Policy and society related implications of automated driving: a review of literature and directions for future research

Dimitris Milakis
Department of Transport and Planning, Faculty of Civil Engineering and Geosciences,
Delft University of Technology
PO Box 5048, 2600 GA Delft, The Netherlands
Email: d.milakis@tudelft.nl, Tel: +31 (0) 15 27 84981

Bart van Arem
Department of Transport and Planning, Faculty of Civil Engineering and Geosciences,
Delft University of Technology
PO Box 5048, 2600 GA Delft, The Netherlands
Email: b.vanarem@tudelft.nl, Tel: +31 (0) 15 27 86342

Bert van Wee
Transport and Logistics Group, Faculty of Technology, Policy and Management,
Delft University of Technology
P.O. Box 5015, 2600 GA Delft, The Netherlands
Email: G.P.vanWee@tudelft.nl, Tel: ++31 (0) 15 27 81144

Working paper
Prepared for the Delft Infrastructures and Mobility Initiative

Delft University of Technology
19.10.2015

Policy and society related implications of automated driving: a review of literature and directions for future research

Dimitris Milakis
Department of Transport and Planning, Faculty of Civil Engineering and Geosciences,
Delft University of Technology
PO Box 5048, 2600 GA Delft, The Netherlands
Email: d.milakis@tudelft.nl, Tel: +31 (0) 15 27 84981

Bart van Arem
Department of Transport and Planning, Faculty of Civil Engineering and Geosciences,
Delft University of Technology
PO Box 5048, 2600 GA Delft, The Netherlands
Email: b.vanarem@tudelft.nl, Tel: +31 (0) 15 27 86342

Bert van Wee
Transport and Logistics Group, Faculty of Technology, Policy and Management,
Delft University of Technology
P.O. Box 5015, 2600 GA Delft, The Netherlands
Email: G.P.vanWee@tudelft.nl, Tel: ++31 (0) 15 27 81144

Abstract

Automated driving has been receiving enormous attention by industry, government and academia. Although high expectations rest on this evolving transportation technology, little is known about its impacts. Most papers published so far have explored technological aspects of vehicle automation and impacts on driver and traffic flow characteristics. However, the interest about the wider implications of automated vehicles is constantly growing as this technology evolves. In this paper, we explore the potential effects of automated driving relevant for policy and society, review literature results about those effects and identify areas for future research. We structure our review based on the ripple effect concept, which represents implications of automated vehicles at three stages: first-order (traffic, travel cost, and travel choices), second-order (vehicle ownership and sharing, location choices and land use, and transport infrastructure) and third-order (energy consumption, air pollution, safety, social equity, economy, and public health). Our review shows that first-order impacts on road capacity, fuel efficiency, emissions, and accidents risk are expected to be beneficial. The magnitude of these benefits will likely increase with the level of automation and cooperation and with the penetration rate of these systems. The synergistic effects between vehicle automation, electrification and sharification can multiply these benefits. However, studies confirm that automated vehicles can induce additional travel demand because of more and longer vehicle trips. Potential land use changes have not included in these estimations about excessive travel demand. Other third-order benefits on safety, economy, public health and social equity still remain unclear. Therefore, the balance between short-term benefits and long-term impacts of vehicle automation remains an open question.

Keywords: Automated driving, policy and societal implications, ripple effect, first-, second-, and third- order impacts

1. Introduction

Automated driving is considered among those technologies that could signalize an evolution towards a major change in (car) mobility. We can infer estimations about the extent of this change by answering the following two questions: (a) Which are the potential changes in mobility and the implications for society associated with the introduction of automated driving, and (b) To what extent are these changes synchronized with broader concurrent societal transformations that could enhance the radical dynamic of such mobility technology? Examples of social transformations could be the digital and sharing economy, the livability and environmental awareness movement and the connectivity, networking and personalized consumption trends.

In this paper, we focus on the first question aiming to (a) explore potential effects of automated driving relevant for policy and society, (b) review literature results about those effects and (c) identify areas for future research. To the best of our knowledge literature does not systematically explore and review studies about policy and society related implications of automated driving. Our contribution aims to fill this gap. Thus far, scholarly efforts have been mainly concentrated on the technological aspects of vehicle automation (i.e. road environment perception and motion planning) and on the implications for driver and traffic flow characteristics. Accordingly, review efforts have focused on the development and operation of vehicle automation systems and the associated technologies (see Gerónimo, López, Sappa, & Graf, 2010; Piao & McDonald, 2008; Shladover, 1995, 2006; Sun, Bebis, & Miller, 2006; Turner & Austin, 2000; Vahidi & Eskandarian, 2003; Xiao & Gao, 2010). Several review studies have also focused on the first-order impacts of vehicle automation with a special emphasis on traffic flow efficiency (see Diakaki, Papageorgiou, Papamichail, & Nikolos, 2015; Hoogendoorn, van Arem, & Hoogendoorn, 2014; Hounsell, Shrestha, Piao, & McDonald, 2009; Scarinci & Heydecker, 2014), and human factor aspects such as behavioural adaptation, driver's workload and situation awareness (see Brookhuis, de Waard, & Janssen, 2001; de Winter, Happee, Martens, & Stanton, 2014; Stanton & Young, 1998). A partial overview of wider implications of automated vehicles has been recently made by Fagnant & Kockelman (2015) with the aim to provide an order-of-magnitude estimation about possible economic impacts of automated vehicles in the US context.

The remainder of this paper is structured as follows. We first describe our methodology (section 2) and then we present a simplified concept to represent the areas of possible policy and society related implications of automated vehicles (section 3). In sections 3, 4 and 5 we present the results of our analysis about the first-, second-, and third- order implications of automated driving respectively. Every sub-section in sections 3, 4 and 5 is structured in two parts. The first part presents the analysis about possible implications of automated driving and their mechanisms (assumptions) and the second one the review of the respective results from the literature (literature results). In section 6 we draw our conclusions and we summarize directions for future research.

2. Methodology

Our methodology involves two steps. First, we develop a simplified concept to represent the areas of possible implications of automated vehicles in a structured and holistic way. Then, we identify (a) the impacts of automated driving and their respective mechanisms, (b) existing literature results about those implications, and (c) research gaps between possible impacts and existing literature results.

We explore the impacts of automated driving and their respective mechanisms based on our own analytical thinking. Then, we review literature results about implications of automated driving based on Scopus- and Web of Science- listed peer-reviewed articles. We searched for articles dated up to September 2015 having in the title, abstract or keywords any combination of the following keywords: advanced driver assistance system(s), (cooperative) adaptive cruise control, autonomous vehicle(s), autonomous car(s), self-driving vehicle(s), self-driving car(s), driverless vehicle(s), driverless car(s), automated vehicle(s), automated car(s), automated driving, robocar(s), and the keywords appearing in table 1 for each area of implications. Research on some implications of automated vehicles is still in its infancy. Therefore, in the case of very limited or no results for a specific field, we expanded our search to Google and Google Scholar aiming to identify any unpublished reports of systematic studies.

This paper focuses on passenger transport and employs the SAE International (2014) taxonomy which defines five levels of vehicle automation. In Level 1 (assisted automation) and level 2 (partial automation) the human driver performs all aspects of driving task assisted by one or more driver assistance systems respectively. In level 3 (conditional automation) the human driver is expected to be available for occasional control of the vehicle, while in level 4 (high automation) and level 5 (full automation) s/he is not. In level 5 the vehicle is expected to drive itself under all roadway and environmental conditions.

3. The ripple effect of automated driving

We use the ripple model to conceptualize the sequential effects that automated driving might bring to several aspects of mobility and society. The “ripple effect” has been widely used to describe sequentially spreading effects of events in various fields including economics, psychology, computer science, supply chain management and scientometrics (see e.g., Barsade, 2002; Black, 2001; Cooper, Orford, Webster, & Jones, 2013; Frandsen & Nicolaisen, 2013; Ivanov, Sokolov, & Dolgui, 2014; Meen, 1999). We present the ripple model of automated driving in figure 1. Driving automation is placed in the center of the graph to reflect the source of the sequential first-, second-, and third- order effects in the outer ripples. The first ripple comprises implications of automated driving on traffic, travel cost, and travel choices. The second ripple includes implications of automated driving with respect to vehicle ownership and sharing, location choices and land use, and transport infrastructure. The third ripple contains the wider societal implications (i.e., energy

consumption, air pollution, safety, social equity, economy, and public health) from the introduction of automated vehicles.

The ripple model of automated driving does not hold the exact same properties of the respective ripple model in physics that describes the diffusion of waves as a function of time and distance. Therefore the ripple model of automated driving should not be taken too strict. Feedbacks can occur in our model. For example, changes in travel cost (first ripple) might influence accessibility and subsequently location choices, land use planning and real estate investment decisions (second ripple), which in turn could affect back travel decisions (e.g., vehicle use) and traffic (first ripple) (see Figure 2). Also, there might be no time lag between sequential effects. For example, vehicle use changes will immediately result in safety or air pollution changes. Finally, it should be clear that effects on fuel consumption, emissions and accidents risk can occur soon after introduction of automated vehicles, yet the wider (societal) impacts on energy consumption, air pollution and safety (third ripple) can be evaluated only after changes in the first two ripples are taken into account (see Figure 2).

4. First-order implications of automated driving

In this section we explore the first-order implications of automated driving on travel cost, road capacity and travel choices.

4.1 Travel cost

Assumptions

We explore potential implications on both the fixed (capital) cost of owning an automated vehicle and the generalized transport cost, which comprises effort, travel time and financial costs of a trip. Fixed costs of automated vehicles will possibly be higher than conventional vehicles due to advanced hardware and software technology involved. The increased fixed cost could influence the penetration rate and subsequently the magnitude of the effects of automated vehicles. The generalized transport cost (GTC), on the other hand, is expected to decrease because of lower effort, time and money needed to travel. First, more travel comfort, enhanced travel safety (see section 6.2), higher travel time reliability and increased travel enrichment (i.e., performance of other activities than driving like working, meeting, eating, sleeping while on the move) will possibly lead to lower values of time. Second, less congestion delays because of increased road capacity (see section 4.2) and reduced (or even eliminated) search time for parking owing to self-parking capability, but also increased use of shared vehicles, would possibly require less travel time. Third, enhanced efficiency of traffic flow along with more fuel-efficient vehicles (see section 6.1) because of lighter design owing to less risk of having an accident could also reduce the monetary cost of travel. Due to shorter headways air resistance will possibly decrease, further reducing fuel use and costs. However, potential increase of vehicle travel demand because of enhanced road capacity, reduced GTC, and/or proliferation of vehicle sharing systems (see section 5.1) and

urban expansion (see section 5.2) in longer term, could compromise travel time and cost savings. The counter effects of increased vehicle demand could include increased congestion delays, longer trips, and more fuel costs.

Literature results

Fagnant & Kockelman (2015) report estimations that current automated vehicle applications cost multiple times the price of a conventional vehicle in the US. However, they estimate that this gap in cost could be gradually reduced to $3000 or even lower with mass production and technological advances of automated vehicles. Regarding components of GTC, several studies have incorporated comfort in terms of longitudinal and lateral acceleration as optimizing metric in their trajectory-planning algorithms (see e.g., Glaser, Vanholme, Mammar, Gruyer, & Nouvelière, 2010; Raimondi & Melluso, 2008). Moreover, multi-objective adaptive cruise control (ACC) algorithms usually incorporate ride comfort (measured in terms of vehicle acceleration) along with safety and fuel consumption as system constraints (see e.g., Dang, Wang, Li, & Li, in press.; Li, Li, Rajamani, & Wang, 2011; Luo, Chen, Zhang, & Li, 2015; Moon, Moon, & Yi, 2009). However, Elbanhawi, Simic, & Jazar (2015) argue in their review paper that several factors of human comfort are largely ignored in research for autonomous path planning systems (i.e. motion sickness, apparent safety (the feeling of safe operation of the automated vehicle) and natural human-like paths. Moreover, research has shown that comfort is not influenced only by vehicle acceleration but also by the time headway when driver is still in the loop. Both Lewis-Evans, De Waard, & Brookhuis (2010) and Siebert, Oehl, & Pfister, (2014) identified a critical threshold for time headway in the area of 1.5 to 2.0 seconds below which driver's perception of comfort reduces significantly.

Besides comfort, several studies have reported results about travel time and fuel savings based on simulation of various control algorithms for automated car-following scenarios and automated intersection management. Studies about fuel savings are presented later in section 6.1. Concerning travel time, Arnaout & Arnaout (2014) simulated a four-lane highway involving several scenarios of penetration rates for cars equipped with cooperative adaptive cruise control (CACC) and a fixed percentage for trucks (10%). They found that travel time decreased exponentially with the increase of CACC penetration rate. Ngoduy (2012) reported that a 30% penetration rate of ACC could significantly reduce oscillation waves and stabilize traffic near a bottleneck, thus reducing travel time up to 35%. Kesting, Treiber, Schönhof, & Helbing (2008) identified travel time improvements even with relatively low ACC penetration rate. Also, Khondaker & Kattan (2015) showed that their proposed variable speed limit control algorithm could reduce travel time up to 20% in a context of connected vehicles compared to an uncontrolled scenario. However, travel time improvements were lower when a 50% penetration rate of connected vehicles was simulated. Zohdy & Rakha (2014) developed an intersection controller that optimizes the movement of vehicles equipped with CACC. Their simulation results showed that the average intersection delay in their system was significantly lower compared to the traffic signal and all-way-stop control scenarios. Similarly, Dresner & Stone (2008) proposed a multiagent reservation-based control

system for efficient intersection management that could widely outperform current control systems like traffic lights and stop signs. According to these researchers, this system could offer near optimal delays (up to 0.35 seconds) about ten times lower than the delays observed in conventional control systems. Chen, Bell, & Bogenberger (2010) proposed a navigation algorithm for automated vehicles that accounts not only for travel time, but also for travel time reliability. Thus, this algorithm can search for the most reliable path within certain travel time constraints using either dynamic or not traffic information. Finally, regarding impacts of shared automated vehicles on travel time the International Transport Forum (2015) reported a reduction of up to 37.9% compared to current travel time of private cars in Lisbon, Portugal based on a simulation study.

4.2 Road capacity

Assumptions

Automated vehicles could have a positive influence on free flow capacity, the distribution of vehicles across lanes and traffic flow stability by providing recommendations (or even determining in higher levels of automation) about time gaps, speed, and lane changes. Enhanced free flow capacity and decreased capacity drops (i.e., less episodes of reduced queue discharge rate) could increase road capacity and thus reduce congestion delays. Nevertheless, benefits in traffic flow efficiency may be highly dependent on the level of automation, the connectivity between vehicles and their respective penetration rates, the deployment path (e.g., dedicated lanes versus integrated mixed traffic) as well as human factors (i.e., behavioural adaptation). Moreover, increased vehicle travel demand could have a negative impact on road capacity owing to more congestion delays and subsequently increased capacity drops. Thus, although the benefits of automated vehicles in the short term are expected to be important, the long-term implications are uncertain and highly dependent on the evolution of vehicle travel demand.

Literature results

Hoogendoorn, van Arem, & Hoogendoorn (2014) concluded in their review study that automated driving might be able to reduce congestion by 50%, while this reduction could go even higher with the help of vehicle-to-vehicle and vehicle-to-infrastructure communication. Several studies have explored traffic impacts of longitudinal automation (i.e., ACC and CACC) based on simulations. Results suggest that ACC can only have a slight impact on capacity (Arnaout & Arnaout, 2014). CACC on the other hand showed positive impacts on capacity (van Arem, van Driel, & Visser, 2006), but these will likely be important (e.g. >10%) only if relatively high penetration rates are realized (>40%) (Arnaout & Bowling, 2011; Shladover et al., 2012). A 100% penetration rate of CACC could theoretically result in double capacity compared to a scenario of all manually driven vehicles (Shladover et al., 2012). Ngoduy (2013) and Delis, Nikolos, & Papageorgiou (2015) have also confirmed better performance of CACC over ACC with respect to both traffic stability and capacity.

Several other studies have confirmed beneficial effects of different types and levels of vehicle automation and cooperation on capacity in various traffic scenarios. Fernandes, Nunes, & Member (2015) proposed an algorithm for positioning and cooperative behavior of multiplatooning leaders in dedicated lanes. Their simulations showed that the proposed platooning system can achieve high traffic capacity (up to 7200 vehicles/hour) and outperform bus and light rail in terms of capacity and travel time. Huang, Ren, & Chan (2000) designed a controller for automated vehicles that requires information only from vehicle sensors. Their simulations in mixed traffic conditions that involved both automated and human controlled vehicles showed that peak flow could reach 5000 vehicles/hour when 70% of the vehicles are automated. Moreover, Michael, Godbole, Lygeros, & Sengupta, (1998) showed via simulation of a single lane automated highway system that capacity increases as the level of cooperation between vehicles and platoon length increases. Several other studies have also reported enhanced traffic flow efficiency because of cooperation and exchange of information between vehicles (e.g., headway and speed, see Monteil, Nantes, Billot, Sau, & El Faouzi, 2014; Yang, Liu, Sun, & Li, 2013) but also between vehicles and infrastructure (e.g., variable speed limits, see Grumert, Ma, & Tapani, 2015). Rajamani & Shladover, (2001) compared the performance of autonomous control systems (those using constant time gap) and cooperative longitudinal control systems (those using inter vehicle communication). These researchers showed analytically that the latter system could indeed deliver capacity benefits reaching a theoretical maximum traffic flow of 3000 vehicles/hour. However, a cooperative system comprising 10-vehicle platoons with a distance between the vehicles of 6.5 m was far more efficient achieving a theoretical traffic flow of 6400 vehicle/hour. Theoretical traffic flow of the cooperative system could increase to 8400 vehicles/hour if distance between vehicles in the platoons would be further reduced to 2 m.

Another group of studies identify significant capacity benefits from automated intersection control systems. Clement, Taylor, & Yue (2004) proposed such a conceptual system where vehicles can move in closely spaced platoons after the start of the green in signalized intersections. These researchers showed analytically that this system could increase throughput by 163% compared to current road intersections even in the case of using quite conservative values for vehicle spacing in the platoons (i.e. 7.2 m). Kamal, Imura, Hayakawa, Ohata, & Aihara (2015) developed a control system which coordinates connected vehicles to safely and smoothly cross a traffic-lightless intersection. Both their estimations and simulations showed an almost 100% increase in capacity compared to the performance of a traditional signalized intersection. Ilgin Guler, Menendez, & Meier (2014) assumed that only a portion of the vehicles are equipped with their intersection control algorithm and tested impacts on delays for two one-way-streets. Their simulations revealed a decrease by up to 60% in average delay per car when penetration rate of the control system-equipped vehicles increased up to 60%.

However, some studies have identified possible trade-offs between increases in capacity and various aspects of automated vehicles. Le Vine, Zolfaghari, & Polak (2015) identified a possible trade-off between comfort level and intersection

capacity. These researchers showed that if passengers of automated vehicles would enjoy comfort levels similar to light rail or high-speed rail (in terms of longitudinal and lateral acceleration/deceleration), intersection capacity reduction could reach 53% and delays could increase up to 1924%. Moreover, Carbaugh, Godbole, & Sengupta (1998) showed that the probability of rear-end crashes in platoons increases as capacity increases, especially when intra-platoon spacing becomes very small (e.g., 1 m). Also, Hall, Nowroozi, & Tsao (2001) pointed to possible capacity reductions in entrance/exit of automated highway systems, while Michael, Godbole, Lygeros, & Sengupta, (1998) showed that capacity in automated highway systems could decrease with the increase of vehicle heterogeneity (e.g., passenger vehicles, buses, and trucks).

4.3. Travel choices

Assumptions

In the short term, the increase of road capacity, the subsequent congestion relief and the decrease in GTC could lead to an increase of vehicle travel demand. However, vehicle travel demand might also increase because of transfers, pick-ups, drop-offs and repositions of ride-sharing and vehicle-sharing vehicles. Moreover, the decrease of GTC could enhance accessibility of more distant locations thus allowing people to choose such destinations to live, work, shop, recreate and subsequently increase the amount of their daily vehicle use. The increase in vehicle use might also be the result of a modal shift from conventional public transport. For example, buses could be gradually replaced by more flexible, less costly and easier to operate automated ride- and vehicle- sharing services. The use of high capacity public transport systems such as trains, metro and light rail is not expected to drop after introduction of automated vehicles, since ride- or vehicle- sharing systems would be very difficult to adequately serve high-demand corridors. Finally, the increase of ride- and vehicle-sharing systems might negatively influence the use of active modes, since automated shared vehicles could effectively serve short distance trips or feeder trips to public transportation. Also, further diffusion of the activities across the city might deter walking and bicycle use. However, we cannot exclude the possibility that people still prefer active modes for short and medium distances for exercise and health reasons or simply because they like cycling or because cycling is cheaper. Moreover, enhanced road safety might also improve (the perception of) safety of bicycling and subsequently positively influence cycle use especially among more vulnerable cycling groups (e.g., older, children, women; see Xing, Handy, & Mokhtarian, 2010; Milakis, 2014).

Literature results

Fagnant and Kockelman (2015) estimated a 26% increase of system-wide vehicle miles traveled (VMT) for a 90% market penetration rate of automated vehicles. This estimation was based on a comparison with induced travel demand caused by enhancement of road capacity after expansion of road infrastructures. Also, Gucwa, (2014) reported an increase in VKT between 4% and 8% for different scenarios of

road capacity and value of time changes because of introduction of automated vehicles. His scenario simulations in San Francisco Bay Area involved increases in road capacity between 10% and 100% and decreases in value of time to the level of a high quality train or to half the current (in-vehicle) value of time. In the extreme scenario of zero time cost for traveling by an automated vehicle the increase of VMT was 14.5%. Additional vehicle travel demand in this study was due to changes in destination and mode choices. Another study confirmed that a modal shift of up to 1%, mainly from local public transport (bus, light rail, subway) and bicycle, to drive-alone and shared-ride modes could be possible because of the ability to multitask in automated vehicles (Malokin, Circella, & Mokhtarian, 2015). Finally, Childress, Nichols, & Coe (2015) used Seattle region's activity-based travel model to explore impacts of automated vehicles on travel demand. They simulated four different scenarios with respect to AV penetration rate and changes in capacity, value of time, parking and operation costs. They concluded that an increase of VMT between 4-20% is likely in the first three scenarios that assumed capacity increases of 30%. Additional VMT was the result of both more and longer trips and also because of a modal shift from public transport and walking to car. Congestion delays appeared in only one out of the first three scenarios that assumed a universal decline of value of time by 65% along with reduced parking costs. In the rest two scenarios (with no or limited impact on value of time) capacity increases offset additional travel demand offering higher network speeds. In the forth and final scenario, a shared autonomous vehicles-based transportation system with users bearing all costs of driving was assumed. Simulation results in this case showed that VMT could be reduced by 35% with no additional congestion delays. Significantly higher user costs per mile (up to about 11 times) induced shorter trip lengths, lower single-occupants vehicle share and an increase of public transport use and walking by 140% and 50% respectively.

Fagnant & Kockelman (2014) on the other hand indicated in their agent-based simulation study that automated vehicle-sharing schemes could result in 10% more VKT compared to conventional vehicles. The reason is that shared automated vehicles will need to move empty or relocate to serve the next traveler. Also, the International Transport Forum (2015) reported in their simulation study for Lisbon, Portugal an increase in VMT over the course of a day that could vary between 6.4% and 90.9% depending on the mode (vehicle-sharing or ride-sharing automated vehicles), the penetration rate and the availability of high-capacity public transport. It should be noted that both studies did not take into account potential changes in travel demand because of the introduction of automated vehicles. For example, Harper, Mangones, Hendrickson, & Samaras (2015) estimated that VMT could increase up to 12% in the US, only from the additional travel demand of the non-driving, elderly populations and people with travel-restrictive medical conditions because of automated vehicles.

5. Second-order implications of automated driving

In this section we explore the second-order implications of automated driving on vehicle ownership and sharing, location choices and land use, and transport infrastructure.

5.1 Vehicle ownership and sharing

Assumptions

The introduction of automated vehicles could facilitate the development of ride- and vehicle- sharing services. Automated vehicles could significantly reduce operational costs (e.g., no driver costs) for ride- and vehicle- sharing services. Such schemes could effectively meet individuals' travel demand needs with lower cost and higher flexibility compared to what todays bus and taxi systems offer to passengers. Subsequently, urban residents could decide to reduce the number of cars they own or even live car-free avoiding the fixed costs associated with car ownership as well.

Literature results

Several studies have simulated transport systems to explore the possibility of automated vehicles to substitute conventional vehicles. Fagnant & Kockelman (2014) simulated operation of shared automated vehicles in a mid-size (similar to the size of Austin, TX) grid based urban area. These researchers reported that each shared automated vehicle could replace around eleven conventional vehicles. The International Transport Forum (2015) simulated different scenarios of automated modes (automated vehicles for ride- and vehicle sharing services), penetration rates and availability of high-capacity public transport. This report indicated that shared automated vehicles could replace all conventional vehicles, delivering equal mobility levels with up to 89.6% less vehicles in the streets (scenario of automated ride-sharing services with high capacity public transport). Another conclusion of this study is that less automated ride-sharing than vehicle-sharing vehicles could replace all conventional vehicles. The reductions in fleet size were much lower (varying between 18% and 21.8%) when the penetration rate of shared automated vehicles was assumed at 50% level and high-capacity public transport was also available. Finally, Spieser et al. (2014) estimated, that only one third of the total number of passenger vehicles would be needed to meet travel demand needs if all modes of personal transportation vehicles were replaced by shared automated vehicles. These researchers used analytical techniques and actual transportation data for the case of Singapore in their study.

5.2 Location choices and land use

Assumptions

Automated vehicles could have an impact at both macro (regional) and micro (local) spatial scale. At the regional scale, automated vehicles could enhance accessibility by affecting its transportation, individual and temporal components (see Geurs & van Wee, 2004 for an analysis of the accessibility components). Less travel effort, travel time and cost and thus lower GTC could have an impact on transportation component of accessibility. People without car access (not owning a car or not being able to drive) may reach activities via (shared) automated vehicles thus influencing the individual component of accessibility. Moreover, (fully) automated vehicles could

perform themselves certain activities (e.g. pick up the children from school or the groceries from super market). This could overcome constraints resulting from temporal availability of opportunities (e.g. stores opening/closing times) and time availability of individuals. Enhanced regional accessibility might allow people to compensate lower travel costs with more distant locations to live, work, shop or recreate. Thus, an ex-urbanization wave to rural areas of former inner city and suburban residents could be possible, subject to land availability and land use policies. Enhanced accessibility may also affect the development of new centers. For example, former suburban employment centers could evolve into significant peripheral growth poles serving increased demand for employment and consumption of new exurban residents. The possibility to eliminate extensive parking lots of such centers because of the self-parking capability of (fully) automated vehicles could further enhance the potential of mixed-use growth in these areas. At the local scale, automated vehicles could trigger changes in streetscape, building landscape design and land uses. First, the capability of self-parking and the opportunity of increased vehicle-sharing services because of automated vehicles could reduce demand for on-street and off-street parking respectively. Subsequently, parking lanes could be converted into high occupancy vehicle lanes, bus lanes, and cycle lanes or to new public space (e.g., parklets, green spaces or wider sidewalks). A reduction of off-street parking requirements could bring changes in land uses (infill residential or commercial development) and in the building design (i.e., access lanes, landscaping). Moreover, surface parking lots and multi-story parking garages in central areas could be significantly reduced enhancing infill development potential for people friendly land uses.

Literature results

Childress et al. (2015) identified potential changes in households' accessibility patterns in Seattle, WA in a scenario where the transportation system of this region is entirely based on automated vehicles. This scenario assumed that driving is easier and more enjoyable (increased capacity by 30% and decreased value of time by 65%), but also cheaper because of lower parking costs. Analysis was performed in a an activity-based model for a typical household type using aggregate logsums to measure accessibility changes compared to a 2010 baseline scenario. Results showed that perceived accessibility was universally enhanced across the whole region. Highest increase of accessibility was observed for households living in more remote rural areas. Changes in accessibility were also associated with an average increase of 20% in total VMT. Increase in travel demand was far higher (up to 30.6%) in outlying areas.

5.3 Transport infrastructure

Assumptions

Increased road capacity because of automated vehicles could reduce future needs for new roads. However, induced travel demand resulting from enhanced road capacity, reduced GTC, and/or proliferation of vehicle sharing systems and urban

expansion may reduce or even cancel out or more than offset initial road capacity benefits. In the latter case (more than offset), additional road capacity may be required to accommodate new travel demand. Automated vehicles will also likely reduce demand for parking, thus less parking infrastructures, either on-street or off-street, will probably be required. Moreover, a reduced need for public transport services in some areas (especially those with low and medium densities) could also lead to public transport service cuts. Finally, pedestrians and cyclists could benefit from more space after the introduction of automated vehicles as a result of road capacity improvements.

Literature results

International Transport Forum (2015) reported that both on-street and off-street parking spaces could be significantly reduced (between 84-94%) in all simulated scenarios that assumed a 100% shared automated vehicle fleet in the city of Lisbon, Portugal. Yet, the reduction was only incremental or even non-existent when these researchers tested scenarios of a 50% mix between shared automated and conventional vehicles. Also, Fagnant & Kockelman (2014) indicated that every shared automated vehicle could eliminate around eleven parking spaces.

6. Third-order implications of automated driving

In this section we explore the third-order implications of automated driving on energy consumption and air pollution, safety, social equity, economy and public health.

6.1 Energy consumption and air pollution

Assumptions

Automated vehicles might result in energy and emission benefits because of reduced congestion, more homogeneous traffic flows, reduced air resistance due to shorter headways, lighter vehicles (a result of enhanced safety), less idling (a result of less congestion delays) and more optimized driver behaviour (a result of vehicle-to-vehicle and vehicle-to-infrastructure communication). Also, automated vehicles might require less powerful engines because high speeds and very rapid acceleration will not be needed for a large share of the fleet (e.g., shared automated vehicles). This could further improve fuel efficiency and limit emissions. We may expect though that privately owned automated vehicles will still offer the possibility for mimicking different human driving styles (e.g., fast, slow, aggressive). We cannot also exclude the possibility that automated will be larger than conventional vehicles serving the need of people to perform various activities while on the move. For example, extra space might be needed to facilitate office-like work (table, docs), face-to-face discussion (meeting table), or sleeping and relaxing (couch, bed). Larger vehicles may limit fuel efficiency gains in that case. Shorter search time for parking and reduced needs for construction and maintenance of parking infrastructures can also lead to environmental benefits. Moreover, a smaller fleet size could be

associated with lower energy and emissions for car manufacturing and road infrastructure development. Nevertheless, potential environmental benefits of automated vehicles could be significantly mitigated by increased travel demand in the long term.

Literature results

Several studies have reported fuel savings from vehicle automation systems. Wu, Zhao, & Ou (2011) demonstrated a fuel economy optimization system that provides human drivers or automated systems with advices about optimal acceleration/deceleration values taking into account vehicle speed and acceleration, but also current speed limit, headway spacing, traffic lights, and signs. Their driving simulator experiment in urban conditions with signalized intersections revealed a decrease in fuel consumption up to 31% for the drivers who used the system. Khondaker & Kattan (2015) reported fuel savings up to 16% for their proposed variable speed limit control algorithm compared with an uncontrolled scenario. Their control system incorporated real-time information about individual driver behavior (i.e., acceleration/deceleration, level of compliance with the posted speed limit) in a context of 100% connected vehicles. Yet, fuel savings were lower when penetration rate of connected vehicles was assumed at 50% level. Also, Li, Peng, Li, & Wang, (2012) showed that the application of a Pulse-and-Gliding (PnG) controller could result in fuel savings up to 20% compared to a linear quadratic (LQ)-based controller in automated car-following scenarios. Other studies have also reported significant fuel consumption savings in field and simulation tests of their ACC and CACC control algorithms (see e.g., Eben Li, Li, & Wang, 2012; Luo, Liu, Li, & Wang, 2010; Wang, Daamen, Hoogendoorn, & van Arem, 2014a, 2014b), including controllers for hybrid electric vehicles (Luo et al., 2015; Vajedi & Azad, in press).

In an intersection context the controller proposed by Zohdy & Rakha (2014) provides advices about the optimum course of vehicles equipped with cooperative adaptive cruise control. These researchers reported fuel savings of, on average, 33%, 45% and 11% for their system compared with the conventional intersection control approaches of traffic signal, all-way-stop, and roundabout, respectively. Moreover, Kamalanathsharma & Rakha (2014) and Asadi & Vahidi (2011) reported fuel savings up to 30% and 47% respectively for their cooperative adaptive cruise controller that uses vehicle-to-infrastructure (traffic signal in this case) communication to optimize vehicle's trajectory in the vicinity of signalized intersections. Finally, Manzie, Watson, & Halgamuge (2007) showed that vehicles exchanging traffic flow information through sensors and inter-vehicle communication could achieve same (i.e. 15-25%) or even more (i.e. up to 33% depending on the amount of traffic information they can process) reductions in fuel consumption compared to hybrid-electric vehicles.

Regarding implications of vehicle automation for air pollution, Grumert et al. (2015) reported a reduction in NOx and HC emissions from the application of a cooperative variable speed limit system, that uses infrastructure to vehicle communication to post individualized speed limits to each vehicle. Emissions were found to decrease with higher penetration rates of this system. Wang, Chen, Ouyang, & Li (2015) also

found that higher penetration rate of intelligent vehicles (i.e. vehicles equipped with their proposed longitudinal controller) in a congested platoon was associated with lower emissions of NOx. Moreover, Bose & Ioannou (2001) found, using simulation and field experiments, that emissions could be reduced from 1.5% (NOx) to 60.6% (CO and CO2) during rapid acceleration transients with the presence of 10% ACC equipped vehicles. Choi & Bae (2013) compared CO2 emissions for lane changing of connected and manual vehicles. They found that connected vehicles can emit up to 7.1% less CO2 for changing from a faster to a slower lane and up to 11.8% less CO2 for changing from a slower to a faster lane. Environmental benefits from smooth reaction of ACC vehicles in traffic disturbances caused by high-acceleration maneuvers, lane cut-ins and lane exiting were also confirmed by Ioannou & Stefanovic (2005).

In a larger scale agent-based study, Fagnant & Kockelman (2014) simulated a scenario of a mid-sized city where about 3.5% of the trips in day are served by shared automated vehicles. These researchers reported that environmental benefits of shared automated vehicles could be very important in all pollutant indicators examined (i.e. SO2, CO, NOx, VOC PM10, and GHG). VOC and CO showed the highest reductions, mainly because of significantly less number of vehicles starts, while impact on PM10, and GHG was relatively small, mainly because of additional travel of shared vehicles to access travellers or to relocate. It should be noted that this simulation study assumed that shared automated vehicle users would not make more or longer trips and that the fleet (both automated and conventional vehicles) would not be electric, hybrid-electric, or using alternative fuels. Finally, in another study focusing on long-term effects of automated vehicles, Greenblatt & Saxena (2015) estimated that autonomous taxis (i.e. battery-electric shared automated vehicles) in 2030 could reduce GHG emissions per vehicle per mile (a) by 87-94% compared to the emissions of internal combustion conventional vehicles in 2014 and (b) by 63-82% compared to the estimated emissions for hybrid-electric vehicles in 2030. Lower GHGs electricity intensity, smaller vehicle sizes and higher cost-effectiveness for (battery) electric vehicles because of increased travel demand explain the significant reductions of GHGs for autonomous taxis. Furthermore, these researchers indicated that autonomous taxis could offer almost 100% reduction in oil consumption per mile compared to conventional vehicles because oil provides less than 1% of electricity generation in the US. Large energy savings of up to 91% per automated vehicle in 2030 were also estimated by Brown, Gonder, & Repac (2014). The energy gains were mainly attributed to more efficient travel and electrification.

6.2 Safety

Assumptions

Over 90% of the crashes is attributed to the human driver (National Highway Traffic Safety Administration, 2008; data for the US context). Typical reasons include, in descending order, errors of recognition (e.g., inattention), decision (e.g., driving aggressively), performance (e.g., improper directional control), and nonperformance

(e.g., sleep). The advent of automated vehicles could significantly reduce traffic accidents attributed to human driver by gradually removing control from the driver's hands. This can be achieved through advanced technologies applied to automated vehicles with respect to, for example, perception of the environment and motion planning, identification and avoidance of moving obstacles, longitudinal, lateral and intersection control, and automatic parking systems. Cyber attacks on automated vehicles could also influence traffic safety.

Literature results

A significant amount of studies have proposed a wide variety of advanced driver assistance systems that can enhance traffic safety levels. These systems include collision avoidance (see e.g., Hayashi, Isogai, Raksincharoensak, & Nagai, 2012; Li, Juang, & Lin, 2014; Shim, Adireddy, & Yuan, 2012), lane keeping (see e.g., Lee, Choi, Yi, Shin, & Ko, 2014) and lane change assistance (see e.g., Hou, Edara, & Sun, 2015), longitudinal speed assistance (see e.g., Martinez & Canudas-de-Wit, 2007) and intersection assistance (see e.g., Liebner, Klanner, Baumann, Ruhhammer, & Stiller, 2013). Advanced longitudinal or lateral multiobjective optimization controllers (see e.g., Khondaker & Kattan, 2015; Wang, Hoogendoorn, Daamen, van Arem, & Happee, 2015), intersection controllers (see e.g., Dresner & Stone, 2008) and path planning algorithms (see e.g., Ferguson et al., 2008; Kuwata et al., 2009) with specific safety requirements can also secure greater levels of safety in higher levels of a automation.

Although advanced driver assistance systems can reduce accident exposure and improve driver behaviour (see Carbaugh et al., 1998; Spyropoulou, Penttinen, Karlaftis, Vaa, & Golias, 2008), behavioural adaptation (i.e. the adoption of riskier behaviours because of over-reliance to the system) may bring adverse effects for traffic safety. For example, Hoedemaeker & Brookhuis (1998) showed that the use of ACC may induce adoption of higher speed, smaller minimum time headway and larger brake force. Rudin-Brown & Parker (2004) indicated lower performance in brake light reaction time and lane keeping for ACC users, while Markvollrath, Schleicher, & Gelau (2011) reported delayed reactions (i.e. speed reduction) for ACC users when approaching curves or entering fog. Xiong, Boyle, Moeckli, Dow, & Brown (2012) showed that drivers' adaptive behaviour and therefore safety implications of ACC are related to trust in automation, driving styles, understanding of system operations, and personalities. Furthermore, safety levels might not substantially increase (or even decrease) until high penetration rates of fully automated vehicles are realized. For example, human driving performance could degrade in higher levels of automation because people have limitations in monitoring automation and in taking on control when required (see Young & Stanton, 2007; Strand, Nilsson, Karlsson, & Nilsson, 2014). Moreover, automated vehicles might negatively influence the driver's behaviour of conventional vehicles in mixed traffic situations by making them adopt unsafe time headways (contagion effect; see Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014).

Cyber attacks could also be an important threat for traffic safety especially in higher levels of automation. According to Petit and Shladover (2015) global navigation satellite systems (GNSS) spoofing and injection of fake messages in the communication between vehicles are the two most likely and most severe attacks for vehicle automation. Amoozadeh et al. (2015) simulated message falsification and radio jamming attacks in a CACC vehicle stream influencing vehicles' acceleration and space gap respectively. These researchers showed that security attacks could compromise traffic safety causing stream instability and rear-end collisions.

6.3 Social equity

Assumptions

Social impacts and distribution effects of the transport system can be significant. Vulnerable social groups such as the poorest people, children, younger, older and disabled people can suffer more from those impacts resulting in their limited participation to society and potentially in social exclusion (Lucas & Jones, 2012). The introduction of automated vehicles could have both negative and positive implications for social equity. Automated vehicles could offer the opportunity to social groups that are currently unable to own or drive a car (e.g., younger, older and disabled people) to overcome current accessibility limitations. However, the first automated vehicles in the market will likely be quite expensive thus limiting these benefits only to wealthier members of those groups for certain time. Safety benefits might also be unevenly distributed among different social groups. Owners of automated vehicles will probably enjoy higher levels of travel safety compared to drivers of conventional vehicles. Moreover, potential spread of urban activities and possible reduction of public transport services (especially buses) might further limit access to activities for poorer social groups. On the other hand, potential conversion of redundant road space to bicycle and pedestrian infrastructures (especially infrastructures that connect with high capacity public transport) could offer accessibility benefits to vulnerable population groups. Finally, the increase of vehicle-sharing services and the subsequent possible decrease of the requirements for construction of off-street parking spaces could increase housing affordability.

Literature results

No systematic studies were found about the implications of automated vehicles for social equity.

6.4 Economy

Assumptions

Automated vehicles could bring significant economic benefits to individuals, the society and businesses, but they may also induce restructuring and possible losses in some industries as well. We distinguish between effects on generalized transport costs (GTC), and other effects relevant for the economy. With respect to GTC effects

improved traffic safety could prevent society from important costs of accidents such as human capital losses, medical expenses, lost productivity and quality of life, property damages, insurance costs and crash prevention costs. A reduction in congestion delays would mean less travel costs for individuals and reduced direct production costs for businesses. If monetary costs of travel for individuals decrease, people could spend an additional part of their income on other goods or services. Moreover, less congestion delays along with increased potential for travel enrichment could result in productivity gains, since individuals could work or even meet on the move. Finally, an increase of shared automated vehicle services would save individuals significant (fixed) costs associated with car ownership without compromising their mobility needs.

We continue discussing other effects. The reduction of off-street parking requirements (ground floor level parking, parking lots or multi story parking garages) could allow the development of more economically productive activities (e.g., residential, commercial or recreational). However, a possible massive reduction of car ownership levels might have a critical negative impact on automotive industry. New business models in this industry are likely to emerge reflecting the convergence between different technologies in automated vehicles, while car related industries might experience losses (e.g., motor vehicle parts, primary and fabricated metal, plastics, and rubber products). Also, jobs in professional and technical services, administration, wholesale and retail trade, warehousing, finance and insurance, and management of automotive companies could be negatively affected from the reduction of turnover in automotive industry. Full vehicle automation could also directly lead to job losses for various professions such as taxi, delivery and truck drivers.

Literature results

A first systematic attempt to provide an order-of-magnitude estimate about both social and private economic impacts of automated vehicles in the US context was made by Fagnant & Kockelman (2015). Their estimation comprised safety, congestion, parking, travel demand and vehicle ownership impacts and was based on several assumptions about market share, the number of automated vehicles, fuel saving, delays reduction, crash reduction and VMT among others. Their results showed that social benefits per automated vehicle per year could reach $2000 (10% market share) and increase up to $3900 (90% market share) if comprehensive costs of crashes with respect to pain, suffering and the full value of a statistical life are taken into account. These researchers also showed that benefits for individuals will likely be small assuming current technology costs at $100.000. Yet, an investment on this technology when purchase price drops at $10.000 seems to generate a positive return rate for many individuals even with quite low values of time.

6.5 Public health

Assumptions

Public health benefits might result from reduced congestion, lower traffic noise, increased traffic safety and lower emissions of automated vehicles. Literature has shown a clear positive association between morbidity outcomes, premature mortality rates, stress and traffic congestion (see Hennessy & Wiesenthal, 1997; Levy, Buonocore, & von Stackelberg, 2010; Miedema, 2007). Furthermore, enhancement of road capacity along with the reduction of on-street parking demand might allow conversion of redundant road space into bicycle and pedestrian infrastructures. Several studies have indicated that provision of such infrastructures is associated with higher levels of use of active modes (Dill & Carr, 2003; Buehler & Pucher, 2012) and subsequently with important public health benefits (e.g., obesity and diabetes; see Pucher, Buehler, Bassett, & Dannenberg, 2010; Oja et al., 2011). However, an increase in vehicle use because of automated vehicles (either more or longer vehicle trips) could also have a negative impact on public health, since levels of physical activity will likely decrease.

Literature results

No systematic studies were found about the implications of automated vehicles for public health.

7. Conclusions

Thus far, literature has mainly explored technological aspects of vehicle automation and impacts on driver and traffic flow characteristics. However, the interest about the wider implications of automated vehicles is constantly growing as this technology evolves. In this paper, we explored the effects of automated driving relevant for policy and society, reviewed literature results about those effects and identified areas for future research. We structured our review based on the ripple effect concept, which represents implications of automated vehicles at three stages: first-order (traffic, travel cost, and travel choices), second-order (vehicle ownership and sharing, location choices and land use, and transport infrastructure) and third-order (energy consumption, air pollution, safety, social equity, economy, and public health). We present general conclusions below and more specific ones for first-, second- and third- order impacts in subsequent sections. We close this section with suggestions for future research on the implications of automated driving.

Literature about policy and society related implications of automated driving is rapidly evolving. Most studies in this review are dated after 2010. The majority of the studies have explored impacts on capacity, fuel efficiency and emissions. Research on wider impacts and travel demand in particular has started picking up during last two years. The implications of automated vehicles for the economy, public health and social equity are still heavily under-researched.

Policy and societal implications of automated vehicles involve multiple complex dynamic interactions. The magnitude of those implications is expected to increase with the level of vehicle automation, the level of cooperation (vehicle-to-vehicle and vehicle-to-infrastructure) and the penetration rate of vehicle automation systems. The synergistic effects between vehicle automation, electrification and sharification can multiply potential impacts of vehicle automation. Yet, the balance between short-term benefits and long-term impacts of vehicle automation remains an open question.

7.1. First-order implications of automated driving

We explored first-order implications of automated vehicles for travel cost, road capacity and travel choices. Fixed cost of automated vehicles will likely reduce over time. GTC will possibly be lower while both road capacity and travel demand will likely increase in the short term.

Vehicle automation can result in travel time savings. Simulations have explored this assumption in highways; intersections; and contexts involving shared automated vehicles. Intersections appear to have more room for travel time optimization compared to highways, while higher penetration rate of vehicle automation systems seems to result in more travel time savings. Literature results also suggest that vehicle automation systems could have lower fuel consumption and subsequently reduced travel cost in the short term. Research on various aspects of the third component of generalized transport cost (travel effort) is rather limited. Most importantly, the impact of vehicle automation on values of time remains a striking gap in the literature. Most, studies have focused on incorporating comfort (in terms of acceleration and jerk) as optimizing metric in path planning algorithms. Yet, human comfort is influenced by many other factors (e.g., time headway) some of which remain unexplored (e.g., motion sickness, apparent safety, natural paths). Therefore, we cannot conclude about the balance of all comfort related effects. Also, studies about vehicle automation impacts on travel time reliability and travel enrichment is scarce.

Research results show that automated vehicles could have a clear positive impact on road capacity in the short term. The magnitude of this impact is related to the level of automation and cooperation between vehicles and the respective penetration rates. A 40% penetration rate of CACC appears to be a critical threshold for realizing significant benefits on capacity (>10%), while a 100% penetration rate of CACC could theoretically double capacity. Capacity impacts of higher levels of vehicle automation could well exceed this theoretical threshold. Nevertheless, certain increases in road capacity could be associated with lower levels of travel comfort and safety.

Most studies show that automated vehicles could induce an increase of travel demand between 4-26%, due to changes in destination choice (i.e. longer trips), mode choice (i.e. modal shift from public transport and walking to car) and mobility (i.e. more trips). Additional increases in VMT up to 90% are possible for shared

automated vehicles because of empty traveling to next customer or repositioning. However, one study indicated that if user costs per mile are very high in a shared automated vehicles based transportation system VMT may be actually reduced. The same study reached mixed non-conclusive results about the trade-off between increased travel demand, capacity increases and congestion delays. No study took into account potential changes in land use patterns, which may also influence future travel demand.

7.2 Second-order implications of automated driving

We explored second-order implications of automated vehicles for vehicle ownership and sharing, location choices, land use and transport infrastructure. Literature results suggest that shared automated vehicles could replace a significant number of conventional vehicles (up about to 90%) delivering equal mobility levels. The substitute effect could vary according to the automated mode (vehicle- vs ride-sharing), the penetration rate and the presence or not of public transport. For example a wide penetration of shared automated vehicles supported by a high capacity public transport system would be expected to have among highest substitution effects. Few studies have explored the impact of automated vehicles on location choices and land use. Simulation results from only one study in the US context showed that automated vehicles could enhance accessibility citywide, but remote rural areas seem to benefit more than other areas in the city. Therefore, these areas show also the highest increases in travel demand. Few systematic studies show also that shared automated vehicles can significantly reduce parking space requirements.

7.3 Third-order implications of automated driving

We explored third-order implications of automated vehicles for energy consumption and air pollution, safety, social equity, the economy and public health. We also included in this section our analysis of first-order impacts on fuel efficiency, emissions and accident risk for consistency reasons. Literature results suggest that automated vehicles can result in fuel savings and lower emissions in the short term and a reduction in GHGs in the long term. Traffic safety can improve in the short term, but behavioral adaptation and low penetration rates of vehicle automation might compromise these benefits. Few studies exist on economic impacts, while no systematic studies were found for social equity and public health implications of automated vehicles.

Various longitudinal, lateral and intersection control algorithms and optimization systems can offer significant fuel savings and lower emissions of NOx, CO and CO2. Studies reviewed in this paper reported fuel savings up to 31% for longitudinal and lateral movement controllers and up to 45% for intersection controllers. Both fuel economy and emissions reduction are reported higher as penetration rate of vehicle automation systems increases. Furthermore, shared use of automated vehicles is associated with reduced emissions (VOC and CO in particular) because of lower number of vehicles starts. Long-term impacts of shared automated vehicles were

also associated by one study with up to 94% less GHGs and nearly 100% less oil consumption per mile compared to conventional internal combustion vehicles.

Regarding traffic safety, literature results suggest that advanced driver assistance systems can reduce accident exposure. Higher levels of automation can further enhance traffic safety. However, as long as human driver remains in-the-loop, behavioural adaptation, namely the adoption of riskier behaviours because of over-reliance to the system, can compromise safety benefits. Moreover, fully automated vehicles might not deliver high safety benefits until high penetration rates of these vehicles are realized. Moreover, cyber attacks such as message falsification and radio jamming can compromise traffic safety as well.

Finally, research on impacts vehicle automation on social equity, the economy and public health is almost non-existent. Results from one study indicate that social benefits per automated vehicle per year could reach $3900 for 90% market share of automated vehicles, while a positive return rate for individuals should not be expected before purchase price drops at $10.000.

7.4 Directions for future research

Various research questions about implications of automated vehicles remain unexplored. In the next paragraphs we discuss possible areas for future research based on gaps we identified between our analysis of assumptions and literature results. We start with suggestions about research on first-order impacts and then we move to second- and third- order impacts. We conclude this section with a discussion on the methodological challenges for the exploration of the implications of automated vehicles.

The impact of vehicle automation on individual components of travel effort (i.e. comfort, travel time reliability, and travel enrichment) remains to a large extent unexplored. For example, how factors such as motion sickness and apparent safety can affect travel comfort of automated vehicles? To what extent vehicle automation systems can reduce travel time variability? How people will utilize available time in automated vehicles? Yet, the most striking gap in the literature is the collective impact of different components of travel effort on values of time for different socioeconomic groups and trip purposes. Evidence about values of time and subsequently GTC can offer valuable input to multiple other related research areas such as the impacts on travel choices, land uses, energy consumption and air pollution. Furthermore, although first-order impacts of vehicle automation on capacity are well-researched, potential trade-offs between additional capacity and GTC associated factors such as travel comfort, safety and travel time reliability remain relatively unexplored. Additional research on travel demand impacts is critical as well. Possible travel demand changes will determine to a large extent the magnitude of several other impacts of automated vehicles. Future studies shall explore travel demand implications not only because of changes in destination choice, mode choice, and relocation of (shared) automated vehicles but also because of possible changes in land uses and parking demand.

Impacts of automation on vehicle ownership could be further explored as well. Thus far, research has answered how many shared automated vehicles can substitute conventional vehicles to serve (part of) current mobility demand. Yet, a more critical question is which will be the size of this substitution effect if we take into account possible changes in travel demand and the willingness of people to own or use shared automated vehicles. Moreover, implications of automated vehicles for all components of accessibility (transportation, land use, individual, and temporal) and subsequently for land uses remain largely unexplored too. Possible changes in urban streetscape and building landscape offer also an area for design research and experimentation. A useful input to the question about infrastructure design will come from the investigation of potential changes in parking and road infrastructures because of vehicle automation. How will changes in parking demand and capacity influence future investments on the amount and type of parking and road infrastructures?

Emission and fuel use effects of vehicle automation are well researched. Though, the magnitude of the effect for different levels of automation and penetration rates could be further tested. Research efforts may also focus on the long-term effects of automated vehicles on energy consumption and emissions taking into account potential travel demand changes, but also additional synergistic effects between vehicle automation, electrification and sharification. The balance between short-term benefits and long-term impacts on energy consumption and emissions is still an open question. Moreover, little is known about safety benefits in transitional contexts of fully automated and conventional vehicles. A better understanding of the types of cyber attacks and their potential impacts on traffic safety is critical too. Finally, an integrated assessment of economic and public health benefits is also missing from current literature. Such an assessment would require input from several other areas including impacts on traffic safety, energy consumption, air pollution, congestion delays, accessibility and vehicle ownership. The exploration of social impacts and distribution effects through the analysis of potential accessibility changes would also contribute to a better understanding of the social implications of automated vehicles.

Several methodological challenges lies ahead for the exploration of the implications of automated vehicles. A critical issue is that this technology (especially higher levels of automation) is still in its infancy. Thus, no adequate empirical data about the use of automated vehicles exist yet. Therefore, studies have mainly utilized micro- and macro- traffic simulation, driving simulators, field experiments and analytical methods to explore first-order implications of automated vehicles on travel time, capacity, fuel efficiency, emissions and safety. For second- and third- order implications the armory of methods need to expand to capture behavioural aspects underlying potential changes due to vehicle automation. Thus, for example qualitative methods such as focus groups or in-depth interviews in combination with quantitative methods like stated choice experiments could be used for exploring questions about impacts of vehicle automation on travel comfort, travel enrichment, value of time, travel and location choices. Agent-based and activity based models could then be used to simulate possible changes in travel demand, vehicle

ownership and other environmental indicators such as energy consumption and emissions. The connection of travel models with land use models (in so-called Land Use – Transport Interaction, or LUTI models) would also allow capturing potential long-term land use impacts, which could also influence travel demand patterns. Alternative approaches could involve empirical models for the analysis of comparable systems and their potential impacts on land use (e.g, valet parking, car-free neighbourhoods, high speed train). Finally, accessibility metrics and measures of inequality could be used in the analysis of social equity impacts of automated vehicles.

Although the widely discussed first-order benefits of automated vehicles were also confirmed by this study, the long-term impacts remain to a large extent still unclear. Further research in a number of areas indicated here could remove these uncertainties. A holistic evaluation of the costs and benefits of automated vehicles could then help urban and transport policies to ensure a smooth and sustainable integration of this new transport technology into our transportation systems.

Acknowledgements

This research was supported by the Delft Infrastructures and Mobility Initiative under Grant C61U01.

References

Amoozadeh, M., Raghuramu, A., Chuah, C., Ghosal, D., Zhang, H. M., Rowe, J., & Levitt, K. (2015). Security Vulnerabilities of Connected Vehicle Streams and Their Impact on Cooperative Driving. IEEE Communications Magazine, (June), 126–132.

Arnaout, G., & Bowling, S. (2011). Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. Journal of Industrial Engineering and Management, 4(4), 699–717. doi:http://dx.doi.org/10.3926/jiem.344

Arnaout, G. M. A., & Arnaout, J.-P. C. (2014). Exploring the effects of cooperative adaptive cruise control on highway traffic flow using microscopic traffic simulation. Transportation Planning and Technology, 37(2), 186–199. doi:10.1080/03081060.2013.870791

Asadi, B., & Vahidi, A. (2011). Predictive cruise control: Utilizing upcoming traffic signal information for improving fuel economy and reducing trip time. IEEE Transactions on Control Systems Technology, 19(3), 707–714. doi:10.1109/TCST.2010.2047860

Barsade, S. (2002). The Ripple Effect: Emotional Contagion and Its Influence on Group Behavior. Administrative Science Quarterly, 47, 644–675.

Black, S. (2001). Computing ripple effect for software maintenance. Journal of Software Maintenance and Evolution: Research and Practice, 13(4), 263–279. doi:10.1002/smr.233

Bose, A., & Ioannou, P. (2001). Evaluation of the Environmental Effects of Intelligent Cruise Control Vehicles. Transportation Research Record, 1774, 90–97.

Brookhuis, K., de Waard, D., & Janssen, W. (2001). Behavioural impacts of advanced driver assistance systems–an overview. European Journal of Transport and Infrastructure Research, 1(3), 245–253.

Brown, A., Gonder, J., & Repac, B. (2014). An Analysis of Possible Energy Impacts of Automated Vehicle. In G. Meyer & S. Beiker (Eds.), Road Vehicle Automation (pp. 137–153). Berlin: Springer. doi:10.1007/978-3-319-05990-7

Buehler, R., & Pucher, J. (2012). Cycling to work in 90 large American cities: new evidence on the role of bike paths and lanes. Transportation, 39(2), 409–432. doi:10.1007/s11116-011-9355-8

Carbaugh, J., Godbole, D. N., & Sengupta, R. (1998). Safety and capacity analysis of automated and manual highway systems. Transportation Research Part C: Emerging Technologies, 6(1-2), 69–99. doi:10.1016/S0968-090X(98)00009-6

Chen, Y., Bell, M. G. H., & Bogenberger, K. (2010). Risk-Averse Autonomous Route Guidance by a Constrained A* Search. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 14(3), 188. doi:10.1080/15472450.2010.484753

Childress, S., Nichols, B., & Coe, S. (2015). Using an activity-based model to explore possilbe impacts of automated vehicles. In Transportation Research Board 94th Annual Meeting. Washington DC: TRB.

Choi, J.-E., & Bae, S.-H. (2013). Development of a methodology to demonstrate the environmental impact of connected vehicles under lane-changing conditions. Simulation, 89(8), 964–976. doi:10.1177/0037549713489603

Clement, S. J., Taylor, M. A. P., & Yue, W. L. (2004). Simple platoon advancement: A model of automated vehicle movement at signalised intersections. Transportation Research Part C: Emerging Technologies, 12(3-4 SPEC.ISS.), 293–320. doi:10.1016/j.trc.2004.07.012

Cooper, C., Orford, S., Webster, C., & Jones, C. B. (2013). Exploring the ripple effect and spatial volatility in house prices in England and Wales: regressing interaction domain cross-correlations against reactive statistics. Environment and Planning B: Planning and Design, 40(5), 763–782. doi:10.1068/b37062

Dang, R., Wang, J., Li, S. E., & Li, K. (n.d.). Coordinated Adaptive Cruise Control System With Lane-Change Assistance. IEEE Transactions on Intelligent Transportation Systems.

De Winter, J. C. F., Happee, R., Martens, M. H., & Stanton, N. A. (2014). Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. Transportation Research Part F: Traffic Psychology and Behaviour, 27, 196–217. doi:10.1016/j.trf.2014.06.016

Delis, A. I., Nikolos, I. K., & Papageorgiou, M. (2015). Macroscopic traffic flow modeling with adaptive cruise control: Development and numerical solution. Computers & Mathematics with Applications. doi:10.1016/j.camwa.2015.08.002

Diakaki, C., Papageorgiou, M., Papamichail, I., & Nikolos, I. (2015). Overview and analysis of Vehicle Automation and Communication Systems from a motorway traffic management perspective. Transportation Research Part A: Policy and Practice, 75, 147–165. doi:10.1016/j.tra.2015.03.015

Dill, J., & Carr, T. (2003). Bicycle Commuting and Facilities in Major US Cities If You Build Them, Commuters Will Use Them. Transportation Research Record: Journal of the Transportation Research Board, 1828(1), 116–123.

Dresner, K., & Stone, P. (2008). A Multiagent Approach to Autonomous Intersection Management. Journal of Artificial Intelligence Research, 31, 591–656.

Eben Li, S., Li, K., & Wang, J. (2012). Economy-oriented vehicle adaptive cruise control with coordinating multiple objectives function. Vehicle System Dynamics, 3114(September), 1–17. doi:10.1080/00423114.2012.708421

Elbanhawi, M., Simic, M., & Jazar, R. (2015). In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars. IEEE Intelligent Transportation Systems Magazine, Fall, 4–17.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations for Capitalizing on Self-Driven Vehicles. Transportation Research Part A: Policy and Practice, 77, 1–20. doi:10.1016/j.tra.2015.04.003

Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. Transportation Research Part C: Emerging Technologies, 40, 1–13. doi:10.1016/j.trc.2013.12.001

Ferguson, D., Howard, T. M., & Likhachev, M. (2008). Motion planning in urban environments. Journal of Field Robotics, 25(11-12), 939–960. doi:10.1002/rob.20265

Fernandes, P., Nunes, U., & Member, S. (2015). Multiplatooning Leaders Positioning and Cooperative Behavior Algorithms of Communicant Automated Vehicles for High Traffic Capacity. IEEE Transactions on Intelligent Transportation Systems, 16(3), 1172–1187.

Frandsen, T., & Nicolaisen, J. (2013). The ripple effect: Citation chain reactions of a nobel prize. Journal of the American Society for Information Science and Technology, 64(3), 437–447. doi:10.1002/asi

Gerónimo, D., López, a. M., Sappa, a. D., & Graf, T. (2010). Survey of Pedestrian Detection for Advanced Driver Assistance Systems. IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(7), 1239–1258. doi:10.1109/TPAMI.2009.122

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: review and research directions. Journal of Transport Geography, 12(2), 127–140. doi:10.1016/j.jtrangeo.2003.10.005

Glaser, S., Vanholme, B., Mammar, S., Gruyer, D., & Nouvelière, L. (2010). Maneuver-based trajectory planning for highly autonomous vehicles on real road with traffic and driver interaction. IEEE Transactions on Intelligent Transportation Systems, 11(3), 589–606. doi:10.1109/TITS.2010.2046037

Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., & Reed, N. (2014). Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control? Transportation Research Part F: Traffic Psychology and Behaviour, 27, 264–273. doi:10.1016/j.trf.2014.03.003

Greenblatt, J. B., & Saxena, S. (2015). Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. Nature Climate Change, 5(September), 860–863. doi:10.1038/nclimate2685

Grumert, E., Ma, X., & Tapani, A. (2015). Effects of a cooperative variable speed limit system on traffic performance and exhaust emissions. Transportation Research Part C: Emerging Technologies, 52, 173–186. doi:10.1016/j.trc.2014.11.004

Gucwa, M. (2014). Mobility and Energy Impacts of Automated Cars. Stanford, CA: Department of Management Science and Engineering, Stanford University.

Hall, R. W., Nowroozi, A., & Tsao, J. (2001). Entrance Capacity of an Automated Highway System. Transportation Science, 35(1), 19–36. doi:10.1287/trsc.35.1.19.10144

Hamersma, H. A., & Els, P. S. (2014). Longitudinal vehicle dynamics control for improved vehicle safety. Journal of Terramechanics, 54, 19–36. doi:10.1016/j.jterra.2014.04.002

Harper, C., Mangones, S., Hendrickson, C. T., & Samaras, C. (2015). Bounding the Potential Increases in Vehicles Miles Traveled for the Non - Driving and Elderly Populations and People with Travel - Restrictive Medical Conditions in an Automated Vehicle Environment. In Transportation Research Board 94th Annual Meeting.

Hayashi, R., Isogai, J., Raksincharoensak, P., & Nagai, M. (2012). Autonomous collision avoidance system by combined control of steering and braking using geometrically optimised vehicular trajectory. Vehicle System Dynamics, 50(sup1), 151–168. doi:10.1080/00423114.2012.672748

Hennessy, D. A., & Wiesenthal, D. L. (1997). The relationship between traffic congestion, driver stress and direct versus indirect coping behaviours. Ergonomics, 40(3), 348–361. doi:10.1080/001401397188198

Hoedemaeker, M., & Brookhuis, K. a. (1998). Behavioural adaptation to driving with an adaptive cruise control (ACC). Transportation Research Part F: Traffic Psychology and Behaviour, 1(2), 95–106. doi:10.1016/S1369-8478(98)00008-4

Hoogendoorn, R., van Arem, B., & Hoogendoorn, S. (2014). Automated Driving, Traffic Flow Efficiency And Human Factors: A Literature Review. Transportation Research Record, 2422, 113–120.

Hou, Y., Edara, P., & Sun, C. (2015). Situation assessment and decision making for lane change assistance using ensemble learning methods. Expert Systems with Applications, 42(8), 3875–3882. doi:10.1016/j.eswa.2015.01.029

Hounsell, N. B., Shrestha, B. P., Piao, J., & McDonald, M. (2009). Review of urban traffic management and the impacts of new vehicle technologies, (June), 419–428. doi:10.1049/iet-its.2009.0046

Huang, S., Ren, W., & Chan, S. C. (2000). Design and performance evaluation of mixed manual and automated control traffic. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, 30(6), 661–673. doi:10.1109/3468.895889

Ilgin Guler, S., Menendez, M., & Meier, L. (2014). Using connected vehicle technology to improve the efficiency of intersections. Transportation Research Part C: Emerging Technologies, 46, 121–131. doi:10.1016/j.trc.2014.05.008

International Transport Forum. (2015). Urban mobility: system upgrade. Paris: OECD/International Transport Forum.

Ioannou, P., & Stefanovic, M. (2005). Evaluation of the ACC Vehicles in Mixed Traffic: Lane Change Effects and Sensitivity Analysis Petros Ioannou , Margareta Stefanovic. IEEE Transactions on Intelligent Transportation Systems, 6(1), 79–89.

Ivanov, D., Sokolov, B., & Dolgui, A. (2014). The Ripple effect in supply chains: trade-off "efficiency-flexibility-resilience" in disruption management. International Journal of Production Research, 52(7), 2154–2172. doi:10.1080/00207543.2013.858836

Kamal, A. S., Imura, J., Hayakawa, T., Ohata, A., & Aihara, K. (2015). A Vehicle-Intersection Coordination Scheme for Smooth Flows of Traffic Without Using Traffic Lights. IEEE Transactions on Intelligent Transportation Systems, 16(3), 1136–1147.

Kamalanathsharma, R. K., & Rakha, H. A. (2014). Leveraging Connected Vehicle Technology and Telematics to Enhance Vehicle Fuel Efficiency in the Vicinity of Signalized Intersections. Journal of Intelligent Transportation Systems, PP(September 2015). doi:10.1080/15472450.2014.889916

Kesting, A., Treiber, M., Schönhof, M., & Helbing, D. (2008). Adaptive cruise control design for active congestion avoidance. Transportation Research Part C: Emerging Technologies, 16(6), 668–683. doi:10.1016/j.trc.2007.12.004

Khondaker, B., & Kattan, L. (2015). Variable speed limit: A microscopic analysis in a connected vehicle environment. Transportation Research Part C: Emerging Technologies, 58, 146–159. doi:10.1016/j.trc.2015.07.014

Kuwata, Y., Teo, J., Fiore, G., Karaman, S., Frazzoli, E., & How, J. P. (2009). Real-time motion planning with applications to autonomous urban driving. IEEE Transactions on Control Systems Technology, 17(5), 1105–1118. doi:10.1109/TCST.2008.2012116

Le Vine, S., Zolfaghari, A., & Polak, J. (2015). Autonomous cars: The tension between occupant experience and intersection capacity. Transportation Research Part C: Emerging Technologies, 52, 1–14. doi:10.1016/j.trc.2015.01.002

Lee, J., Choi, J., Yi, K., Shin, M., & Ko, B. (2014). Lane-keeping assistance control algorithm using differential braking to prevent unintended lane departures. Control Engineering Practice, 23(1), 1–13. doi:10.1016/j.conengprac.2013.10.008

Levy, J. I., Buonocore, J. J., & von Stackelberg, K. (2010). Evaluation of the public health impacts of traffic congestion: a health risk assessment. Environmental Health: A Global Access Science Source, 9, 65. doi:10.1186/1476-069X-9-65

Lewis-Evans, B., De Waard, D., & Brookhuis, K. a. (2010). That's close enough-A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. Accident Analysis and Prevention, 42(6), 1926–1933. doi:10.1016/j.aap.2010.05.014

Li, K.-R., Juang, J.-C., & Lin, C.-F. (2014). Active collision avoidance system for steering control of autonomous vehicles. IET Intelligent Transport Systems, 8(6), 550–557. doi:10.1049/iet-its.2013.0056

Li, S. E., Peng, H., Li, K., & Wang, J. (2012). Minimum fuel control strategy in automated car-following scenarios. IEEE Transactions on Vehicular Technology, 61(3), 998–1007. doi:10.1109/TVT.2012.2183401

Li, S., Li, K., Rajamani, R., & Wang, J. (2011). Model predictive multi-objective vehicular adaptive cruise control. IEEE Transactions on Control Systems Technology, 19(3), 556–566. doi:10.1109/TCST.2010.2049203

Liebner, M., Klanner, F., Baumann, M., Ruhhammer, C., & Stiller, C. (2013). Velocity-based driver intent inference at urban intersections in the presence of preceding vehicles. IEEE Intelligent Transportation Systems Magazine, 5(2), 10–21. doi:10.1109/MITS.2013.2246291

Lucas, K., & Jones, P. (2012). Social impacts and equity issues in transport: An introduction. Journal of Transport Geography, 21, 1–3. doi:10.1016/j.jtrangeo.2012.01.032

Luo, L., Liu, H., Li, P., & Wang, H. (2010). Model predictive control for adaptive cruise control with multi-objectives: comfort, fuel-economy, safety and car-following. Journal of Zhejiang University SCIENCE A, 11(3), 191–201. doi:10.1631/jzus.A0900374

Luo, Y., Chen, T., Zhang, S., & Li, K. (2015). Intelligent Hybrid Electric Vehicle ACC With Coordinated Control of Tracking Ability , Fuel Economy , and Ride Comfort. IEEE Transactions on Intelligent Transportation Systems, 16(4).

Malokin, A., Circella, G., & Mokhtarian, P. L. (2015). How Do Activities Conducted while Commuting Influence Mode Choice? Testing Public Transportation Advantage and Autonomous Vehicle Scenarios. In 94th Annual Meeting of the Transportation Research Board.

Manzie, C., Watson, H., & Halgamuge, S. (2007). Fuel economy improvements for urban driving: Hybrid vs. intelligent vehicles. Transportation Research Part C: Emerging Technologies, 15(1), 1–16. doi:10.1016/j.trc.2006.11.003

Markvollrath, Schleicher, S., & Gelau, C. (2011). The influence of Cruise Control and Adaptive Cruise Control on driving behaviour - A driving simulator study. Accident Analysis and Prevention, 43(3), 1134–1139. doi:10.1016/j.aap.2010.12.023

Martinez, J.-J., & Canudas-de-Wit, C. (2007). A Safe Longitudinal Control for Adaptive Cruise Control and Stop-and-Go Scenarios. IEEE Transactions on Control Systems Technology, 15(2), 246–258. doi:10.1109/TCST.2006.886432

Meen, G. (1999). Regional House Prices and the Ripple Effect: A New Interpretation. Housing Studies, 14(6), 733–753. doi:10.1080/02673039982524

Michael, J. B., Godbole, D. N., Lygeros, J., & Sengupta, R. (1998). Capacity Analysis of Traffic Flow Over a Single-Lane Automated Highway System⋆. ITS Journal - Intelligent Transportation Systems Journal (Vol. 4). doi:10.1080/10248079808903736

Miedema, H. M. E. (2007). Adverse effects of traffic noise. In T. Garling & L. Steg (Eds.), Threats from car traffic to the quality of urban life. Problems, causes, and solutions (pp. 53–77). Oxford, UK: Elsevier.

Milakis, D. (2014). Will Greeks Cycle? Exploring Intention and Attitudes in the Case of the New Bicycle Network of Patras. International Journal of Sustainable Transportation, 9(5), 321–334. doi:10.1080/15568318.2013.770586

Monteil, J., Nantes, A., Billot, R., Sau, J., & El Faouzi, N. (2014). Microscopic cooperative traffic flow: calibration and simulation based on a next generation simulation dataset. IET Intelligent Transport Systems, 8(6), 519–525. doi:10.1049/iet-its.2013.0035

Moon, S., Moon, I., & Yi, K. (2009). Design, tuning, and evaluation of a full-range adaptive cruise control system with collision avoidance. Control Engineering Practice, 17(4), 442–455. doi:10.1016/j.conengprac.2008.09.006

National Highway Traffic Safety Administration. (2008). National Motor Vehicle Crash Causation Survey. Report DOT HS 811 059. Washington DC: NHTSA.

Ngoduy, D. (2012). Application of gas-kinetic theory to modelling mixed traffic of manual and ACC vehicles. Transportmetrica, 8(1), 43–60. doi:10.1080/18128600903578843

Ngoduy, D. (2013). Instability of cooperative adaptive cruise control traffic flow: A macroscopic approach. Communications in Nonlinear Science and Numerical Simulation, 18(10), 2838–2851. doi:10.1016/j.cnsns.2013.02.007

Oja, P., Titze, S., Bauman, a., de Geus, B., Krenn, P., Reger-Nash, B., & Kohlberger, T. (2011). Health benefits of cycling: A systematic review. Scandinavian Journal of Medicine and Science in Sports, 21(4), 496–509. doi:10.1111/j.1600-0838.2011.01299.x

Petit, J., & Shladover, S. E. (2015). Potential Cyberattacks on Automated Vehicles. IEEE Transactions on Intelligent Transportation Systems, 16(2), 546–556.

Piao, J., & McDonald, M. (2008). Advanced driver assistance systems from autonomous to cooperative approach, 1647(September). doi:10.1080/01441640801987825

Pucher, J., Buehler, R., Bassett, D. R., & Dannenberg, A. L. (2010). Walking and cycling to health: A comparative analysis of city, state, and international data. American Journal of Public Health, 100(10), 1986–1992. doi:10.2105/AJPH.2009.189324

Raimondi, F. M., & Melluso, M. (2008). Fuzzy motion control strategy for cooperation of multiple automated vehicles with passengers comfort. Automatica, 44(11), 2804–2816. doi:10.1016/j.automatica.2008.04.012

Rajamani, R., & Shladover, S. E. (2001). Experimental comparative study of autonomous and co-operative vehicle-follower control systems. Transportation Research Part C: Emerging Technologies, 9(1), 15–31. doi:10.1016/S0968-090X(00)00021-8

Rudin-Brown, C. M., & Parker, H. A. (2004). Behavioural adaptation to adaptive cruise control (ACC): Implications for preventive strategies. Transportation Research Part F: Traffic Psychology and Behaviour, 7(2), 59–76. doi:10.1016/j.trf.2004.02.001

SAE International. (2014). Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems. Warrendale, PA: SAE International.

Scarinci, R., & Heydecker, B. (2014). Control Concepts for Facilitating Motorway On-ramp Merging Using Intelligent Vehicles. Transport Reviews, 34(6), 775–797. doi:10.1080/01441647.2014.983210

Shim, T., Adireddy, G., & Yuan, H. (2012). Autonomous vehicle collision avoidance system using path planning and model-predictive-control-based active front steering and wheel torque control. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 226(6), 767–778. doi:10.1177/0954407011430275

Shladover, S. E. (1995). Review of the State of Development of Advanced Vehicle Control Systems (AVCS). Vehicle System Dynamics (Vol. 24). doi:10.1080/00423119508969108

Shladover, S. E. (2006). Automated vehicles for highway operations (automated highway systems). Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 219(1), 53–75. doi:10.1243/095440705X9407

Shladover, S. E., Su, D., & Lu, X.-Y. (2012). Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow. Transportation Research Record: Journal of the Transportation Research Board, 2324, 63–70. doi:10.3141/2324-08

Siebert, F. W., Oehl, M., & Pfister, H. R. (2014). The influence of time headway on subjective driver states in adaptive cruise control. Transportation Research Part F: Traffic Psychology and Behaviour, 25(PART A), 65–73. doi:10.1016/j.trf.2014.05.005

Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., & Pavone, M. (2014). Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore. In G. Meyer & S. Beiker (Eds.), Road Vehicle Automation SE - 20 (pp. 229–245). Springer International Publishing. doi:10.1007/978-3-319-05990-7_20

Spyropoulou, I., Penttinen, M., Karlaftis, M., Vaa, T., & Golias, J. (2008). ITS Solutions and Accident Risks: Prospective and Limitations. Transport Reviews, 28(5), 549–572. doi:10.1080/01441640801886605

Stanton, N. A., & Young, M. S. (1998). Vehicle automation and driving performance. Ergonomics, 41(7), 1014–1028. doi:10.1080/001401398186568

Strand, N., Nilsson, J., Karlsson, I. C. M., & Nilsson, L. (2014). Semi-automated versus highly automated driving in critical situations caused by automation failures. Transportation Research Part F: Traffic Psychology and Behaviour. doi:10.1016/j.trf.2014.04.005

Sun, Z., Bebis, G., & Miller, R. (2006). On-Road Vehicle Detection : A Review. IEEE Transactions on Pattern Analysis and Machine Intelligence, 28(5), 694–711.

Turner, J. D., & Austin, L. (2000). A review of current sensor technologies and applications within automotive and traffic control systems. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 214(6), 589–614. doi:10.1243/0954407001527475

Vahidi, a., & Eskandarian, a. (2003). Research advances in intelligent collision avoidance and adaptive cruise control. IEEE Transactions on Intelligent Transportation Systems, 4(3), 143–153. doi:10.1109/TITS.2003.821292

Vahidi, A., & Eskandarian, A. (2003). Research advances in intelligent collision avoidance and adaptive cruise control. IEEE Transactions on Intelligent Transportation Systems, 4(3), 143–153. doi:10.1109/TITS.2003.821292

Vajedi, M., & Azad, N. L. (n.d.). Ecological Adaptive Cruise Controller for Plug-In Hybrid Electric Vehicles Using Nonlinear Model Predictive Control. IEEE Transactions on Intelligent Transportation Systems.

Van Arem, B., van Driel, C., & Visser, R. (2006). The impact of Co-operative Adaptive Cruise Control on traffic flow characteristics. IEEE Transactions on Intelligent Transportation Systems, 7(4), 429–436.

Wang, M., Daamen, W., Hoogendoorn, S. P., & van Arem, B. (2014a). Rolling horizon control framework for driver assistance systems. Part I: Mathematical formulation and non-cooperative systems. Transportation Research Part C: Emerging Technologies, 40, 271–289. doi:10.1016/j.trc.2013.11.023

Wang, M., Daamen, W., Hoogendoorn, S. P., & van Arem, B. (2014b). Rolling horizon control framework for driver assistance systems. Part II: Cooperative sensing and cooperative control. Transportation Research Part C: Emerging Technologies, 40, 290–311. doi:10.1016/j.trc.2013.11.024

Wang, M., Hoogendoorn, S. P., Daamen, W., van Arem, B., & Happee, R. (2015). Game theoretic approach for predictive lane-changing and car-following control. Transportation Research Part C: Emerging Technologies, 58, 73–92. doi:10.1016/j.trc.2015.07.009

Wang, Z., Chen, X. M., Ouyang, Y., & Li, M. (2015). Emission Mitigation via Longitudinal Control of Intelligent Vehicles in a Congested Platoon. Computer-Aided Civil and Infrastructure Engineering, 30, n/a–n/a. doi:10.1111/mice.12130

Wu, C., Zhao, G., & Ou, B. (2011). A fuel economy optimization system with applications in vehicles with human drivers and autonomous vehicles. Transportation Research Part D: Transport and Environment, 16(7), 515–524. doi:10.1016/j.trd.2011.06.002

Xiao, L., & Gao, F. (2010). A comprehensive review of the development of adaptive cruise control systems. Vehicle System Dynamics, 48(10), 1167–1192. doi:10.1080/00423110903365910

Xing, Y., Handy, S. L., & Mokhtarian, P. L. (2010). Factors associated with proportions and miles of bicycling for transportation and recreation in six small US cities. Transportation Research Part D: Transport and Environment, 15(2), 73–81. doi:10.1016/j.trd.2009.09.004

Xiong, H., Boyle, L. N., Moeckli, J., Dow, B. R., & Brown, T. L. (2012). Use Patterns Among Early Adopters of Adaptive Cruise Control. Human Factors: The Journal of the Human Factors and Ergonomics Society, 54(5), 722–733. doi:10.1177/0018720811434512

Yang, S., Liu, W., Sun, D., & Li, C. (2013). A New Extended Multiple Car-Following Model Considering the Backward-Looking Effect on Traffic Flow. Journal of Computational and Nonlinear Dynamics, 8(1), 011016. doi:10.1115/1.4007310

Young, M. S., & Stanton, N. A. (2007). Back to the future: brake reaction times for manual and automated vehicles. Ergonomics, 50(1), 46–58. doi:10.1080/00140130600980789

Zohdy, I., & Rakha, H. (2014). Intersection Management via Vehicle Connectivity: The Intersection Cooperative Adaptive Cruise Control System Concept. Journal of Intelligent Transportation Systems, 00, 1–16. doi:10.1080/15472450.2014.889918

Implication	Keyword
Travel cost	Cost, travel time, comfort, value of time, travel time reliability
Road capacity	Capacity, congestion, traffic flow
Travel choices	Travel choice(s), mode choice(s), travel behaviour, travel distance, vehicle kilometres traveled, vehicles miles traveled, modal shift
Vehicle ownership and sharing	Vehicle ownership, car ownership, vehicle sharing, car sharing, ride sharing, shared vehicle(s)
Location choices and land use	Location choice(s), land use(s), accessibility, residential density, urban form, urban structure, urban design
Transport infrastructure	Road infrastructure(s), road planning, road design, intersection design, parking infrastructure(s), public transport service(s), transit service(s), cycle lane(s), cycle path(s), sidewalk(s), pavement(s)
Energy consumption and air pollution	Fuel, energy, emissions, pollution
Safety	Safety, accident(s), crash(es), risk, cyber attack(s)
Social equity	Social equity, social impact(s), vulnerable social group(s), social exclusion
Economy	Economy, productivity, business(es)
Public health	Public health, human health, morbidity, mortality

Table 1: Keywords used to identify scholarly articles about implications of automated vehicles.

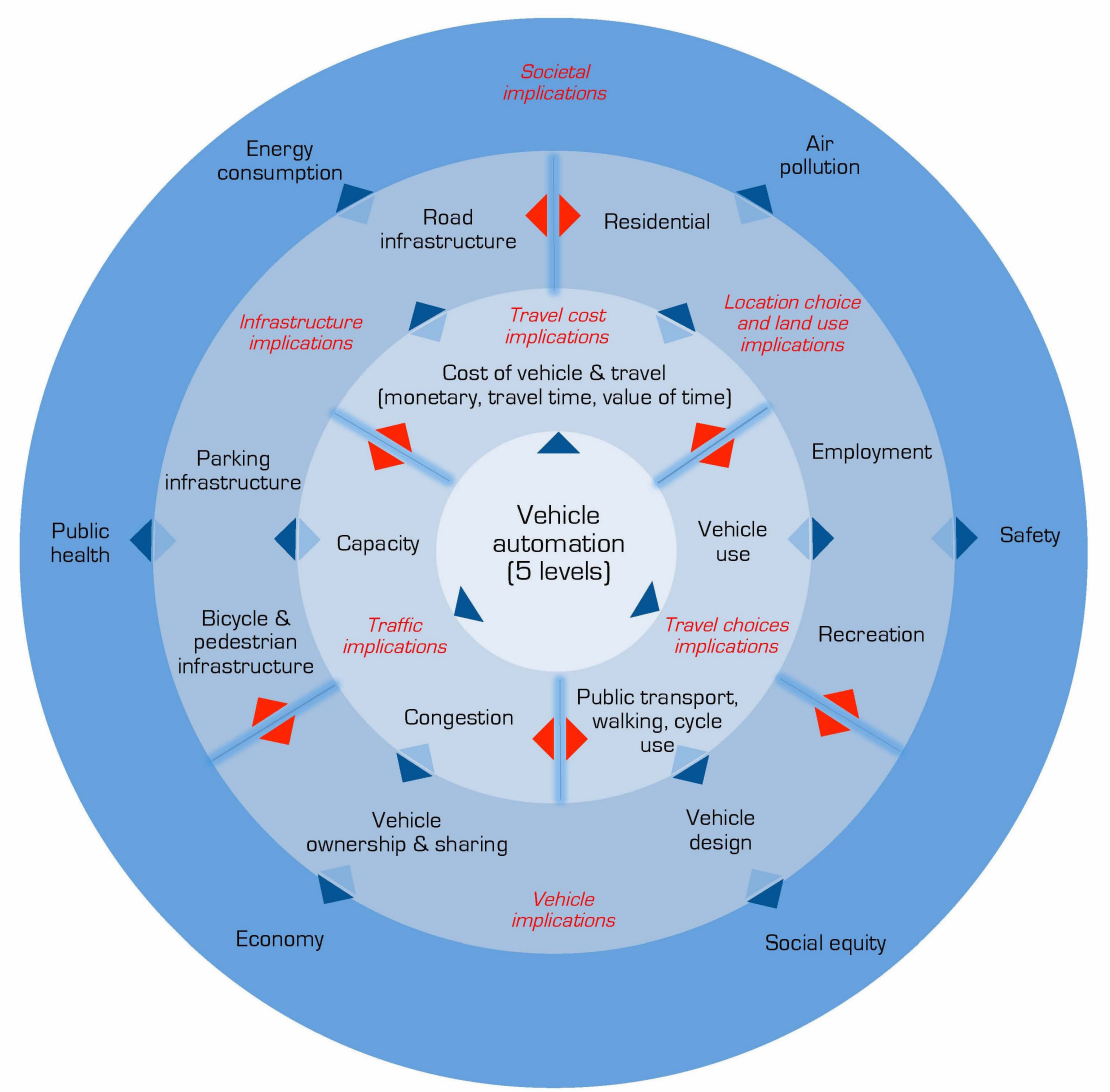

Figure 1: The ripple effect of automated driving.

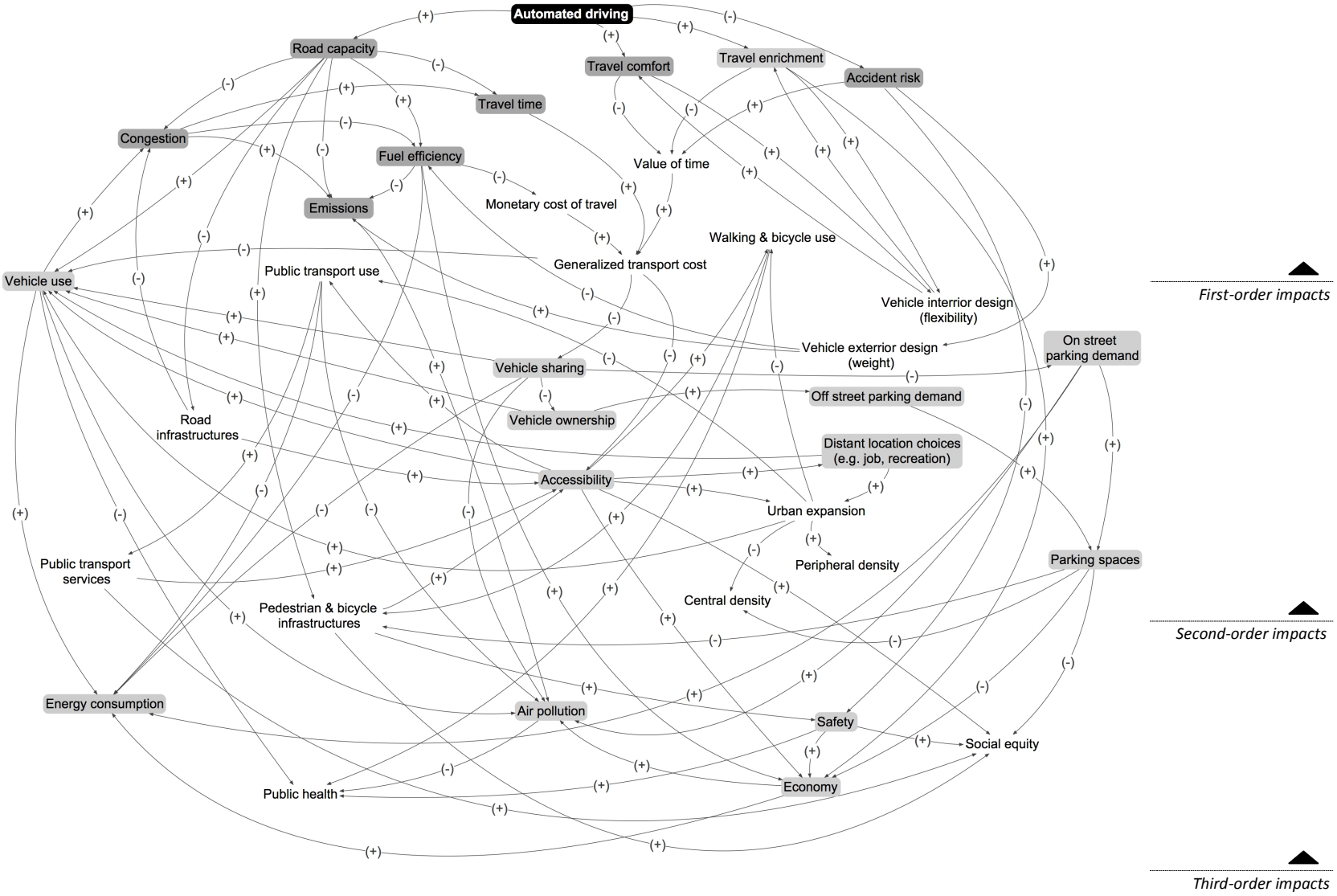

Figure 2: Causal diagram of possible implications of automated driving. Positive and negative causal links indicate that two factors change in the same and opposite direction respectively. The darker the grey-shade the more studies have explored implications of automated driving for this factor. No shade means that we did not identify any studies about this factor.