Report on the Impacts of Vehicle Automation

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PBL Netherlands Environmental Assessment Agency

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1 Introduction

This report presents a review of the key impacts of vehicle automation on transport behavior, road capacity, and mobility innovations as reported in the literature. It intends to help prepare the models that will be applied to estimate the equilibrium between transport supply and demand in The Netherlands in future scenarios. Of particular interest are the years 2040 and 2060.

The report is based mostly on scientific literature in the field but it also includes so-called grey literature like reports and expert opinions. It departs from the knowledge that the Department of Transport & Planning had already collected recently and updates it with the most current body of literature that results from recent studies in the field.

The report is mostly focused on fully automated vehicles (AVs) (Level 5 SAE) since these are the most disruptive in the mobility and traffic system. Despite that, we will start the report by looking at the forecasted adoption of the different automation levels over the next years.

The report considers both connected automated vehicles (CAVs) and non-connected AVs due to the importance that connectivity can have in the transport systems' performance namely regarding road capacity. The Level of detail that the report dwells on is at a network Level since the knowledge here gathered is to support changes/improvements in the national transport model in The Netherlands. Elements like traffic intersections and special road design elements are considered to be too detailed and are depending on other constraints therefore they are deemed not useful for the discussion that is required.

An important reference and departure point for this report is the MANTRA[1] project funded by CEDR where a research team, including TU Delft, has worked on mapping the most important impacts of vehicle automation for operating national roads. But we also use all the literature that has been published and is publicly available online in the most recent years. As an important disclaimer, we must note, that it is still not possible to give a precise estimation of most of the effects mentioned in this report. There is still a great deal of uncertainty as it will be shown.

The report is structured in the following sections. It starts with a road map for the development and deployment of this technology. Then it presents the forecasting exercises on the adoption of vehicle automation. This is followed by new modes of transport in

[1] MANTRA – Making full use of Automation for National Transport and Road Authorities (mantra-research.eu)

passenger and freight transport that can emerge in the future. It continues with the impacts on road traffic capacity and traffic efficiency. The report ends with the most important impacts of vehicle automation on travel behavior in its many dimensions, among others: trip generation, accessibility, Value of Travel Time (VoTT), mode choice, and route choice.

2 Road map of technology development

2.1 Current situation

The current situation is that today hands-off eyes-off is possible and allowed on separate roads, and conditionally (called ALKS - automated lane keeping systems - SAE L3); Regulations exist in Germany and France for this. For ADS L4, implementation regulations exist, and experimental applications are all over the place. Rivium Park Shuttle in Rotterdam is one of the few that is a true service. Cruise and Waymo in the USA offer services, but very very limited so they could be called experimental still.

In Figure 1 it can be seen the current sales (2022) of L3 vehicles in Europe. The chart shows that this number is over 1M in 2022 and is predicted to be 3.5M in 2025.

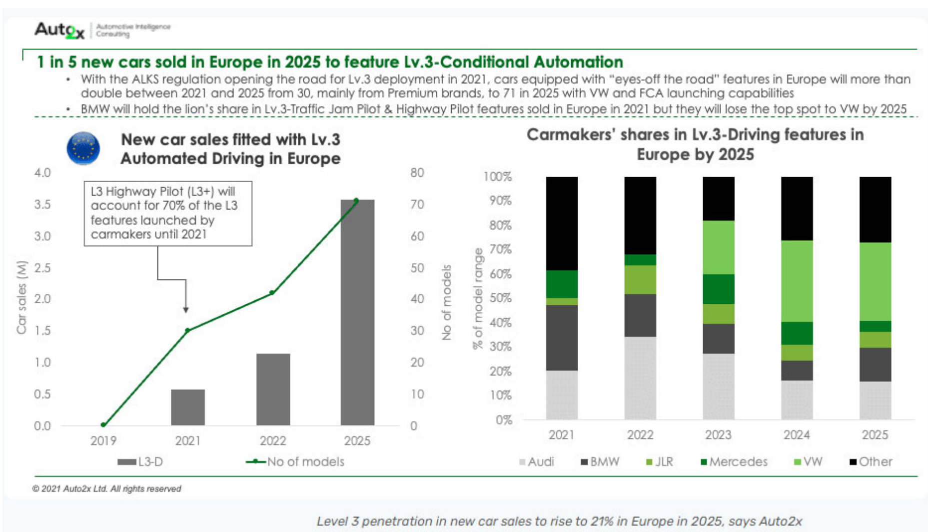

Figure 1: L3 Conditional Automation[2]

2.2 Roadmap

ERTRAC has one of the most comprehensive visions for what needs to happen in technology development and its implementation in this decade up until 2030 (ERTRAC, 2022). The

[2] Level 3 autonomous driving in Europe to reach 20% penetration in 2025, says Auto2x (auto2xtech.com)

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objective of the roadmap "is to provide a joint stakeholder view on the long-term development of Connected, Cooperative and Automated Mobility in Europe". The report has a vision for 2050 in terms of desired societal impacts but in the shorter term, there is the need to set up an agenda for 2030 with very concrete steps that need to be implemented that trigger an outlook to the year 2040.

The Agenda for 2030 is a near-term list of objectives for the development of separate domains offering a large variety of use cases. The outlook for 2040 envisions the use cases widening up and growing together. It delivers the use cases accompanied by the development of business models. It establishes the intermediate points between what is happening now and the long-term vision. According to ERTRAC the vision for 2050 is one where automation domains will be linked and transport modes are synchronized for the benefit of everyone.

They distinguish two many environments: the "highway automation" and the "low-speed automation" locations such as the urban and rural areas.

In what concerns highway automation ERTRAC expects "infrastructure Support for Automated Driving applications including further increasing ODD when it comes to weather conditions or quality of road surface as well as AI-based decision making in traffic interaction". Highways will be able to handle higher speeds in automation with corresponding physical and digital infrastructure. Dedicated lanes in space and time for buses and trucks will be established.

Low-speed use cases will further evolve and will be combined to face the traffic complexity challenges of urban environments. Delimited areas grow and merge into full urban autonomy services for passengers and freight. The market will increase for the different applications and as they merge geographically and technologically we are talking about a major category of AVs application that ERTRAC calls the low-speed automation scheme.

The following graphs (Figure 2 and Figure 3) represent a logical order of use cases, which will have their fully industrialized rollout for high market uptake with a focus in the 2030s on the two main approaches of high speed with limited complexity of traffic and lower speeds but covering the full traffic complexity.

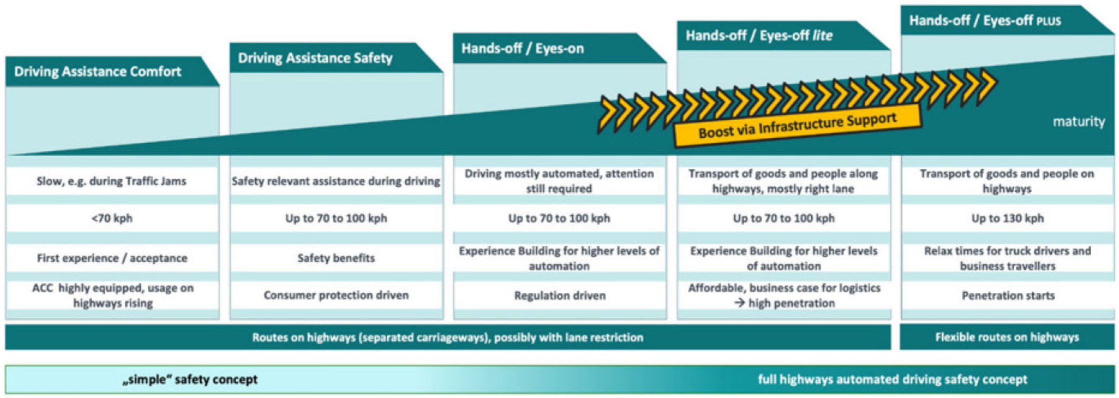

Figure 2 Outlook on highway automation. Source: (ERTRAC, 2022)

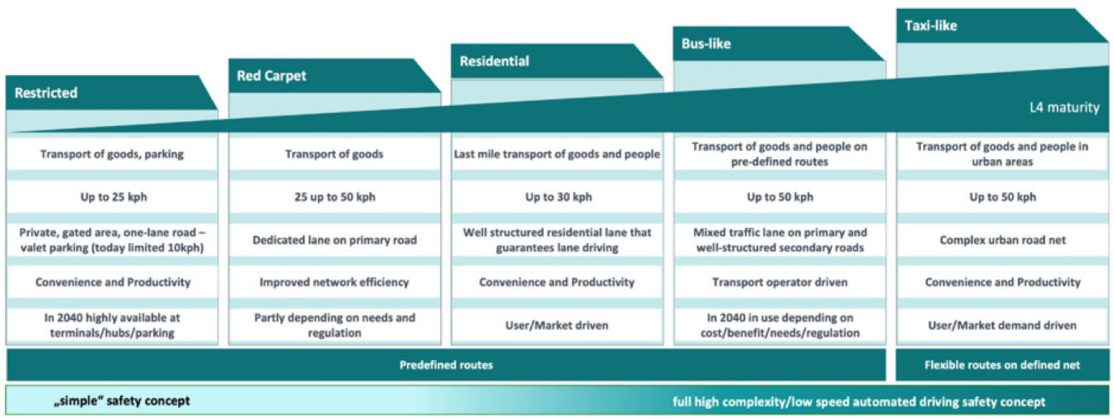

Figure 3 Outlook on low-speed automation. Source: (ERTRAC, 2022)

Beyond the use cases in the schemes above there will be other use cases coming up. Rural autonomy will expand on specific routes reaching out to more remote settlements. These are the most complex scenarios, where the high speed on rural roads including oncoming traffic will find only limited infrastructure support. It is expected that only with a high effort on specific measures to limit the complexity, the driverless operation will be available.

3 Adoption of automated vehicles

3.1 Thinking by analogy

Predicting the share of privately owned AVs in the fleet is an important research topic. Based on a literature review study, Calvert et al. (2017) expect a lengthy transitional period extending well into the 2030s where only low vehicle automation is present on a significant number of vehicles. Calvert et al. (2017) suggested that by 2035 the adoption of adaptive cruise control (ACC) and ACC with lane change assistance will be around 20%, and high automation will be below 10%. Instead, vehicle cooperation is expected to be above 35%. More positive predictions from a group of members of the IEEE stated that the share in 2040 will most probably reach 75% of the fleet ("IEEE News releases," 2012). Litman (2015) used deployment cycles, cost, and adoption rates of other automotive technologies to conclude that a 50% adoption will be the most likely scenario for 2050 and that a 75% figure will only be possible by 2060. Bierstedt et al. (2014) agree with this scenario however they refer that benefits such as a lower accident rate resistance may diminish with time. A move away from the vehicle ownership model to one 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 helped by the growth of carsharing systems (Jorge and Correia, 2013), which is leading to a decrease in vehicle ownership (Martin and Shaheen, 2010).

More recently Litman revised the topic of estimating the shares of AVs in a new report titled "Autonomous Vehicle Implementation Predictions: Implications for Transport Planning" (Litman, 2023). Litman states that "Optimistically, autonomous vehicles will be safe and reliable by 2025, and become commercially available in many areas by 2030. If they follow the pattern of previous vehicle technologies, during the 2030s and probably the 2040s, they will be expensive and limited in performance, sometimes unable to reach destinations or requiring human intervention when they encounter unexpected situations". He also predicts that by the same year of 2030 shared Automated vehicles (SAVs) will become widely available for a cheaper price, but he is quite skeptical about the added quality of such services, casting doubts about the waiting time and traffic congestion.

The following Table 1 summarizes the main findings according to the referred literature for each level of automation.

Table 1: Market penetration of the different levels of automation in papers or grey literature published until 2023. Adapted and extended from: (Nieuwenhuijsen et al., 2018)

	Range	
Market penetration Level 1	0–10% in 2000 10–20% in 2015	(Kyriakidis et al., 2015; Shladover, 2000, p. 19)
Market penetration Level 2	0–5% in 2015	(Kyriakidis et al., 2015)
Market penetration Level 3	Average of three scenarios: 8% in 2030	(McKinsey, 2023)
Market penetration Level 4	Introduction in 2018–2024 Highway and some urban streets before 2030 Average of three scenarios: 4% in 2030	(Shladover, 2015) (McKinsey, 2023)

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Market penetration Level 5	Market introduction between Market introduction: 2030 18% in 2040 43% in 2060 90% in 2080 No L5 vehicles in 2030.	(Milakis et al., 2017), (Bierstedt et al., 2014), (Litman, 2015) (Litman, 2023) becomes more pessimistic. (McKinsey, 2023)

The latest fleet composition estimations by Litman can be seen in the following chart:

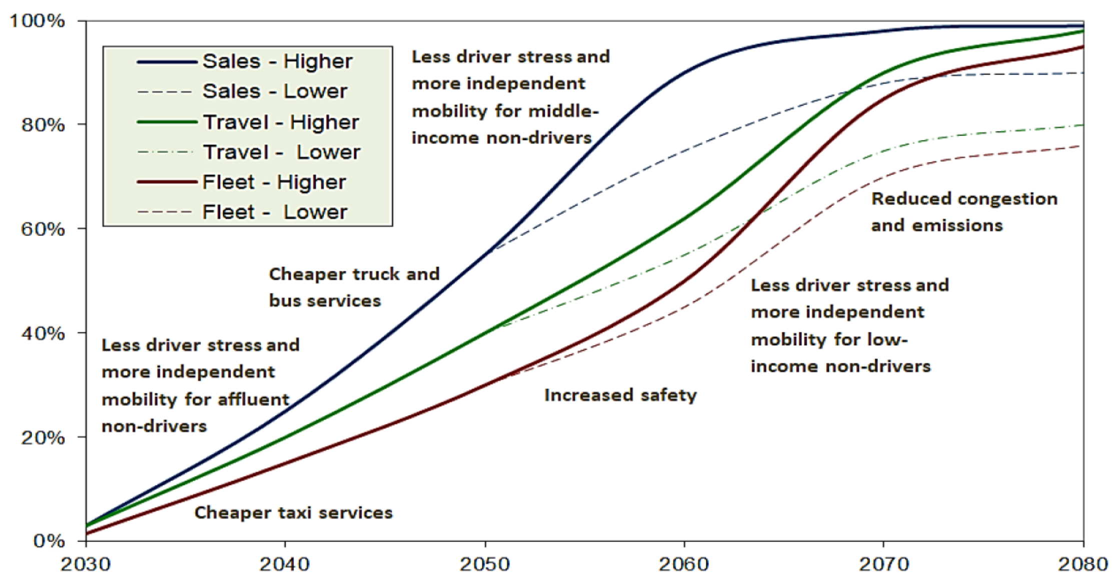

Figure 4: Forecast for sales, amount of travel, and fleet according to (Litman, 2023)

The McKinsey Center for future mobility produced the results that can be seen in Figure 4, in there one can see the uncertainty that pertains to the question of predicting the fleet sizes. One aspect that is highlighted in the chart is the uncertainty around the highest levels of automation that they considered to be feasible until 2035: Level 3 and Level 4. The percentage in 2030 varies from 4% (delayed scenario) to 57% (accelerated case).

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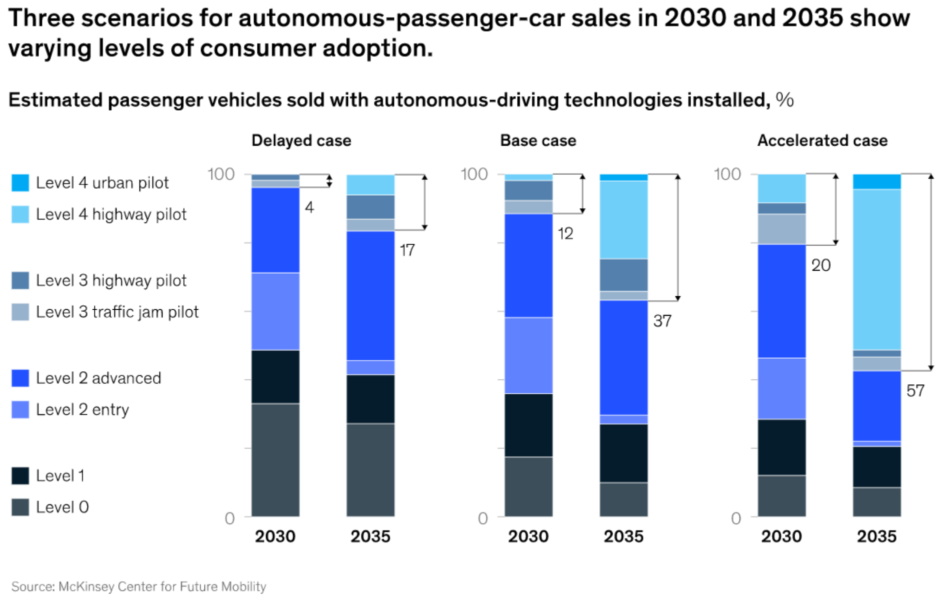

Figure 5: Scenarios for autonomous vehicles sales 2030 and 2035

Despite their value as a measure of what travelers are expecting from the transportation systems it is important to state that an estimation of the future car fleet has to be done as much as possible independently of stated preferences and forecasting done by the consumers because these can be highly biased. The expert opinion helps but it may be biased as well.

Moreover thinking by analogy regarding other types of technology adoption in the past can contribute to understanding the sources of uncertainty around the market development for automated vehicles, however, this is a very specific technology that crosscuts travelers' behavior, available technology, and political support, therefore, it makes it an extra challenging system for predictions.

None of these studies have captured the complexity of different interacting factors on market penetration using quantitative methods. A framework that can capture the different aspects of the system unambiguously and relates these aspects to each other is needed.

3.2 System Dynamics approach

Nieuwenhuijsen et al. (2018) applied System Dynamics (SD) to explore the diffusion of AVs accounting for the complexity of several relevant interrelated components. In the current literature, simulation studies, and field tests are combined to form an extensive amount of data on the possible effects of AVs. However, these data are mostly focused on the effects on traffic and not so much on other types of impacts, such as the effect on ownership. Despite a relative lack of information on how this complex system should behave the authors argue that there are enough indicators available on some of the different model components of this system that can be used to quantify some key relations within the framework.

When lacking direct data, an alternative similar system may be observed and tentative relationships may be extracted to fill in the gaps. This work is not supposed to be a closed and final model of how this technology will evolve. It was the first tentative on shaping the complex system, formed between society and companies, that leads to vehicle automation development. Later, it will be possible to change some of these parameters or relationships according to more knowledge that is being gathered year by year, therefore the contribution of this model is mostly done on the discussion of the modeling framework with a critical perspective and some initial conclusions on the model application to the Dutch case-study under different scenarios. The causal loop diagram of the system complexity can be seen in Figure 6.

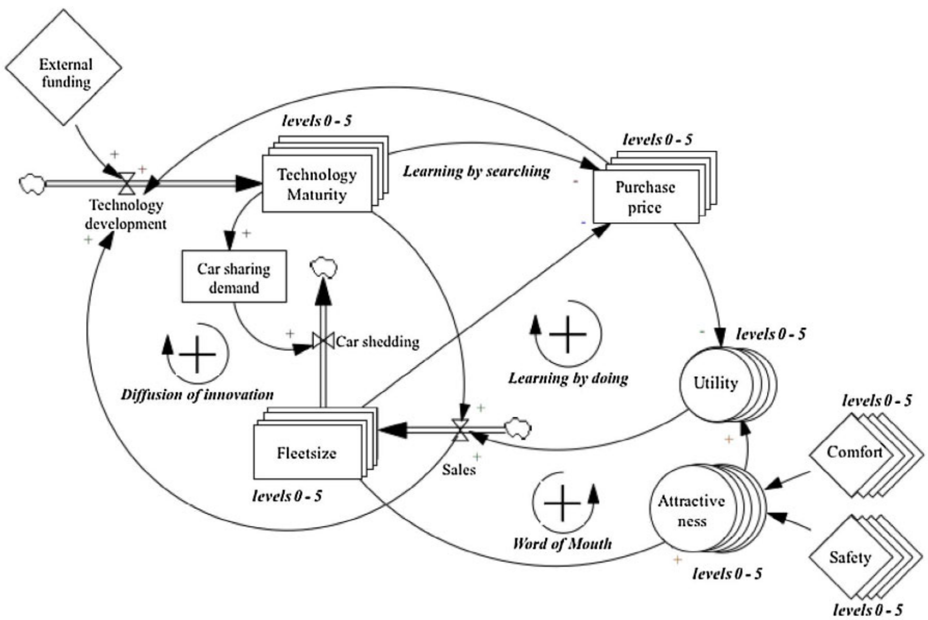

Figure 6: System Dynamics model for the diffusion of levels of automation. Source: (Nieuwenhuijsen et al., 2018)

The share of vehicles at each Level for an optimistic scenario (so-called AV in Bloom) is what can be seen next in Figure 7. In this figure, it's possible to see that Level 4 and Level 5 automation should already have picked up traction in the past decade which is not the reality. Despite Tesla saying that they are almost there, full vehicle automation continues not to be available. In this figure, it can also be seen Level 3 vehicles being 50% of the fleet in 2025. That is also not expectable on Dutch roads.

According to this scenario, in 2030, the Level 4 and Level 5 vehicles would represent a percentage of 15% each. In 2040 Level 5 would pick up and represent about 40% of the vehicle fleet. In 2050 Level 5 AVs would reach 60% and in 2060, 75%. From 2050 until 2060 Level 4 starts to fade away given the take-up of more advanced technology with the Level 5 vehicles. According to this simulation only in 2100 can we expect a fleet of Level 5 that is closer to 100%.

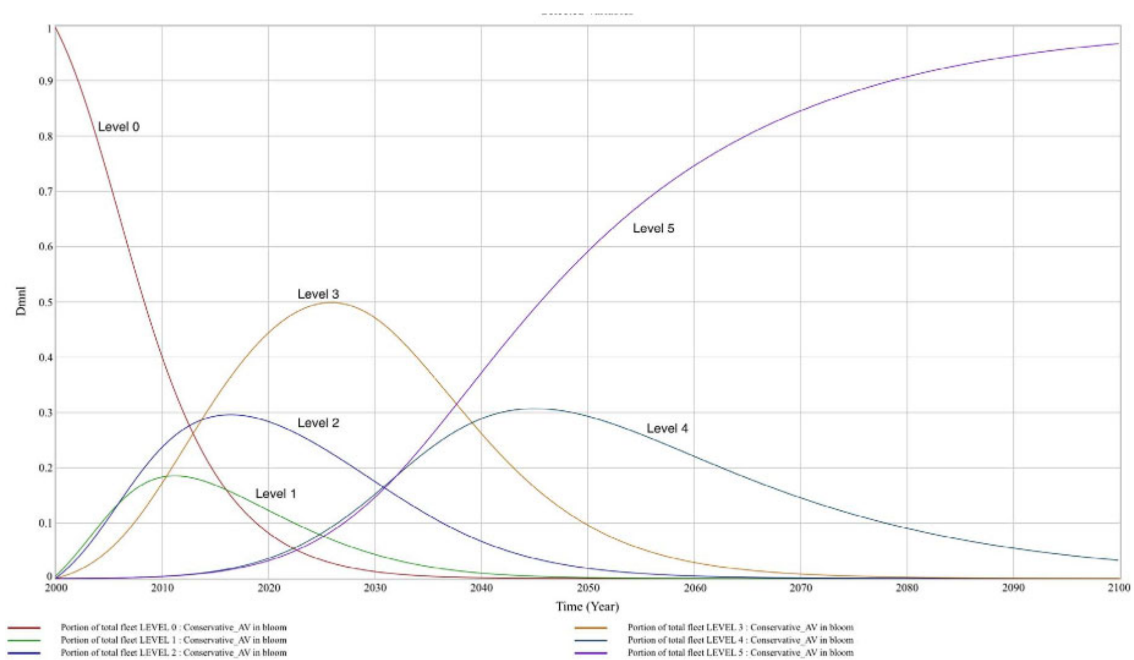

Figure 7: Market penetration of AVs in Bloom scenario. Source: (Nieuwenhuijsen et al., 2018)

In a more pessimistic scenario (AVs in doubt), we have a different reality. It's only in 2030 and 2040 that a small share of AVs starts becoming part of the car fleet. The slope of the growth of these vehicles is very small. This is probably a bit too pessimistic if we look at what Tesla and other companies are doing, e.g., Waymo with their shared AVs. Under this scenario, half of the vehicles in 2030 will be Level 2 vehicles and Level 3 will account for 20% of the fleet.

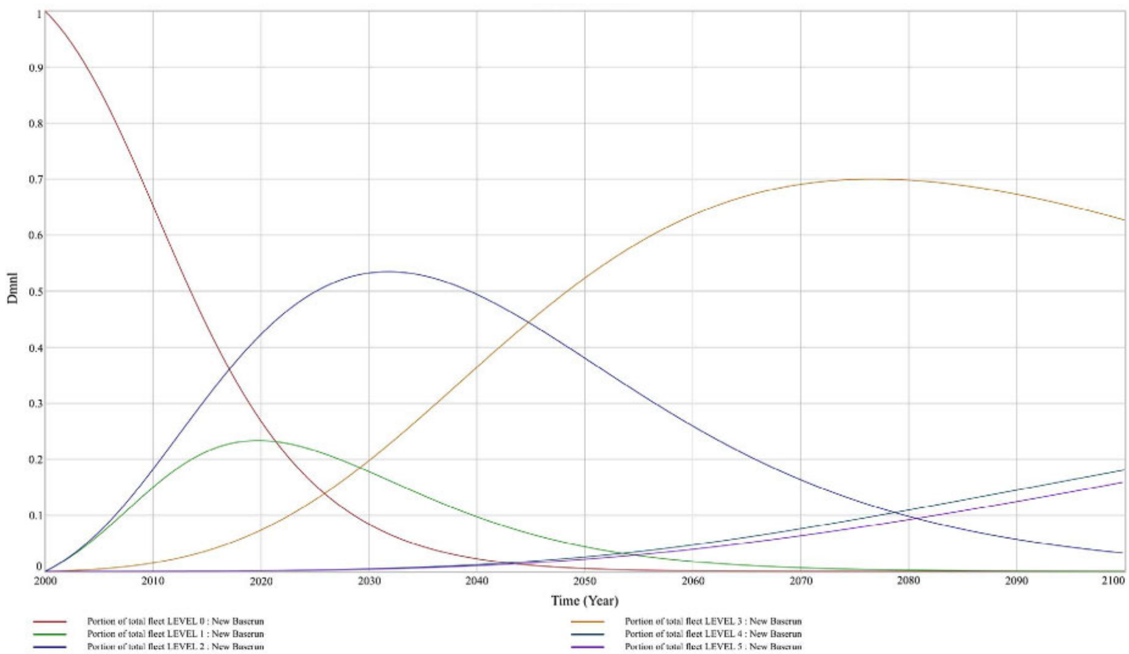

Figure 8: Market penetration with the pessimistic scenario of Avs in doubt. Source: (Nieuwenhuijsen et al., 2018)

The reality will very likley lie between these two scenarios. For convenience, and having in mind all disclaimers about how difficult is to do these predictions, we present these results in a table:

Table 2: Estimation of penetration of the different levels of automation. Source: built with data from (Nieuwenhuijsen et al., 2018)

	2030	2040	2050	2060	(…)	2100
Range on the share of Level 0	[2%, 8%]	[0%, 3%]	[0%, 0.5%]	0%	(…)	0%
Average of Level 0	5.0%	1.5%	0.25%	0.0%	(…)	0.0%
Range on the share of Level 1	[5%, 18%]	[2%, 19%]	[0%, 4.5%]	[0%, 2%]	(…)	0%

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	2030	2040	2050	2060	(...)	2100
Average of Level 1						0.0%
Range on the share of Level 2	[18%, 53%]	[7%, 50%]	[2%, 38%]	[3% ,26%]	(...)	[0%, 4%]
Average of Level 2	35.5%	38.0%	20.0%	14.5%	(...)	2.0%
Range on the share of Level 3	[20%, 48%]	[26%, 36%]	[10%, 52%]	[3%, 64%]	(...)	[0%, 63%]
Average of Level 3	34.0%	31.0%	31.0%	33.5%	(...)	31.5%
Range on the share of Level 4	[1%, 15%]	[1.5%, 30%]	[3%, 30%]	[5%, 22%]	(...)	[4%, 19%]
Average of Level 4	8.0%	15.8%	16.5%	13.5%	(...)	11.5%
Range on the share of Level 5	[1%, 15%]	[1.5%, 38%]	[3%, 60%]	[5%, 74%]	(...)	[19%,96%]
Average of Level 5	8.0%	19.8%	31.5%	39.5%	(...)	57.5%

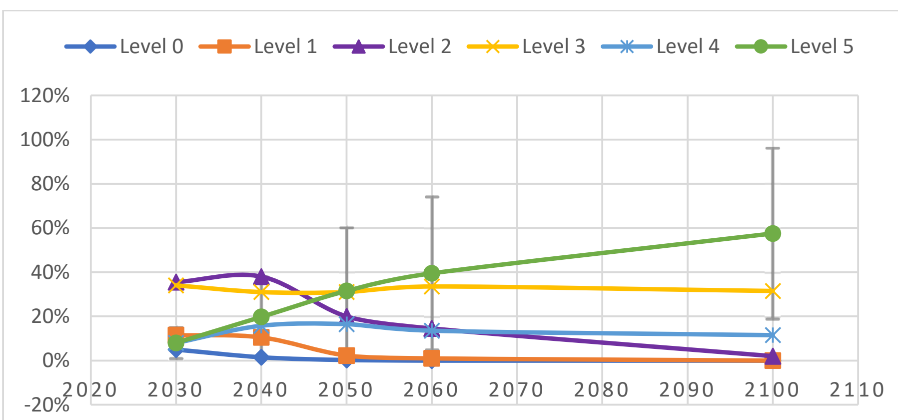

Figure 9: Estimation of mean market penetration of the different levels of automation and error for Level 5. Source: based on data from (Nieuwenhuijsen et al., 2018)

The general trend, independently of the more optimistic or pessimistic scenario, is one of rise and fall of the intermediate levels of automation as the technology matures. In a network modeling study where the authors model the adoption of the vehicles as a function of their performance on the network as well as the tech maturity it was concluded that “market penetration of CAVs at the early stage of introduction is low due to the high purchase cost. With the development of CAV technology and mass production, fully automated CAVs may gradually dominate the market, while partially automated CAVs tend to be squeezed out of the market” (Xie and Liu, 2022).

4 Impacts on creating new transport modes

4.1 Passenger transport

4.1.1 Automated modular transit systems

In addition to the automation of existing passenger transport modes, the most impactful new transport mode envisioned to be enabled by automation is modular transit (see Figure 10 for an example). A modular transit system includes a certain number of trailer modules that can attach to a main module for long-distance trips (the main leg of a tour) or detach to serve short-distance trips (first/last mile) (Zhang et al., 2020). Autonomous modular vehicle technologies offer increased flexibility to public transit systems, which can reduce passenger wait time, in-vehicle time, and walking time, increase vehicle utilization, and mitigate common bus operation issues such as bus bunching (Khan et al., 2023).

Khan et al. (2023) utilize a discrete macroscopic simulation framework that copes with passenger arrivals, departures, boardings, and lightning in a n aggregate manner, to estimate the magnitude of reduction in average transit travel time using a bus-splitting strategy via modular buses to be 18-37%. Using a mathematical model that measures the performance of a modular transit system that offers door-to-door service and enables en-route transfers between trailer modules, (Zhang et al., 2020) conclude that this system can significantly improve service rate (up to 25%) as well as vehicle occupancy rate. It should be noted that many operational decisions and trade-offs are involved with designing modular transit systems. Increasing the number of modules can improve passenger service rate and the number of riders; however, this leads to higher travel distance and lower occupancy rates (Zhang et al., 2020). Considering similar operating assumptions and using a mathematical programming model, (Tang et al., 2023) report an estimated 11% reduction in passenger waiting time, 23% reduction in in-vehicle time, 40% reduction in walking time, and a 100% increase in operational cost of modular transit systems.

The above-mentioned findings imply that a well-designed modular transit system can affect travel mode choice by attracting more travelers from other modes due to its higher service rate and geographical coverage. However, it will be significantly more costly than a regular bus system (with or without drivers). The results reported from the literature regarding the magnitude of modular transit systems' impacts must be treated with caution as the technology is at its early stages, and fully operational cases of such systems have not been observed in practice yet. Moreover, there are safety concerns regarding passenger transfers inside a moving module as well as operational concerns concerning modules being able to attach and detach in congestion. All these issues must be resolved before a modular transit system can become operational and deliver the expected benefits.

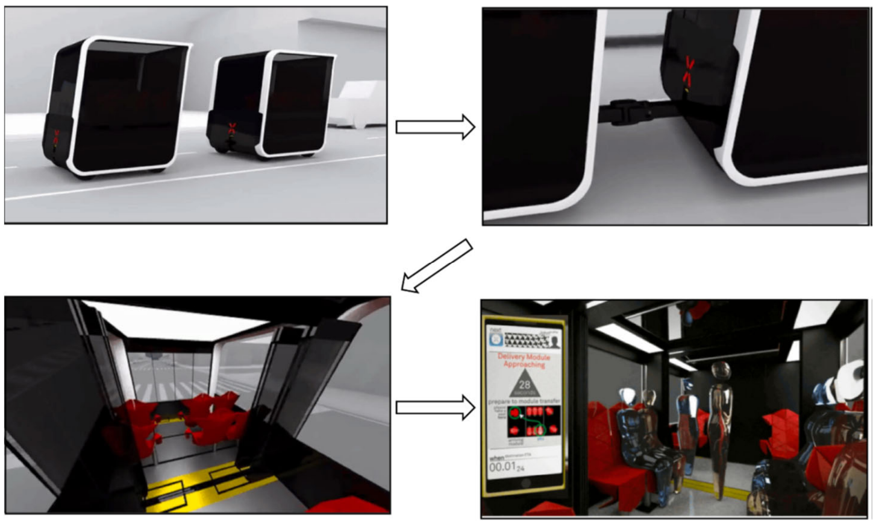

Figure 10 Passengers transfer between coupled modular buses in motion (Sources: https://www.next-future-mobility.com)

4.1.2 Automated micro-vehicles in passenger transport

Another new transport mode that is expected to be enabled by vehicle automation is autonomous micro-vehicles. There are different types of micro-vehicles with applications in passenger transport and in logistics. We will discuss passenger transport here and logistics application in the next section.

A micro-passenger-vehicle or a micro car is usually less than three meters in length, lightweight, and usually with one or two seat(s) and one or two doors. Simulation studies have shown that manually-driven micro-cars can reduce emissions by increasing the traffic throughput if their speed is close to the average speed of other vehicles and vice versa (Mu and Yamamoto, 2013a, 2013b). Regarding autonomous micro-cars, (Tanveer et al., 2022) utilize a microscopic simulation framework and conclude that using these vehicles alongside autonomous (regular-size) vehicles can lead to a reduction in congestion and an increase in traffic throughput (by up to 18%). These improvements can be amplified when the average vehicle occupancy is less than two (i.e., low-occupancy regular-size vehicles are replaced by micro-vehicles) and when the flow penetration rate of micro-vehicles increases.

4.2 Freight transport

When it comes to AVs in road freight transport, the main expected benefits are a reduction in the number of crashes by enhancing general safety and reducing the number of accidents related to driver distractions, improving the driver shortage situation in the trucking industry by reducing driving stress and long driving hours, improving driver health by allowing more rests, improving fuel economy, reducing the parking space requirements by eliminating the rest-related parking, and more flexible hours of service in logistics operations (Shahandashti et al., 2019). However, there are many possible applications and use cases, each with specific requirements, costs, and benefits in its own right, particularly within the context of CAVs (rather than just AVs without connectivity). Table 3 and Table 3 summarize some connected and automated truck technology applications and their estimated costs according to (Slowik and Sharpe, 2018). We will discuss some of the key use cases and applications below.

4.2.1 Truck platooning

A platoon is a group of vehicles traveling very close to each other and connected via cooperative adaptive cruise control (CACC) to accelerate, decelerate and cruise together (Sivanandham and Gajanand, 2020). The first vehicle is typically referred to as the leader and the rest of the vehicles are called the followers or platooned vehicles. There are many possible scenarios for platooning implementation, which will be discussed below, and each scenario has slightly different requirements and benefits. But regardless of the implementation scenario, the main benefit of platooning is fuel efficiency due to the reduction of air drag, particularly for the following vehicles. Closer gaps between the vehicles lead to higher fuel economy but they also demand higher communication reliability for safety reasons. Although there are studies that conclude that platooning can improve road safety as well and increase road capacity via reduced spacing between the vehicles, other studies argue that a platoon of trucks can cause safety issues such as within-fleet collisions and cut-in situations (when other vehicles change lanes to cross the platoon), especially for merging and diverging maneuvers (Axelsson, 2017).

It is crucial to remember that platooning does not necessarily require automation, but its benefits are amplified with AVs. When it comes to human involvement and the type of vehicles in platoons, there are three main types of platooning, namely, human-driven platoons, driverless platoons, and hybrid platoons (Bhoopalam et al., 2018). The first two categories are self-explanatory. The third category, namely hybrid platoons, could involve different combinations of human-driven vehicles (HVs) and AVs. The benefits from the reduced air drag do not depend on the platoon type. However, the lead vehicle can affect the fuel economy of all vehicles in the platoon due to the driving style (e.g., eco-driving) since all vehicles in the platoon accelerate and decelerate together. Regarding the labor cost, clearly, driverless platoons are the most cost-effective ones and human-driven platoons are the least cost-effective. Hybrid platoons fall between the two categories and can be closer to driverless or human-driven in terms of labor cost savings depending on the composition of the platoon.

When it comes to the planning aspect of platooning, there are two main types of platooning, namely, scheduled platooning (with fixed or flexible routes), and real-time or dynamic platoon planning (Bhoopalam et al., 2018). In most situations, there is a trade-off between possibly adjusting the departure time or taking a longer route to join a platoon and the fuel efficiency of traveling with a platoon as well as the possibility of resting (in the case of human-driven trucks). Therefore, platooning can affect the departure time and route choice of trucks. Another important aspect of platoon planning is the combination of platooning with vehicle routing. When all vehicles belong to the same fleet or company, platoon planning can be combined with vehicle routing to simultaneously optimize departure time and route choices of all vehicles to optimize for desired criteria (e.g., minimum fuel consumption) while satisfying the operational and demand constraints. However, when several truck operators are involved, the problem gets more complicated and some cooperation among different operators is required to take advantage of the efficiency of platooning. In addition, depending on the connectivity technology used for platooning, vehicles produced by some Original Equipment Manufacturers (OEMs) are not compatible with others.

As mentioned before, the main benefit of platooning is fuel saving but the exact amount of fuel reduction depends on many factors. The amount of savings reported in the literature based on real-world testing and test tracks range between 2.8% and 22% for the platooned vehicles and 0% to 10% for the lead vehicle (Slowik and Sharpe, 2018). Table 5 provides a summary recounted in (Slowik and Sharpe, 2018) that shows the wide range of fuel savings due to platooning reported in the literature.

Since the costs and benefits of truck platooning depend on the implementation scenario, which is defined by all the factors mentioned above, it is crucial to distinguish between the different scenarios and their respective costs and benefits when considering platooning in modeling and impact analysis studies.

4.2.2 Teleoperated driving

Teleoperated or remote driving is a technology that can complement connected and automated driving by enabling the remote operation of partially automated vehicles outside their operational design domain and being a fallback option for Level 4 and Level 5 AVs in edge cases such as extreme weather conditions and road closures (Majstorović et al., 2022). Teleoperated driving refers to a system where a human or robot operates a vehicle from a distance (usually a control center) using a teleoperation interface and a communication link (Neumeier et al., 2018). Teleoperation can include remote driving, remote assistance, and remote monitoring of CAVs operations.

A large fleet of vehicles of different automation levels can be teleoperated using a small number of teleoperators (d'Orey et al., 2016). This could include remote monitoring of Level 5 AVs, remote assistance to highly and partially automated vehicles, and remote driving of vehicles with automation levels. This flexibility as well as potential labor cost savings makes teleoperation a viable option for complementing automated road freight transport and other commercial applications of AVs such as automated taxi fleets. It is worth noticing that one of the main barriers to the deployment of AVs in logistics operations is the fact that currently, drivers have other responsibilities in addition to driving such as monitoring the vehicle and the load, dealing with documentation, checking in and out in ports and terminals, etc. Most of those tasks can be efficiently handled by a teleoperator given the proper interface in the vehicle and communication link, which are current research topics. Moreover, teleoperation can complement truck platooning in all its possible scenarios (remote driving in the case of human-driven platoons and remote monitoring in the case of self-driving platoons). Therefore, future scenarios including teleoperation are likely to be relevant for many commercial applications of automated driving with the most prominent ones being automated trucking and automated taxi fleets.

The main benefits of teleoperated driving in logistics operations are remotely involving humans to manage specific tasks that are very difficult to automate, extra fall back for safety in edge cases, and lower labor costs. According to d'Orey et al. (2016), teleoperation can revolutionize taxi operations and urban mobility by offering a cost-effective door-to-door service. Currently, several European projects (e.g., 5G-Blueprint) are working on technological and operational solutions for the deployment of teleoperation with a focus on applications in logistics operations due to the promise of being cost-effective. The exact extent of cost savings due to teleoperation is dependent on the configuration of the fleet and the control center (vehicle-to-teleoperator ratio, composition of vehicles with different automation levels, teleoperation service level, take over time, etc.).

4.2.3 Automated micro-vehicles in logistics

Although automated/autonomous micro-vehicles with logistics applications are not expected to have a significant direct impact on road traffic, they might affect traffic volumes by reducing the number of road freight transport vehicles due to taking over some city logistics applications. Therefore, we briefly mention them here.

Currently, there are many different types of automated/autonomous micro-vehicles with logistics applications under testing and development. (Baum et al., 2019) studied 39 different types of automated micro-vehicles with applications in food/grocery delivery, post/parcel delivery, maintenance services, spare parts supply, and mobile sales rooms. These vehicles can operate on roads (e.g., maintenance micro-vehicles), footpaths (e.g., last-mile parcel delivery vehicles), or on dedicated infrastructure (e.g., rail roads and magnetic strips in ports, terminals, and factory yards). Regarding the human involvement level, they can be fully autonomous or remotely operate/supervised.

The success rate and the extent to which these vehicles can become mainstream is difficult to predict at the moment. What can be said at this point in time is that the main driver behind the development of such applications is profitability and the existence of promising business models, which appears to favor last-mile delivery solutions. According to (Baum et al., 2019), delivery robots are likely to be the most prevailing form of micro-vehicles and hit the market first.

Table 3 Examples of automated and connected vehicle technology applications in on-road heavy-duty trucking (Slowik and Sharpe, 2018)

Technology applications	Technologies used	Description	Commercially available?	Example companies
Lane departure warning	Sensors such as cameras, processing software	These systems send an audible or haptic warning to drivers when there is risk of the vehicle unintentionally drifting outside of the lane. This technology is considered Level 0 because it does nothing more than alert a driver. (National Academies of Sciences, Engineering, and Medicine, 2017).	Yes	Mobiley, Meritor Wabco
Blind spot detection	Sensors such as cameras and radar, processing software	Blind spot detection devices can detect if other vehicles are located in the driver's blind spots and notify the driver. The alerts can be audible, haptic, or visual. Like lane departure warnings, blind spot detection alerts are considered Level	Yes	Mobileye, Meritor Wabco, Volvo

Automatic braking	Sensors such as cameras and radar, processing software	Automatic braking systems can detect the speed and distance of vehicles ahead of them and automatically apply the brakes if needed. This technology is considered Level 0 because the feature provides momentary intervention and is not sustained.	Yes	Scania, DAF, Daimler, Meritor Wabco, Volvo, Bendix
Automated manual transmissions (AMT)	Electronic control unit, hydraulics, software	Automated manual transmissions control the operation of the clutch and gear selection automatically, based on information gathered from vehicle sensors. AMTs are an enabling technology and are generally required on all Level 1+ autonomous trucks.	Yes	Eaton, Volvo, Daimler
Eco driving systems	On-board diagnostics, monitoring and processing software, telematics	A system that monitors human driving and provides real-time advice and feedback for drivers to achieve greater fuel performance, for example by moderating highway speed and by smoothing acceleration and braking.	Yes	TomTom, Ruptela, SmartDrive
Automated lane keeping	Sensors such as cameras or radar, processing software	These systems monitor the vehicle placement within road lane markings. If the vehicle is departing the lane, the system corrects the lateral direction automatically. The technology is considered Level 1.	Yes	Scani, Merito r Wabc o
Adaptive cruise control (ACC)	Sensors such as radar, processing software	Adaptive cruise control adjusts vehicle speed, controlling throttle and braking, based on the speed of the vehicle in front of it in order to maintain a set distance. ACC technology is considered Level 1.	Yes	Meritor Wabco, DAF, Volvo, Bendix
Predictive cruise control (PCC)	GPS, topographical mapping data, processing software	Predictive cruise control combines cruise control with GPS and topographical data inputs, altering vehicle speed to optimize performance over various types of terrain. PCC technology provides maximum benefits in conditions with rolling hills. The technology is considered Level 1. PCC and ACC can be active simultaneously or the functions could be offered separately.	Yes	Kenwort, DAF
Platooning	Sensors such as radar, processing software, could also include vehicle communications using DSRC	Platooning is when groups of vehicles travel close together to minimize aerodynamic drag. Truck platooning typically includes sets of two or three trucks paired together using sensor and communication technologies. At basic levels, ACC alone (Level 1) could enable truck platooning. More advanced platooning technology controls for both longitudinal (ACC) and lateral (automated lane keeping) movements and	Yes (Level 1), Level 2 systems are pre-commercial	Peloton, Volvo, Uber ATG, Daimler

		is considered Level 2.		
Highly automated trucking	Will likely include cameras, radar, LiDAR, DSRC, processing software.	Highly automated trucks will be capable of operating autonomously without human intervention in limited environments such as dedicated areas or highway lanes. Highly automated trucks (Level 4+) are not commercially available for on-road applications today, but there are a few examples of their use in mining and farming operations.	No	Daimler, Uber ATG
Telematics	GPS, DSRC, or other wireless communications technology, asset management software	Telematics systems combine telecommunications and informatics, which is the collection, classification, storage, retrieval, and dissemination of information. Telematics equip fleet managers with valuable real-time data such as vehicle location, speed, service needs, weather, road conditions, and driver performance. Telematics are expected to complement connected and autonomous vehicles, for example by enabling the transmission and processing of communications data from nearby vehicles, or by facilitating identifying opportunities to link vehicles to form a platoon.	Yes	Zonar, Geotab, Openmatics

Table 4 Estimated costs for examples of autonomous and connected truck technologies and technology applications (Slowik and Sharpe, 2018)

Study or reference	Technology or application	Technology description	Cost	Time frame	Notes
Waymo (2017)	LiDAR	Considered the most robust sensing technology for processing images.	$75,000	"A few years ago" (unspecified)	$75,000 "top-of-the-range" LiDAR units by 90%.
			$7,500	2017	
Nordrum, A. (2016)	DSRC modules	V2V communications hardware.	$100 to $200	Around 2016	Cost estimates are for DSRC module made by NXP.
Harding et al. (2014)	V2V communications	V2V communications equipment and functions.	$341 to $350	2020	NHTSA estimates the cost of V2V equipment and communications functions for light-duty vehicles. The technologies include DSRC transmitter/receiver, DSRC antenna, electronic control unit, GPS, GPS antenna, wiring, and displays.
U.S. Environmental Protection	Automated manual	A transmission that facilitates truck shifting by utilizing a computer and	$5,100	2013	EPA and NHTSA estimate the cost of automated manual transmissions for medium- and heavy-duty vehicles and
			$3,750	2018	

Agency [EPA] and NHTSA (2016a)	transmission	eliminating the manual shifter and clutch.			report the values in 2013 dollars.
National Academies of Sciences, Engineering, and Medicine (2017)	Blind spot detection system	A system of sensors that identifies vehicles in the driver's blind spots and provides a warning.	$250 to $850	Available today	Cost estimates are for aftermarket system cost.
National Academies of Sciences, Engineering, and Medicine (2017), Mobileye (2017a)	Mobileye Advanced Driver Assistance System	Driver assistance through collision avoidance intelligent vision sensor technologies.	$850 with $150 installation	Available today	A driver alert safety package that offers a variety of alerts and driver assistance features including forward collision warning, lane departure warning, headway monitoring and warning, pedestrian and cyclist warning, intelligent high beam control, turn signal reminder, and low visibility indicator.
Meritor Wabco (2017, n.d.)	Meritor Wabco OnGuard Active	Radar-based sensor system identifies potential collisions and sends warning notifications to drivers.	Not disclosed	Available today	The collision mitigation system also includes adaptive cruise control and active braking applications. More than 120,000 OnGuard collision mitigation systems have been sold in North America and are being used by more than 200 fleets.
DOT (2014)	Adaptive cruise control	Vehicle technology to dynamically control longitudinal movement and maintain consistent following distance.	$3,000	Around 2006	Cost estimates not explicit to heavy-duty vehicles. Assumed to include sensing technologies (cameras, radar) and processing software.
			$2,000	Around 2014	
International Council on Clean Transportation (ICCT, 2017)	Predictive cruise control	A technology that alters vehicle speed to optimize performance over various types of terrain based on GPS and topographical data.	$760	2030	The study reports the estimated 2030 vehicle technology costs and reports the values in 2015 dollars.
EPA and NHTSA (2016)	Predictive cruise control	A technology that alters vehicle speed to optimize performance over various types of terrain based on GPS and topographical data.	$953	2018	
			$766	2027	
Daimler AG (2015)	Predictive cruise control	A technology that alters vehicle speed to optimize	$1,300 with installation (€1,500)	2015	Cost estimate indicates the advertised cost (excluding VAT) in Germany to purchase and install the retrofit technology. Based on typical mileage

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					of 81,000 miles/ year, the technology payback period from fuel savings (up to 5%) is advertised as less than 1 year.
American Trucking Associations Technology and Maintenance Council (2015)	Adaptive cruise control and lane keeping assist	Vehicle technologies for longitudinal and lateral controls.	$3,000	Available today (in light-duty vehicles)	
Janssen, Zwijnenberg, Blankes, & Kruijff (2015)	Platooning	Technology that enables vehicles to travel close together to minimize aerodynamic drag.	About $11,900 per truck (€10,000)	2015	
NACFE (2016)	Platooning	Technology that enables vehicles to travel close together to minimize aerodynamic drag.	$1,500 – $2,000 per truck	2016	to enable two- truck platooning, based on industry interviews from unnamed fleet manager and technology developer.
Roland Berger (2016)	Level 1	Incremental technology costs (above Level 0) for Level 1 to Level 5 truck automation.	$1,800	Unspecified	
	Level 2		$6,900		
	Level 3		$13,100		
	Level 4		$19,000		
	Level 5		$23,400		

Table 5 Fuel savings demonstrated in example truck platooning projects (Slowik and Sharpe, 2018)

Source	Lead vehicle	Platooned vehicle(s)	Team	Study method	Technologies used	Description
Auburn University (2017)	0.4% to 5.3%	8.6% to 10.2%	4.5% to 7%	Evaluated using "SAE Type II FE test" at TRC Ohio	Radar, DSRC-based V2V communications, satellite positioning, actuation for vehicle controls, and human-machine interfaces	Testing of one platooned and one lead truck at following distances from 30 to 150 feet at 65 mph. Tests were conducted at the Auburn test track using Peterbilt 579 tractors with 53-foot trailers using Peloton's truck platooning system. Because longitudinal movement is automated, and drivers were responsible for steering, the technology is considered Level 1.
Peloton Technology (2017)	4.5%	10%	7%	Real-world testing	DSRC V2V communications, radar collision mitigation	Testing of one platooned and one lead truck at a following distance of 36 feet.

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					system, front	
Lammert, Duran, Diez, Burton, & Nicholson (2014)	2.7% to 5.3%	2.8% to 9.7%	3.7% to 6.4%	Evaluated on test track	Radar, DSRC V2V communications, vehicle braking and torque control interface, cameras, driver displays	Testing of one platooned and one lead Peterbilt Class 8 tractor-trailers vehicles at the Continental Tire Proving Ground test track in Texas. Conducted with varying speeds, following distances, and vehicle weights.
Safe Road Trains for the Environment Project (SARTRE, 2014)	2% to 8%	8% to 13%	Not reported	Evaluated on test track	Camera, radar, and laser to support adaptive cruise control, V2V communications	Testing of one platooned and one lead Volvo FH12 rigid truck at the IDIADA test track in Spain at following distances of 16 to 82 feet (5 to 25 meters) at 53 mph (85 km/h).
NACFE (2013)	4.5%	10%	Not reported	Real-world testing on I-80	Radar	Testing of one platooned and one lead Peterbilt 386s model year 2011 tractor trailers in Salt Lake City, Utah. Conducted at 64 mph with 36-foot following distance using Peloton platooning technology. Vehicles were fully loaded.
Tsugawa (2013)	0% to 9%	12% to 22%	9% to 15%	Evaluated on test track	Radar, laser scanner, adaptive cruise control, V2V communications	Testing of two platooned trucks and one lead truck at the AIST test track in Japan traveling 50 mph (80 km/h) at distances from about 15 to 65 feet (4.7 to 20 meters). Vehicles were unloaded.
Browand, McArthur, and Radovich (2004)	5% to 10%	10% to 12%	8% to 11%	Evaluated on test track	Electronic longitudinal control system	Testing of one platooned and one lead Freightliner 2001 Century Class tractor- trailers at the Crows Landing runway in California. Conducted with varying speeds and following distances, and the trucks were empty.
Bonnet and Fritz (2000)	3% to 9%	9% to 21%	Not reported	Evaluated on test track	Electronic tow bar	Testing of one platooned and one lead Mercedes-Benz ACTROS semi-trailer trucks at the Papenburg test track in Germany. Conducted at 37 mph and 50 mph (60 km/h and 80 km/h) with following distances from about 15 to 53 feet (4.5 to 16 meters). Vehicles were partially loaded.
	2% to 6%	13% to 17%	Not reported	Simulation	Simulation	Simulation to extrapolate potential fuel savings at 50 mph (80 km/h) when trucks are fully loaded and weigh up to 40 tons.

NACFE (2016)	3% to 5%	8% to 19%	4%	Compilation of literature review and interviews	Not applicable	Summary findings based on desk research, events, and industry interviews with fleets, manufacturers, and platooning technology developers in North America. Values based on following distance of 40 to 50 feet.

5 Impacts on road traffic capacity

Level 5 AVs are expected to impact capacity, traffic flow efficiency, and stability. However, the capacity on our roads can also be influenced by lower automation levels. Advanced driver assistance systems (ADAS), which give vehicles more computational power, better safety features, navigation systems, and other driver-experience-enhancing mechanisms, are quickly becoming standard features for high-end vehicles. Among other features focused on safety (detection of vehicles in the blind spot) or convenience (auto parking), some influence traffic flow and capacity, such as ACC, collision avoidance systems, lane-keeping assistance, and lane changing.

A comprehensive literature review on the effect of AVs on capacity was presented in an earlier report (Milakis et al., 2015). At the time, limited empirical studies on ACC and CACC could be found in the literature, and most of the research on the effects of AVs on the capacity and traffic flow relied on simulations. The first empirical test of CACC on the roads showed that a platoon of vehicles could be string stable even with low time headways of 0.7s (Ploeg et al., 2011). Another empirical study on public roads with four test vehicles in CACC mode showed that CACC could reduce a trailing vehicle's response time to any change in the speed of the leading vehicle (Milanes et al., 2014). Thus, the empirical study showed that the CACC could enhance string stability. The experiment was for high-speed range, but Milanes et al. (2014) did not evaluate the collision-free for low-speed ranges. Based on empirical data of time gap selection, Shladover et al. (2012) concluded that ACC would not have impacts on capacity because drivers select similar gaps than when they are manually driving. In contrast, with CACC, the capacity could increase up to 4000 veh/h/lane if all vehicles have this technology (Shladover et al., 2012). The increase in capacity was projected to be either linear or quadratic in profile, depending on whether non-CACC vehicles are equipped with dedicated short-range communications or not.

Since 2015, many new studies can be found in the literature on simulations of ACC and CACC effects. More interestingly, several empirical studies have been carried out with both commercial and test vehicles from different research institutions worldwide. In the following, we review the advances in the last seven years, i.e., between 2015 and 2022, related to the influence of automation and connectivity on road capacity and traffic flow efficiency.

5.1 Urban roads

CACC can benefit traffic efficiency in urban arterials, especially in terms of active vehicle-to-everything communications (V2X) and cooperation. Some studies focus on how connectivity and automation can improve the operation of intersections. For example, Dresner and Stone (2004) proposed a reservation-based system to allow AVs to cross intersections with a different control mechanism than traditional traffic lights. This work has recently been extended to incorporate both HVs and AVs by Levin and Boyles (2016). Their simulation results show how the intersection delay decreases linearly with the proportion of AVs.

A recent empirical study suggests that through arterials, longer platoons (of seven vehicles) are more likely to break up compared to shorter platoons of three vehicles (Calvert and Van Arem, 2020). The stops at intersections increased the likelihood for other vehicles to cut into the platoon but, at the same time, allowed the test vehicles to regroup when traffic was not too heavy. Although the deployment of CACC is technically possible, the empirical study's findings regarding how well it affects traffic flow on urban arterials were still inconclusive. The flow at intersections, not the flow on the road between them, determines the efficiency of the arterials.

5.2 Motorways

Talebpour and Mahmassani (2016) considered different types of vehicles with different automation and connectivity capabilities. They study the string stability of the different vehicles given the various technological capabilities. They show that CAVs can improve string stability for different market penetration rates. Additionally, according to their investigation, automation is more effective at limiting the formation and propagation of shockwaves. Further, Talebpour and Mahmassani (2016) investigated the effects of different market penetration on capacity on a one-lane highway stretch with an on-ramp in the middle of the segment. Considering a mainline flow of 1800veh/h and a ramp flow of 360veh/h and, through simulations, they observed that at low market penetration rates (below 50%), there is an increase in scatter in the fundamental diagram, and after that point, the scatter decreases. The flow breakdown was prevented for different market penetration rates (70% for AVs and 90% for CVs), and a stable flow of approximately 2000 veh/h was observed. Further, when considering a mix with 10% regular vehicles (i.e., HVs without connectivity) and 90% mix of human-driven connected vehicles (CVs) and AVs, they observe flow rates as high as 2500 veh/h. They conclude that at low market penetration rates of AVs, the throughput increase is linear with the increase in market penetration of CVs and that these technologies may at least double the capacity of the single-lane roads.

Calvert et al. (2017) expect that a lengthy transitional period where only low vehicle automation is present leads to a negative effect on traffic flow, i.e., lower capacities due to larger desired time gaps and a slightly higher capacity drop (the reduction in flow at bottlenecks once congestion starts to build up). Their hypotheses are supported by other researchers and the empirical calibration of time gaps from a test performed at TU Delft (Gorter, 2015). The experimental results suggested that only penetration rates exceeding 70% will improve traffic flow.

A key parameter related to the capacity of the road is the time gap. However, calibrating car-following models from empirical data to estimate values of time gap is not a simple endeavor. A recent study by Punzo et al. (2021) compared the time gap calibrated for different models among human-driven vehicles and automated vehicles. Some models (IDM, FVDM with constant time headway) lead to lower time gap parameters (and less variation) for ACC vehicles (from AstaZero data in Sweden) compared to HDVs (from NGSIM data in the US). However, other model assumptions (e.g., Gipps) don't present the same results, indicating that the time gaps of HDVs might be lower than AVs. Thus, there is a need for further research on the matter.

According to the estimation results of a simple car following model by (Shi and Li, 2021a), the safety buffer for AVs could decrease when using longer time gap settings. Thus, the authors conclude that higher safety can only be achieved when compromising traffic efficiency. (Shi and Li, 2021a) show a trade-off between stability and mobility, although the conclusions vary significantly for different speed ranges. Another study (Shi and Li, 2021b) calibrates a fundamental diagram based on high-resolution trajectory data with multiple commercial vehicles (two Lincoln MKZs and one Audi Q7 with ACC) following one another. This calibration study concludes that, in comparison to current human-driven-vehicle traffic, the shortest ACC headway setting can increase road capacity to above 3000 veh/h, whereas other headway choices may result in a reduction in road capacity (to less than 1500 veh/h for the longest ACC headway setting).

5.2.1 Elimination of stop-and-go traffic

Human driving behavior has been proven to spontaneously generate traffic congestion in the form of stop-and-go traffic in a homogeneous road stretch without any apparent reason (Stern et al., 2018; Tadaki et al., 2013). This phenomenon is referred to as "phantom jam" or stop-and-go traffic and arises from the fact that perturbations are amplified by drivers. Current technology and traffic management strategies cannot dampen these stop-and-go waves. Fortunately, recent simulation-based studies (Ghiasi et al., 2019; Talebpour and Mahmassani, 2016; Yu et al., 2021) indicate that under a high market penetration rate of automated (or connected) vehicles, we could mitigate (or eliminate) stop-and-go traffic if the longitudinal control of the vehicles is designed carefully.

In recent years, an increasing interest has been in evaluating whether a low MPR of AVs could also eliminate stop-and-go and increase traffic stability. The first study in this direction analyzed the stability and controllability of a ring road with 20 vehicles and a single AV to control traffic oscillations (Cui et al., 2017). They showed that string stability could be achieved, but the effectiveness of such control is limited when the model has noise. Later, Jiang et al., (2021) proposed a deep reinforcement learning control trained with real vehicle trajectories. The controller was implemented into a single CAV behind an HV followed by a platoon of HVs. The oscillations of the CAV were damped by 54%. In comparison, HVs oscillations were reduced by 8-28%, and the authors concluded that CAVs behaving selflessly could act as traffic stabilizers.

In 2018, an empirical study on a circular track with 22 vehicles demonstrated that traffic oscillations could be dampened by adjusting the speed of a single controlled vehicle (Stern et al., 2018). More recently, a large-scale US experiment introduced 100 automated vehicles trained with artificial intelligence into motorways. Their preliminary results suggest that a 5% MPR of such vehicles may be enough to dampen the stop-and-go waves[3].

Regarding the analysis of currently available ACC vehicles, there is a consensus that they are not string stable, i.e., they amplify the perturbations. Motivated by the lack of empirical studies on the performance of commercially available vehicles with some type of automation, Gunter et al (2020) collected data since 2015 on multiple luxury vehicles through car following experiments. Both under minimum and maximum car-following settings, these vehicles were reported to be string-unstable. Similarly, Shang and Stern (2021) conclude that both human drivers and commercially available ACC have a string unstable behavior, although theoretical ACC can have a sting stable behavior under certain speed ranges.

Moreover, recent studies also explore the fact that a single AV could measure the state of multiple vehicles ahead (Chen et al., 2009; Donà et al., 2022). This multi-anticipatory ACC was shown to dissipate the stop-and-go formation through simulations.

5.2.2 Lane-changing capabilities

Lane changes influence the freeway capacity and the stability of traffic flow. Some authors claim that lane changes can cause a capacity drop phenomenon. Therefore, there is a hope that lane-changing maneuvers can be improved through automation and connectivity,

[3] This work is not published but a video is available: https://www.youtube.com/watch?v=PA3lyoCZnP0&t=1s.

leading to larger capacities, higher stability of traffic flow, and lower capacity reduction when the capacity drop occurs.

Tilg et al. (2018) studied the effect of CAVs on waving sections' capacity, by assuming that CAV technology not only will reduce headways but also the required gaps for lane changing. Further, they assumed that the lane-changing behavior of CAVs can be controlled by optimizing the lane-change position of CAVs. They showed that the capacity drop (15% flow reduction without control) in weaving sections can be significantly reduced even for low market penetarion rates (5%). The capacity drop could potentially be reduced to less than 3% for the case where all vehicles are CAVs and receive an optimized lane-changing position. Further, they investigated the impact of reduced reaction times on the capacity drop, which leads to a flow rate of approximately 3300 veh/h/lane. Combining the lane change optimization with the reduced reaction time they observed flow rates as high as 3800 veh/h/lane.

Olia et al. (2018) proposed a framework to integrate lane changes of AVs in a mixed-traffic environment. Their results suggest that the capacity increase can reach 6450 veh/h/lane when all vehicles are CAVs (i.e., with 0.5s desired headways). Instead, if AVs are not cooperative (i.e., 1s desired headways), the capacity ranged from 2046 veh/h/lane to 2238 veh/h/lane, depending on the market penetration. They relied on PARAMICS to evaluate these results and assume different car-following models, reaction times, and lane-changing mechanisms for HVs and AVs.

5.2.3 Dedicated lanes for automated vehicles

Some studies consider the impact on traffic of considering dedicated lanes for AVs. For example, Fernandes and Nunes (2015) presented an algorithm for multi-platooning leaders' cooperation in dedicated lanes. Based on simulations they showed that the capacity can increase up to 7200 veh/h. Later, Talebpour et al. (2017) used simulations to study the effects of designating one lane of a four-lane highway for AVs. They analyzed the effect of a dedicated lane on travel time reliability and traffic flow dynamics and concluded that for market penetration higher than 30%, the flow could be significantly increased.

The use of segregated and mixed lane policies was further studied by Chen et al. (2017). In their analytical work, they provide a general theoretical framework to shed light on AVs' influence on motorways' operational capacity. The authors derived the effective capacity of a mixed road considering the platoon size and the microscopic characteristics of the car-following model. By extending the simplified Newell's car-following model (Newell, 2002) for mixed traffic where the critical spacing depends on the type of vehicle (AVs and HVs) and the type of leader they are following. Chen et al. (2017) concluded that while AVs and HVs segregation can result in lower capacities, allowing mixed-use policies can achieve larger capacities. Depending on the AVs' market penetration, an analytical formulation was used to determine the best policy and distribution of AVs. A similar analytical study (Ghiasi et al., 2017) aimed to determine the optimal number of dedicated lanes given certain CAVs characteristics. They propose a Markov chain model to describe spatial headway distributions of mixed traffic along a highway segment. Their model can consider stochastic headways with different types of distributions. Based on their analysis, they argue that under certain CAV conditions, one dedicated (managed) lane can significantly increase the capacity.

Later, Ye and Yamamoto (2018) constructed the fundamental diagram aggregating the flow and density across the three lanes when none, one, or two of the lanes are dedicated to CAVs. They assumed a desired time gap for CAVs of 0.5 s. They consider three different levels of ACC performance with desired time gaps varying from 1.1 s to 0.5s. They show that the three policies yield similar fundamental diagrams at high MPR (above 70%). Instead, with low MPR (below 30%), having one or two dedicated lanes for CAVs considerably worsens the traffic flow, particularly at low densities (free-flow states). Instead, if the dedicated lanes with CAVs can travel at higher speeds (higher speed limits), having two dedicated lanes leads to higher capacities for mid-range MPR. They conclude that low to medium MPR rates between 30% and 60% can be used to get the optimal system performance (with two dedicated lanes).

It is important to note that the use of dedicated lanes has been claimed to influence the behavioral adaptation of HVs (Rad et al., 2021). Using a driving simulator, they studied how human drivers choose the headways and accept merging gaps under different scenarios. They concluded that HVs driving in the lane next to the dedicated lane exhibited shorter gap acceptance and drove closer to their leaders. These results suggest that the capacity increases achieved by a dedicated lane for AVs are not limited to that lane, but the capacity on the regular lanes with HVs can also sustain higher flows.

6 Impacts on traveler’s behavior: VOTT, accessibility, trip rate, route choice, and mode choice

6.1 Value of Travel Time (VoTT)

The Value of Travel Time (VoTT) is the amount of money that a traveler is willing to pay to reduce his/her travel time. It is therefore an opportunity cost or a trade-off. The VoTT, has two important functions in transport modeling and appraisal. Firstly, the mode choice depends on the relative difference in utility of the different modes, including the disutility of traveling; and secondly, this value is paramount for the appraisal of transport project, namely the construction of new roads, since one of the main benefits that these projects yield is a reduction of travel time. If the VoTT is large then those benefits will be large, motivating investments in road infrastructure and other projects.

One of the biggest advantages of AVs is the potential for relieving the driver of driving duties and using that time for other worthwhile activities. Any such beneficial use of time has substantial implications for our travel decisions and consequently to travel demand modeling because a lower VoTT will necessarily result in fewer benefits. Citing the literature on multitasking, especially in public transport modes, several authors have suggested that the VoTT would be smaller in an AV, compared to that for a driver in a manually driven vehicle (Wadud et al., 2016; Wardman and Lyons, 2016). The numerical value of the VoTT thus sits at the center of the debate on the travel demand impacts of AVs.

It is accepted that VoTT depends on the ability to engage in other activities during traveling, although a direct relationship between VoTT and the type of activities has not been established so far. In the context of AVs, there are three – somewhat separate – strands of literature that deal with the travel time use issue. The first, followed by early researchers like Wadud et al. (2016), simply borrow VoTT from other studies that might be assumed to mimic the behavior in an AV, such as the VoTT of a car passenger or the passenger in public transport.

The second, followed by early researchers such as Kyriakidis et al. (2015) and Bansal and Kockelman, (2017) investigate how people might spend their time in AVs. These studies use questionnaire surveys asking the respondents about their intended activities. Wadud and Huda (2019) conducted a stated intention survey similar to previous studies, but substantiate their results by asking chauffeur-driven car users about their time use now, assuming the time use behavior in chauffeur-driven cars mimics that in AVs. The authors found a strong correlation between stated intention about activities to be done in AVs and current activities done in chauffeur-driven cars.

The third stream of literature estimates the VoTT in AVs directly, generally using stated choice experiments. Nevertheless, there are only a few such studies so far, which are summarized in Table 1. Among these, Steck et al. (2018) estimated VoTT for commute trips in Germany and find support in favor of a reduced VoTT in AVs. The authors found that the VoTT in a private AV is 31% lower and exclusive-use on-demand AVs should lead to a 10% smaller VoTT than that in manually driven vehicles. Correia et al. (2019) also found similar results in the Netherlands – a 26% reduction of VoTT for commute trips in an AV with an interior layout of a mobile workspace. They also found for the dutch population that a leisure-oriented design did not reduce the VoTT. This seems to be connected to what people consider to be leisure which is not the same across the population, some people like jogging others computer games. In fact, the type of activity in those categories of work and leisure plays a very important role, for example office jobs are possible in an AV but clearly not manufacturing jobs (which are significantly less common in The Netherlands). The authors also ran the survey with a sample of people where the AVs were described as chauffeur-driven vehicles and they obtained similar results.

In Switzerland, Hörl et al. (2018) reported a reduction of VoTT of 31% for the exclusive use of on-demand AVs, which is substantially larger than what Steck et al. (2018) found. Although Steck et al. (2018) could not find any substantial differences between VoTT in exclusive-use and shared-use automated on-demand mobility services, Hörl et al. (2018) indeed reported a smaller reduction in the shared-use case, which is expected. It is well known that sharing a vehicle with other passengers in a small space has implications on comfort and trust and as a consequence in the VoTT (Correia and Viegas, 2011).

A factor affecting the possibility of work or leisure activities in an AV is the proneness of vehicle occupants to motion sickness. For example, Wadud and Huda (2019) showed that people prone to motion sickness engage in different type of activities (more thinking and planning than working or studying), which may affect the VoTT differently too. Measures for motion sickness in AVs have already been developed. In most other studies mentioned above, it is assumed that comfort is very high, probably higher than what can be achieved today with very comfortable vehicles.

Enam et al. (2022) measured the VoTT in the US and found great differences between people with very different attitudes toward using new mobility technologies and overall trust in AVs. This goes to show that more subjective elements such as taking a risky behavior, loving cars, or loving gadgets can have a strong effect on the VoTT. Kolarova and Cherchi (2021) using data from a stated preference survey in Germany found that “Trust in technology” and “Travel Experiences” are great determinants of the VoTT and that these are conditioned by the socio-demographic strata such as gender and age.

The VoTT in the shared-use case is especially important for mode choice since it has a role in the choice between owning an AV and using an AMoD service, with effects on travel demand. Interestingly, Gao et al. (2019) found that the VoTT in automated ride-hailing services is higher than the VoTT in a manually driven private vehicle; this discrepancy is a result of a lack of trust in AVs, which was not separated in the study.

More recently a study in the USA demonstrates a similar reduction in VOTT as in Europe (Zhong et al., 2020). The authors looked at commuter trips but in three contexts: urban, suburban and rural. They have identified a decreasing trend in the VOTT respectively for those three environments. Interestingly the percentage reduction between conventional vehicles and the autonomous vehicle and shared autonomous vehicle also differs in those three environments where the percentage reduction is greater for the suburban travelers, those that typically have to do longer commutes.

In summary, although some of the numbers may vary between the studies, the qualitative conclusion from all of them is that the VoTT in AVs, especially private ones, can be statistically significantly lower compared to that for the current car driving experience. For shared mobility services, the reduction will likely be less significant than for privately owned vehicles (Table 6).

Table 6: Value of Travel Time (VoTT) in Automated Vehicles estimated in the literature

Study fro most recent to oldest	Country	Trip type	VoTT manual car	VoTT autonomous private	VoTT autonomous exclusive use service	VoTT autonomous shared use service
(Zhong et al., 2020)						USD17.58 (reduction of 14.43%)
Kolarova and Cherchi (2021)	Germany	Commute	-	EUR5.65	-	EUR4.42 (reduction of 21%)
Gao et al. (2019)	USA	-	USD24.47	-	USD28.03 (increase of 14%)	-
Correia et al. (2019)	Netherlands	Commute	EUR7.47	EUR5.50 (interior work vehicle) (reduction of 26%)	-	-
Steck et al. (2018)	Germany	Commute	EUR6.60	EUR4.59 (reduction of 30%)	EUR5.94 (reduction of 10%)	-
Horl et al. (2018)	Switzerland	-	CHF9.57	-	CHF6.63 (reduction of 30%)	CHF7.90 (reduction of 17%)

6.2 Land Use, Accessibility, and equity

Automation can affect accessibility by potentially altering its four components (Geurs and Wee, 2004). Firstly, by reducing the VoTT, automation reduces the total perceived costs of traveling by private car, affecting the transportation component. As such, people could accept jobs, shopping, leisure, or living farther from what they are used to now. These have direct implications for land use in the long term. Automation could therefore increase urban sprawl or even exurbanisation toward rural areas, subject to land use regulations (Milakis et al., 2016). Increased demand, however, could increase congestion and thus harm accessibility, too. This will lead to a new equilibrium where energy spending could be higher not contributing to the energy-saving goals that the EU aims for.

Secondly, Level 5 AVs could perform some activities on their own, e.g. picking up shopping, or dropping off children at school. This allows overcoming the temporal and individual constraints (e.g. shop closing hours, competition between job and children's activities) to improve accessibility (Correia and Van Arem, 2016; Milakis et al., 2017).

Thirdly, on-demand mobility services are expected to become substantially cheaper in a driverless environment than they are now. As such, car-based mobility services are expected to become more affordable to users who cannot afford a car now. This also has large implications for access to job or leisure opportunities that would otherwise have been difficult to avail without owning a car. Automated dynamic ridesharing could also serve low-density regions where other forms of public transport, e.g. buses, are not viable, further improving accessibility. A shift to shared mobility could also increase urban density by removing the need for parking infrastructure and have further land-use implications (Bagloee et al., 2016). On the other hand, by lowering the costs of providing on-demand transport we could be observing soon a multiplication of robotaxi initiatives coming to cities where public transport is clearly more efficient. In a recent study, the authors were able to demonstrate the great financial advantages of not needing drivers in shared taxi systems to provide first and last-mile services in high-density areas which can potentially bring back cars to areas for which other solutions are more environmentally friendly (Stevens et al., 2022).

The limited modeling studies so far show substantial improvements in accessibility, the definition of which could vary between studies. The effects on accessibility could also be different depending on geography, current transport supply, and socio-economic characteristics. Childress et al. (2015) report an increase in accessibility resulting from a private AV future, in the Puget Sound region in the US. Childress et al. (2015) report that accessibility would improve the most in low-density urban and remote rural areas. Meyer et al. (2017) also report an improvement in accessibility in their three scenarios of automation, with well-connected exurban and rural municipalities in Switzerland benefitting the most. These results, therefore, agree that low-density areas are likely to enjoy the largest improvement in accessibility. The accessibility benefits in these modeling exercises result from improving network capacities due to automation together with the lower VoTT; as such, V2X connectivity is vital for realizing these accessibility benefits.

Childress et al. (2015) and Meyer et al. (2017) also consider demand increases but still, they report improvements in accessibility, especially in cases where it does not adversely affect the network performance. Through expert elicitation, Milakis et al (2018) highlight the uncertainties and elicit three viewpoints: a) accessibility impacts are uncertain due to induced demand nullifying reduced transport costs; b) accessibility will change due to two opposing changes in land use (densification of centers and suburbanization); and c) only a segment of the society could enjoy the benefits of AVs, with significant social equity concerns.

In a more recent modeling study, Legene (2018) used a system dynamics approach for the dynamics of urban areas. They considered the land use component and the transport component dividing the city into different zones. The objective was to understand what land use dynamics can be expected from different usages of AVs. Two distinct scenarios were considered. In one scenario, Avs are mostly private and they 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 center. This demonstrates the importance of policies in shaping the effects of AVs. If shared vehicles are incentivized and private AVs are penalized we could be observing very different spatial effects on accessibility compared to the private ownership current paradigm.

More recently (Llorca et al., 2022) using agent-based modeling concluded that AVs compete with public transport and contribute to reducing the demand for more sustainable mass transportation systems. The average commute distance could go up to double the current one, however, the impact on the distribution of the population could be marginal. The urban sprawl caused by the lower value of VOTT is compensated y the increase in the attractiveness of the core of the cities which benefit from improved public space. The same had been concluded in a master thesis research work that used also agent-based modeling of the Land Use and Transport system but also included the added attractiveness of redesigned streets in The Netherlands (Hollestelle, 2018). The improvements can bring back people to city centers.

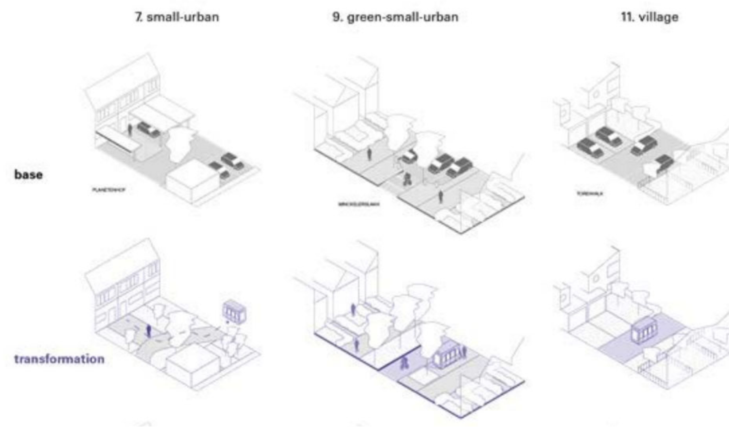

Figure 11: Research by design envisioning urban street space transformations with AVs in The Netherlands. Source: (Hollestelle, 2018)

Lee and Kockelman (2022) studied the benefits of providing Shared Automated Vehicles in the region of Dallas-Fort Worth. They found that most of the vulnerable populations will benefit more from SAVs however in the case of people aged over 65 there is a lower level of access improvement. In the zones with more vulnerable persons, the range of differences in welfare impacts is widened as fares rise. The authors suggest that careful attention should be paid to disadvantaged groups and thoughtful policy should be carried out to ensure that such technology is also helping these groups of the population. A recent review study finds that such concerns are not yet prioritized in research, "considerations for people with low incomes and people of color are not well represented, nor are personal security issues within shared vehicles, or models for deploying AVs in rural communities" (Emory et al., 2022).

6.3 Trip rate

While there is a substantial number of studies that model the effects of vehicle automation on total travel demand, studies that focus on the number of trips are few. Like the VoTT above, the effects on the number of trips also depend on whether AVs will be owned or used to provide mobility services and their relative share.

Wadud et al. (2016) suggested that there are two types of effects on car trips in an owned-AV future. Firstly, there could be new car trips from the elderly or the disabled, who are resigned to a reduced-mobility lifestyle now; this is supported by (Harper et al., 2016) as well. Secondly, there could be a larger number of trips from existing car users due to the reduced VoTT, or from a modal shift toward automated cars. Although several researchers focus on the modal shift and increased travel demand, e.g., Wadud et al. (2016), Harper et al. (2016), Milakis et al. (2017), Auld et al. (2018), they often do not provide separate estimates for trips and instead focus on Vehicle Mileage Travelled.

Schoettle and Sivak (2015) analyzed the time synchronization of households' vehicle trips in the US and find that vehicle ownership could go down by 43%, with a concomitant increase in the rise of empty trips to allow the same trips to take place. Some of the estimates for trips are presented in Table 2, which clearly shows the potential to increase the number of car trips. However, none of these estimates are predictions or forecasts, rather than the result of what-if scenarios, e.g. what if all the elderly started to travel as much as the middle-aged group, or what if the household trips can be made by a fewer number of cars.

The net effects of on-demand mobility services often termed as shared AVs collectively, on the number of trips remain uncertain. Nearly every exclusive-use mobility service vehicle (similar to Uber or taxis) is certain to have empty trips between dropping off a passenger and picking up the next one. While this may increase (if the services are cheaper than the current total costs of ownership and use of private vehicles) or not (if the marginal cost nature of the mobility services becomes dominant) the total passenger trips in autonomous mobility vehicles, will almost certainly increase total vehicle trips due to the empty trips and vehicle miles (Childress et al., 2015). On the other hand, shared-use of mobility services (more than one traveler in each ride), could reduce the number of total car trips since one vehicle trip can replace several car trips. Once again, estimates for the reduction in the number of trips are scarce.

Martinez and Viegas (2017) used agent-based modeling for reproducing a future shared automated vehicle (SAV) system (where passengers need to share their rides) operating in the city of Lisbon substituting all the trips that are currently done by private car, bus, and other modes except the metro system. They concluded that the vehicle kilometers would go down even though these vehicles would need to relocate often to pick up their clients or to anticipate future demand.

Another aspect of the number of trip changes due to vehicle automation is the great focus of the literature on commuter trips. These are, in fact, the higher number of trips typically in urban areas. However, neglecting tourism and leisure trips is ignoring a potentially big market for the adoption of AVs in the developed world. Not needing to drive a car to do tourism can potentially lead to a large increase in the market for tourism AVs. This remains to be quite unexplored in the literature (Thomopoulos et al., 2021).

Given the assumptions in the underlying models and the uncertainty in the share between ownership and automated on-demand mobility services in the future, the potential effects of automation on the number of car trips are highly uncertain. However, automation would almost certainly increase the number of car trips if "ride-shared" on-demand mobility services are not realized on a mass scale in the future (Table 7).

Table 7: Effect of vehicle automation on total trips

	Country	Timeline	Trip type	Increase in the number of trips	Key assumptions
Childress et al. (2015)					Different scenarios
Wadud et al. (2016)	USA		Total car trips	2%-10%	New trips by the elderly and the disabled
Kroger et al. (2018)	Germany	2035	Total car trips	2.2%-8.3%	Owned vehicle scenario
Kroger et al. (2018)	USA	2035	Total car trips	3.1%-7%	
Truong et al. (2018)	Victoria, Australia		Total car trips	7.31%	New trips by elderly, young (follows Wadud et al. 2016) + mode switch

6.4 Route choice

The distances that will be traveled as automation penetrates the vehicle fleet will depend on the type of usage of these vehicles where the most impactful distinction is associated with the choice between public transport or private transport. It is argued that private automation will be associated with longer distances because with a lower VoTT (Correia et al., 2019) already mentioned in this report the disutility of traveling will be lower for the same travel distance (Wadud et al., 2016).

That change of utility in the short term may mean longer routes but also more time spent on congestion as passengers will not feel their time inside the vehicle (Correia et al., 2015; de Almeida Correia and van Arem, 2016; Milakis et al., 2016). In the longer run, a lower disutility of traveling may mean a willingness to move farther away from work locations (typically in the city centers) which will then lead to a longer commuter distance. Once installed, these longer distances may be difficult to tackle if the spatial structure of urbanized regions is already changed (Correia et al., 2016; Wadud et al., 2016). Land use is very hard to tweak and it is one of the great determinants of mobility patterns and their sustainability.

Other researchers argue that there could be an inverse movement back to living in city centers as these become more attractive due to the reallocation of public space from parking to other more attractive uses such as wider sidewalks or parks (Hollestelle, 2017). What effect will dominate the other is still to be seen and again it depends on what technology will allow doing inside an AV as well as human preferences of traveling and living.

Given a certain trip from A to B choosing routes in the future could be done according to the system optimal principles if AVs (Level 5) constitute the majority of the fleet. The so-called social routing can reduce travel times by about 10 to 20% (Kashmiri and Lo, 2022). This is not even considering the higher efficiency of CAVs in the traffic flow. Nevertheless, such social routing requires coordination and overall information on the status of each vehicle on the network which creates some computational challenges.

Regarding public transport, the risk is more focused on the empty kilometers that may be generated by shared vehicle systems (Martinez et al., 2014). Results in the literature point to the need for fewer vehicles to satisfy the same demand once vehicles become Level 4 or Level 5 and start to be incorporated into taxi and Uber-like systems (Fagnant et al., 2015; International Transport Forum, 2015). However, the other side of the coin is the need to relocate such vehicles as they move to pick up clients in other parts of the network (Jorge et al., 2014; Liang et al., 2020; Martínez et al., 2017; Wang et al., 2019). Current Uber systems are already creating more traffic congestion due to the added empty kilometers but also to the added demand of people who used to use public transport and who find it much more comfortable now to just request a ride (Growth et al., 2017; Schaller, 2018). As discussed before in this report the great determinant of shared vehicle efficiency is if these vehicles are shared by several people at the same time which doubles and triples their transport capacity. Individual trips are generally not bringing any benefits except in cases where accessibility is enhanced like in low-density areas.

6.5 Mode choice

Of all the effects of vehicle automation, mode choice is one of the most explored in the scientific literature, on par with the effects on traffic capacity (already discussed in Section 4). Researchers have been exploring the potential mode changes that result from the introduction of this technology both as private and public transport vehicles as discussed above. Mode choice depends on many factors including trip distance and travel time, trip motive, available transport alternatives, and travel costs. It is complex to assess mode choice before new alternatives are introduced into the market which is the case with AVs. Many times what researchers have available are stated choice surveys whereby people state what they would do if they were in a certain situation. Several of these experiments have been done in recent years and they help understand the impact of AVs on the shares of car and public transport demand (Correia et al., 2019; Yap et al., 2015, 2016).

Vehicle automation may come in essentially two forms: private cars or public transport systems as previously introduced. Researchers and practitioners have been discussing the pros and cons of both uses of vehicle automation but most likely the future will be a mix of both uses. Regarding public transport, there are already many pilot systems under operation in Europe and the United States with pod-like buses (Alessandrini, 2017; Alessandrini et al., 2015). In the Netherlands, a Level 4 system running in its own segregate path, the Park shuttle[4] bus connection in Rotterdam, has been in operation for two decades now.

In public transport usage of vehicle automation, it is foreseen that with the cheaper operation costs (no drivers needed) and flexibility to operate the system (vehicles can be sent anywhere at any time to other areas of operation), it will be possible to offer a better quality of service to the populations (Stevens et al., 2022; Winter et al., 2016, 2018a). This can be done with smaller vehicles (cars in carsharing systems) (Liang et al., 2018) or buses (in a more traditional public transport approach). These systems are expected to be used essentially in urbanized regions and one of the most useful usages will be as last/first-mile transport. For long-distance intercity transport still, high-capacity public transport systems such as rail continue to be seen as the best option to transport many people most sustainably. The role of robotaxis in connecting different cities thus using the freeway network is difficult to assess as this will represent a management challenge: moving vehicles from one city to another may represent great vehicle stock imbalance which will lead to a high price to be paid by the passengers. These robotaxis can be driven in any optimal way desired by their operators but there could also be the case of, if imposed by law, a specific behavior being imposed by public authorities for a certain part of the network as discussed regarding the social optimal route choice in the previous section.

Private cars in the future can be fully automated under all Operational Design Domains (Level 5 automation) and in that case, we are talking about vehicles that can become almost like private living rooms where people would be able to have leisure time or even work. This can shift demand toward private cars, if prices are competitive, with the difference that with an improved experience, people are willing to stay longer in their vehicles which can add to the traffic congestion as an occupant does not have the incentive to change his/her behavior.

In a recent study in The Netherlands, researchers explored the added attractiveness of Avs used as shuttles either with fixed service or on-demand. Researchers found that the on-demand service was mainly perceived as an advantage for current public transport users but not by car users or even active modes users. These results may mean that enhancements that

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[4] ParkShuttle - Wikipedia

are seen as revolutionary brought by vehicle automation to current public transport systems are mostly going to benefit those who are already interested in public transport (Öztürker et al., 2022).

In summary, it is at this point impossible to estimate the demand that both modes of transport will have (private or public) since it is depending greatly on what the technology will allow doing in a car, the price of the vehicles, shared mobility market take-up (Nieuwenhuijsen et al., 2018) and whatever policies authorities will implement in the future to achieve the desired outcome on the mobility system: locally and on a national level (Milakis et al., 2016).

6.6 Departure time

It is expected that AVs, once the penetration rate is high enough, increase the road capacity, possibly resulting in higher traffic flows during peak hours without an increase in travel time. That will depend on the interplay between supply and demand. On the other hand, it is possible that being able to do (work-related) activities during a trip in an AV might result in a better spread of peak travels (i.e., leaving at a different moment in time while working the same number of hours), and thereby reducing the number of trips performed during peak hour.

Nearly 50% of drivers intend to perform work-related activities such as phoning or mailing while driving a Level 5 AV according to a large survey by (Kyriakidis et al., 2015). Correia et al. (2019) found that work activities may in fact lead to a lower VoTT in an AV as compared to leisure activities, showing that working in a car can add utility to what is typically an unproductive part of the day. Nevertheless, there is uncertainty in these results, for example, a survey on public opinion about self-driving vehicles by Schoettle and Sivak (2015) showed that only 4.9% of the respondents at that time would perform work-related activities during driving. It's important to notice the year in which these papers have been published that is because the public perception regarding AVs has greatly evolved. It's paramount to continue monitoring these intentions and behavior.

It is indeed difficult to verify whether the intention of drivers is identical to their actual future behavior due to the non-existence of AVs on the highways today. One might say that activities performed during a train trip are an indicator of activities that will be performed in an autonomous private vehicle. Therefore, Cyganski et al. (2015) also asked for activities currently performed during train trips. However, the results showed that working while traveling by train only plays a minor role. This is explained by stating that both people do not want to spend their time working while traveling, but also that there are various types of jobs that cannot be executed while traveling. In that regard, different countries may have very different expected behavior depending on the job market structure. In the same questionnaire, a question on the benefits of AVs was asked, showing that people merely wanted to perform leisure activities. 30% of the respondents indicated that they would (sometimes) perform work-related activities, identical to the activities performed on the train.

Another comparison with a current existing travel mode was made by Wadud and Huda (2019). They showed that there exists a high correlation between intended activities in Level 5 AVs and the current performed activities in chauffeur-driven cars. He also showed different behavior for both the outbound (e.g., morning peak) and inbound (e.g., evening peak) travels. Whereas working is the most popular activity on the first, people like to relax during their return trip. (Correia et al., 2019) also measured the willingness to work on a chauffeur-driven vehicle and found similar results.

It can be concluded that the number of trips during peak hours will not decrease remarkably after the first introduction of AVs. Some people will perform work-related activities, probably to start later or be home earlier. Only the effect of increased capacity might result in more demand during peak periods in terms of the number of vehicles, but this aspect remains unclear and will not appear with low penetration rates.

6.7 Travel Reliability

Travel reliability here is seen from a broader perspective since most often the term is associated with travel time reliability. This is for sure a very important component of reliability but not the only one. Reliability is considered to be associated with certainty in being able to do a trip in the expected travel time. Thus it surely includes the travel time but also the existence or not of a certain transport system to serve transport needs.

If AVs are used as public transport will bring the advantage of fast reaction and acting in a demand-responsive way, potentially reaching virtually any point in a city or region. This flexibility may increase the response of the transport system, therefore, providing more reliable service to the clients (Winter et al., 2018b). When operating in scheduled-based systems the difference to today's public transport service should not be very different in that respect since today's transit services are very much optimized, and drivers can catch up very fast to maintain a proper schedule.

When looking at a generalized use of AVs in the future (public and private) and the driving of such cars on the road, there will be an effect on the reliability of the travel times on the network as a result of the proven stability that they will have, especially if these vehicles are connected (Wang et al., 2017). That stability is essential to decrease the variance of travel times on the road. Not to be confused with travel time since this depends on traffic congestion and therefore on the total demand that will exist in the future. “Drivers care not only about the amount and value of time per trip, but also the value of reliability, that is, how likely is it that a trip can be completed within some expected time costs of congestion” (Rubin, 2016).

One of the causes of travel time instability and variability is for sure the incidents and accidents that happen on the network (Kwon et al., 2011; Tu et al., 2008). Departing from a point where these incidents and accidents will decrease as a result of a lower probability of human error then we can expect that the reliability would be increasing in the future. If on the other hand, possibly only during a transition period, there are failures of the AVs under some conditions, for example, extreme weather, there could be the case where the reliability would decrease for some time before it could increase taking advantage of the full capabilities of the AVs.

7 Conclusions

Vehicle automation has been evolving and the penetration of vehicles equipped with automated functions is increasing in Europe. Sales of Level 3 vehicles are starting and there is a strategy to deploy increasing levels of automation in two distinct environments namely the highway corridors and the slow speed more urban environments.

The specific shares for each type of vehicle are still under great uncertainty depending on the safety of the technology, support from the infrastructure, users’ adoption, and new business models namely the pervasive deployment of shared automated vehicle systems.

New modes of transport for passengers and freight may be further enabled by automation such as modular transit systems which are mainly a research topic nowadays but there is the intention to make them a reality. Smaller lighter electric automated vehicles are also being put forward as a possibility to tackle the energy shortages and make the transport system more efficient. What the influence of such vehicles can be on the roads is still a question mark. Truck platooning has been the subject of important pilots and it seems to be a fixed point in the roadmap for vehicle automation in highways.

In most studies aiming to study the impact of AVs on traffic flow, all vehicles are assumed to follow the same driving logic (e.g., no heterogeneity behavior among AVs), and their effects on traffic flow are frequently assessed by considering multiple scenarios with different market penetration rates. Furthermore, various studies use different modeling assumptions (multiple car-following models) to simulate autonomous driving behavior. Similarly, the assumptions of the impact on traffic flow variables, such as the time gap or reaction time, vary significantly among the theoretical studies (Ghiasi et al., 2017). Therefore, there is yet to be a consensus on AVs' impacts on traffic flow (e.g., if capacity will increase linearly or quadratically with the MPR) and how large this capacity increase can be. In the last years, there has been a consensus that the reduction of the time gap (and consequent increase in capacity) can only be achieved with high MPR or the presence of connectivity. The stability impact of adaptive cruise control has been thoroughly investigated in the literature. The overall agreements suggest that while the ACC can be designed to be string stable (and eliminate the stop-and-go phenomenon), the commercially available ACC are generally string unstable. Several recent large-scale empirical experiments hope to bring more clarity to this debate in the next few years once the data has been analyzed.

The report has thoroughly reviewed the literature that focuses on changes in traveler's behavior in its main indicators. The VOTT which is a particularly important indicator of how much more or less attractive trips in vehicles can be once they are automated is mostly estimated to be reduced which will naturally have an impact on how attractive trips will be but simultaneously how willing people are to stand in traffic congestion for example. It can potentially exacerbate these congestion effects which means more energy waste but it may not lead to so much economic loss since people can still have a few activities in the cars.

The country will face changes in accessibility in its urban, suburban but also rural areas. Farther areas will be accessible due to the lower VOTT however due to changes in urban street design resulting from the automation it's also possible that there will be a return to the city while more of the public space is given back to pedestrians and cyclists. The balance between these two effects is still in doubt.

The number of trips is expected to increase, either by the fact that people who cannot drive today will be able to use a car or because comfort increases. The cost of using shared mobility can also decrease which will contribute to more people transferring from public transport to shared vehicles, which in turn can have consequences on increasing urban traffic congestion.

Vehicle automation can lead to changes in how vehicles are routed on the network, but these changes are still in the far future because they are depending on the adoption of the highest level of automation whereby the vehicles are able to fully drive themselves from A to B. The so-called social or system traffic assignment whereby the objective is to reduce the network travel times is only possible if the route of each vehicle can be decided by a central computer. But it could lead to travel time reductions of 10% to 20% if the number of trips stays the same.

Mode choice is one of the most important questions associated with vehicle automation. Automation can change the current paradigm of public transport services, in terms of experience but also in terms of frequencies and coverage. But on the other hand, vehicle automation can also completely change the experience of owning a private car. If a car will look like a sort of private living room, then people may not want to share such a space with other people. Research is pointing in both directions and it's difficult again to understand where the demand will move to. First and last-mile public transport solutions are emerging as one the most important applications of vehicle automation in transit systems. A few successful case studies exist but we are still far from business-as-usual deployment therefore travelers, despite being more optimistic about the technology, are still mostly not experienced with ridding such shuttles.

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