. The first was chosen as the 2–3 pm bin, since it is the one that is the closest to the "average" traffic condition. The second case considers the 7–8 am rush-hour peak. Results are summarized in Fig. 2 (left). With about 200,000 vehicles availability is about 90 % on average, but drops to about 50 % at peak times. With 300,000 vehicles in the fleet, availability is about 95 % on average and about 72 % at peak times.

In a real MoD system passengers would typically wait for the next available vehicle rather than leave the system immediately if no vehicles are available upon booking. Thus, it is important to characterize how the availability criterion relates to customer waiting times in a practical system. We characterize the customer waiting times through simulation, using a closed-loop rebalancing policy inspired by the loss model, where rebalancing is performed every 30 min by minimizing the distance travelled by rebalancing vehicles while evenly distributing the free vehicles across all the stations. For the average-demand case, a fleet of 200,000 vehicles corresponds to expected booking times of less than a minute, to which one must add the pickup driving time, for a total of about 3 min between booking and pickup.

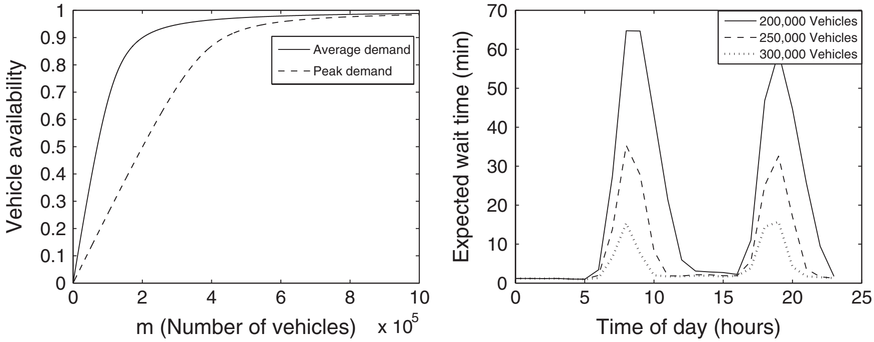

Fig. 2 (*Left*) Performance curve with 100 regions, showing the availability of vehicles versus the size of the system for both average demand (2–3 pm) and peak demand (7–8 am). (*Right*) Average wait times over the course of a day, for systems of different sizes

Figure 2 (right) shows simulations results of average wait times over the course of a day. For 250,000 vehicles, the maximum wait times during peak hours is around 30 min, which is comparable with typical congestion delays during rush hour. With 300,000 vehicles, peak wait times are reduced to less than 15 min. To put these numbers into perspective, in 2011 there were 779,890 passenger vehicles operating in Singapore [25].

6 Financial Analysis

Other benefits notwithstanding, financial considerations will undoubtedly factor into if and when cities switch to an AMoD system. To understand the costs associated with such a move, we consider the total mobility cost (TMC) for users in two competing transportation models. In each case, we consider not only the explicit costs to access mobility, but also hidden costs attributed to the time invested in various mobility-related activities. Within this framework, our analysis indicates that an AMoD system is a financially viable alternative to private vehicle ownership in Singapore. Moreover, to gain an appreciation for the financial benefits of installing AMoD systems in other markets, we provide similar estimates for a typical city in the US. Throughout, all costs are reported in US dollars, with an assumed exchange rate of 1.25 SGD/USD.

The competing transportation models will be referred to as Systems 1 and 2. In System 1, users access personal-mobility by purchasing (or leasing) a private vehicle. Vehicles in System 1 must be operated by a human driver and are referred to as *human-driven cars* (HDCs). In this way, System 1 represents personal mobility as we know it today. Conversely, in System 2, users access personal mobility by subscribing to a shared AMoD fleet of vehicles. Vehicles in System 2 are referred to as *shared self-driving cars* (SSDCs).

Based on the findings in Sect. 5.2, estimates for an AMoD fleet size in Singapore correspond to a sharing ratio of approximately 3.5–4.5. For simplicity, we will assume that, on average, 4 people effectively share a single SSDC.

6.1 The Explicit Cost of Mobility

For System *i*, the cost of service (COS_i) is defined to be the sum of all explicit costs associated with accessing mobility. For example, in System 1, COS_1 reflects, among other expenditures, the costs to individually purchase, service, park, insure, and fuel a private vehicle. In Singapore, the estimated annual cost to own a mid-sized car, including parking expenses, is approximately $18,162/year [26]. In the US, assuming an annual mileage of 21,580 km/year, and factoring in the $1,992/year spent on parking [27], the equivalent figure is $11,315/year [28]. The disparity between Singaporean and US numbers is due primarily to hefty ownership taxes and traffic tolls within Singapore.

In System 2, fielding a fleet of SSDCs will, initially, require retrofitting production vehicles with the sensors, actuators, and computational power required for automated driving. While still relatively expensive, it is expected that with technological advancement, the needed components and customizations will become more affordable. Assuming some economies of scale for large fleets, we estimate the necessary retrofit of a mid-sized car can be completed for a one-time fee of $15,000. Automated capabilities will gradually be incorporated into production cycles, with fully automated vehicles eventually rolling off assembly lines. Cost savings associated with mass production suggest these figures have the potential to be significantly smaller in coming years and as AMoD systems become more prevalent.

From the fleet-sizing arguments of Sect. 5.2, one SSDC in System 2 can effectively serve the role of 3.5–4.5 HDCs in System 1. However, this reduction in vehicles on the road requires a typical SSDC to drive much farther, per day, than an HDC in System 1. Consequently, a typical SSDC in System 2 will depreciate at a faster rate than an HDC in System 1. Accounting for both usage-driven and age-related depreciation, we conservatively estimate that a SSDC will have an average lifespan of 2.5 years [29]. Moreover, these high utilization rates and the shared nature of SSDCs will require significant maintenance and cleaning budgets to uphold high levels of customer safety and satisfaction.

The routine of a typical SSDC consists of dropping off one passenger and immediately departing to pick up a new passenger. A positive side-effect of this functionality is a drastic reduction, as compared to System 1, in the demand for parking spaces on high-value land. Moreover, should an overabundance of SSDCs develop, e.g., in the hours after the morning rush to work, surplus SSDCs can park themselves in structures or on lots occupying low-valued land (or even earn extra revenue providing a solution for logistics, e.g., shipping parcels and goods within the city). With respect to fuel usage, the central authority that manages System 2 may negotiate bulk fuel deliveries and benefit from discounted rates. Additionally, SSDCs may be programmed to drive in fuel-efficient ways, e.g., by employing gradual acceleration and proactive breaking techniques to realize further savings. Tallying the aforementioned costs on a fleet-wide scale and distributing the sum evenly among the intended user base (i.e., the entire population) gives a COS_2 of \$12,563/year in Singapore and \$9,728/year in the US.

According to COS values, it is more affordable to access mobility in System 2 than System 1. However, the analysis thus far does not reflect the value of the time saved in System 2 by avoiding the more burdensome mobility-related obligations in System 1. For example, users in System 2 not only avoid paying for parking, as reflected in COS_2, they also spare themselves the hassle of searching for parking spaces. As the following discussion attests, accounting for these factors further substantiates the financial advantages of AMoD technology.

6.2 The Hidden Cost of Mobility

Following an approach first pioneered to explore the hidden costs of owning a personal computer in the 1980s [30], we define the value of time (VOT) to be the monetary valuation of the total time invested in mobility related activities. For example, in System 1, VOT_1 reflects, among other commitments, the time spent taking a car to get a tuneup, paying (or contesting) traffic tickets, renewing license plates, and driving the car. The total mobility cost of System i is then given by $\mathrm{TMC}_i = \mathrm{COS}_i + \mathrm{VOT}_i$, $i = 1, 2$.

The American National Household Travel Survey estimates that an individual spends 465 h/year in their car [31]. In addition, drivers begin and end each trip by spending an estimated 4 min traveling to or from their parked vehicle [32], or, at an average of 3.8 trips per day [33], 175 h/year. Factoring in the time required to renew license plates, pay tickets, tow a broken-down vehicle, wait while the vehicle is serviced etc., we estimate the total time spent on vehicle ownership and operation related activities in System 1 to be 885 h/year in the US. Similar studies are not yet available for Singapore. However, given an average travel distance of 19,000 km/year [25], and the average driving speed on roads, private vehicle owners in Singapore spend, on average, 458 h/year driving in their car. Factoring in the time parking and other related activities brings this total to 747 h/year.

To monetize the preceding values, we use the Value of Travel Time Savings (VTTS) numbers laid out by the Department of Transportation (DOT) for performing a Cost Benefit Analysis (CBA) of transportation scenarios in the US [34, 35]. The CBA is used by governments to decide whether or not to proceed with major traffic-related projects, e.g., bridge construction or highway expansion. For various trip scenarios, the VTTS is expressed as a fraction of the median income based on the level of comfort for various in-car trips; less comfortable scenarios incur higher costs. For example, in free-flowing traffic, personal trips on local roads are priced at 50 % of the median wage (\$10.80/h in Singapore and \$12/h in the US)

[36]. Business trips on local roads are valued at 100 % of the median wage [37]. Personal trips between cities are considered a greater inconvenience; as such, they are priced slightly higher, at 75 % of the median wage. Traveling on heavily congested traffic increases the VTTS to 150 % of the median wage [38]. Similar values are available for pricing other-driving related activities, e.g., parking a car.

Applying the appropriate VTTS values based on actual driving patterns gives VOT_1 = \$14,460/year in Singapore and \$18,295/year in the US. Adding in the associated COS gives an annual TMC_1 of \$32,622/year or \$1.72/km in Singapore and \$29,610/year or \$1.37/km in the US. The latter value is significantly higher than the \$0.49/km reported by AAA for travel in the US [39]. Furthermore, for all the media attention paid to gasoline prices, fuel costs comprise only six percent of TMC_1.

To compute VOT_2, we take a closer look at the activity breakdown associated with taking a trip in an AMoD system. This includes the time spent requesting, waiting for, entering, traveling in, and exiting an SSDC. Given the capabilities of an SSDC, users in System 2 spend no time parking and limited time walking to and from the vehicle. We assume that requesting an SSDC would take no more than 1 min, and that the fleet is sized such that users wait, on average, no more than 5.5 min for a requested vehicle to show up. Given AMoD systems do not yet exist, there are no published VTTS value for the time spent traveling in a SSDC. We price sitting comfortably in an SSDC while being able to work, read, or simply relax at 20 % of the median wage. This is significantly lower than the average of 67 % of the median wage rate used to compute VOT_1.

Working from the figures above, VOT_2 is \$4,959/year in Singapore and \$5,527 in the US/year, approximately one third of the corresponding VOT_1. For an individual who is a high wage earner or spends an above average amount of time traveling by car, the gains are even greater.

6.3 Alternate Mobility Models

To further illustrate how the shared and automated nature of System 2 reduces the TMC for the average user, we briefly consider three additional systems. System 3 consists of Shared Dual-Mode Cars (SDMCs). An SDMC is driven by a human when one or more passengers is onboard, but drives autonomously when vacant. SDMCs therefore have the ability to rebalance themselves in order to meet the travel demand. System 4 is comprised of Personal Self-Driving Cars (PSDCs), each functionally equivalent to an SSDC, but owned and operated by a single individual. Finally, System 5 models a world in which human-driven taxis provide personal mobility (in place of private cars) for the population. For each system, we used similar techniques to estimate the TMC for installations in both Singapore and the US. (The taxi model was only evaluated in Singapore, due to the central role played by taxis in Singapore's transportation system, and to the numerous different ways taxi services are operated throughout the US.)

Table 1 Summary of the financial analysis of the mobility-related cost for the mobility models discussed in the text

	Cost (USD/km)						Yearly cost (USD/year)					
	Singapore			United States			Singapore			United States		
	COS	VOT	*TMC*	COS	VOT	*TMC*	COS	VOT	*TMC*	COS	VOT	*TMC*
HDC	0.96	0.76	*1.72*	0.52	0.85	*1.37*	18,162	14,460	*32,622*	11,315	18,295	*29,610*
SSDC	0.66	0.26	*0.92*	0.45	0.26	*0.71*	12,563	4,959	*17,522*	9,728	5,527	*15,256*
SDMC	0.66	0.51	*1.17*	0.45	0.50	*0.95*	12,563	9,683	*22,246*	9,728	10,835	*20,563*
PSDC	1.09	0.22	*1.31*	0.62	0.21	*0.83*	20,712	4,160	*24,872*	13,408	4,567	*17,976*
Taxi	1.06	0.26	*1.32*	–	–	–	20,169	4,959	*25,128*	–	–	–

The average Singaporean drives 18,997 km in a year, the average American drives 21,581 km in a year

6.4 Discussion

A summary of the COS, VOT, and TMC of the five systems is provided in Table 1. Remarkably, combining COS and VOT figures, the TMC for SSDCs is roughly half of that for HDCs in both Singapore and the US. To put this into perspective, these savings represent about one third of GDP per capita. On a relative basis, the savings afforded by AMoD technology in Singapore stem largely from the ability to split the hefty cost of car ownership. In the US, the savings are predominantly the result of being able to travel more comfortably and eliminate parking activities.

From the preceding arguments, the true cost to access mobility includes not only an explicit financial investment, but also a significant investment of valuable time. These factors combined, our analysis reveals it is much more affordable to access mobility in an AMoD system compared to traditional mobility models based on private vehicle ownership.

7 Conclusions and Future Directions

This chapter has provided analytical guidelines for rigorously sizing Automated Mobility-on-Demand (AMoD) systems based on transportation data. Results suggest that an AMoD solution could meet the personal mobility need of the entire population of Singapore with a fleet whose size is approximately 1/3 of the total number of passenger vehicles currently in operation. Moreover, a financial analysis indicates AMoD systems are a financially viable alternative to more traditional means of accessing personal mobility.

Given the multifaceted nature of AMoD systems, the results reported herein suggest a number of issues that deserve further investigation. An important aspect that needs to be addressed is the impact of an AMoD system on traffic congestion. Even though our analysis shows that an AMoD system could provide mobility to the entire population with far fewer vehicles than are currently on the road, it is also the case that these vehicles will be traveling more; in fact, the total distance traveled by all vehicles (often referred to as Vehicle Miles Traveled, or VMT)—and thus the load on the road network—will be greater, due to vehicles traveling empty, e.g., to pick up customers. Another important aspect is latent demand: it may be the case that the availability of a new convenient and economical mode of transportation may actually increase the demand for mobility. Given these competing forces, it is as yet unclear what the effect of AMoD systems will be on travel times and congestion levels, which is an important topic for future research.

Acknowledgements This work was partially supported by the Singapore National Research Foundation, under the Future Urban Mobility SMART IRG program. The authors are grateful to the Land Transport Authority of Singapore for providing access to the HITS data.

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Automated Truck Platoon Control and Field Test

Xiao-Yun Lu and Steven E. Shladover

Abstract This chapter presents the results of experiments on coordinated automatic longitudinal control of a platoon of three Class 8 tractor-trailer trucks, using 5.9 GHz DSRC with 100 ms update intervals for coordination. The trucks were tested not only in constant-speed cruising conditions, but also through acceleration and deceleration profiles, up and down grades, and in platoon join and split maneuvers using the DSRC coordination. These tests showed good vehicle following accuracy, ride quality and platoon stability. The desired gaps between the trucks were varied between 10 and 4 m to evaluate the effects of aerodynamic drag reductions on fuel savings. The most complete set of drag data, at the 6 m gap, shows fuel savings of about 4–5 % for the lead truck and in the range of 10–14 % for the following trucks. The effects of platoon gap variations between 10 and 4 m were more difficult to determine with certainty because strong ambient winds during those tests led to large differences in the results depending on the truck direction of travel, but the results imply a significant potential for larger savings at the shorter gaps.

Keywords Vehicle automation · Heavy-duty truck control · Platooning · V2V DSRC · Field test · Longitudinal maneuvers · Fuel economy

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-05990-7_21, © Springer International Publishing Switzerland 2014

1 Introduction

Heavy-duty truck (HDT) longitudinal control modeling and control were developed before for two trucks and field tested [1–5] at the California PATH Program. The pioneering work on this topic was done by the CHAUFFEUR project under the leadership of Daimler-Benz between 1996 and 2004 [6–8]. More recently, truck platooning control systems have been developed and tested in several countries. In 2005–2009, the KONVOI industrial/university project at RWTH Aachen University tested a platoon of four heavy-duty trucks spaced at 10 m following distance [9] on test tracks and on public Autobahns in Germany. The European Commission funded SARTRE project developed and tested platooning with two leading trucks and three following passenger cars [10]. A four-truck automated platoon was demonstrated with 4 m following distance in Japan's Energy ITS Project [11–13], with average fuel economy gains of 15 %. A new European Commission funded project called Companion, led by Scania, will be studying truck platooning with an emphasis on the logistics and back-office supporting functions [14].

Truck control is very challenging due to several factors:

- Mass dominant: low power/weight ratio, large mass leads to large inertia, and performance is very sensitive to road grade
- Time delays: actuator response delay, particularly pneumatic brake and transmission retarder, and sensor data filtering delays are the major hurdles to practical string stability [15] for truck platooning
- Auxiliary power consumption: especially engine cooling fan (about 10 % of engine power for the test trucks):
- Very limited acceleration capability: fully loaded truck acceleration capability on a flat road is close to zero at cruising speed.
- Other internal and significant external disturbances: including sensor detection error, unevenness of the road and road grade, aerodynamic drag due to wind, and notably, gear shifting.

Therefore, longitudinal control design and fine tuning need to push the controller bandwidth to the maximum possible to accommodate the delays and disturbances. To achieve this, it is necessary to reduce the mismatch between the real truck dynamics and the dynamic model assumed for the control design as much as possible. The limit on power or torque at higher vehicle speed is another big challenge to longitudinal maneuvers. Due to those limits, an HDT cannot behave like a car. Instead, the trajectory planned for the feed-forward part of the control system, needs to be well-designed and finely tuned for real-time implementation.

This chapter will focus on the design of the maneuvers and field testing at highway speed. It is organized as follows: Sect. 2 presents the design, implementation and testing of the truck platoon control system; Sect. 3 considers the longitudinal maneuver capability of these automated trucks; Sect. 4 is dedicated to fault detection and handling which is an essential element of automated vehicle platooning; Sect. 5 is the data analysis for control performance of all the maneuvers including fuel economy benefits; Sect. 6 gives some concluding remarks.

2 Design, Implementation and Testing of Automated Truck Platoon

2.1 Using DSRC in Automated Truck Control

For automated vehicle platooning, reliable inter-vehicle communication is essential to maintain string stability. A 5.9 GHz DSRC radio, the Savari Onboard Unit (SOBU), was used. The data packets broadcast by the vehicles were less than 200 bytes long, which is rather small. The vehicle status information is broadcast by each truck, and each truck uses the information broadcast by the other trucks that is relevant for its use.

2.2 Development of Automated Truck Platoon

In order to demonstrate the viability of the automated truck platoon concept, it was necessary to show that the platoon could be operated under a realistic range of operating conditions, not just under the simplest or most ideal conditions. The required operating conditions are not only steady-state cruising at a constant speed, but also speed changes, platoon join and split maneuvers and ascending and descending highway grades.

The most challenging maneuver is platooning up/down a grade because the truck has very limited torque available for maneuvering at higher speeds due to its low power-to-mass ratio. The limited torque has to be used for both distance and speed control, as well as overcoming the grade ascending a hill. Considering that the electronic braking systems (EBS) did not function as expected for two of the three trucks, platooning going down a grade was also challenging. When the ambient temperatures are high during the testing, the engine cooling fan has to be used, which alone draws 10 % of the engine power, producing a large disturbance to the control system.

2.3 Truck System Modeling and Control System Structure

Truck system modeling for control design was based on a model developed for a prior set of two-truck platoon tests in 2003. Detailed modeling of each component is reported in [1, 5]. The overall system modeling and control system structure is depicted in Fig. 1.

The three trucks used for control implementation and testing are Freightliner Century Class tractor-trailer combination with extended sleeper cab. The engine is a Cummins N14-435EI rated at 435 HP, combined with an Allison 4060 automatic transmission.

The control system structure and implementation were described in [2–5]. The truck drive-train model used for longitudinal control design is the same as that developed in 2003 [1–3].

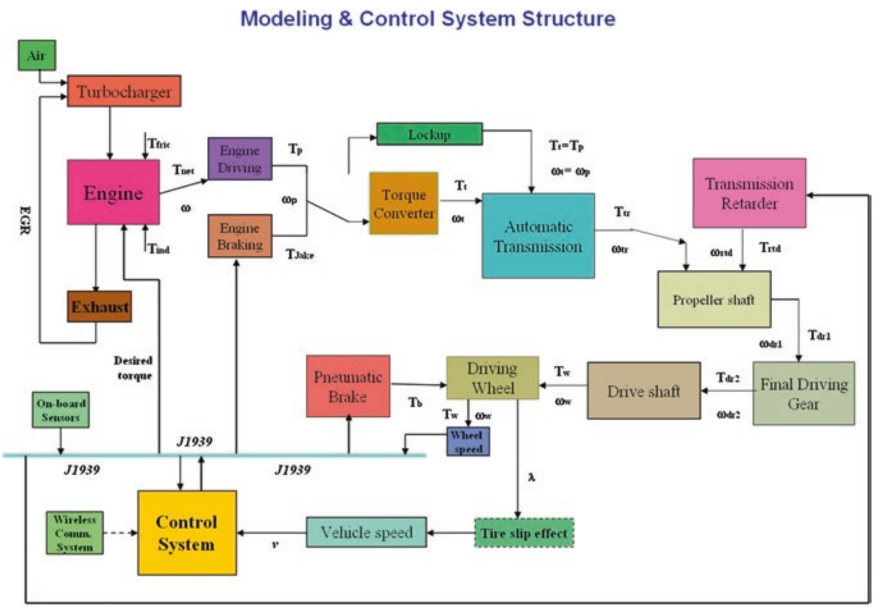

Fig. 1 Truck modeling, sensor reading, information passing and control system

2.4 Sensors and Actuators

As depicted in Fig. 1, most vehicle information is obtained through the truck's internal J1939 data bus. Engine control is based on the built-in torque control of the engine control system. Brake system control includes three parts: Engine compression brake (Jake brake), transmission retarder, and pneumatic brake. Their control actuations are also realized through the J-1939 bus.

Each of the three trucks was equipped with an Eaton-Vorad EVT-300 Doppler radar for forward collision warning and adaptive cruise control. One truck also has a DENSO lidar, which has an azimuthal scanning capability, and another has been equipped with a single beam MDL lidar, which has no scanning capability. The full complement of sensors and actuators on the trucks is shown in Fig. 2.

2.5 Practical String Stability for Vehicle Platooning

As discussed in detail in [15], practical string stability in automated vehicle platooning needs to take into account the following factors:

- Time lags in sensors and actuators
- Pure time delays in sensor measurement and signal processing
- Model mismatches
- Measurement noises
- External disturbances from the environment, including the road and wind

Fig. 2 Sensors and actuators installed on three trucks

Without those factors, one could theoretically achieve asymptotic string stability from a control design viewpoint—tracking errors diminishing from the platoon head to the end. In such an ideal case, people could talk about a platoon of arbitrary length (number of vehicles). However, with the aforementioned factors taken into account, the situation is quite different: the platoon length is limited by the afore mentioned factors and the bandwidth of the feedback control on each vehicle. In general, the larger the accumulated time delay and disturbances, the shorter the platoon that can be formed and maintained; and the larger the control bandwidth, the longer the platoon that can be achieved.

2.6 Control System Implementation and Field Tests

The first set of high-speed highway tests of the truck platoon was conducted on Nevada SR-722, to the west side of Austin, NV, in September 2010. This is a straight, almost flat, section of two-lane highway with such a low daily traffic volume (AADT 60 vehicles) that it was practical for Nevada DOT to authorize temporary closure during each individual test run. The truck control computer systems are PC-104 configurations with mechanical hard disks, which were installed horizontally with four air suspensions as shock absorbers.

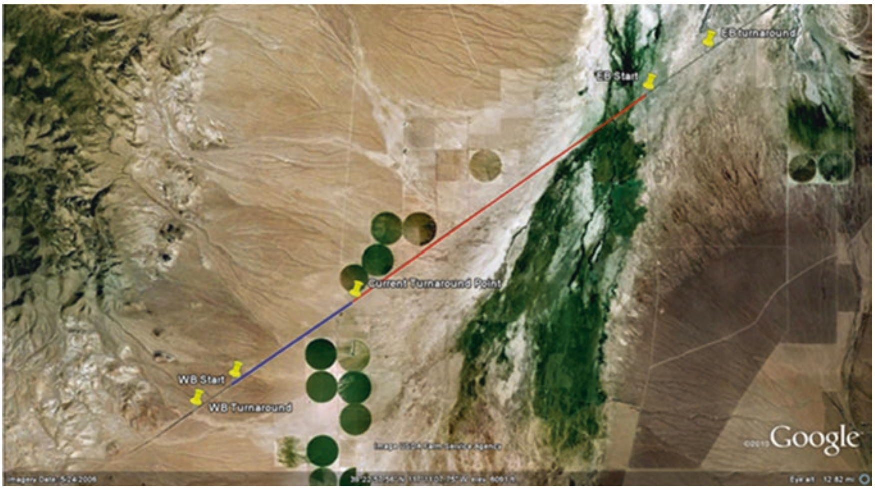

Fig. 3 SR722 in Austin Nevada. The *red section* is almost flat; the *blue section* contains a hill with Grade Levels A, B, and C

The roadway test section on SR-722 in Nevada is marked in Fig. 3. It was used for tests in September 2010 and May 2011.

2.7 Test Results

The following parameters have been plotted against global time to show the performance of the truck platoon control system:

- Measured speed in [mph]—essentially wheel speed. Since the road surface was dry during the tests, the speed could be considered as true vehicle speed;
- Speed tracking error [m/s] and distance tracking error [m];

For measuring the speed and distance tracking, maximum values and Root Mean Square (RMS) errors have been used to quantify the error values based on the test data. Two configurations have been tested:

- Configuration 1: Blue Truck; Gold Truck; Silver Truck
- Configuration 2: Blue Truck; Silver Truck; Gold Truck

Using those two configurations for platooning tests has two purposes: (a) to check the robustness of the controller with respect to different configuration; (b) to conduct fuel economy analysis for different platoon configuration to exclude the possibility of bias caused by vehicle characteristics. These tests were conducted with the truck tractors pulling identical 53-ft. empty box trailers to provide a realistic representation of the aerodynamic drag effects typical in long-haul trucking.

The following Table 1 lists the RMS and maximum errors for speed and distance tracking respectively. It can be observed that both speed and distance

Table 1 Speed and distance tracking error (RMS and Max) for tests in September 2010

Data#	Dir	Max spd [mph]	Des dist [m]	Blue—1st				Gold—2nd				Silver—3rd			
				Distance error [m]		Speed error [m/s]		Distance error [m]		Speed error [m/s]		Distance error [m]		Speed error [m/s]	
				RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max	RMS	Max
1	W	53	6	0.1197	0.2910	0.0271	0.1550	0.9388	1.6170	0.0703	0.2880	0.4392	1.0960	0.0922	0.3840
2	E	53	6	0.0953	0.2450	0.0228	0.1110	0.7998	1.4360	0.0597	0.2160	0.3827	1.0110	0.0840	0.3360
3	W	53	6	0.1183	0.2790	0.0256	0.1550	0.4195	1.0250	0.0687	0.2640	0.5508	1.2500	0.0903	0.3600
4	E	53	6	0.0809	0.2010	0.0245	0.1350	0.8375	1.5140	1.5140	0.2400	0.4275	0.9750	0.0690	0.3240
5	W	53	6	0.1219	0.3520	0.0269	0.1330	0.6610	1.2960	0.0683	0.2160	0.3332	0.8620	0.1003	0.3840
6	E	53	6	0.0840	0.2000	0.0253	0.1350	0.7712	1.4820	0.0648	0.2640	0.3280	0.9110	0.0818	0.2820
7	W	53	6	0.1202	0.3480	0.0263	0.1550	0.2525	0.6860	0.0758	0.2400	1.1738	2.0910	0.0813	0.3840
8	E	53	6	0.0784	0.2070	0.0236	0.1300	0.6287	1.2740	0.0680	0.2640	0.5488	1.1900	0.0780	0.5160
Mean		53	6	0.1023	0.2654	0.0253	0.1386	0.6636	1.2913	0.2487	0.2490	0.5230	1.1733	0.0846	0.3713

tracking error are within acceptable ranges for platoon operations (speed error less than 0.25 m/s RMS and distance error less than 0.7 m RMS). It is noted that the distance and speed tracking errors of the second truck is slightly larger than the third truck, which might be caused by a combination of several factors including: different lidar sets used, difference in aerodynamic drag, and the second truck being offset about 0.3–0.5 m to the right to maintain wireless communication line of sight between the first and third trucks..

3 Maneuver Capability of Automated Trucks

The following maneuvers have been developed for three-truck platooning.

- Variable maximum speed with constant following distance
- Simultaneous splitting/joining of trucks to platoon
- Simultaneous splitting followed by simultaneous joining
- Individual splitting/joining
- Individual splitting followed by individual joining
- Preliminary fault detection and handling:
  - Level 1 faults: driver is alerted to take over control immediately;
  - Level 2 faults: trucks will split to a longer distance and continue platooning;
  - Level 3 faults: all three trucks will continue platooning unless another fault appears;
- Grading up and down a hill.

These maneuvers were tested in the following sequence:

- tested in simulation
- implemented in real-time code and tested in static run—all the software and most hardware are running without the vehicle moving, with the clutch disengaged;
- tested at low speed at short PATH test track at the University of California Richmond Field Station
- tested at high speed on SR722 in Austin, Nevada, in May 2011.

3.1 Variable Maximum Speed with Constant Following Distance

Maximum speed for the platoon is specified as a function of location. The trajectory planning is conducted automatically based on the current speed and the desired maximum speed, while taking into account the truck acceleration/deceleration capabilities at the corresponding speed. The objective of this maneuver is to test the string stability of three trucks platooning as the platoon speed fluctuates. This maneuver was tested on a 5 mile long stretch of flat road as indicated in the Fig. 3

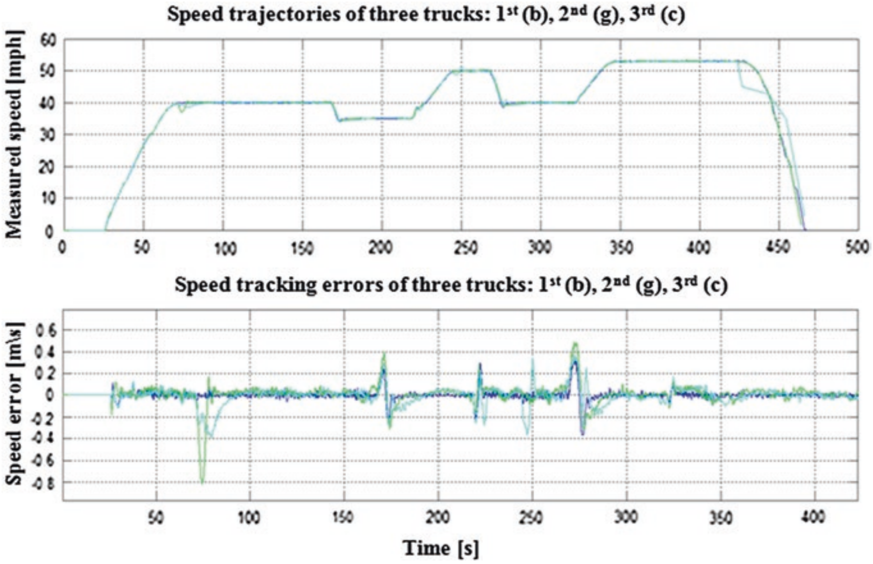

Fig. 4 Variable maximum speed platooning of three trucks. *upper* measured speed trajectories, and maneuver ID; Speed changes are 0 → 40 → 35 → 50 → 40 → 53 mph; *lower* speed tracking errors of three trucks

red section. The following figures show the speed trajectories, speed errors, distance tracking errors and other values (Fig. 4).

3.2 *Individual Splitting/Joining*

This maneuver is slightly different from the simultaneous splitting/joining. Although the speed trajectory planning is the same, the maneuver times and locations of the second and the third trucks are different. For the splitting, the third truck needs to maneuver first with a double-length split. After the completion of the third truck's split, the second truck begins to split to its desired distance. The total splitting time is 50 s and the total joining time is 70 s. After the maneuver, the distances between the first and the second trucks and between the second and the third trucks are the same.

3.3 *Simultaneous Splitting/Joining*

For this maneuver, the leading truck follows its speed trajectory and virtual distance. The second and the third truck are expected to split/join from their current following distance to a new specified distance at the same time. This means that

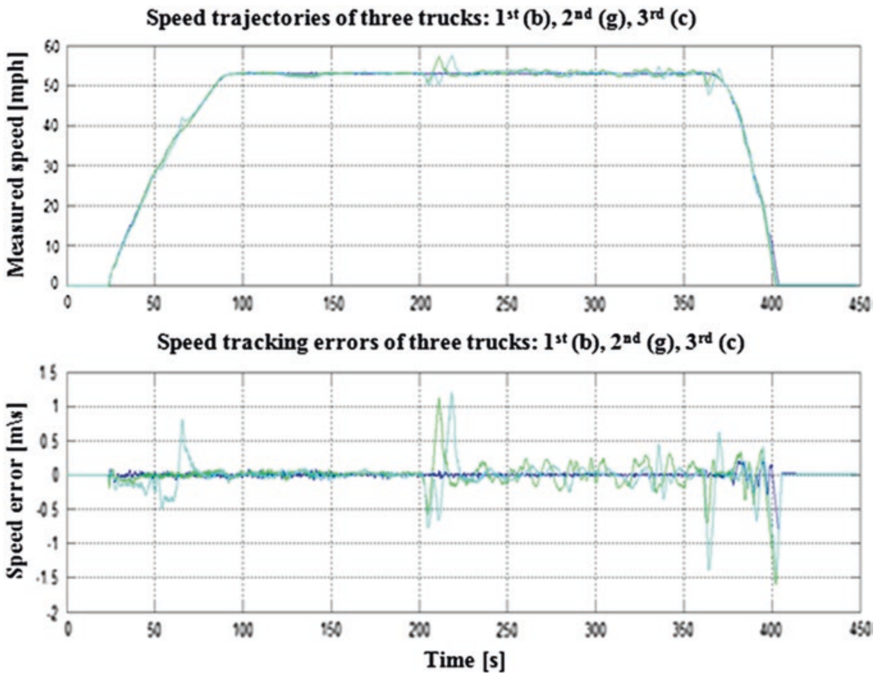

Fig. 5 Simultaneous splitting followed by simultaneous joining for the second and the third truck to a pre-specified distance; *upper* speed trajectory; *lower* speed tracking error

the third truck will have to split (increase inter-vehicle distance) or join (reducing inter-vehicle distance) relative to the first truck by twice as much as the second truck. After the maneuver, the inter-vehicle distances are the same.

Those two maneuvers have been tested along the 5 mile long flat stretch on SR 722 in Austin, Nevada. The total splitting time is 25 s and the total joining time is 35 s. Figure 5 shows the results of one test with the splitting maneuver followed by the joining maneuver.

3.4 Ascending and Descending a Hill

Road grade is an extra challenge to heavy-duty-truck (HDT) platooning, particularly at higher speeds. As mentioned before, truck acceleration/deceleration capability decreases significantly as speed increases, even on a flat road. This is partly because a HDT has a very low power to weight ratio. Figure 6 shows the speed trajectories and speed tracking errors of all three trucks ascending a hill. The road Grade Levels are A (<0.5 %), B (0.5–2.5 %) and C (2.5–4 %). It is noted that, in the speed up phase (before 150 s) for ascending the hill, the acceleration decreases for higher road grade as indicated with arrows.

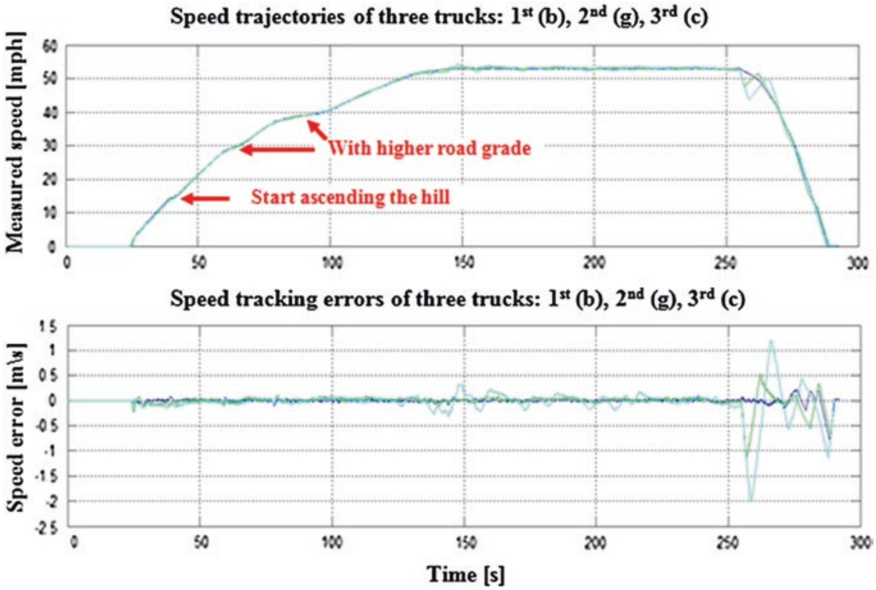

Fig. 6 Ascending a hill with road grade at 53 mph: measured speed and speed tracking error; the slope of the speed curve (or acceleration) decreases when road grade increases

4 Fault Detection and Handling

The currently implemented fault detection and handling capability is rudimentary, just to improve safety during the testing and to alert the truck drivers and researchers working on the trucks about potentially unsafe conditions that they may not recognize immediately themselves. An operational system for use by normal truck drivers in their daily driving would need a much more comprehensive fault detection and handling system, capable of handling all possible fault conditions. Major faults that are detected and handled include: control computer, DSRC communication, radar and lidar, some critical J-1939 bus data reading, and air brakes. Fault types and suggested operation scenarios for handling the faults are displayed with four colors of LEDs. Professional drivers in operation of the trucks for the tests were trained in advance in how to recognize different faults and what actions to take for safety. Fault detection and handling for vehicle longitudinal control have been discussed in detail before in [16].

5 Fuel Economy Analysis

Energy saving through reduction of aerodynamic drag is one of the most important expected benefits from close-formation automated platoon driving. Therefore, it is important to understand how much energy could be saved under different operation conditions. The key variables investigated here were the effects of the position within the platoon and the inter-vehicle spacing. All tests were conducted at a single speed, since the dependence of aerodynamic drag on speed is a well-known quadratic relationship. The test site was at an altitude of 6,000 ft. (1,800 m), where the air density is only 80 % of the density at sea level. This means that the drag savings should be expected to be significantly larger at sea level.

The fuel consumption is obtained by integration of the fuel consumption rate obtained from the fuel injector signals on the J-1939 bus for each vehicle individually during the cruising phase, when the reference speed of the platoon is constant. The fuel consumption tests were conducted on a day with almost no wind. The data are averaged in two directions which cancels any small effects of wind and grade. Before testing the platooning of three trucks, each truck was tested individually to obtain the baseline fuel consumption. The energy saving results were obtained by comparing the fuel consumption in the baseline case and the platoon case, which showed that:

1. The second vehicle consumed 6 % less fuel than the leader, and the third vehicle consumed 11 % less than the leader when platooned at 6 m gap.
2. The fuel consumption rates of each truck in the platoon at 6 m gaps compared to single truck runs by the same trucks were:

- First truck fuel reduction: 4.3 %
- Second truck fuel reduction: 10 %
- Third truck fuel reduction: 14 %

The carefully controlled 2003 measurements on a two-truck automated truck platoon reported by Browand et al. [17] indicated that at the 6 m gap, the front truck would save 7 % and the following truck would save 9 % compared to their fuel consumption when driven individually. By comparison, the more recent three-truck tests indicate a smaller reduction in the fuel saving by the front truck, but a significant improvement in the fuel saving by the following trucks. This improvement in the following truck fuel consumption is attributable to the extension from two trucks to three trucks in the platoon.

However, the second truck was not completely lined up with the first truck and the third truck (about 0.3–0.5 m lateral offset to the right). This was intended to let the DSRC antennas of the three trucks stay within line of sight of each other for reliable communication. This offset distorted the fuel consumption measurements for the second and the third trucks, with the second truck experiencing higher drag and the third truck lower drag than they would have experienced if they had been fully aligned. This is why these preliminary results are not consistent with other published results for multiple-truck platooning, which all show the most significant drag reductions for the middle trucks.

6 Concluding Remarks

The automated truck platoon tests demonstrated several important results:

(a) The DSRC communication system at 5.9 GHz, with 100 ms update intervals, has sufficient capabilities to support this most demanding of V2V communication applications. However, dual antennas will be necessary for reliable DSRC communications to maintain line of sight among antennas on all trucks under all road conditions, including curves and grade changes, without requiring lateral offset of the middle truck.

(b) A platoon of three tractor-trailer trucks was successfully driven under automated longitudinal platoon control, maintaining adequate tolerances on longitudinal gap variations while cruising and maneuvering. On an essentially flat section of road, the RMS error in vehicle-following gap was maintained within 0.7 m, a small fraction of the nominal gap.

(c) The truck platoon was tested for a range of target inter-truck following gaps, beginning with 10 m. As the performance at each gap was verified to be satisfactory, shorter gaps were attempted, going as short as a 4 m gap by the end of the testing period. These results show the basic technical feasibility of closely-coordinated longitudinal control of heavy trucks in a platoon, maintaining short gaps using the combination of DSRC radio communications and radar and lidar ranging sensors.

(d) The DSRC radios were also used to coordinate maneuvers among the trucks, with a particular focus on platoon joining and splitting maneuvers. These maneuvers were performed in different combinations, simultaneously and sequentially for the joins and splits between the first and second and the second and third trucks. The sequential maneuvers are to be preferred for future implementations because the simultaneous maneuvers require significantly larger speed changes by the third truck.

(e) The trucks were also maneuvered through a sequence of speed profile changes to test the ability of the followers to follow the leader. The rate of speed changes for these maneuvers had to be limited based on power limitations of the trucks. The speed change tests showed that the second truck followed the first with an effective lag of 0.8 s, and the third truck followed with an effective lag of 1.2 s relative to the first. The rms errors of gap and speed between the trucks throughout the speed change tests were 0.22 m and 0.01 m/s (averaged over all test runs) and 0.57 m/s (max among all the test runs) between the first and second trucks and 0.25 m and 0.07 m/s (averaged over all test runs) and 0.65 m/s (max among all the test runs) between the second and third trucks.

(f) One of the largest potential benefits from truck platooning is the saving of energy and, accordingly, CO_2 emissions based on reductions in aerodynamic drag. The direct fuel consumption of the trucks was monitored throughout the testing through their engine controllers' fuel injection systems, and the trends in fuel consumption were studied to provide initial estimates of the benefits that could be gained. All the trucks in the platoon save fuel when they are driven at close spacing within the platoon. The lead truck saves less than the followers save, and there is some inconsistency in the results regarding the savings by the second and third trucks. Nevertheless, we should expect the first truck in a platoon at 6 m gaps to be able to save 4.3 % of its normal fuel consumption in steady cruising on flat roads at 85 km/h, with the following trucks saving 10–14 %. Because these results were measured at an altitude of

6,000 ft. (1,800 m), where the air density is only 80 % of that at sea level, the relative savings at sea level should be more significant since the total aerodynamic drag should be about 25 % higher than it was at the high-altitude test site (while the other losses would be unchanged).

When we consider that many long-distance trucks in the U.S. cruise at speeds around 115 km/h (71 mph) rather than the 85 km/h speed of these tests, their aerodynamic drag could be 80 % higher than we measured since the drag increases with the square of the speed. Combining this effect with the altitude effect, the typical aerodynamic drag experienced by trucks operating in long-distance revenue service could be twice as high as it was in our tests. Following the rule of thumb that aerodynamic drag accounts for about half of fuel consumption of trucks at highway speed, this implies that the fuel savings that would be experienced in practice could be 50 % higher than what we measured in these tests.

(g) A limited fault detection and identification system was implemented on the experimental trucks to provide visible indicators to the truck driver and the researcher observing from the passenger seat about the status of the truck control system, so that they would be made aware of potential problems as soon as possible. This was found to be particularly important and useful for faults on one truck that may not otherwise be apparent to people traveling in another truck with which it is closely coupled.

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Erratum to: An Analysis of Possible Energy Impacts of Automated Vehicles

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Erratum to:
Chapter "An Analysis of Possible Energy Impacts of Automated Vehicles" in: G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility, https://doi.org/10.1007/978-3-319-05990-7_13

In the original version of the book, the title "An Analysis of Possible Energy Impacts of Automated Vehicle" of Chapter 13 has been changed to read as "An Analysis of Possible Energy Impacts of Automated Vehicles". The erratum chapter and the book have been updated with the change.

The updated online version of this chapter can be found at https://doi.org/10.1007/978-3-319-05990-7_13

G. Meyer and S. Beiker (eds.), *Road Vehicle Automation*, Lecture Notes in Mobility,
https://doi.org/10.1007/978-3-319-05990-7_22,