Vehicle automation and transport system performance

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26 Vehicle automation and transport system performance

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1 INTRODUCTION

It is expected that by 2050 the population living in urban areas will rise from 54 percent in 2014 to 66 percent of the world's population, accompanied by a total population growth from 7.2 billion to 9.6 billion (United Nations – Department of Economic and Social Affairs 2014). In 2007 the 300 major cities in the world accounted for more than 50 percent of the global gross domestic product (GDP) and this figure is expected to grow to 60 percent by 2025 (McKinsey 2011). While concentration may lead to some economies of scale by making viable high-capacity public transport (PT), the reality is that large conurbations are made of different land-uses and densities which result in different trip rates and mobility patterns which hinder the sole use of PT. Moreover, mobility is becoming more diverse in time and location, resulting from greater needs for activity participation and available income for travelling.

Roads in that perspective were one of the main drivers for making mobility patterns more diverse in the previous decades because they have provided the opportunity to travel by private vehicle, a mode that has low variable costs, is door to door and very comfortable. In fact the length of motorways in the 27 countries of the European Union (EU) grew by 67 percent from 1990 to 2009, supported by accessibility policies in the several countries and endorsed by the European Commission. The use of cars has leveraged economic growth and provided, especially in western countries, freedom and quality of life which has been quite difficult to replace by other modes, even in countries with high-quality public transport such as the Netherlands. Despite the great use of PT and bicycles, the country is one of the most congested in the world (INRIX 2014).

The great usage of private motorized vehicles as the main mode of transport has produced what economists call externalities: pollution increase, both locally and globally; lost time in congestion; road accidents with both material and human costs; and land-use opportunity costs stemming from great areas occupied by transport infrastructures such as highways and parking lots. Only accounting for pollution and time lost in traffic, the EU estimates that every year 1 percent of GDP is lost in congestion where urban traffic is responsible for 40 percent of carbon dioxide (CO_2) emissions and 70 percent of emissions of other pollutants arising from road transport (European Commission 2007).

Several approaches are being used for mitigating these effects and tackling urban congestion, such as: traffic management with control systems and information provision to travelers; congestion charging and other car use restriction mechanisms; mobility alternatives such as shared systems; and improving public transport. Among these approaches an increased interest has been shown towards vehicle automation in the past

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two decades, although futurists and science fiction writers have early imagined driverless vehicles running in the cities of the future. Today it is possible to say that vehicle automation, as it was imagined by these futurists, may become a reality in the next few decades. Many research groups all over the world are currently working on vehicle automation and the first pilots are starting to roll out from design to reality. However, technologies do not simply develop because of their innovative technical features. They are structurally integrated within forms of economic, social and political life, which can heavily affect adoption likelihood of technologies (Feitelson and Salomon 2004). Thus, despite the fast technological development in this field, there is great uncertainty about deployment of automated vehicles and potential subsequent changes to traffic, mobility and cities.

This chapter is intended for the reader who wants to understand what vehicle automation is, its main research questions, and what are its main implications. We also provide guidance on the methods that have been used or could be used to assess its impacts, hence allowing future research on this topic.

The chapter is organized as follows: we start with the definition of vehicle automation, then we describe two types of deployment of the automated vehicles that may occur in the near future. This is followed by a theoretical framework on the effects of vehicle automation. The chapter continues with describing the models, methods and tools that can be applied to study the impact of vehicle automation at three main levels: traffic, mobility and urban form. The chapter ends with a discussion and a conclusion.

2 DEFINITIONS OF VEHICLE AUTOMATION

In order to obtain a thorough understanding of automation in road transport, a clear definition of vehicle automation is crucial. In this section, automation refers to the transport system including all of its components, such as vehicles, drivers, users, infrastructure, information systems and applications. The term automation is often used to define a process in which automation takes over control from the human. In this context, the level in which the driver is still 'in the loop' is used in order to discriminate between the different levels of vehicle automation.

An often used classification of vehicle automation is the one formulated by Gasser and Westhoff (2012), although other similar classifications have been also suggested (see for example, National Highway Traffic Safety Administration 2013; SAE International 2014). They distinguish four different levels of automation, namely:

- level 1: driver assistance;
- level 2: partial automation;
- level 3: high automation; and
- level 4: full automation.

In driver assistance, the driver permanently maintains either longitudinal (speed choice, car-following) or lateral control (lane-keeping, merging, lane-changing, overtaking). Other tasks can be automated to a certain extent by an advanced driver assistance (ADA) system. Examples of driver assistance systems are adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC). Adaptive cruise control is a system providing support in longitudinal control through maintaining a desired speed and time headway. This system can be overruled by the driver. Cooperative adaptive cruise control is a system which provides support for longitudinal control as well. The difference compared with ACC is that in CACC the vehicles extend their field of view to several predecessors through vehicle-to-vehicle (V2V) communication.

Partial automation entails the situation in which a system takes over both longitudinal and lateral control. The driver is required to permanently monitor the system and is required to take over control at any time. In the third level, high automation, the system also takes over longitudinal and lateral control, but the driver is no longer required to permanently monitor the system. Nevertheless the driver must be prepared to respond adequately to a take-over request by the system. On the highest level, full automation, the system again takes over longitudinal and lateral control. However, in case a take-over request by the system is not carried out, the system will return to minimal risk condition by itself (Gasser and Westhoff 2012).

Besides the distinction between the different levels of automation, often the term cooperative systems is used such as in the context of CACC. In general, cooperative systems in the context of automation of vehicles entail systems which rely on V2V or communication between vehicles and the infrastructure (V2I), or both.

In this chapter we deal with the several levels of automation. It is relevant to describe the advances on the intermediate levels of automation since these are stepping stones to reach the final level of full automation. Hence when we refer to an automated vehicle in the text we are referring to the several levels of automation (1 to 4). We will use the 'fully automated vehicle' term for the level 4 automation and often the term 'semiautomated vehicle' for levels 1, 2 and 3.

3 DEPLOYMENT STAGING

In the previous section we described several definitions and a classification of automated vehicles. Despite the fact that there are more doubts than certainties in regards to how these vehicles' deployment will take place both in time and space, in the current section we provide a perspective into the deployment staging of vehicle automation. In general, a distinction can be made between two different approaches (van Arem and Tsao 1997):

- geographical approach; and
- functional approach.

In the geographical approach, the implementation of most (if not all) aspects of the highest level of automation (that is, full automation: level 4) will take place in one step, while the geographical areas of implementation expand gradually. The functional approach, however, is based on the assumption that the functionality of fully automated vehicles cannot be realized suddenly and, therefore, intermediate steps must be identified and optimized. An intermediate step towards full automation can be defined as any discernible increment whose realization may encounter considerable difficulties. Reality has shown already that the functional approach best represents the current development towards full automation.

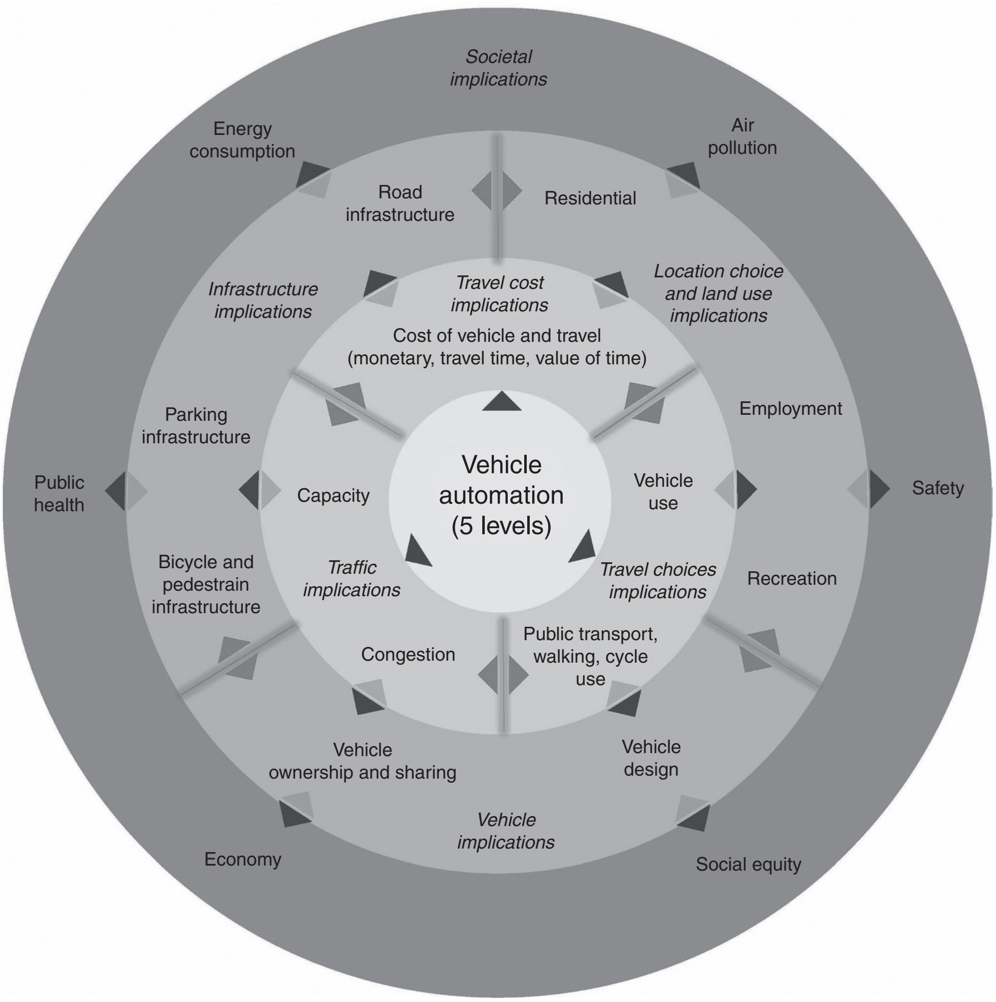
So, which intermediate steps towards full automation can be identified? It is obvious that the different levels of automation as described in the previous section can be viewed as intermediate steps towards full automation. However, it is also possible to make a more detailed roadmap towards full automation. In this context in (Shladover 2000) a functional deployment staging roadmap is provided. In this approach the focus is mainly on automated highway systems (AHS). They state that automated safety warning systems and control assistance systems can be viewed as a starting point towards fully automated vehicles. They distinguish two parallel paths from automated safety warning systems and control assistance systems. According to Shladover (2000) the applicability of the different paths may be different for different regions. For instance, in some locations V2V communication may be combined with ACC to provide CACC before the introduction of dedicated lanes. In other regions, protected lanes for trucks may be provided first before V2V communication is introduced. When automated vehicle steering actuation is added to CACC vehicles along with lane-sensing functionalities, basically the level of partially automated vehicles is reached. Adding V2I communication will, according to (Shladover 2000) lead to the first single lane AHS. However, in order to acquire fully automated highway systems, link and network control as well as lane-changing control is needed. According to (Shladover 2000) adding these features is the last step toward complete AHS. Regarding the deployment staging of automated vehicles in urban environments, there are no studies at this moment that establish a deployment staging. This reflects the great uncertainty of the automated vehicles technology and roll-out, especially in critical environments such as urban areas where the interaction with pedestrians, cyclists and other automobiles occurs at a much higher rate.

4 THEORETICAL FRAMEWORK

In this section, we use the ‘ripple effect’ model (Milakis et al., 2015a) to represent the innovative nature of automated driving technology and the sequential effects that this change might bring to mobility, urban form and other societal fields (see Figure 26.1).

The first ripple includes implications of automated driving with respect to traffic, travel cost and travel choices. According to Hoogendoorn et al. (2014) driving automation could have an impact on free flow capacity, flow stability, distribution of vehicles across lanes, capacity drop and therefore on effective capacity by assisting drivers or even controlling vehicle headways and vehicle speed. Capacity increases may be accompanied by congestion delay reductions and therefore lower travel time and subsequently lower cost of travel. Travel cost may be also reduced through lower VTTS because of increased travel enrichment (more useful use of time while travelling), less driving stress, more comfort, and less risk of accidents. Vehicle travel cost reductions[1] may subsequently trigger changes in travel choices both in terms of more VKT (because of enhanced accessibility in more distant locations) and a modal shift from public transport to car.

The second ripple includes implications of automated driving with respect to vehicle ownership and sharing, vehicle design, location choices and land use, and transport infrastructures. Capacity improvements might reduce the need for conventional road infrastructure investments (Silberg et al., 2012; Eugensson et al., 2013; Fagnant and Kockelman, 2015; Litman, 2014; Wagner et al., 2014) and free up road space for



Source: Milakis et al. (2015a).

Figure 26.1 The ripple effect of automated driving

pedestrian and bicycle infrastructures. Moreover, fewer parking spaces in central areas may be required because fully automated vehicles will likely be able to self-park in peripheral, less expensive locations (Begg, 2014; Fagnant and Kockelman, 2015). The development of fully automated vehicles could also facilitate car- and ride-sharing schemes, which may lead urban residents to live car-free or reduce the numbers of cars they own and subsequently the requirements in residential parking spaces. However, we cannot exclude the possibility that automation might attract more people to own a vehicle, thus increasing needs for residential parking. Reduced travel costs might also affect households' residential, employment and recreation location decisions. Enhanced accessibility in more distant areas could trigger an exurbanization wave of inner city and suburban residents. Infill development of current suburban employment centers and malls could also follow, supported by the elimination potential of current extensive parking lots (see Townsend, 2014; scenario Atlanta 2028).

The third ripple contains the long-term wider societal implications from the introduction of automated vehicles such as energy consumption, air pollution, safety, social equity, economy and public health. Such implications result cumulatively from the previous two ripple effects, while interactions among those impacts are possible, as in every ripple. To indicate the complexity in assessment of such effects, we focus on energy consumption. Automated vehicles might increase fuel efficiency because of lighter vehicles (a result of enhanced safety), less congestion delays, optimized driving behavior, and less parking search time. On the other hand total VKT might increase because of transfers, pick-ups, drop-offs and repositions of ride-sharing and car-sharing vehicles (see International Transport Forum, 2015), relocation of households in exurbs, travelling in more distant locations for commuting or recreation purposes or simply new car trips. Thus, the overall effect on energy consumption is uncertain and also highly dependent on transport policies that might be applied in the meantime (for example, road pricing to curb induced demand from capacity improvements). Implications on the economy, social equity or public health are also heavily dependent on the total effect of other fields in the same ripple such as air pollution, energy consumption and safety.

5 MODELS, METHODS AND TOOLS FOR ASSESSING THE IMPACT OF AUTOMATED VEHICLES

This section discusses the application and results of applying models, methods and tools to analyze the impacts of the deployment of automated vehicle technology. The impacts refer to the micro level dealing with traffic flows performance, such as the level of service (first ripple in Figure 26.1), but also refers to the impact on mobility at a macro level (some elements of both the first and second ripples in Figure 26.1). The latter entails possible changes in travel behavior, such as trip rate, trip scheduling as well as mode choice. Despite the scarcity of studies on the effect of vehicle automation on the built environment, we also point in this chapter to the type of approach that can be followed to assess these effects (second ripple in Figure 26.1). Hence this section is divided in three main subsections, one for each type of effects.

5.1 Impacts on the Traffic System Level

The impact of vehicle automation on traffic flow efficiency is the topic that has received more attention from the research community in the past years. The main research question underneath this significant body of research is whether the different levels of automation are able to increase the throughput of vehicles on the existing road infrastructure, hence taking a traffic engineering perspective. In fact the relationship between vehicle automation and traffic flow efficiency is complex, as its effect may be assumed to be dependent on many different factors. For example, besides the instrumental settings of the automated systems, the effects on traffic-flow efficiency may also be dependent on human factors, such as user acceptance and behavioral adaptation owing to the changed role of the driver.

In this section we review some exemplary studies in this field. We want to inform on the measured impacts but also explain the methods and tools that have been used to study the influence of each particular system configuration, helping the reader on selecting a method for his own studies. In general it is possible to say that most studies on the influence of vehicle automation on traffic-flow efficiency have been conducted using microscopic simulation. These studies have usually started with the statement of the main assumptions that were made with regard to the behavior of drivers of the automated vehicles, the surrounding manually driven vehicles as well as the vehicle control architecture.

A distinction can be made between general and specific micro-simulation software for the purpose of simulating vehicle flows. The difference between these two is that the latter have a higher level of detail with respect to the vehicle dynamics and sensor capabilities of each automobile (agent). The advantage of general micro-simulation software is that these packages are able to simulate a large number of vehicles, allowing for the reproduction of realistic traffic conditions. At present, general micro-simulation software packages, such as AIMSUN and VISSIM (PTV) do not yet include models of automated driving.

Current efforts of the community are focused on implementing a high level of vehicle dynamics in a general microscopic simulation framework which considers several vehicles interacting simultaneously so that future scenarios of great numbers of automated vehicles deployed on the roads can be tested. For example, in the California PATH program a microscopic simulation tool was built to be able to analyze multiple merge junctions (Antoniotti et al. 1997). In this context, other researchers have developed their own research tools. For instance, Kala and Warwick (2013) have created their simulation model in Matlab, where they simulate the automated vehicle dynamics in mixed traffic.

Nevertheless observing the state of the art, it is possible to conclude that most research has mainly focused on the influence of driver assistance systems on traffic-flow efficiency (intermediate level of automation) instead of full automation. The two most studied systems are related to vehicle cruise control and they differ in the possibility of having or not having cooperation between the vehicles in this process (ACC and CACC). Most of these studies use as their key performance variable the capacity of the road infrastructure, however, owing to the different assumptions with regard to vehicle headways, type of vehicle mix (whether it is the same automated vehicle or different brands) and penetration rate of automation, the fleet comparisons are sometimes difficult to make. The normal capacity of a motorway is between 1880 and 2200 vehicles and the minimum headway in normal traffic is approximately 1.5–2.0 seconds (Calvert et al. 2011). The experimental configuration may also play a relevant role, this may happen through different network configurations (number of lanes, speed limits and size of bottleneck) but also the simulation method itself.

Van Arem et al. (1996) were one of the first in using micro simulation to test the effects of ACC on traffic flow. The authors used a simulation model called MIXIC (Van Arem and De Vos 1997) which simulates traffic on a link level. Hence the behavior of the driver was defined by three main components: the lane-changing, the longitudinal following and the interaction with the ACC (switching it on and off). They found that the effects of

ACC, despite contributing to the stability of traffic (standard deviation), can be negative for capacity. For a straight road of three lanes, they took into consideration a total of four combinations of ACC, with penetration rates of 20 percent and 40 percent and time gaps of 1.0 second and 1.5 seconds. As a result of ACC, average travel time in all four scenarios increased, which implies a decrease in free-flow capacity. In three of the scenarios, there was a small increase in travel time (from 1 percent to 4 percent).

However Kesting et al. (2010) later simulated the effect of ACC on traffic-flow efficiency by implementing behavioral models in their vehicular traffic model. In the study the authors concluded that, on average, for every 1 percent increase in the number of vehicles with ACC there could be an increase of 0.3 percent in the capacity of the link.

Several studies have focused on building their simulation models using the agent-based approach. For instance, Hallé and Chaib-draa (2005) used the principles of agent-based modelling for studying collaborative/cooperative driving systems. Furthermore, Van Middlesworth et al. (2008) used the agents' intelligence to manage thousands of autonomous vehicles in intersections where they concluded that for not-too-busy intersections the autonomous vehicles can outperform the traditional stop signs: vehicles spend less time waiting and consume less fuel.

Arnaout and Bowling (2011) used F.A.S.T (Flexible Agent-based Simulator of Traffic) to model a road with four lanes in scenarios with and without an entry slip road and they concluded that CACC had a positive effect on capacity (up to +60 percent for a penetration rate of 100 percent). They presumed that CACC vehicles maintain a headway of 0.5 seconds if they are driving behind another CACC and 0.8 to 1.0 when behind another vehicle.

Calvert et al. (2011) have studied the effect of different penetration rates of CACC vehicles on shock waves in a motorway in Amsterdam. On the A1 motorway there was a bottleneck owing to a narrowing of the road from four to three lanes which created shock waves that had an impact on the A10 motorway. For that purpose they used a special plug-in of the traffic simulation software Paramics, called ITS Modeller. The ITS Modeller (Tideman and Noort 2013) is an advanced modeling framework developed to allow the modelling of ITS applications in Paramics. It allows users to override the standard models for driver and vehicle behavior, both for the tactical driving level, that is, speed and lane choice, and for the strategic level, that is, route choice. In the simulation they found that for CACC penetration rates of 5 percent, 10 percent 25 percent, 50 percent, 75 percent and 100 percent, the increase in the total number of arrivals (indicator for flow) was 0 percent, 3 percent, 10 percent, 22 percent, 39 percent and 68 percent, respectively. In each scenario, there was a traffic jam at the bottleneck, but above a penetration rate of 25 percent, the severity of the shock waves was much lower. Above a penetration rate of 50 percent, the shock waves do not impact the A10 motorway and for a penetration rate of 100 percent, there were no shock waves at all.

Besides traffic simulators the driver's behavior under different ADA systems can be studied using driving simulators. The use of driving simulators offers more possibilities to, for example, devising critical conflict situations that are possible with instrumented vehicles. The literature provides many studies related to driver safety, the attention of the driver and vehicle automation.

An early example of such a driving simulator is the simulator developed by StSoftware (van Wolffelaar and van Winsum 1992). This driving simulator consists of three screens which are, compared with each other, placed at an angle of 120 degrees, a driver's seat mock-up and software interfacing of this mock-up to a central computer system. Driving simulators have, for example, been used to understand the impact of vehicle platoons on non-platoon drivers in mixed traffic (Gouy et al. 2014). In their study Gouy et al. found that platoons with short headways may cause unequipped vehicle drivers to go below the safe limit.

In some cases both simulation and physical experiments were combined to arrive at reliable conclusions on the performance of some systems. One of the first real-life experiments of cooperative driving was that by Baber et al. (2005) in which three small vehicles were used to test the effect of cooperation in an unsignalized intersection and in overtaking another vehicle. Bose and Ioannou (2003) used a traffic simulation model based on an early definition of vehicle dynamics (Pipes 1953) in order to simulate traffic flows with manual and semiautomated vehicles. Next, they validated their results by setting up an experiment with instrumented vehicles. They were able to demonstrate that the presence of semiautomated vehicles in mixed traffic (for an experiment with 10 vehicles following a lead vehicle in a single lane) reduces pollutant emissions both in smooth and rapid acceleration conditions, for instance, the reduction of nitrogen oxides (NO_x) could up to 0.4 percent in smooth conditions and 6.6 percent in rapid acceleration.

Physical trials have been used mainly in testing automation in transit systems. Automation in transit is not new, there are currently many tram and metro lines operating without a driver in cities like Paris or Barcelona. Moreover automation is the basis for the so-called Personal Rapid Transit (PRT) system that is a flexible door-to-door public transport with small-capacity vehicles that have their own dedicated infrastructure. There are several examples in the world of its application but probably one of the most well know is that of London Heathrow Airport, the ULTra (Urban Light Transit). Based on these notions combined with the more recent development of vehicle automation that we have been describing, there are several projects that are testing in pilot experiments the use of automated road transit systems. That is the case with CityMobil2 (Alessandrini 2014) in which several field experiments are being run in the EU to test the possibilities of automating bus systems. These are key experiments to test technology but also the sensitivity of travelers to its characteristics, such as demand responsiveness or the absence of a driver.

5.2 Impacts at the Transport System Level

There are scant studies regarding the impact of autonomous vehicles in the global mobility system either urban or interurban, mainly because there is a lack of modelling and methods applied to the issue of understanding what is going to happen as a result of the introduction of autonomous vehicles in our cities and regions.

There are, however, a number of reports that tentatively enumerate the expected effects on the transportation system. These reports have been written by transport research experts based on their experience and results of studying transport demand and supply.

Bierstedt et al. (2014, p. 4) state that there are 'potentially dramatic changes to the transportation planning and engineering profession' and they refer to some of the factors that will influence the automated vehicles adoption and typical use, hence the degree with which it will affect the total number of VKT. In that list, besides the instrumental characteristics of the new vehicles such as speed and safety, they state that the 'quality of service offered by alternative modes of travel, which will vary by urban setting' Bierstedt et al. (2014, p. 2) will play a role on that indicator, clearly acknowledging the importance of competition between modes and assuming that, at least in the medium term, autonomous vehicles will coexist with the other modes. The extent to which they will compete or complement each other is still a question to be answered.

Mode choice in transport science is classically explained by maximum utility theory whereby a set of attributes of the modes and socio-demographic variables of the travelers sum to the utility of using a particular mode of transportation. Time and cost are typically the main attributes and, although there are many studies that measure the weights of these variables on mode choice, there is no particular study on quantifying the changes in the weights that are expected to be obtained by the utility of the automated vehicles. Particularly it is expected that there will be changes on the VTTS inside a private vehicle, since travelers will be able to use that time in more productive activities compared to the use of a conventional vehicle. The perceived differences between regular transit systems and hypothetical automated transit systems are difficult to foresee, since the experience should not change radically. Building these models will allow the estimation of the number of travelers that will transfer from normal vehicles, transit or even from walking or cycling, the latest leading to more VKT. It is not possible to study this topic by using revealed preferences among the population because the technology is not being used yet, however, some studies are currently in progress with stated preference techniques. These experiments will allow the valuation of the attributes as well as more symbolic and affective factors associated with car use. This valuation will be able to position the automated vehicle either as a modified private vehicle or as an enhanced transit system.

Predicting the share of privately owned automated vehicles in the fleet is an important research topic among peers. A group of members of the Institute of Electrical and Electronics Engineers (IEEE) stated that the share in 2040 will most probably reach 75 percent of the fleet (IEEE News releases 2012). Litman (2014) used deployment cycles, cost and adoption rates of other automotive technologies to conclude that a 50 percent adoption will be the most likely scenario for 2050 and that a 75 percent figure will only be possible by 2060. Bierstedt et al. (2014) agree with this scenario, however, they state that benefits such as a lower accident rate resistance may diminish with time. A move away from the vehicle ownership model to a model more similar to mobile phones with a subscription may help decrease the time that a vehicle is in the hands of the owners, say the same researchers. This can be fostered by the growth of carsharing systems (Jorge and Correia 2013; Correia et al. 2014; Jorge et al. 2015), which is leading to a decrease on vehicle ownership (Martin et al. 2010).

Shared vehicle systems are very important for the discussion on the effect of autonomous vehicles in future cities. Having vehicles with level 4 automation means that these vehicles can be used in practice as a transit system that provides trips for lower costs compared with taxis (no driver costs), it is a sort of carsharing system where the vehicle does not have to be picked up at a specific point, it can be called and drop-off the traveler at any point of the operational area. A door-to-door transit system constituted by private vehicles has been a reality for many decades with the so well-known taxi systems, at least since people could telephone to ask for one to arrive at their doorstep. Some innovations in the use of information to better manage these systems have been studied, such as allowing for more than one service to be attended and the request being made by mobile phone, the so-called taxi-sharing system. In these systems it is foreseen that, even if vehicles still have drivers, routes and clients are chosen centrally by an intelligent dispatcher. This system has been tested using agent-based modelling and results show that these are able to satisfy a great part of travelling demand in an urban area (Martinez et al. 2014).

Automation can only make these systems cheaper and more flexible. Fagnant and Kockelman (2014) used agent-based simulation to study the implications of having a fleet of autonomous vehicles in a city for serving part of its mobility needs. They took the current carsharing usual modal share, 3.5 percent of the trips, and tested different operational scenarios in their own agent-based model of a 'mid-sized city, perhaps the size of Austin'. They concluded that each automated vehicle would be able to replace 11 conventional vehicles but could incur 10 percent more travelling to reach the next traveler due to be picked-up. Using the same technique, the International Transport Forum (ITF) built a model to test the introduction of 100-percent autonomous fleets of taxis to satisfy transport demand in a city (International Transport Forum, 2015). They modelled a mid-size European city (Lisbon, Portugal) where the only public transport mode that is maintained besides the automated taxi is the metro system. Results showed that fleets always decrease: with metro each automated vehicle could remove nine out of 10 cars in the city if a maximum 5-minute waiting period is to be guaranteed, while without metro the number stays at five vehicles removed per automated vehicle. The ITF also explored the coexistence between autonomous vehicles and conventional vehicles, and in this case the vehicle numbers reduction is not so significant, with a possible increase if the metro system is also disabled which shows that there could be problems in the early stages of market penetration.

Spieser et al. (2014) had the same objective, however, in their case they tested the substitution of all vehicles for automated vehicles for the city of Singapore. They preferred to use an analytical mathematical formulation to find the minimum fleet size constrained to a minimum quality of service to be provided to the clients (waiting time and vehicle availability), where they concluded that with one-third of the total number of passenger vehicles currently in operation it would be possible to meet the total personal mobility needs of the entire population.

Brownell and Kornhauser (2014) used travel demand for the state of New Jersey and they concluded that the smart para-transit model appears to be economically viable, requiring a fleet size between 1.6 and 2.8 million six-passenger vehicles (lower than the current fleet) to meet the state's travel demand in its entirety, at a cost to consumers of \$16.30 to \$23.50 per person per day. Zhang and Pavone (in press) used queueing theory instead to study the replacement of the taxi demand in Manhattan for a fleet of automated vehicles concluding that 8000 vehicles would be enough to satisfy the existent demand (roughly 60 percent of the existing fleet). What these models never discuss are the behavioral implications of such a system when it is known that sharing vehicles with strangers has proven to entail a perceived disutility that is hard to break (Correia et al. 2013).

At the level of estimating the impacts on mobility of automated classic bus systems there is no record of any modelling research. As mentioned in the previous section, there are field experiments being put into practice through some large-scale projects in which the assessment of the public response is part of the evaluation.

5.3 Impacts at the Spatial Level

Transportation technology is among the factors that have historically shaped urban form. It has played a key role on urban development and evolution from the creation of the first urban settlements when spatial division of labor (specialized crafts and agricultural labor) was possible, to the industrial rail-based city and the post-industrial sprawled agglomerations. Three main city types have been identified according to the prevailing transport technology (see Newman and Kenworthy 1996; Muller 2004): the walking city (up to the nineteenth century; high density, mixed use and organic structure), the transit city (mid-nineteenth to mid-twentieth century; medium density, mixed use and centralized) and the automobile city (mid-twentieth century – today; low density, separated uses, decentralized). Automated vehicles appear as the next potential disruptive innovation for mobility. To what extent can this new transportation technology have significant implications for urban form? Thus far, no empirical studies have examined this question since the technology is still in its infancy. In this section, we explore potential mechanisms through which automated vehicles could have an impact on urban form and we suggest possible methods to investigate those impacts. We analyze implications at both macro (regional) scale and micro (neighborhood) scale, and also potential interactions between them (see Milakis et al. 2015a; see also Milakis et al. 2015b for a discussion on interactions between urban form and travel at different spatial scales).

Accessibility changes are the mechanism through which transportation technology and thus automated driving could cause spatial implications at the regional scale. According to Geurs and van Wee (2004) accessibility has four components: land use, transportation, temporal, and individual; see also Chapter 3 in this volume. The land-use component reflects the supply, demand and the confrontation of supply and demand for opportunities. The transportation component expresses the disutility of travel including travel time, costs and effort. The temporal component reflects the temporal availability of opportunities, but also time availability of individuals to reach opportunities. Finally, the individual component reflects the heterogeneity with respect to needs, abilities and opportunities of individuals. Thus far, accessibility changes owing to advances in transportation technology were mainly associated with changes in the transportation component and travel speed in particular (Banister 2011; Marchetti 1994). Speed increases gave people the opportunity to travel further within certain travel time budgets (Marchetti 1994), allowing, in parallel, cities to evolve from a maximum radius of 2.5 kilometers in ancient Greek and Roman era to over 20 kilometers in contemporary urban agglomerations. In the case of automated vehicles, speed will probably have minimum impact on urban form in comparison to the implications of other potentially radical changes in the transportation, individual and temporal components of accessibility.

Automated vehicles are expected to affect the transportation component of accessibility by primarily reducing travel effort, but also constraining travel time and cost. Travel effort will possibly be reduced because of a considerable increase of travel comfort, enhanced travel safety and reliability, and more productive use of travel time. Lower travel times could be expected because of congestion delay and parking search-time reductions resulting from capacity increases and self-parking functionality, respectively. Monetary cost reductions might also be possible. Automated vehicles are expected to be more fuel-efficient because of lighter vehicles (a result of enhanced safety), less congestion delays, optimized driving behavior and parking-space search.[2] Moreover, the opportunity of people without a car or without the ability to drive a car (for example, those who are disabled or elderly) to access activities via (shared) automated vehicles can affect the individual component of accessibility. Finally, the possibility of automated vehicles to drive themselves to certain locations to accomplish an activity (for example, pick up the children from school or groceries from the supermarket) may overcome temporal constraints either with respect to opportunities (stores opening/closing times) or regarding individuals themselves (time availability). However, the question that arises is, how are such radical accessibility enhancements able to affect urban form? We can identify three possible spatial implications at the regional scale: a new exurbanization wave, the emergence of new urban centralities and further densification of primary city centers.

According to urban and regional economic location theory people make trade-offs between commuting costs and lower rent or higher earnings from their job (see Alonso 1964; Muth 1969). Thus, houses with lower accessibility to jobs are less attractive to people, and jobs that require longer commute times must compensate them with higher salaries. Likewise, locations with higher accessibility have higher growth potential and, consequently, higher real estate values (see Hansen 1959). The accessibility enhancement associated with the introduction of automated vehicles might allow people to compensate lower commuting costs with more land and greater living conditions in a more distant location. Thus, enhanced accessibility could trigger an exurbanization wave of inner city and suburban residents. The magnitude of this new wave of exurbanization will depend on the extent of accessibility improvements that automated vehicles will offer, land availability and land-use policies. For example, in a restrictive land-use context (for example, involving growth boundaries) significant accessibility enhancement might lead not to a sprawled low-density development, but to a decentralized concentration of growth in surrounding smaller satellite settlements. Accessibility enhancement because of automated vehicles might also affect location of new centralities within the urban context. Current suburban employment, retail and recreation centers might incrementally transform into significant peripheral growth poles serving demand of new exurban residents. The infill mixed-use growth potential in these areas could be further enhanced by the elimination possibility of current extensive parking lots, since automated vehicles will likely be able to park themselves in remote peripheral locations. The infill development potential is also high in existing main centers, where opportunity costs of parking facilities are significantly higher since this land could be used for residential, retail or other land uses, new buildings and/or landscaping. Such real estate changes may subsequently lead to further densification of primary city centers.

Land-use transportation models and accessibility-based location models in particular could help explore potential spatial implications at the regional scale from the advent of automated vehicles. Indicators such as the widely used potential accessibility could offer such estimations by measuring accessibility of an area to all destinations of interest. According to Geurs and van Wee (2004) it is important that the parameters of the potential accessibility function are estimated based on recent empirical data of travel behavior in the area under study. Thus far, such empirical data do not exist, since automated vehicles technology is still in its infancy. Therefore, the estimation of behavioral parameters related to generalized transportation costs (for example, VTTS) will probably involve a dynamic continuous process that will unfold as the technology evolves. Sequential exploratory research designs that will involve qualitative (for example, scenario exercises, focus groups or in-depth interviews) and quantitative methods (for example, stated choice experiments) in two interactive consecutive phases might be methodologically appropriate for exploring such travel behavior changes. More advanced accessibility-based location models (see, for example, IPRUD, Wegener 1982; RURBAN, Miyamoto and Udomsri 1996; MUSSA, Martínez 1996; DELTA, Simmonds 1999; UrbanSim, Wadell 2002) could also be utilized to explore location choices within a transport ecosystem that includes automated vehicles. These models can predict location choices of households and firms using discrete choice models that include both accessibility indicators and other attributes of potential locations (Wegener 2014; see also Wegener 2004; Hunt et al. 2005 for a comprehensive review of these models).

The introduction of automated vehicles could also trigger spatial implications at the micro (neighborhood) scale (that is, streetscape, building landscape and land uses) through two main mechanisms: (1) reduction of the amount of parking spaces (on-street, off-street and surface) in urban areas, and (2) vehicle motion stability and automated intersection management.

Automated vehicles are anticipated to be able to drive themselves to peripheral parking lots after dropping off passengers, reducing the need for parking spaces in urban areas (especially in commercial and work establishments). Moreover, potential development of automated vehicle sharing schemes may lead urban residents to live car-free or reduce the numbers of cars they own and, consequently, constrain the number of parking spaces needed in residential buildings. According to a simulation study done by the International Transport Forum (2015), on-street parking spaces could be eliminated in all scenarios involving a mix of shared automated vehicles with public transportation and significantly reduced in case of mixing with conventional cars. Elimination of on-street parking would allow converting parking lanes into new mobility space (for example, high-occupancy vehicles lanes, bus lanes or cycle lanes) or stationary public space (for example, parklets, green spaces or wider sidewalks). A reduction of off-street parking could trigger changes with respect to land uses (that is, residential or commercial development), building design (that is, access lanes, landscaping) and housing affordability, since building construction costs would be lower. Finally, a reduction of surface parking lots and parking garages in high-value land areas could enhance infill development, alleviating in parallel both aesthetic degradation and other important environmental problems such as the heat island effect.

Automated vehicles will likely be able to precisely navigate on roads by detecting road lanes (Aly 2008; Li et al. 2014), road boundaries (Wijesoma et al. 2004), spatial layout and multiple characteristics of road terrain (Fritsch et al. 2014), and road signs (de la Escalera et al. 2003). Automated vehicles could possibly be able to navigate themselves even in road contexts without speed lanes or in unstructured environments (Ferguson et al. 2008; Kala and Warwick 2014). Moreover, V2V and V2I communications along with vehicles' improved precision control and sensing could allow multi-agent control systems to manage intersections, making traditional traffic lights and signs redundant (Dresner and Stone 2008: Omae et al. 2010). The streetscape redesign potential resulting from both automated vehicles motion stability and automated intersection management is significant. Road lanes could be narrowed providing extra capacity that could be used as an additional mobility or stationary space. Moreover, several aspects of intersection design could be reconsidered, such as the clear sight triangles, vehicle paths, traffic lights and signs. The way that automated vehicles and pedestrians or cyclists will interact (for example, via sensors or voice) is also critical for the design of intersections (Chen et al. 2014).

Close cooperation among traffic engineers, roadway engineers, urban planners, urban designers and architects will allow capturing the full land use, streetscape, and building redesign potential resulting from changes associated with vehicle automation. The change in design standards will probably be a slow, incremental process that will evolve in parallel with technological progress of automated vehicles. In the meantime, design scenario exercises involving a variety of experts could help identify emerging challenges towards safer and more livable streets.

6 CONCLUSIONS

In this chapter we provided an overview of what vehicle automation is, how this technology could evolve and what the potential impacts on future traffic conditions, mobility and urban form are. We proposed the ripple effects model to conceptualize implications of vehicle automation at different time horizons. The first ripple includes short-term implications of automated driving with respect to traffic, travel cost and travel choices. The second ripple includes medium-term implications of automated driving with respect to transport infrastructures, location choices and vehicle ownership. The third ripple contains the long-term wider societal implications such as energy consumption, emissions, congestion, health, economy, social equity and safety. Based on the ripple effects model, we focused our analysis on three major areas of impacts: traffic, mobility and urban form. For these three areas we provided a review of the main methods that have been used to estimate impacts and their results. We also identified possible methods for studying the relative unexplored impacts of vehicle automation.

We found that most research has focused on traffic impacts of the intermediate levels of vehicle automation, where ACC and CACC have a prominent position. These studies have mostly used simulation as their main method, either with commercially available tools or by building their own. The main conclusion is that in most traffic conditions there is a non-negligible positive impact on traffic capacity. However, there is some uncertainty in the case of mixed fleets, indicating that the transition for vehicle automation may face an initial period where benefits will not be observable. What is missing in this field of research are the impacts on an urban traffic environment, since most of the studies have focused on highways capacity. Also ignored is the estimation of traffic safety impacts of this technology; researchers have not yet established research methods to study this relevant topic.

The impacts of vehicle automation in mobility have been less explored and then only recently. There is a significant knowledge gap in characterizing travelers' behavior, particularly in their attitude toward using driverless vehicles. No demand models have been estimated with that purpose in mind; therefore, it is not possible currently to have an estimation of the VTTS associated with these vehicles and compare them with private vehicle ownership and public transport. Simulation techniques, such as agent-based modelling, are used to estimate the mobility effects of shared automated vehicle fleets, which are foreseen to substitute the conventional private ones. Results show significant fleet reductions from the shared system, either as a single-trip service or in a car-pooling mode with multiple trips being satisfied per vehicle at a time.

The introduction of automated vehicles is expected to influence urban form both at the macro (regional) and the micro (neighborhood) scale. The magnitude of the effects is expected to be proportional to the level of automation, with fully autonomous and cooperated vehicles showing the stronger influence. At the regional scale, accessibility changes associated with automated vehicles could cause a new exurbanization wave, influence new urban centralities and lead to further densification of primary city centers. At the local level, parking elimination, motion stability of automated vehicles and automated intersection management could allow significant changes in land use, streetscape and building landscape design. Nevertheless, the impact of vehicle automation on cities remains a relatively unexplored research area. However, interest in the implications for urban form is expected to keep rising as vehicle automation technology evolves towards fully automated vehicles.

NOTES

1. It should be noted that the fixed costs of automated vehicles are expected to be higher than those of conventional vehicles, which might affect penetration rate of different levels of vehicle automation and, subsequently, the magnitude of their effects.
2. The total travel cost and time benefits will ultimately depend on the level of induced demand (VKT) after introduction of automated vehicles and potential travel demand management strategies (for example, road pricing; see Fagnant and Kockelman 2015).

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