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Scenarios of automated driving based on a switchboard for driving forces - an application to the Netherlands

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Abstract

Automated driving developments should be considered when making decisions about investments in physical and digital infrastructure. This paper proposes four scenarios for automated driving developments in the Netherlands in 2040 and 2060 taking into account uncertainties regarding future penetration rates, the level of connectivity, the operational design domain, and the expected impacts of automated driving: 1) Late transition, 2) Automated vehicles on main roads, 3) Car-topia, and 4) Share-topia. To derive these scenarios, an extended switchboard method is introduced in which multiple driving forces for automated driving can be varied. The main driving forces were identified based on expert surveys. For each scenario, a modelling approach is used to compute the impact of automated driving on vehicle kilometres driven and congestion. The extended switchboard method offered more flexibility than existing scenario methods. The model-based impact assessment provided more conservative and probably more accurate insights into the expected impacts of automated driving on vehicle kilometres driven and congestion than expert estimates from the literature. The results show that in all scenarios automation leads to an increase in the number of trips, vehicle kilometres driven and congestion. In the scenarios with autonomous vehicles, congestion is expected to increase up to 17%. The higher the penetration rates of connected automated vehicles, the smaller the increase in congestion (1.5% -11%). The results indicate that investments in digital infrastructure are needed to prevent capacity reduction due to autonomous driving. The scenarios "car-topia" and "share-topia" may require additional physical infrastructure on motorways and regional roads, and/or the implementation of demand management strategies.

1 Introduction

Over the past decade many developments have taken place in the field of automation of cars, trucks, and public transport. The penetration rate of Level 2 partially automated vehicles in mixed traffic is increasing, and Level 3 conditional automation on motorways is now supported by EU-legislation. In 2021 about 1.5 million cars were sold with level 3 features and this number is expected to increase to 3.5 million in 2025 (AUTO2X, 2024). In August 2023, a Californian commission allowed two self-driving car companies to commercially operate Level 4 automated vehicles 24 hours a day on all roads in San Francisco (The Guardian, 2023). Although, an accident with a driverless taxi led to suspension of the operating permit of one of the companies in October 2023 (Los Angeles Times, 2023), developments are still progressing. At the same time, governments have been investing in cooperative, connected and automated mobility (CCAM) to facilitate communication between vehicles, infrastructure, and other road users to increase the safety of future automated vehicles and to enable platooning of vehicles (European Commission, 2016). In platoons, time headways between vehicles can be reduced which increases the road capacity and reduces energy use. For freight transport, truck platooning has gained momentum since 2014. Inter-brand platooning technology is an important next step for truck platooning (ENSEMBLE, 2021). For on-demand shuttles and buses, Hagenzieker et al. (2020) concluded that there are many pilots across Europe in which the vehicles predominantly operate at low speeds and low capacities on short operation routes. Most shuttles still have a steward on board, due to legislation, technological challenges, as well as passengers requesting them, raising concerns regarding efficiency.

A key question that needs to be answered to guide future policies and investments in infrastructure is what impact the above developments in automated driving will have. Kroesen et al. (2023) showed that, although experts' opinions towards automated vehicles are generally favourable as they believe automated vehicles reduce congestion, greenhouse gas emissions, and traffic accidents, they are becoming less optimistic about these positive effects over time. In fact, they showed that there is a group of experts with a positive outlook on automated vehicles and a group of experts with a negative outlook on automated vehicles who believe that automated driving will lower the value of travel time (VoTT), thereby increasing travel demand, emissions, and congestion levels. In line with this, Snelder et al. (2022) showed that with respect to the deployment of vehicles with higher forms of automation there are still many uncertainties which lead to questions about expected societal impacts and success and failure factors for automated driving.

The above illustrates that developments in automated driving are progressing, yet there are still many uncertainties regarding future penetration rates, the level of connectivity, the operating conditions including weather, geographical and time of day constraints (i.e., where and when they can drive), traffic and roadway characteristics (operational design domain), and the expected impacts of automated driving. Despite this uncertainty, governments must continuously decide on whether or not investments in physical and digital infrastructure are needed and/or can be postponed. Uncertainty is particularly problematic for investments in physical infrastructure because it has a lifespan of decades. Often scenario-based approaches are used to deal with uncertainties. In the Netherlands, Milakis et al. (2017a) developed scenarios for automated driving applying the intuitive logics scenario development method (Bradfield, et al., 2005; Amer, et al., 2013; Wright, et al., 2013) to identify four plausible future development paths and estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. In other countries automated driving scenarios have been developed as well. For example, Brendon et al. (2017) specified four scenarios for automated driving for Sweden using expert judgements to derive penetration rates for AVs and impacts on vehicle kilometres travelled. However, because not all recent developments in automated driving are included in these scenarios, they require an update based on experiences and lessons learned. Furthermore, the impact assessment for the different scenarios in those studies was purely based on expert judgement, whereas it is extremely difficult for experts to oversee to which extent automation impacts congestion and emissions. Afterall, this requires insights into how the time in vehicles can be used and how that in turn affects activity patterns, destination, mode, and departure time choice. It also requires insights into how automated driving affects time headways between vehicles and therewith the capacity of roads. The combination of the two determines the impact on congestion. Finally, Miskolczi et al. (2021) specified four urban mobility scenarios until the 2030s focusing on a combination of automation, shared mobility and electrification based on a systematic literature review of 62 scientific documents including 52 mobility scenarios. These scenarios are purely descriptive and do not contain an impact assessment.

To specify scenarios, typically an intuitive logics method is used in which the two driving forces with the highest median values for impact and uncertainty are selected and placed on two axes, where the four quadrants represent four possible future scenarios (Amer, et al., 2013). For example, Milakis et al. (2017a) identified 5 driving forces for automated driving (Technology, Policy, Customers' attitudes, Economy and Environment), and found that Technology and Policy had the highest impact and uncertainty resulting in four scenarios with high or low technological developments and restrictive or supportive policies. A disadvantage of this method is that the other driving forces can only be implicitly addressed in the description of the scenarios. To overcome this problem, Oirbans (2021) introduced a switchboard which can be described as a morphological chart depicted with sliders; one for each driving force. The slider of each driving force can take a low and high value. A question that remains unanswered is how a small selection of meaningful scenarios can be selected out of the large set of scenarios that can be created with such a switchboard.

This paper aims to develop new scenarios for automated driving for the Netherlands in 2040 and 2060 including an impact assessment of automated driving for each scenario. This paper contributes to the existing literature by introducing an extended switchboard method to derive scenarios in such a way that multiple driving forces for automated driving can be considered and varied in the scenario specifications. To limit the number of scenarios, the switchboard method is extended with a decision tree approach, that uses the expected impact of driving forces to select scenarios. Secondly, it contributes to the existing literature by using a model-based approach to compute the impact of automated driving for all scenarios on vehicle kilometres driven and congestion. The scenarios themselves are a third contribution.

To develop the scenarios, this paper considers automation of passenger cars and trucks as well as automation of public transport including the introduction of shuttles, shared taxis, and on-demand public transport services. For these vehicles six levels of automation are distinguished: L0 no automation, L1 driver assistance, L2 partial automation, L3 conditional automation, L4 high automation and L5 full automation (SAE International, 2021). Furthermore, a distinction is made between autonomous vehicles (AVs) and connected automated vehicles (CAVs) that can communicate with each other and the infrastructure. The term (C)AVs includes both AVs and CAVs and both cars and trucks. The ripple model of Milakis et al. (2017b) showed that automated driving can have traffic and travel impacts (first ripple), infrastructure and location choice impacts (second ripple), and economic and wider societal impacts, such as impacts on air pollution safety, equity, and public health (third ripple). The focus of this paper is on the first-order implications of automated driving as these are the most direct implications of automated driving. Based on expert input and a literature study, the impact of automated driving on the VoTT and road capacity is determined. For the four scenarios specified in this paper, the implications on destination choice, mode choice, route choice, vehicle kilometres driven, and congestion are determined using a strategic traffic and transport model that uses the impact of automated driving on the VoTT and road capacity as input. The second and third-order implications are briefly discussed in the discussion section.

Section 2 presents the literature overview on automated driving implications. More specifically, it focuses on the adoption and market penetration rates of AVs, implications on the VoTT and capacity implications as these are important for the scenario development and model-based impact assessment. Section 3 presents the method that is used to specify scenarios for automated driving and to assess the impacts of those scenarios. Section 4 present the results. The last section presents the conclusions and recommendations and discusses the implications for infrastructure investments.

2 Literature overview on first order implications of automated driving

This section presents an overview of literature regarding the adoption and market penetration rates of AVs (section 2.1), VoTT implications (section 2.2) and capacity implications (section 2.3) as these are important for the scenario development and model-based impact assessment.

2.1 Penetration rates

The adoption and market penetration rate of privately owned (C)AVs will depend on many factors like customer attitudes, available technology, and political support, making it a particularly complex system to obtain accurate predictions. Early studies suggested positive predictions with up to 75% of market penetration of vehicles with L5 automation by 2060 (Bierstedt, et al., 2014; Litman, 2015; Milakis, et al., 2017b), while more recent forecasts predict that these vehicles only have a market penetration rate of 43% (Litman, 2023). 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.

Variable	Range	Source
Market penetration Level 1	0–10% in 2000; 10–20% in 2015	(Kyriakidis, et al., 2015; Shladover, 2000)
	12% in 2030; 10% in 2040; 2% in 2050	(Nieuwenhuijsen, et al., 2018)i
Market penetration Level 2	0–5% in 2015	(Kyriakidis, et al., 2015)
	35% in 2030; 38% in 2040; 20% in 2050	(Nieuwenhuijsen, et al., 2018)[i]
Market penetration Level 3	34% in 2030; 31% in 2040; 31% in 2050	(Nieuwenhuijsen, et al., 2018)[i]
Market penetration Level 4	Introduction in 2018–2024 Highway and some urban streets before 2030	(Shladover, 2015)
	8% in 2030; 16% in 2040; 17% in 2050	(Nieuwenhuijsen, et al., 2018)[i]
Market penetration Level 5	25% in 2035; 50% in 2035–2050 75% in 2045 – 2060; 90% in 2055	(Bierstedt, et al., 2014; Litman, 2015; Milakis, et al., 2017b)
	8% in 2030; 20% in 2040; 32% in 2050	(Nieuwenhuijsen, et al., 2018)[i]
	Market introduction: 2030 18% in 2040; 43% in 2060; 90% in 2080	(Litman, 2023)
	No L5 vehicles in 2030.	(McKinsey, 2023)

[i] Numbers reported from (Nieuwenhuijsen, et al., 2018) are averages of optimistic and pessimistic scenarios.

2.2 Impact of automated driving on the Value of Travel Time

L5 (C)AVs are expected to allow their users to engage in non-driving activities while travelling, ranging from work and study activities, to reading the news, making phone calls, playing games, and watching movies (Pudãne, et al., 2019). Although the lower levels of automated vehicles offer less flexibility to perform other activities than driving, they may still change how passengers experience traveling by car, and, in turn, may lead to changes in the so-called Value of Travel Time (VoTT). The VoTT signifies the money travellers are willing to pay to cut travel time, affecting long-term decisions on residential location choice, destination choice, and car ownership, and short-term decisions on trip frequency, mode choice, departure time choice, and route choice. Research suggests that (C)AVs might reduce VoTT compared to manual vehicles, but this is influenced by socio-demographics, such as age and gender (Wadud, et al., 2016; Wardman & Lyons, 2016). Recent studies in the USA and Europe confirm a decrease in VoTT with (C)AVs, varying by region (Zhong, et al., 2020). Suburban commuters experience the most significant reduction in VoTT. Overall, a reduction of 26%-32% in the VoTT is expected for private AVs (Steck, et al., 2018; Correia, et al., 2019; Zhong, et al., 2020). For shared automated vehicles (SAVs) a reduction of 14%-21% is expected (Hörl, et al., 2018; Zhong, et al., 2020; Kolarova & Cherchi, 2021).

2.3 *Impact of automated driving on road capacity*

The assumptions concerning the impact on traffic flow variables, such as time headways and reaction times, vary significantly among theoretical studies. These variations range from 0.3 seconds to 2 seconds for headways between CAVs and AVs. Elibert et al. (2019) conducted a meta-analysis comparing 67 studies and found that the average time headway for Adaptive Cruise Control (ACC) (1.44s) was larger and had a larger variability than for human drivers (1.17s). In recent years, there has been a growing consensus that reducing the time headway (resulting in increased capacity) can only be achieved with a high Market Penetration Rate (MPR) (>70%) or the presence of connectivity (Calvert, et al., 2017). However, there is still no consensus whether the capacity will increase linearly or quadratically with the MPR.

2.4 *Conclusions based on the literature overview*

Based on the literature overview it can be concluded that there is still a lot of uncertainty regarding the market penetration rates of different levels of automated vehicles in the future. For example, recent studies expect penetration rates of 18-19% for L5 vehicles in 2040 and 43% in 2060, whereas earlier studies predicted much higher penetration rates of L5 vehicles: 50% in 2035–2050 and 75% in 2045 – 2060. According to the literature a reduction of the VoTT of 26%-32% can be expected for private AVs and 14%-21% for shared AVs. The capacity effects of (C)AVs are also quite uncertain. AVs are expected to increase time headways between vehicles on average from 1.17s to 1.44s (+23%), therewith reducing capacity. A reduction of time headways can only be achieved with a high MPR (>70%) or the presence of connectivity. A scenario-based approach can help to deal with these uncertainties in a coherent way to guide future policies and investments in infrastructure.

3 Methodology

To develop scenarios for automated driving and assess their mobility impacts, a mix of expert consultation, literature consultation (previous section) and transport modelling was used as shown in Figure 1.

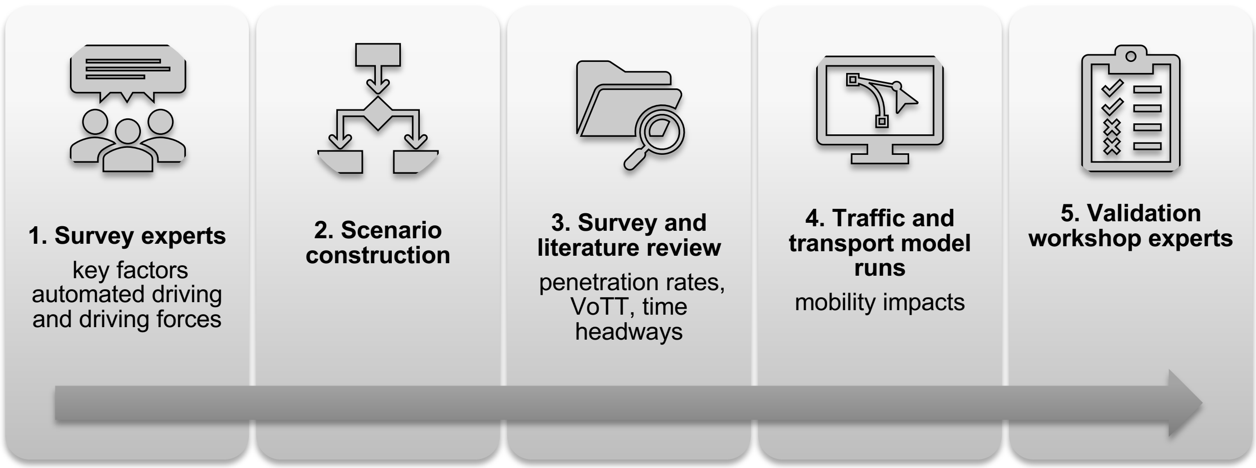

Figure 1. Steps to develop scenarios and assess mobility impacts

In the first step, a group of 23 national and international experts were asked to indicate the key factors influencing the development of automated driving. The experts were selected based on their expertise in automated driving developments and/or impact assessment of automated driving. Secondly, the experts were selected in such a way that they represent different stakeholders that are relevant for automated driving developments: universities, knowledge institutes, consultancy firms, road operators and vehicle authorities. A total of 12 experts from 9 different organisations completed the survey. On average, they had 7 years of research experience in the field of automated driving. Compared to other studies on automated driving, a response from such a large and diverse group of stakeholders is unique. For example, Milakis et al. (2017a) consulted only 5 experts from one university. Through an online survey, the experts could fill in an unlimited number of factors influencing the development of automated driving. Per factor, they were asked to give a description and an indication on a scale of 1 to 5 of how big the expected impact of that factor is. For the resulting factors from the survey, the underlying driving forces were determined and grouped by the authors of this paper, hereafter "the researchers". For each driving force, the potential impact and predictability of its future state (uncertainty) was determined.

In the second step, the scenarios were constructed. As explained in the introduction, typically the two driving forces for automated driving with the highest median values for impact and uncertainty are selected (Amer, et al., 2013) to generate four scenarios. However, a disadvantage of this method is that the other driving forces can only be implicitly addressed in the description of the scenarios. Therefore, an extended switchboard method is introduced, in which all important driving forces can be considered. For each scenario, a choice can be made on how the different driving forces will evolve. For example, for the driving force 'technological developments', a choice can be made whether additional investments in the technology for automated driving are high or low or anything in between. If only the low and high options are considered, this results in $2^{(\text{number of driving forces})}$ potential scenarios that can be constructed. For example, if there are 5 driving forces that each can take 2 values, 32 scenarios (=2^5) can be constructed. If intermediate steps are also considered, this number is even higher ($\text{steps}^{\text{number of driving forces}}$). The stakeholders involved in the research indicated that they prefer to have four scenarios, since four scenarios are still manageable and offer enough diversity. To select four scenarios out of all options, a decision tree was constructed by the researchers. The driving force with the greatest impact on automated driving developments, as identified in step 1, is placed on top. The driving force with the second greatest impact is placed in the second layer, and so on. To limit the scenarios to four, some related driving forces were combined. For example, the driving forces "National and EU policies" and "Government Investments" were combined because they are often interconnected - governments are more likely to invest in physical and/or digital infrastructure if supportive policies are in place. Therefore, the process of creating the decision tree is not purely algorithmic; it integrates the results from step 1 with expert design. The researchers also decided to define scores per driving force, i.e., "high", "intermediate", and "low" based on the investment/effort needed. The resulting four scenarios are presented in section 4.2.

In the third step, a survey among the same group of experts as in step 1 was conducted to determine, for the different scenarios, the impact of automated driving on penetration rates, time headways between vehicles and the VoTT and to determine the impact of automated driving on the number of car trips, the average trip length, the number of vehicle kilometres and the total travel time. A total of 4 experts completed the second survey. The low response may be caused by the level of expertise needed to provide these numbers. To compensate for the low response rate, the results were enriched with insights from the literature overview as presented in section 2. The final values considered are described in detail in section 4.3.

In the fourth step, model runs with the Dutch National Model System (NMS) (Smit, et al., 2021) were performed, where the inputs consisting of the penetration rate of (C)AVs, VoTT and passenger car unit (PCU) values for (C)AVs have been defined based on the results of the literature overview and the second survey (step 3). The PCU values for (C)AVs were computed based on the differences in time headways between regular vehicles and (C)AVs. The NMS is a multimodal strategic disaggregated tour-based model which includes a nested mode, departure time, and destination choice model and a quasi-dynamic traffic assignment model that simulates route choice, and congestion and computes the flows and travel times. The NMS is an established model that has been extensively validated and has been adjusted to model the effects of AVs, see Smit et al. (2017) for details. The demand models can be run separately for people with a regular car and for people with a (C)AV. These models determine the mode, departure time, and destination choice for the main trips of a tour and for secondary non-home-based trips. For the people with (C)AVs the travel time is multiplied with a comfort factor, representing the reduction in VoTT. For the traffic assignment automated driving and platooning are implemented as separate user classes, with their own VoTT and PCU values on specific parts of the infrastructure. The changes in VoTT and PCU values affect the route choice and travel time computation for each class. Model runs were performed for all four automatic driving scenarios for the years 2040 and 2060.

In a final fifth step, the findings were validated in a workshop with 4 external experts not involved in the previous steps, each with over 10 years of experience in the field of automated driving and active involvement in European committees and working groups focused on the development and regulation of automated vehicles on European roads. The experts were asked to reflect on scenarios and the automated driving developments across the different scenarios (Step 2), on the assumptions regarding the penetration rates of various levels of (C)AVs, the VoTT, the time headways of (C)AVs (Step 3), and the impact on the number of trips, trip length, and vehicle kilometres travelled (Step 4 results).

4 Results

In this section the results are described. Section 4.1 describes the key factors and driving forces resulting from the step 1. Section 4.2 describes the results of the second step in which the scenarios for automated driving were constructed. Section 4.3 describes the results from a survey and combines those results with findings from the literature to derive the model input for the different scenarios (step3). In section 4.4, the results from the model runs are described (step 4). Finally, section 4.5 describes the results from the expert validation (step 5).

4.1 Key factors and driving forces

In the survey, a total of 45 partially overlapping factors influencing the development of automated driving were identified by the 12 experts who participated. These key factors were grouped into 7 underlying driving forces as shown in Table 2. The average expected impact on a scale of 1 to 5 of that factor is shown in the column on the right of Table 2.

Table 2. Key factors and driving forces for automated driving.

Driving forces	Key factors	Average impact
Vehicle technology	Sensor developments; Capabilities and limitations (C)AVs; Operational Design Domain; Capabilities of mixed traffic driving; Quality algorithms; Electrification	4.7
Government policies	EU/national/regional/local policy automatic driving; Innovative opportunities for testing (C)AVs (virtual reality, scenario-based, pilots etc.); Legislation; Stepwise introduction of automatic vehicles; Environmental measures; Restrictive car policies	4.7
Government investments	C-ITS; Physical and digital infrastructure developments; Quality infrastructure	4.3
Customer attitude	Comfort; Driver training; Human-centred design of automation functions; Acceptance and willingness to use (C)AVs; Impact on and acceptance by other road users; Social acceptance of risks of automated driving; Social status of (C)AVs; Willingness to use shared vehicles	4.4
Shared mobility services	Developments shared mobility services	4.0
Business case	Business case & Social impact; Investments industry; Vehicle ownership; Added value of automation	4.1
Transport system	Added value of (C)AVs in the transport system; Safety; Waiting time automated shared vehicles; Multidisciplinary cooperation stakeholders; System approach	4.3

4.2 *Scenarios construction*

To construct the scenarios, the driving factors identified in the previous section were included in a switchboard as is shown in Figure 2. In this switchboard, 'low' means not much additional investment/effort compared to the current situation, and 'high' means large investment/effort. The driving force "Business case" is not explicitly included in the switchboard, because it is assumed that investments by different stakeholders only take place if the business case and/or social impact is positive. The driving force "Transport system" is also not included in the switchboard because the incorporation of (C)AVs into the transport system is a result of the developments in the other driving forces, i.e., actions taken by the car/truck industry (OEMs) and governments.

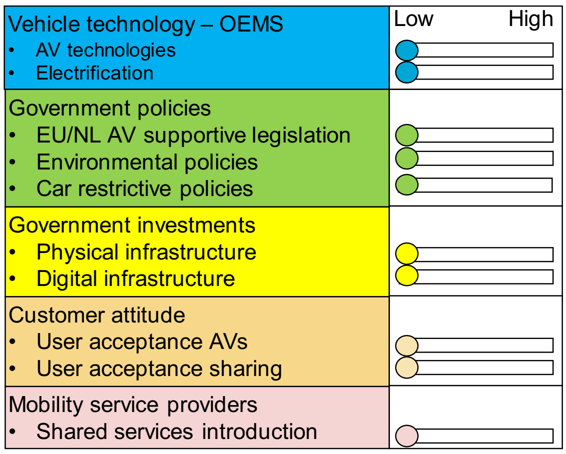

Figure 2. Switchboard of driving forces

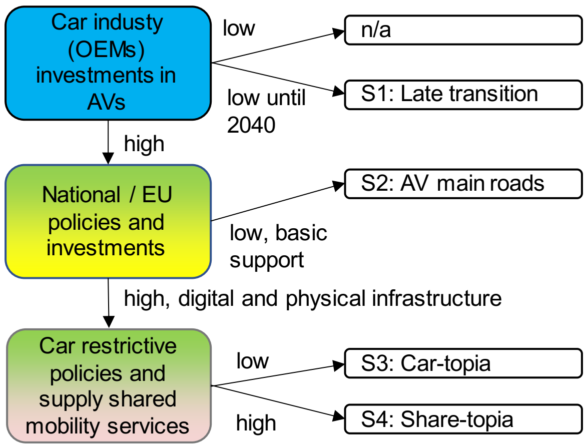

Figure 3. Scenario tree

The switchboard in Figure 2 offers the possibility of creating many different scenarios. Given that three steps were chosen ('low', 'medium', 'high') in the methodology, 59 049 (=3^{10}) scenarios can be constructed. Therefore, the actions of different stakeholders have been prioritised based on the expected impact of each driving force as presented in the previous section. The investments of the OEMs are a prerequisite for the development of automated driving. It is assumed that they will invest only if they expect high user acceptance of (C)AVs. Policies and investments by the EU and national governments can further drive the development of automated driving. Finally, the introduction and acceptance of shared services is important for automated driving which will only flourish if at the same time car restrictive policies are taken by local governments. Based on this logic, the scenarios were drawn up as shown in the decision tree in Figure 3. Note that customer attitude is eventually not used as a distinctive driving force, because the customers can't take actions to introduce (C)AVs. A positive attitude is however a prerequisite for the success of automated driving and the attitudes may very per scenario. In the remainder of this chapter the scenarios are described in more detail.

Scenario 1: Late transition

Figure 4 shows the switchboards for the first scenario "late transition". To meet the climate goals, all effort of OEMs goes first into electrification. The scarcity of materials that are needed for the batteries forces the OEMs to spend all their innovation budgets on electrification instead of automation. By consequence (C)AV developments slow down. Governments decide not to invest in physical and digital infrastructures for (C)AVs. Therefore, only the penetration rate of L2 AVs increases over time until 2040. They are allowed to drive in automated mode on motorways and regional roads. Since electrification is believed to solve all environmental problems, no further car restrictive policies are taken leaving hardly any market opportunities for shared vehicles.

Towards 2060 OEMs invest in AV technology because they see benefits for their customers and want to increase their market share. Local governments believe that AVs will only lead to a reverse modal-shift from active modes and public transport to cars, which they don't want because of negative liveability and health effects. They also fear unsafe interactions with vulnerable road users and additional delays at intersections. Customers see the added value of driving in automated mode on motorways and regional roads and embrace the AVs. However, like governments, they are sceptical for driving on local roads. As a result, in this scenario, L4 private AVs can only drive on motorways and regional roads.

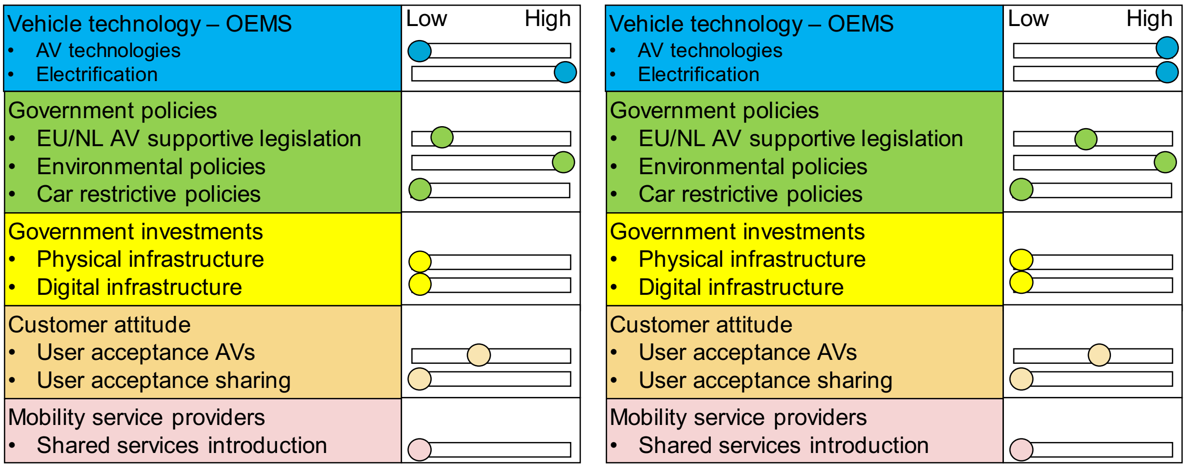

Figure 4. Switchboards scenario 1– late transition (left 2040, right 2060)

Scenario 2: AV main roads

Figure 5 shows the switchboards for the second scenario "AV main roads". In this scenario, OEMs invest directly in AV technology. This scenario is almost identical to scenario 1 2060 – late transition. The difference is that the developments go faster, and the same situation is reached as early as 2040. Towards 2060, national and regional governments decide to invest in digital infrastructure for private connected automated vehicles (CAVs) to increase the capacity of roads and avoid extra congestion. For safer implementation and cost-saving strategies, governments invest in physical and digital infrastructure for L4 public transport automation. As a result, there are L4 private CAVs on motorways and regional roads and there is dedicated infrastructure for L4 public transport automation.

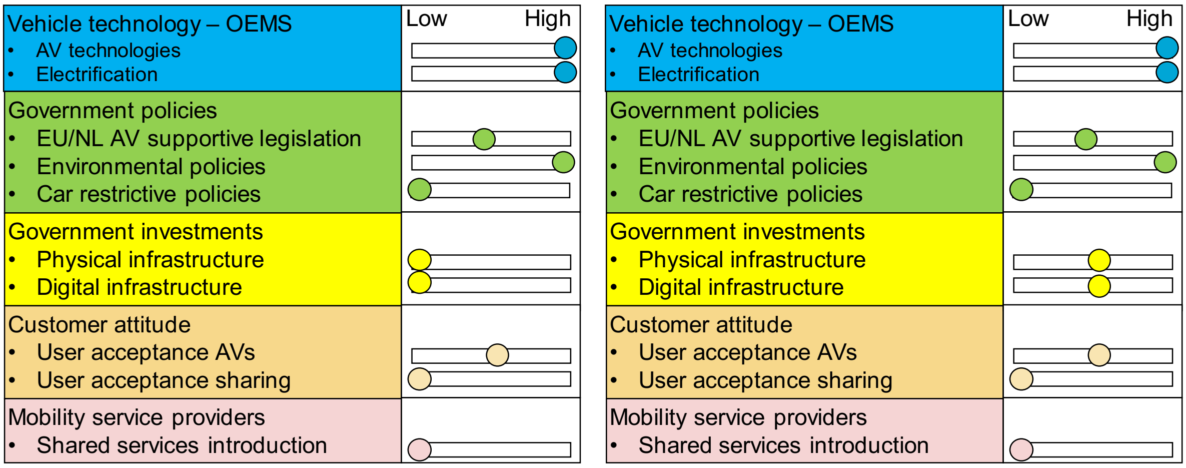

Figure 5. Switchboards scenario 2– AV main roads (left 2040, right 2060)

Scenario 3: Car-topia

Figure 6 shows the switchboards for the third scenario "car-topia". This scenario is almost identical to scenario 2 2060 – Automated vehicles main roads. The difference is that the developments go faster, and the same situation is reached as early as 2040. Towards 2060 OEMs, governments and customers are all very supportive of (C)AVs as they are found to have a positive impact on safety and driving comfort. OEMs invest in vehicle technology ensuring that they can drive everywhere in full automated mode (L5). Electrification is proving to be a catalyst for the introduction and adoption of (C)AVs and vehicles are built in such a way that all hardware for (C)AVs is in place or can be installed via a retrofit. Software can be continuously updated. Governments invest in physical and digital infrastructure for automated driving and allow vehicles on all roads. They even require implementation of automated driving functions in all vehicles. Customers prefer to stay in their private vehicles. Combined with the fact, that governments don’t see the need for car restrictive interventions, sharing doesn’t become popular. Why share if you can still drive to your destination? By 2060, public transport is fully automated to reduce the operating costs.

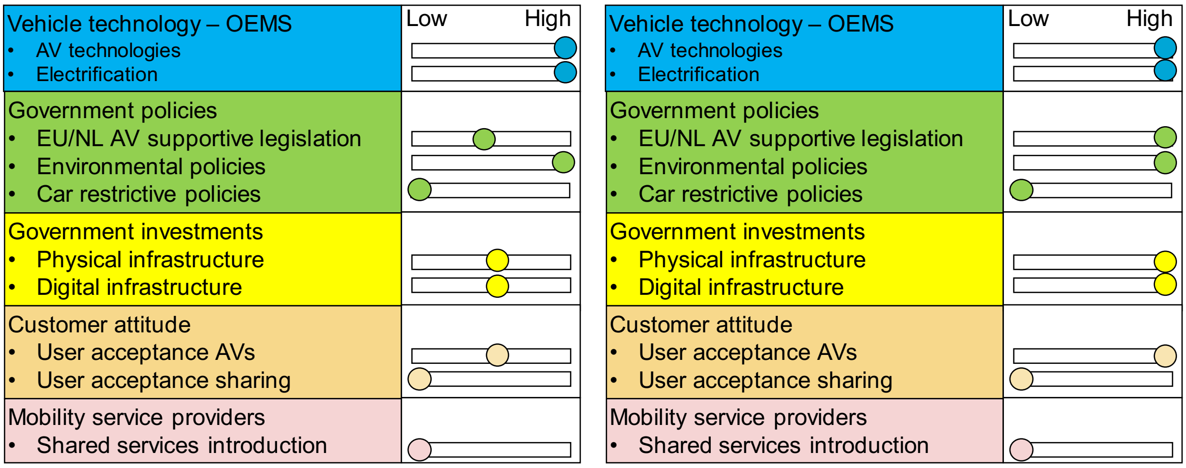

Figure 6. Switchboards scenario 3– car-topia (left 2040, right 2060)

Scenario 4: Share-topia

Figure 7 shows the switchboards for the fourth scenario “share-topia”. This scenario is comparable to scenario 3, except for the fact that local governments decide to take restrictive interventions to reduce the use of private cars, because of a scarcity of space and liveability issues. They allow SAVs on their roads to facilitate a specific set of trips (e.g., disabled people, large groceries etc.), but prohibit private (C)AVs in some private car-free zones. Because the vehicles are automated and electric the costs per trip are acceptable. On-demand shuttles services complement the PT system. In 2040, the customers’ attitude towards sharing improved because they see the added value and it helps them to reach their destinations. By 2060, customers fully trust automated vehicles and a large group is intrinsically motived to share vehicles.

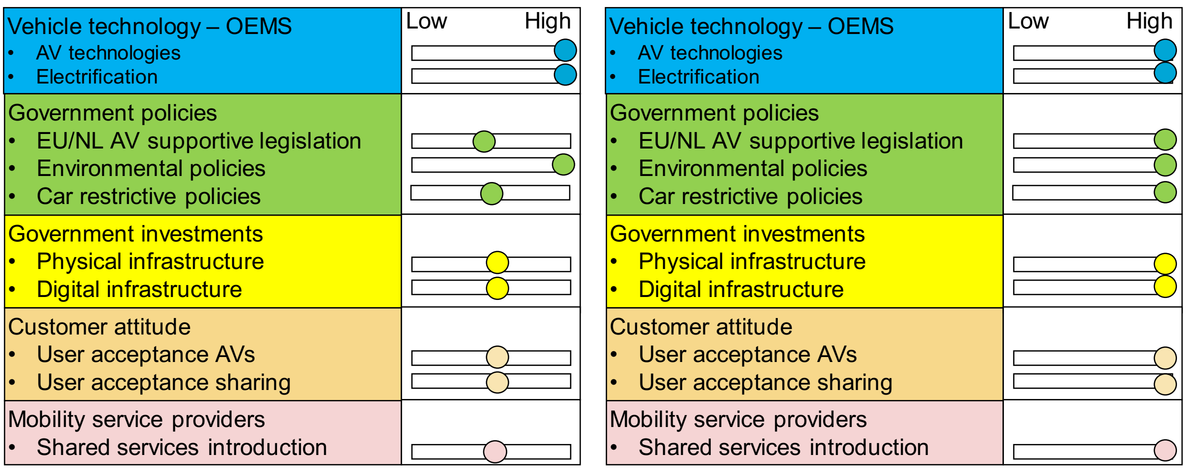

Figure 7. Switchboards scenario 4– share-topia (left 2040, right 2060)

Summary automated vehicles per scenario

Table 3 summarizes the level of automation for each scenario. In this table AV means (autonomous) automated vehicle and CAV connected automated vehicle.

Table 3. Scenario overview.

Scenario	2040	2060
S1 Late transition	L2 AVs on motorways and regional roads.	L4 AVs on motorways and regional roads.
S2 AV main roads	L4 AVs on motorways and regional roads. Only low critical connected applications.	L4 CAVs on motorways and regional roads. L4 dedicated infrastructure for public transport automation.
S3 Car-topia	L4 CAVs on motorways and regional roads. L4 dedicated infrastructure for public transport automation	L5 private CAVs. L5 public transport.
S4 Share-topia	L4 CAVs on motorways and regional roads L4 dedicated infrastructure for public transport automation. Private car-free zones	L5 private CAVs. Private car-free zones. L5 public transport. New shared services complement PT (shuttles, shared rides)

4.3 Penetration rates, VoTT, time headways

The group of experts who provided input regarding factors influencing the development of automated driving were asked in this step to estimate the penetration rates of different levels of automated driving for each scenario via an online survey. They were also asked to estimate the impact of automated driving on the VoTT and the time headways between vehicles as indicator for capacity and the impact of automated driving on the number of trips, average trip length, vehicle kilometres and travel times. The results are summarized in this section. The results from the literature (section 2) are also summarized in this section to provide a comprehensive overview. At the end of this section, it is explained how the model inputs were derived based on these findings.

Penetration rates

Figure 8 and Figure 9 show the survey results for penetration rates of cars and trucks. For cars, it is expected that in 2040 penetration rates of L0/1/2 vehicles are higher than 50% in all scenarios, for L3/4 the penetration rates vary between 10% – 38%. Even though L5 vehicles are not part of the 2040 scenarios, some experts still expect a small percentage of L5 vehicles in scenario 3 “car-topia” and scenario 4 “share-topia. In 2060”, the penetration rate of L3/L4 (C)AVs is expected to increase to 38%-64% depending on the scenario. In scenario 3 and 4, the penetration rate for L5 vehicles in 2060 is expected to be 27% and 31% respectively. The ranges for these numbers are quite large, indicating that the estimates of the different experts differ quite a bit. The results for trucks show a similar pattern. However, it is expected that automation of trucks goes a bit faster, because the penetration rates for L3/L4/L5 trucks are generally higher than for cars.

The literature highlights that the penetration rate for each type of vehicle is still uncertain since its development and adoption highly depends on the safety of the technology, infrastructural support, users’ adoption, and new business models. This might help explain the large variation in the survey results, which are filled in by experts with possibly varying points of view and expectations of development and adoption paths and speeds. The consulted experts in the survey have lower average expectations of automated driving than can be expected based on the literature (e.g., 18-19% for L5 vehicles in 2040 and 43% in 2060).

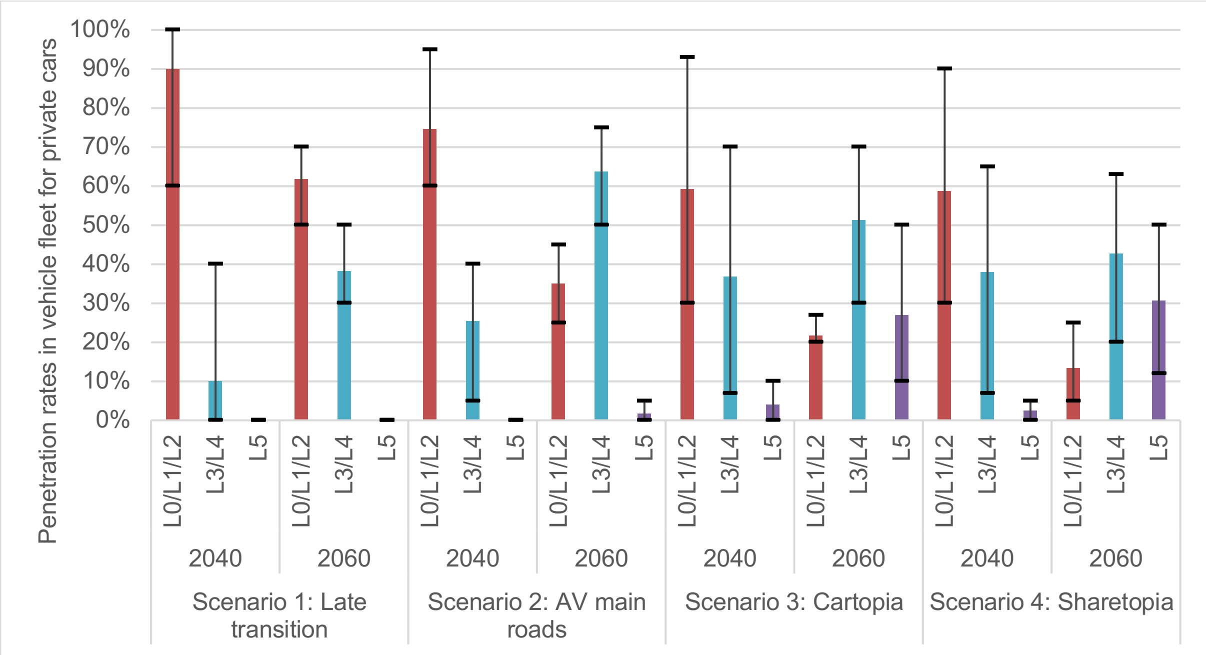

Figure 8. Penetration rates in vehicle fleet for private cars

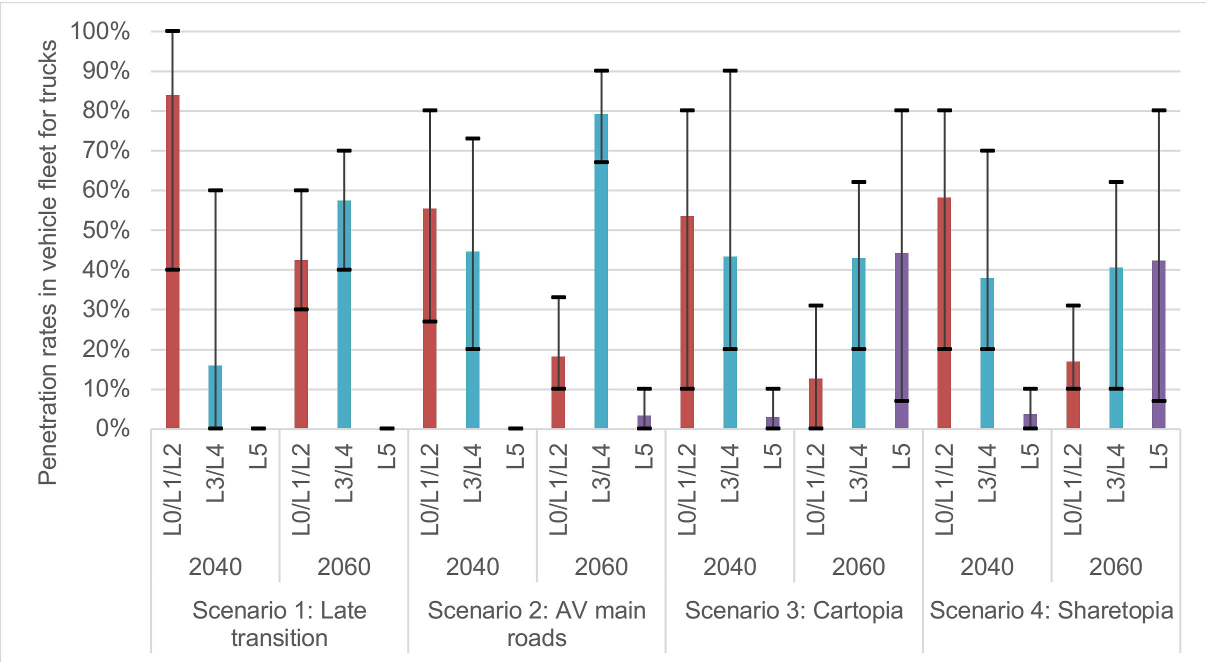

Figure 9. Penetration rates in vehicle fleet for trucks

Value of travel time

When looking at VoTT, L5 is expected to have the biggest impact. For private cars, the experts expect that the VoTT reduces with 14% on average. However, the range is quite large. One expert expects a decrease in VoTT of 40%. For L3/L4 an average decrease of 9% is expected. The reduced VoTT in L3/L4 vehicles applies only when driving on roads where the vehicles can operate in automated mode. Private cars show a larger reduction than shared cars. For SAVs one expert even expects an increase in VoTT, which might be explained by the fact that the vehicle is shared with others. In literature a reduction of 26%-32% in the VoTT is expected for private L5 AVs. For shared L5 AVs a reduction of 14%-21% is expected (Horl et al. 2018; Zhong et al., 2020; Kolarova and Cherchi, 2021). These expectations exceed the expectation of the experts consulted in the survey.

Time headways

In the survey, the experts were asked to give an estimate of the expected time headways between a (C)AV and its predecessor. This is an approximation for the impact on capacity. If the time headways decrease, vehicles can drive closer to each other which has a positive impact on the capacity. Besides time headways, other factors like the response time, acceleration and deceleration possibilities and lane change behaviour also affect the capacity, but these were not included in the survey, to keep the time needed to answer the questions within an acceptable range.

A decrease of time headways (read: increase in capacity) is expected for AVs (-16%) and CAVs (-22%), where the decrease is bigger for CAVs. However, some extreme values have been reported. A time headway of 0.2 seconds for autonomous vehicles is highly unlikely and a time-headway of 2.0 seconds for CAVs is also highly unlikely. These outliers clearly affect the averages. It appears that these outliers have been reported by one expert that might have misunderstood the question. When excluding the outliers, a 4% increase of time headways (= decrease in capacity) is expected for AVs and a decrease of 24% for CAVs. The increase in time headways for AVs is much smaller than the literature suggests (+23%).

Model inputs

The National Model System was used to compute the potential impacts of these four automated driving scenarios for the future years 2040 and 2060 on vehicle kilometres driven and congestion. The model inputs are primarily based on the expert survey, and for some aspects complemented by findings from literature. As mentioned earlier, the experts' expectations and the findings from the literature do not always align. Since the survey was specifically designed to collect the model input data for the four scenarios, this source was preferred over the literature that only provided partial information. Furthermore, the experts' expectations are more conservative than the literature. This conservative approach provides a more solid foundation for making "no-regret" decisions on infrastructure investments. An overview of the model inputs is presented in Table 4.

For the penetration rates of (C)AVs per scenario, the expert survey estimates for L3/L4/L5 were averaged, because the NMS can only deal with one category of (C)AVs. The shares of L3/L4/L5 were used to determine the impact on the VoTT (in the NMS this input comfort factor). For the VoTT of L5 (C)AVs the findings from the literature are used, as these were considered more reliable by the researchers and the experts involved in the validation (see section 4.5). The comfort factor, representing the reduction in VoTT, can be specified for the trip purposes "work", "business" and "other". The comfort factor "business" is assumed to be the same as for "work". For "other" half the effect is assumed. The comfort factor is calculated as a weighted average of the different types of (C)AVs (L3/4/5). Finally, the impacts on time headways have been converted into PCU-values for (C)AVs. According to the literature, PCU factors depend on the differences in vehicle space (length*width), speed and time headways (Srikanth & Mehar, 2017). Since occupied space and speed are similar for (C)AVs and regular vehicles, the PCU factors in this paper are approximated based on the changes in time headways. For the scenarios with penetration rates of (C)AVs substantially lower than 70%, it is assumed that the PCU factors will not change, because the reduction in time headways can only be achieved when penetration rates are high as explained in section 2.3. The road type "Main" indicates that (C)AVs are allowed to drive on the main roads, i.e. motorways and main regional roads. Since the NMS is a national model, private car free zones and SAVs in cities have not been modelled. Another limitation in the NMS is that automated public transport cannot be modelled. Finally, truck platooning is not modelled either. These limitations have to be taken into consideration when interpreting the results.

Table 4. Model input.

	S1: Late transition		S2: AV main roads		S3: Car-topia		S4: Share-topia	
	2040	2060	2040	2060	2040	2060	2040	2060
Penetration rate (C)AV	10%	40%	25%	67%	40%	75%	37%	75%
Of which share L3/L4 AV	100%	100%	100%	97%	88%	67%	95%	60%
Of which share L5 AV	0%	0%	0%	3%	12%	33%	5%	40%
Type AV	AV	AV	AV	CAV	CAV	CAV	CAV	CAV
Comfort factor	0.91	0.91	0.91	0.90	0.89	0.84	0.91	0.89
PCU factor	1.05	1.05	1.05	0.8	1	0.8	1	0.8
Road types	Main	Main	Main	Main	Main	All	Main	All

4.4 Model results

Figure 10 shows for all scenarios the expected impact of C(AV)s on the number of trips, trip lengths and vehicle kilometres travelled by car. In the scenarios with low penetration rates the impacts on these indicators are smaller than 2%. Scenario 3 "car-topia" shows the largest increase in car trips: 2.5%. The increase in the number of car trips comes at the expense of public transport (20-30% decrease) and cycling/walking (50-60% decrease). The maximum increase in vehicle kilometres will be 15% by 2060 when penetration rates of CAVs are high (75% in scenarios 3 and 4). 90% of this increase are additional car kilometres, mostly due to longer trips. Only a small fraction of the extra kilometres come from public transport (5-10%) or walking/cycling (1-5%). As mentioned above, the automation of public transport has not been included in the model. This would probably partially offset the modal shift from public transport to the car.

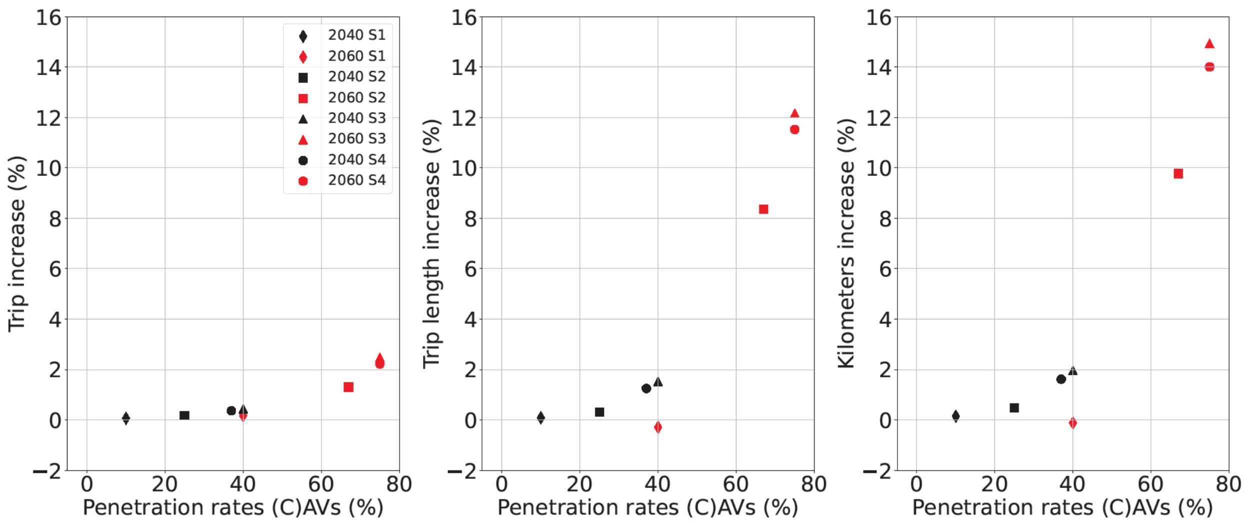

Figure 10. Percentage change car trips, trips length and car kilometres travelled

Figure 11 shows the percentage change in vehicle delays (i.e., congestion). The figure shows that congestion first increases with increasing penetration rates and decreases as penetration approach 70% and CAVs hit the market. This can be explained by the fact that AVs reduce the VoTT leading to an increase in vehicle kilometres travelled. However, the increase in road capacity only emerges with high penetration rates. Based on the survey and literature it is assumed that AVs lead to a 5% decrease in capacity, which is a conservative estimate. As a result, congestion increases. However, for the scenarios with a high share of CAVs it is assumed that the capacity increases with about 20% leading to a smaller increase in congestion. The societal cost of this initial large increase in congestion caused by (C)AVs may be partially compensated by a lower VoTT. But this effect only applies to (C)AV 'drivers'. Since (C)AV drivers have a lower VoTT than drivers in a regular car the impact of the congestion is smaller for (C)AV drivers than for drivers of regular vehicles. As a result, drivers of regular vehicles will shift their routes partially to non-motorways.

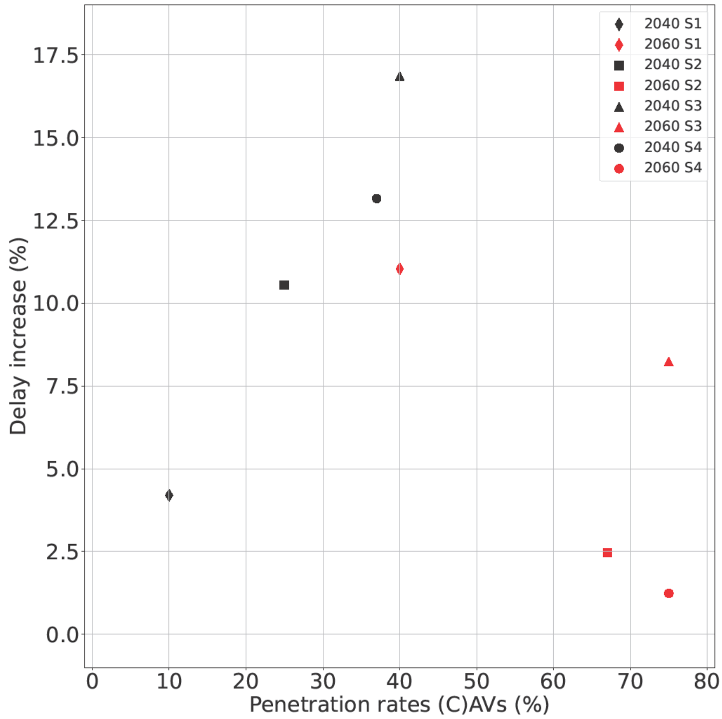

Figure 11. Percentage change delays

Comparison with effects from the literature and expert estimates

In the online survey experts were also asked about the expected impacts of (C)AVs in the different scenarios. In line with the model results, the experts expected that automated driving makes cars more attractive leading to more trips and an increase in average trip length and vehicle kilometres travelled and in increase in travel times. However, they expect that the effect will be much bigger than the model shows. By 2040, the experts expect a 2%-16% increase in vehicle kilometres travelled and 1%-9% in total travel times. In 2060, the effects in the first two scenarios will still be limited to a 15%-19% increase in vehicle kilometres and a 9%-11% increase in travel times. In the third "car-topia" scenario, an average increase of 58% in vehicle kilometres is expected, as well as a 42% increase in total travel times. In the fourth scenario, limiting the use of private cars in cities leads to fewer private car kilometres in cities and an increase in shared car kilometres. The experts consulted by Milakis et al. (2017a) also expected a larger increase in vehicle kilometres driven (i.e., 10%-71% by 2050). A possible explanation could be that that the model takes the interactions and in particular inertia in travel behaviour based on historic developments into account. Experts could overestimate the magnitude of those changes. Further research is needed to test this hypothesis and understand why experts' estimates are much higher than the model results.

4.5 Validation

Four external experts not involved in the previous steps were invited in a workshop to discuss and possibly add to the scenarios including an assessment of the impact of automated driving on all indicators.

Scenarios

Overall, the scenarios were perceived as good scenarios that highlight the driving forces well. They agreed that it is important to consider the introduction of connectivity, automation of cars, truck platooning, last-mile solutions and sharing. The most important remarks were:

- Connectivity: the physical infrastructure may not change much, but some changes may be required to reduce complexity and make automated driving possible. Digital infrastructure is expected to be very important to avoid a capacity reduction that autonomous vehicles may cause. CAVs are expected to be able to drive closer to each other therewith increasing the capacity. In the scenarios it is important to make clear when CAVs are introduced and whether truck platooning is possible. In all scenarios where CAVs are mentioned connected automated trucks and cars are considered.

- L2/L3 automation: L2 and L3 technology is already there, so scenario 1 2040 "late transition" may be too pessimistic. On the other hand, the scenario may still be realistic because the adoption may not be very high in 2040, because distances travelled on motorways are not that long resulting in limited benefits. Therefore, there is no strong incentive to have L2/L3 cars on motorways and the cost are still high. If the operational design domain (ODD) is extended and/or dedicated lanes are constructed this may change.
- L5 automation: the fact that level 5 automation is possible in 2060 in two scenarios is considered too optimistic although 2060 is still far away and it is hard to predict what will happen. Some experts even think that L5 will never happen. On the other hand, there are already on-demand vehicles that are highly or fully automated in certain neighbourhoods in the United States and Asia. According to the definition, this is still L4, because they can't drive in all cities. However, for that neighbourhood this can also be considered L5 (or L4+) because they can drive everywhere in that neighbourhood. This will spread to larger areas/cities/neighbourhoods and maybe also to the Netherlands. It is suggested to focus on L4+. This is very interesting and more probable.
- The scenario share-topia is more likely than the scenario car-topia given the current political climate, which focuses on reducing, or at least not increasing, car traffic and the space needed for parking in cities.
- Stakeholders can have a large impact. For instance, the government can change the infrastructure to make cars less attractive. Therefore, the political decisions have a big impact on how transport will evolve and how likely the different scenarios are.

Impact of AVs

Penetration rates: the experts think that it is difficult to estimate penetration rates for private cars. They agreed that the penetrations rates for automated trucks could be higher than for automated cars because they have a higher renovation rate, and the economic benefits are higher.

VoTT: the fact that people can do other things in AVs can indeed reduce the VoTT significantly. The results from the survey seem a bit low, but this could be explained by the fact that some people may not be able to do other things in the car because of motion sickness. The fact that the decrease in VoTT for shared vehicles is lower than for non-shared vehicles is logical and can be explained by perceived safety risks and less comfort.

Time headways: the experts expect higher differences between CAVs and AVs than between AVs and human-driven vehicles (HDVs). They think that a time headway of 0.6 or 0.7 is the minimum because otherwise there is no string stability and people don't dare to be in these vehicles anymore (perceived safety). More redundancy is needed at low headways (higher cost). Therefore, the step from 1.0s to 0.8s is less expensive than from 0.8s to 0.6s. The investment budget may be a limiting factor. Furthermore, some countries have regulation stating that the headway cannot be <1s and it is expected that there will be European legislation for this as well. It will be difficult to change the legislation to go below 1.0s when there are still HDVs on the road, because that would require different legislation for AVs than for HDVs. Therefore, legislation may be more limiting than technological feasibility. Finally, car manufacturers tend to be cautious and avoid liability issues. They maintain an increased safety zone, and this may not change much with connectivity. Because manufacturers are not primarily interested in the capacity, but more in safety and comfort, the question is if the government can demand lower headways. The question is also who should invest? Investments in shorter headways may reduce the need for investments in extra physical road infrastructure.

Finally, the conclusion that automation leads to more trips, longer trips, and more vehicle kilometres travelled is shared by the experts.

5 Discussion, conclusions, and recommendations

In this paper four new validated future scenarios for automated driving for 2040 and 2060 have been developed based on literature and expert consultation. The scenarios consider important developments in connectivity and automation of cars, truck platooning, last-mile solutions and sharing. The extended switchboard method that was introduced offered the flexibility to consider multiple driving forces in the scenario specification which are all relevant for automated driving. The method therewith contributes to the existing literature on scenario specification that typically only considers two driving forces. The decision tree approach that was incorporated into the switchboard method proved effective in limiting the number of scenarios. The combination with model-based impact assessment for each scenario is a second contribution to the literature providing more conservative and probably more accurate insights into the expected impacts of automated driving on vehicle kilometres travelled and congestion than the experts' estimates. Further research is needed to explain the differences between the model results and experts' estimates. A way to approach this is by monitoring and analysing the usage of (C)AVs (e.g., personal characteristics of the users, types of trips for which they are used, activities that are done in the vehicles and impact on trip distances), and the effects of (C)AVs on driving behaviour and road capacities.

The results indicate that investments in digital infrastructure are needed to avoid a capacity reduction that may be caused by AVs. Since automation is expected to lead to an increase in vehicle kilometres travelled and travel times (despite the increase in capacity of CAVs), it can be beneficial to invest in extra infrastructure. However, the reduction in VoTT reduces these additional benefits. Especially, the third and fourth scenario may require extra physical infrastructure on motorways and regional roads, but potentially also on local (non-car-free) roads to make vehicle automation on these roads possible. In addition, governments can implement demand management strategies to stimulate a modal shift to more sustainable modes such as walking, cycling and public transport, and therewith reduce the car kilometres travelled. This can for example be realized by shifting urban road space to bike- and bus lanes, and by introducing road and parking pricing. Combining both approaches, i.e., increased physical infrastructure and demand management strategies, could provide a more comprehensive solution by addressing capacity issues and promoting a modal shift to sustainable transport modes. Governments play an important role in the implementation of automated driving. They can largely determine in which scenario we will end up. Therefore, they should decide if scenario 3 and 4 are desirable future scenarios and, if so, they can develop appropriate regulations, invest extra in physical infrastructure, or take alternative interventions. The scenarios have been developed for the Netherlands; however, the results are also relevant for many other European countries as European regulations and collaboration play an important role in the development of automated driving.

This paper showed that the experts' expectations regarding penetration rates, VoTT, and time headways and the findings from the literature do not always align. A choice was made to use the more conservative experts' expectations as input for the model runs because they provide a more solid foundation for making "no-regret" decisions on infrastructure investments. It is recommended to do a sensitivity analysis for each scenario to get additional insights into more extreme situations that may occur.

The NMS uses the impact of automated driving on the VoTT, and PCU factors as input to compute destination, mode, departure, and route choice effects. However, this model does not fully consider household interaction, and time and space restrictions of people (e.g., constraints on the start and end time of activities related to opening hours), resulting in an overestimation of effects. It is recommended to explore the use of activity-based models to assess the impact of automated driving, as these models are better equipped to account for household dynamics and time and space constraints.

Furthermore, not all automated driving developments could be modelled. The effects of private car-free zones, SAVs in cities, automated public transport, and truck platooning could not be modelled. Except for truck platooning these developments are expected to cause a modal shift to non-car modes, thereby mitigating the anticipated increase in car kilometres resulting from the automation of cars. It is recommended to do additional model runs to explore the impacts of private car-free zones, SAVs in cities, public transport automation, and truck platooning. This requires improvements of the strategic models in such a way that all these developments can be incorporated into one modelling framework.

The focus of this paper was on first-order effects of automated driving (Milakis, et al., 2017b). Second-order effects on infrastructure were discussed above. In addition, the introduction of SAVs may lead to a reduction in car ownership. and space needed for parking. Furthermore, automated driving can also have other second-order effects on residential location choices and land use (Snelder, et al., 2022). For example, people may decide to live further away from their work, resulting in urban sprawl, and an increase in vehicle kilometres and congestion. It is recommended to use a Land Use and Transportation Interaction model (LUTI) to assess the impact of automated driving on location choice. Economic and wider societal impacts, such as impacts on air pollution safety, equity, and public health (third ripple), have not been considered in this paper. Regarding safety, in the Netherlands, about 20%-25% of all delays on motorways are caused by accidents (Snelder, et al., 2013). On one hand, it is expected that (C)AVs are safer than HDVs, and that a subset of these accidents can be avoided by (C)AVs. On the other hand, commercially available adaptive cruise control is generally unstable (Gunter, et al., 2020) which can lead to increased traffic congestion and potentially more accidents. These impacts need to be considered when making regulations and infrastructure investments. It is therefore recommended to analyse in more detail what the expected impact is of (C)AVs on accidents and delays caused by accidents. Weather conditions like fog, snow, and heavy rain can make driving in automated mode difficult. It is recommended to analyse how weather conditions affect automated driving now and in the future as technology advances and how that affects travel times. Regarding equity, (C)AVs tend to benefit higher-income travellers, and may harm lower-income people, because of the negative externalities of (C)AVs in terms of increased vehicle kilometres and congestion, negative environmental impacts, and extra space needed for road infrastructure. To assess equity impacts, future studies should define more user classes based on income levels and evaluate the effects on trip lengths and delays for each class. In conclusion, when making infrastructure decisions and planning supportive demand management strategies, it is crucial to also consider the second and third-order effects of automated driving.

Contributor statement

Snelder, de Clercq, Homem de Almeida Correia, ‘t Hoen, Madadi, and Martinez wrote the manuscript with support from Sharif Azadeh, and van Arem. De Clercq conducted the survey. All authors contributed to the development of the scenarios. Homem de Almeida Correia, Madadi, and Martinez studied the literature. ‘t Hoen performed the model analysis with support from Snelder.

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Conflict Of Interest (COI)

There is no conflict of interest.

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