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10. Automated driving on the path to enlightenment?

Maaike Snelder, Gonçalo Homem de Almeida Correia and Bart van Arem

INTRODUCTION

The development of automated cars started about a century ago as a curiosity, almost part of some kind of science fiction depiction of the future. Naturally underlying the innovation was the objective to save time that could be used in more enjoyable ways. At that time improving traffic, safety, and energy consumption were not among the priorities of car makers.

The first radio-controlled driverless car was introduced to the public on the McCook Air Force test base in Dayton, Ohio, USA on 5 August 1921 (Kröger, 2016).

> In the summer of 1925, Houdina's driverless car, called the American Wonder, traveled along Broadway in New York City—trailed by an operator in another vehicle—and down Fifth Avenue through heavy traffic. It turned corners, sped up, slowed down and honked its horn. Unfortunately, the demonstration ended when the American Wonder crashed into another vehicle filled with photographers documenting the event. (Engelking, 2017, p. 1)

This first failure stresses the importance of safety for the people within the vehicle and other road users, which cannot be solved without proper technology. This technology would only become available decades later (US Department of Transportation, 1994).

Technology such as advanced driver assistance systems (ADASs) like blind-spot monitoring, adaptive headlights systems, obstacle and collision warning, lane-keeping support, emergency braking systems, and eco-driving support hit the market for private cars later in the 20th century. In 2014 the deployment rate averaged over 28 European countries was 2.7–12.6 percent for five safety-related ADASs and 23 percent for eco-driving support (Kyriakdis et al., 2015). In that period there was a lot of optimism about automated driving. It was expected that by 2021 the majority of vehicles would drive automatically (Underwood et al., 1991).

From 2010 onward more advanced automated driving projects gained momentum. In 2019 Tesla vehicles equipped with autopilot had already 6.9 percent of the market in the Netherlands (Autoweek, 2021). Waymo, formerly the Google self-driving car project, has introduced a ride-hailing service in Phoenix, Arizona (Waymo, 2021). Their vehicles can drive autonomously on certain roads under certain conditions. For freight transport, Waymo has introduced automated trucks, which promise to provide continuous uninterrupted driving along with flexible scheduling and routing at lower operating costs.

It is important to understand that automation is not a binary property of vehicles. The Society of Automotive Engineers provides a taxonomy with detailed definitions for six levels of driving automation, ranging from no driving automation (level 0) to full driving automation (level 5) (SAE International, 2021). When vehicles are fully automated, a driver is no longer needed. For people without a driver license, that opens a whole new world of opportunity, because all of a sudden they can use automated cars for their trips. Former car drivers become passengers who can do all kinds of activities within a vehicle that they couldn't do before. This innovation in transport might have a huge impact on daily activity and travel patterns. The impact of lower levels of automation will be less disruptive, but still substantial. Each level of automation can be considered an innovation in transport because at every level the automation increases safety and driving comfort and has potential other implications as described in more detail in this chapter. At levels 1–2, the driving automation system provides the driver with longitudinal and lateral control, that is, adaptive cruise control (ACC) as well as lane-keeping and parking support. However, at these levels, the driver is still responsible for monitoring the environment. At level 3, the automated driving system (ADS) monitors the environment and executes driving tasks in certain operational design domains (ODDs), allowing the drivers to avert their attention from driving tasks while being ready to take back control in case of a failure when approaching difficult driving conditions. Level 4 is expected to handle the fail-safe situation autonomously; however, the ODD is still limited. This implies that levels 3–4 might need dedicated infrastructure or roads with other specific infrastructure requirements. Finally, at level 5, the vehicles can drive safely anywhere at any time. However, level 5 vehicles are not to be expected in the near future due to their demanding safety requirements in any ODD (Shladover, 2016).

Besides automation, connectivity plays an important role. When vehicles can communicate with each other (V2V) and with the infrastructure (V2I and I2V), they can drive at much shorter time headways, which increases the road capacity and reduces energy use. With respect to I2V communication, five levels for infrastructure support for automated driving (ISAD) have been recently specified, ranging from A to E (Carreras et al., 2018). E represents no infrastructure support, D represents static digital information like digital map data complemented by physical reference points, C represents dynamic digital information provided to automated vehicles (AVs) in digital form, like dynamic road signs and dynamic information about warnings, incidents, and weather conditions, B represents cooperative perception, which means that the infrastructure is capable of perceiving microscopic traffic situations and of communicating to vehicles (I2V), and A represents the highest infrastructure support level where AVs are guided by the infrastructure to optimize traffic flow by sending out gap and lane change advice messages.

For freight transport truck platooning has gained momentum since 2014. Janssen et al. (2015) wrote a white paper that explained why truck platooning is the future of freight transportation, also emphasizing that companies benefit from lower fuel consumption and improvements in (driver) productivity while society benefits from fewer accidents, less congested roads, and lower carbon emissions. Since then, the automotive industry and numerous start-ups have been involved in many successful real-world trials. Since 2018 the European project called ENSEMBLE has been working on inter-brand platooning technology, which is an important next step for truck platooning. In September 2021 a platoon consisting of seven trucks, one from each leading European manufacturer, is expected to drive from a logistics hub to Barcelona harbor (ENSEMBLE, 2021).

In public transportation, automation technologies were introduced in the early 1980s, with the first automated metro in Europe starting operation in 1983. In 1999 the Rivium ParkShuttle in the Netherlands brought automated public vehicles onto the roads with the very first automated shuttle (Transdev, 2021). Hagenzieker et al. (2020) presented an overview of 118 pilots with automated shuttles, that is, vehicles with predominantly low speeds, low capacities, and short operation routes, across Europe. They conclude that the vast majority of automated bus system pilots operate on an on-demand basis and as an access and egress mode for main facilities and/or public transport lines. Most pilots still have a steward on board, due to legislation and technological challenges as well as passengers requesting them, raising concerns regarding (e.g. economic) efficiency. For a more complete view of the implications of automation for public transport the reader may consult Correia (2021).

Based on the above, it can be concluded that many developments have taken place in the past century in the field of automation of cars, trucks, and public transport. This is especially true for the lower levels of automation in combination with electrification. An important next step, and a potential game changer, is the transfer of control from the driver to the vehicle. However, this is challenging as various circumstances fall outside of the ODD of many partially automated vehicles (Calvert et al., 2020).

With respect to the deployment of vehicles with higher forms of automation there are still many uncertainties, which lead to questions about expected societal impacts and success and failure factors for automated driving. To address these questions, this chapter describes the expected societal impacts of automated cars levels 3, 4, and 5, truck platoons, and automated shuttles, and derives success and failure factors for these innovations in transport based on findings from the STAD (Spatial and Transport Impacts of Automated Driving) research project and associated work by the authors. The chapter starts out from the STAD project because it is one of the few projects about the societal impacts of automated driving. Particular topics that were taken into account were 1) travel and location choice behavior, 2) freight and logistics applications, 3) infrastructure service networks, 4) urban design and traffic safety, 5) spatial structure and economy, 6) integrated model for the impacts of automated driving, and 7) use cases and demonstrators. A complete overview of the project can be found in van Arem (2021). Note that other aspects like legislation and technological developments are also crucial for the success of automated driving, but were outside the scope of the STAD project. Therefore, this chapter describes the impact of automated driving that can be expected once the legislative and technological challenges have been resolved.

SOCIETAL IMPLICATIONS OF AUTOMATED DRIVING

In this chapter, the conceptual ripple model presented by Milakis et al. (2017a) is used to describe the societal implications of automated driving (see Figure 10.1). The ripple model represents a metaphor of how the impacts of driving automation propagate over time from changes in traffic and travel characteristics (first ripple or first-order) to spatial implications such as infrastructure and location choice (second ripple or second-order) and ultimately to economic and societal changes (third ripple or third-order). The ripple model of automated driving should not be taken too strictly, because feedback loops can occur and sometimes the time delay between successive effects in different ripples can be negligible. The general idea is that with an increase in penetration rates of higher levels of AVs the expected societal impacts in all ripples will be higher. The paper of Milakis et al. (2017a) includes a literature review that describes what was known about the impacts mentioned in the ripple model up to 2017. This section enriches these insights with the findings of the STAD research project and associated research work and derives the most important success and failure factors for automated driving based on these findings. In Figure 10.1 the ripple model is reproduced with the identification of where each of the STAD research topics fit. The next subsections will present the results organized per each of the ripple levels (categories marked in bold).

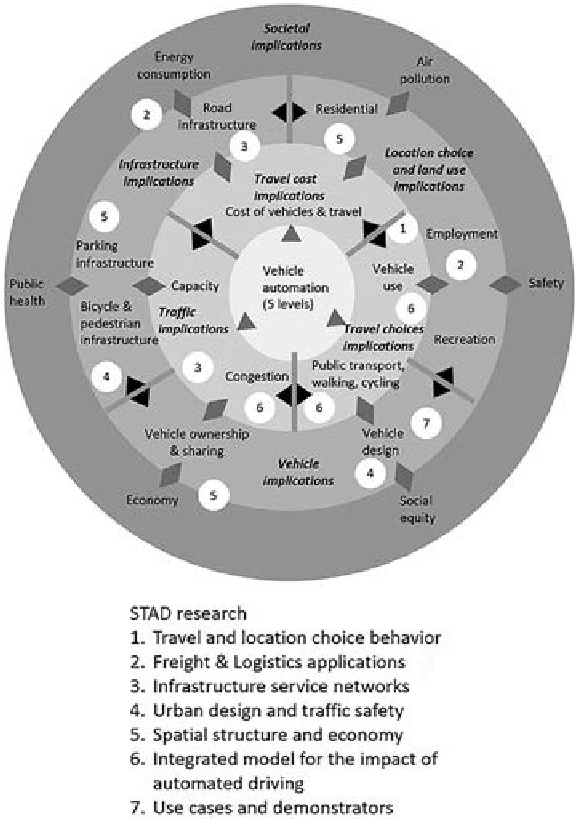

Figure 10.1 Mapping of STAD research project onto the ripple model of Milakis et al. (2017a)

First-Order Implications of Automated Driving

Based on their literature review, Milakis et al. (2017a) concluded that the fixed costs of AVs will very likely be higher than for conventional vehicles due to the advanced hardware and software technology involved. The price difference could be gradually reduced to $3000 or even less with mass production and the technological advances of AVs. Regarding the generalized transport costs, these are expected to decrease because of 1) a reduction in costs per kilometer, 2) increased road capacity (> 10 percent when the penetration rate is higher than 40 percent and vehicles are connected), 3) reduced travel times, 4) reduced search time for parking, 5) a potential decrease in the value of time because of more travel comfort, 6) enhanced travel safety, 7) higher travel time reliability, and 8) the possibility to perform activities other than driving, like working, meeting, eating, or sleeping. It was noted that the enhanced road capacity and reduced generalized travel costs might increase vehicle travel demand (3–27 percent), vehicle kilometers driven, and congestion. Below, the findings from the STAD project and related research with respect to the first-order implications of automated driving are summarized, resulting in success and failure factors for automated driving. The focus was on travel choice implications and traffic implications. Travel costs implications have not been studied.

Travel choices implications

The research about travel and location choice behavior aimed to understand the impact of level 5 vehicle automation on activities and travel behavior. Based on focus group research among 27 commuters (Pudãne et al., 2019) and a stated activity-travel survey among 509 commuters in the Netherlands (Pudãne et al., 2021), it was concluded that AVs are expected to allow their users to engage in a broad range of non-driving activities while traveling. Pudãne et al. (2019) classified on-board activities in four quadrants according to their novelty and priority level: 1) current activities with high priority like work, study, eat, apply make-up; 2) new activities with high priority like prepare dinner, wash oneself, brush teeth, do administration; 3) current optional activities like read news, check phone, make phone calls; and 4) new optional activities like exercise, play games, watch movies. This classification is helpful in understanding the potential re-arrangements of daily activities. It was found that the availability of on-board activities influences the (time-geographic) constraints of daily activities and may lead to complex re-arrangements of daily activity patterns especially for the high-income and higher-educated groups. This re-arrangement of activities may have a substantial impact on trip patterns during the day and therefore on congestion levels. Engaging in any activity during travel worsens congestion, at least when assuming that AVs do not increase bottleneck capacity (Pudãne, 2020). In a parallel study on the value of travel time (VOTT) inside an AV, Correia et al. (2019) ran a stated preference survey comparing a conventional vehicle with an AV with an office interior and an AV with a leisure interior in commuter trips. A sample of travelers in the Netherlands answered the survey, from which it was possible to estimate a lower VOTT in an AV prepared for work when compared to the current VOTT in a conventional car while the leisure vehicle was not perceived as more attractive. The authors attribute this difference to the difference of performing both activities in a car in relation to performing them at the usual place. In fact, the VOTT of working in a car can be demonstrated as being the result of the difference between the experience of working at a "normal" workplace and the experience of working while traveling. Following this logic, the

VOTT of the leisure car is the difference between having leisure at a "normal" place and the experience of having leisure inside a car. It can be concluded that both activities are seen as being very different, with the work vehicle providing a more equivalent experience to current work than the leisure vehicle, which seems to provide an experience that is far from what the respondents considered to be their current leisure experience (Pudãne and Correia, 2020). This research shows that the type of activity can lead to a very different experience, thus adding to the uncertainty of the effects of vehicle automation.

Traffic implications

Snelder et al. (2019) developed a model to explore the modal shift and traffic implications of connected and automated driving (level 3/4 and level 5) and shared mobility. It is an explorative iterative model that uses an elasticity model for destination choice, a multinomial logit model for mode choice, and a network fundamental diagram to assess traffic implications. The model uses literature-based assumptions in combination with findings from the other STAD research projects about the impact of AVs on capacity, VOTT, monetary cost per kilometer, and other user preferences captured by the mode-specific constant as an input. Because the impact of AVs on the costs, VOTT, and mode-specific constants are highly uncertain, a sensitivity analysis was carried out. The model was applied in a case study of the Dutch province of North-Holland, in which the potential impacts of automated and shared vehicles and mitigating interventions were explored. In this case study, four scenarios were explored, in which 100 percent of the vehicles have SAE-level 3/4 or 5 and people have a low or high willingness to share. A 100 percent penetration rate was chosen to get insights into maximum effects. The results show that a shift to automated private cars and automated taxis can be expected. This increases the accessibility of many regions for many people, including for those who are not allowed to drive. In the most extreme scenario, L5-no-sharing, the share of car trips including new modes increases from 41 percent to 68 percent. In the scenario with a high willingness to share (L5-sharing) the share of car trips including new modes increases to 62 percent. The increased mobility has negative effects on congestion. The results of the sensitivity analyses for scenario L5-sharing showed that varying the mode-specific user preferences (i.e. mode-specific constant) that were not explicitly included in the utility function had the largest impact. If the new concepts appear to be less attractive than we assumed, their total modal share might reduce from 62 percent to 44 percent. Charging the ownership costs to the user also makes a large difference. It reduces the modal share of the new modes to 46 percent. Owners of the automated (shared) taxis and vans will likely do this at least to some extent. A strong mix of interventions will be needed to keep delays at the same level as in the reference scenario. This is especially the case in (very) highly urbanized areas. In other areas, the interventions can be more modest.

Success and failure factors related to the first-order implications of automated driving

Based on the expected first-order implications of automated driving, it can be concluded that the fact that people can spend their time in AVs in a better way is an important success factor for automated driving. A reduction in cost per kilometer adds to the success of AVs, whereas higher ownership costs are a potential failure factor. An increase in capacity, in the case of cooperative AVs, can also be a factor for success. A reduction in public transport trips and walking and cycling and an increase in car trips and vehicle kilometers driven can however be a failure factor, especially if the increase in traffic volumes is larger than the increase in capacity, resulting in more congestion.

Second-Order Implications of Automated Driving

Vehicle automation can have second-order implications on vehicle ownership and vehicle design, location choices and land use, and transport infrastructure. With respect to vehicle ownership, Milakis et al. (2017a) concluded that shared AVs could replace from about 67 percent up to over 90 percent of conventional vehicles, delivering equal mobility levels. Concerning land use, it was concluded that AVs could enhance accessibility citywide, especially in remote rural areas, triggering further urban expansion. AVs could also have a positive impact on the density of economic activity at the center of the cities. With respect to transport infrastructure, the focus has been on required parking spaces. It was concluded that parking demand for AVs could be shifted to peripheral zones. On the one hand, parking demand for shared AVs can be high in city centers, if the vehicle is not allowed to move without people in it. On the other hand, shared AVs could significantly reduce parking space requirements by up to over 90 percent. The overall reduction of the conventional vehicle fleet and parking spaces could vary according to the automated mode (vehicle-sharing, ridesharing, shared electric vehicle), the penetration rate of shared AVs, and the presence or absence of public transport. Below, the findings from the STAD project and related research with respect to second-order implications of automated driving are summarized, resulting in additional success and failure factors for automated driving.

Vehicle implications

According to the ripple model, automated driving may have implications on vehicle ownership and sharing and on the design of vehicles. Ostermeijer et al. (2019) developed a model to explore what the potential implications on vehicle ownership and on car demand are when households own private AVs of level 4/5 that will be parked at locations in the periphery, where parking costs are relatively low. First, they developed an approach to estimate implicit residential parking costs and then examined the effect of these costs on household car ownership. They applied their approach to the four largest metropolitan areas of the Netherlands and found that for city centers, annual residential parking costs are around €1000, or roughly 17 percent of car ownership costs, and are more than double the parking costs in the periphery. The disparity in parking costs explains around 30 percent of the difference in average car ownership rates between these areas and corresponds to price elasticity of car demand of about −0.7. They concluded that when private AVs of level 4/5 can be parked at locations in the periphery, this is expected to increase car demand by around 8 percent in the center and 5 percent in the urban ring, and that there would be no change in the periphery. When AVs are shared and therefore parking costs approach zero, car demand is predicted to increase by around 14 percent in the center, 11 percent in the urban ring, and 5 percent in the periphery.

The design of AVs might affect the crossing behavior of pedestrians and bicycles at intersections. To understand the impact of the design of AVs and urban intersections on crossing behavior, Nuñez Velasco (2021) used a virtual reality platform. The role of several characteristics of AVs, such as their physical appearance, whether there is a driver present in the vehicle, and the presence of external communication interfaces (i.e. screens mounted on AVs to communicate with other road users), were investigated. Concerning crossing intentions of pedestrians, it was concluded that a zebra crossing and larger gap size between the pedestrian and the vehicle increases the pedestrian’s intention to cross. In contrast to what was expected, participants intended to cross less often when the speed of the vehicle was lower. Despite that the vehicle type affected the perceived risk, no significant difference was found in the crossing intention. However, pedestrians who did recognize the vehicle as an AV had, overall, lower intentions to cross (Nuñez Velasco et al., 2019). For cyclists, the gap size and the right of way were found to be the primary factors affecting the crossing intentions of the individuals. The vehicle type and vehicle speed did not have a significant effect on the crossing intentions. Cyclists’ statements of whether they trusted AVs more or less as compared to conventional vehicles were found to be a stronger predictor of the crossing intentions compared to their trust in AVs by itself. Furthermore, those that reported being low risk-seeking cyclists had a higher intention to adapt their speed than those that reported being high risk-seeking cyclists. Overall, a positive relation was found between cycling speed adaptation and perceived behavioral control, and a negative relation between cycling speed adaptation and perceived risk, when interacting with an AV compared to a conventional vehicle (Nuñez Velasco et al., 2021).

Rad et al. (2020) used models to simulate on a screen different crossing situations in the context of having to catch a train in a serious gaming environment. Respondents needed to observe the situation and choose to cross or to wait for the next gap. In some experimental configurations, the AVs communicated their intention to continue or not to continue their trajectories using lights. The subjects of the experiment were also asked to fill in a questionnaire about usual behavior in traffic, as well as attitudes and risk perceptions toward crossing roads. The results of generalized linear mixed models applied to the data showed that besides the distance from the approaching vehicle and existence of a zebra crossing, pedestrians' crossing decisions are significantly affected by their age, their familiarity with AVs, the communication between the AV and themselves, and whether the approaching vehicle is an AV. Moreover, the introduction of latent factors as explanatory variables into the regression models indicated that individual-specific characteristics like willingness to take risks and violate traffic rules and trust in AVs can have additional explanatory power in the crossing decisions (Rad et al., 2020).

Location choice and land use implications

Legêne et al. (2020) and Hollestelle (2018) studied the spatial impacts of automated driving. Legêne et al. (2020) developed a geospatially disaggregated system dynamics model for the city of Copenhagen and focused on explaining the effects of vehicle automation on the city structure. The analysis led to two distinct scenarios. In one scenario, AVs lead to more vehicle use, which leads to more urban sprawl and more congestion as a consequence. In the other scenario, more shared use of cars leads to less traffic and more open space in the city through converting parking space and road infrastructure. Hollestelle (2018) combined a transportation model with an agent-based location choice model and a research-by-design approach. He concluded that urban centers in particular are vulnerable to induced travel demand, which threatens accessibility levels and facilitates the process of suburbanization. However, when this decrease in accessibility is compensated by increased travel comfort and spatial quality gains, the opposite might occur.

According to the ripple model, automated driving may also have an impact on employment and jobs in different areas. With respect to implications on employment, the focus of the STAD project has been on the impact of truck platooning on employment. With progressing technology, drivers may rest while being in the truck. One step further is that drivers are not required anymore in some of the trucks in a platoon. Hence, platooning technology has a significant impact on the jobs of truck drivers. Driver acceptance of this emerging technology is, therefore, an important factor in the implementation of platooning and, consequently, automated driving in general. Bhoopalam et al. (2021) concluded, based on focus groups, that drivers foresee that platooning will eventually become a reality and that it will have a negative impact on the quality of their work and their job satisfaction.

Infrastructure implications

The introduction of AVs might have an impact on road infrastructure, parking infrastructure, and bicycle and pedestrian infrastructure. With respect to road infrastructure, Madadi (2021) claims that reaching a high market penetration rate of fully automated vehicles will be a gradual process that will take several decades. Thus, for a long time, a heterogeneous mix of traffic with AVs of different automation levels and regular vehicles on the roads will be inevitable. During this transition period with mixed traffic, relying on driving automation technology alone without infrastructure support might compromise the potential safety and efficiency gains of AVs. A proper infrastructure can support AV functionalities, extend their ODD, and improve safety for all road users, while lack of proper infrastructure can negatively influence these factors. Madadi et al. (2021) developed an optimization model that determines which motorways and regional roads in a network can best be upgraded to a so-called connected AV-ready subnetwork where AVs and non-automated vehicles can drive in mixed traffic, dedicated lanes, or dedicated links (i.e. road sections). The optimization is based on a trade-off between infrastructure adjustment costs and network performance benefits because of lower total travel cost, a decrease in total travel time, and a minor increase in total travel distance (Madadi et al., 2020). For the upgrade to an AV-ready subnetwork a multi-stage optimization model was developed that not only determines which roads should be upgraded, but also when they should be upgraded. One of the main conclusions is that different network layouts for accommodating AVs in road networks are relevant for different market penetration rates of AVs. For lower market penetration rates, AV-ready subnetworks, which are suitable for AVs in mixed traffic, appear to be the most efficient configuration. However, starting from an around 30 percent market penetration rate, dedicated AV lanes become relevant, and can efficiently host the AVs. Road types play a crucial role in the choice of network configuration as well. Motorway on-ramps and off-ramps, single-lane roads, and major regional roads that include sections with a single lane have been shown to be appropriate for mixed traffic, while dedicated AV lanes are most suited for motorways. Finally, it was concluded that an effective AV-ready subnetwork including an appropriate selection of links (~20 percent) to be upgraded with infrastructure adjustments to accommodate AVs can deliver a large proportion of the benefits (~70 percent) obtainable from upgrading infrastructure on all links with significantly lower investment cost.

Truck platooning may also have implications on infrastructure investments. Bhoopalam et al. (2018) conducted a literature review about truck platoon planning and the impact of platooning on routing and network design. They concluded that parts of the network may be heavily used by platoons and require infrastructural changes such as reinforcement of roads, new lanes, and additional communication support in tunnels. Also, since the starting locations of trucks influence platooning opportunities, there is an incentive to move facilities such as warehouses and depots closer to each other to achieve economy of agglomeration.

Boersma et al. (2018a) used existing cases of automated driving to derive success and failure factors for automated driving with a specific focus on the implementation of automated shuttles in the Netherlands like the Rivium Parkshuttle in Rotterdam, the WEpod in Ede/Wageningen (Boersma et al., 2018c), and a shuttle in Appelscha (Boersma et al., 2018b), as well as on an automated mini bus in the Oku-Eigenji area in Japan (Boersma et al., 2019). An important conclusion is that the focus of most pilots has been on technical feasibility with short route lengths and low speeds. The pilots showed that it is technically feasible to operate without a steward on board. However, attention should be given to the space needed for the vehicle and remaining space for other road users. Furthermore, it is advisable to control intersections where automated shuttles cross other traffic. In order to make automated shuttles more accessible, future pilots should aim to roll out transit lines throughout larger (and denser) areas where there is actual demand for shuttles. Current legislation in many countries, requiring stewards on board and low operating speeds, is mentioned as an important factor that withholds automated bus systems and shuttles from practical implementation and utilization (Hagenzieker et al., 2020). At the same time, safety and monitoring are crucial for the success of automated driving (Santoni de Sio et al., 2022).

Success and failure factors related to the second-order implications of automated driving

Based on the expected second-order implications of automated driving it can be concluded that the fact that AVs of level 4/5 can park themselves at locations in the periphery, where parking costs are relatively low, is a success factor for automated driving, because it saves money for users and reduces local parking pressure. The fact that AVs enable people to live further away from their work locations is a success factor as well because it enables them to live at more preferred locations. At the same time, both can be a failure factor when they result in more congestion and urban sprawl. More shared use of vehicles is a success factor because it leads to less traffic and better spatial quality in cities. Investments in physical road infrastructure, including AV-ready subnetworks, dedicated lanes, controlled intersections, and zebra crossings, and investments in digital infrastructure, including monitoring, supervision, and even remote control, are other success factors for automated driving. Carefully selecting the right location for automated driving systems, and especially shuttles where there is actual demand for them, is important for the success of these systems. Current legislation in many countries with respect to stewards on board and operating speeds is a failure factor. Finally, drivers' acceptance of truck platooning is an important factor in its implementation and, consequently, automated driving in general.

Third-Order Implications of Automated Driving

The third ripple focuses on the societal implications of AVs. Milakis et al. (2017a) found that fuel savings can be achieved by various longitudinal, lateral (up to 31 percent), and intersection control (up to 45 percent) algorithms and optimization systems for AVs. Vehicle automation can lead to lower emissions of NOx, CO, and CO_2 and advanced driver assistance systems and higher levels of automation (level 3 or higher) can enhance traffic safety. A higher level of automation, cooperation, and penetration rate could lead to higher fuel savings and even lower emissions. The shared use of AVs could further reduce emissions. Impacts on long-term energy consumptions, long-term air pollution, social equity, the economy, and public health were still uncertain in 2017. The research in the STAD project with respect to the third ripple was limited to the impact of truck platooning on fuel cost savings, as explained below.

Energy consumption

Truck platooning has an impact on fuel costs because of short headways between vehicles as well as on associated emissions. Bhoopalam et al. (2020) developed an optimization technology to match trucks into platoons. They showed that when platoons of two or three trucks are formed, > 98 percent of the vehicles can be matched in a platoon, > 89 percent of the kilometers driven can be as part of a platoon, < 3 percent of the vehicles have to take a detour, and 8.8–9.5 percent fuel savings can be achieved.

Success and failure factors related to the third-order implications of automated driving

It can be concluded that fuel savings and lower emissions are a success factor for automated driving. Other third-order implications of automated driving have not been studied extensively. Impacts on safety, social equity, public health, and the economy still need to be studied.

Overview of Success and Failure Factors for Automated Driving

The previous section illustrated that automated driving can have both positive and negative first-, second-, and third-order impacts and that the impacts depend on many different success and failure factors. This section combines all the insights to give a coherent set of success and failure factors for automated driving (see Figure 10.2). It should be noted that there is a difference between automated driving technologies that can still progress within our current mobility system (including the legal and policy context) and automated driving functions like sustained level 3 and level 4 automation and beyond that require that fundamental challenges with respect to human factors, technology, infrastructure, and legislation are addressed at the same time. Yet, this does not mean that these higher levels of automation are not feasible. The first car was considered dangerous a century ago, and ACC, automatic braking, and autopilot systems were all considered to face strong barriers (of different kinds) before their introduction. And still they were introduced.

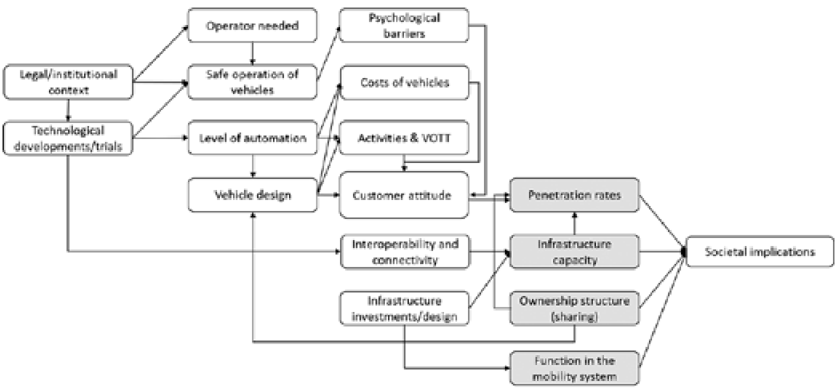

Figure 10.2 Success and failure factors and relationships for automated driving

The previous section illustrated that the penetration rates, the infrastructure capacity, ownership structure (sharing), and the function in the mobility system determine to a large extent how large and how positive or negative the societal implications will be. These factors (indicated in gray) depend in their turn on many other factors as described below.

Penetration rates will increase when customers have a positive attitude toward AVs and are willing to buy or use (in the case of shared vehicles) the vehicles. Note that there is not one average customer, but the attitude of customers depends on their socio-demographic and economic characteristics. The willingness to buy or use an AV depends on the ownership and usage costs of the vehicles, on the VOTT, and on vehicle design. When people can do more activities in a vehicle, they will be more inclined to use AVs. The costs of the vehicles, the VOTT, and the vehicle design depend on the level of automation and technical developments and trials or pilots to test the technological feasibility of AVs. Customer attitude also depends on psychological barriers to using and interacting with AVs. Safe operation of vehicles, including a trustworthy combination of human/machine-operated driving, monitoring, and service tasks and including safe interaction with pedestrians and cyclists, might reduce these psychological barriers. Legislation to force safe operation and to allow automated driving on the roads is a precondition for the success of automated driving.

The impact of automation on *infrastructure capacity* is also important for the success of automated driving. As explained before, the capacity might slightly reduce when AVs are not connected to each other and/or the infrastructure. However, when they are connected, capacity is expected to increase, which will have a positive impact on travel times. Reduced travel times will encourage more people to buy or use AVs, which results in higher penetration rates. Investments in physical and digital infrastructure can thus increase the success of automated driving. STAD research showed that it is not necessary to invest in all roads at once. Investing in a carefully selected selection of roads can already result in large benefits.

The *ownership structure* of AVs, or the extent to which people are willing to share vehicles, has a huge impact on the size of the vehicle fleet and required space for parking. If people are not only willing to share vehicles, but are willing to share rides, this is expected to lead to a substantial reduction in congestion.

Finally, the *function of AVs in the mobility system* is important for the success of automated driving. For example, automated shuttles for first and last mile transport compete with other modes of transport like (shared) bikes and public transport. Therefore, it is important to carefully select locations where demand is expected to be high enough to operate with a positive benefit–cost ratio. Another important notion is that when AVs become “too” attractive, they might cause a modal shift from walking, cycling, and public transport to AVs, which potentially has negative impacts on congestion, livability, and public health. This calls for a clear vision on the role of AVs within the mobility system, taking societal goals into account.

It is argued by business experts that AVs are in the “trough of disillusionment” according to Gartner’s hype cycle (Hull, 2021). According to this hype cycle (a methodology developed and used by consultancy firm Gartner to explain how a technology or application evolves over time) the AV technology has passed the periods “Technology Trigger” and “Peak of Inflated Expectations” and is now in this trough. The question is whether this technology will get past the trough and start on its way on the “Slope of Enlightenment” toward the “Plateau of Productivity”. Innovation theories (see Part I of this book) and the results of this chapter may give some food for thought on this question. First, as this chapter shows, it is clear that realizing an AVs system involves the initiatives of, and adaptations by, many actors, like firms, users, institutions, and governments. The AV innovation, therefore, fits perfectly one of the conclusions of Greenacre's (2012) review on modern innovation theories: "innovation is a dynamic, systemic process, arising out of the interplay between actors and institutions, and involving both knowledge flows and market interactions in a context of inherent uncertainties." So, evolving in a context of uncertainty is inherent to all innovations, but perhaps too much uncertainty at a certain point in time slows down the innovation process so that it falls into a trough. This chapter clearly conveys the current broad level of knowledge uncertainty related to AVs. There is uncertainty in the potential social implications of the technology, in user acceptance, in profitability for firms producing or using the technology, and so forth. Second, to speculate on passing through the trough to the Slope of Enlightenment the literature on the dynamics of transitions in socio-technic systems may be helpful. In a paper on the transition pathways from horse-drawn carriages to automobiles (1860–1930) in the United States, Geels (2005) showed that particular niches played a crucial role in the final wider adoption of the gasoline human-driven automobiles. So, to speculate if the AV technology will get past the trough, it is perhaps best to analyze in the near future if there is growth of this technology in a particular niche (or in niches), such as in automated shuttle buses applications.

CONCLUSIONS AND RECOMMENDATIONS

In this chapter the societal impacts of automated cars (level 3, 4, and 5), truck platoons, and automated shuttles have been discussed based on the ripple model (Milakis, 2017b) and these findings have been used to derive success and failure factors for automated driving. First- and second-order implications have been extensively studied. More research however is needed to fully understand the third-order implications of automated driving with respect to air pollution, safety, social equity, the economy, and public health.

With respect to methods and models it can be concluded that the "ripple model" of automated driving (Milakis, 2017b) has proven to be a useful model to analyze the societal impacts of automated driving. Current "classic" tools and methods have been considered too rigid and unsuitable to assess the impacts of automated driving given all the interactions in the ripple model. Several new approaches are emerging, such as the ones that have been developed within the STAD research project. Virtual reality and simulation models have been developed to analyze interactions of AVs with pedestrians and cyclists and to study changes in activity and travel patterns. Exploratory traffic and transport models have been developed to assess the impact of automated driving on modal split and congestion, taking uncertainties that are related to the introduction of AVs into account. Truck platoon planning algorithms have been developed to assess the impact of truck platooning. An optimization model has been developed for adaptive planning of road networks for automated driving. Finally, spatial models have been developed to assess the spatial implications of automated driving. These developments are an important step toward a brand-new generation of models and tools that are needed to assess the societal implications of automated driving. Besides new models, also new data collection methods are required as input to the models and to calibrate and validate them.

This chapter showed that in the short term "autopilot" systems can increase traffic safety and they have an effect on VOTT and can therefore cause a modal shift from walking, cycling, and public transport to the car. Investments in physical and digital infrastructure for automated driving quickly pay off. Upgrading 20 percent of the motorways and regional roads will allow AVs to drive 70 percent of the kilometers in automatic mode (Madadi et al., 2021). At low penetration rates, investments in AV-ready subnetworks for mixed traffic are recommended. At higher penetration rates (> 30 percent), dedicated lanes for AVs can yield additional benefits. For freight transport, truck platooning is expected to bring benefits for companies from lower fuel consumption and improvements in (driver) productivity while providing society benefits from fewer accidents, less congested roads, and lower carbon emissions. STAD research showed that for platoons of two trucks, the energy savings and improvement of the traffic flow outweigh the time needed to form the platoon. Automatic shuttles are seen as a promising solution for first and last mile transport. They can operate safely at low speeds on many roads. The behavior of the shuttles should be adapted to the expectations of cyclists and pedestrians. When crossing the road, pedestrians pay attention to speed, zebra crossings, and gap size between the pedestrian and the vehicle. The vehicle type and level of automation appeared to be less relevant. Communication of automatic vehicles with cyclists and pedestrians can make crossing easier.

In the longer term, automated driving can lead to changes in activity planning, travel patterns, and destination choice. When level 4/5 shared vehicles hit the market, less parking space and more drop on/drop off places will be needed. The freed-up parking space would lead to an increase in prosperity for non-car users because this space can be used for other purposes.

The societal impacts of automated driving are highly uncertain and will depend to a large extent on the penetration rates of AVs, infrastructure capacity, ownership structure (sharing), and the function of the AVs in the mobility system. Legislation and technological developments and trials/pilots are a precondition for the success of automated driving.

Overall, it can be concluded that it is still uncertain whether or not the higher levels of AVs will reach the "Slope of Enlightenment". Fundamental challenges with respect to human factors, technology, infrastructure, and legislation need to be addressed at the same time. The fact that automated driving can contribute to many societal goals increases the chance that this technology will become a success. However, based on the findings of this chapter it can also be concluded that they are not a "silver bullet" to create accessible and livable cities and regions. Therefore, it is recommended to focus on all travel modes including cycling and public transport and to invest in automation, connectivity, sharing, and electrification. A multimodal vision on future mobility systems along with quadruple helix stakeholder engagement will be needed to decide where and when to invest in different solutions.

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