PBL - Scenarios automated driving 2040/2060

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Introduction

The "Welvaart en Leefmilieu (WLO)" future outlook by the PBL (Planning Office for the Living Environment) and the CPB (Central Planning Bureau) is an important basis for policy decisions for the design of the physical living environment in the Netherlands. The PBL is working on a new WLO outlook for 2040/2060. They would like to know to what extent the development of automated driving should be included in the WLO scenarios. Therefore, they have asked the TU Delft to answer the following research questions:

- What are possible future scenarios, how likely are these scenarios and what factors determine in which scenario we will end up?
- What is the bandwidth of possible impacts of automated driving on the value of time, capacity and traffic conditions considering the development of market penetration rates over time?
- What are the implications of the scenarios for infrastructure policies and investments in the next 8 years?

Figure 1 summarizes the approach that has been used to answer these questions. First the key factors and driving forces for automated driving have been identified based on a survey with external experts and a literature review. They key factors and driving forces have been discussed in a workshop with PBL. During this workshop it was also discussed what the expected impact of the driving forces is and how they could be prioritised. In the next step scenarios have been constructed using these driving forces. Finally, the expected impact of automated driving has been estimated by experts and a validation workshop was organized with external experts to review and validate the results.

1. Identify factors and driving forces for automated driving (workshop 1)
2. Determining the impact of the driving forces (workshop 1)
3. Constructing scenarios (workshop 2)
4. Estimating the impact of automated driving for each scenario
5. Review of the scenarios (workshop 3)

Figure 1: Approach

Based on this approach four future scenarios have been defined for automated driving for the Netherlands for 2040 and 2060, including a quantitative estimate of:

- the expected penetration rates;

- the effect of automated driving on time headways (approximation for capacity) and the value of time;
- the effect of automated driving on the number of trips, the average trips length, the number of vehicle kilometres travelled and the total travel times.

A distinction is made between different levels of automation for passenger cars, trucks and shuttles: Level 0 (L0): No Automation; Level 1 (L1): Assisted Driving Automation; Level 2 (L2): Partial Automation; Level 3 (L3): Conditional Automation; Level 4: High Automation (L4); Level 5 (L5): Full Automation.

The next sections describe the approach and results of each step. The conclusions and recommendations are described in the last section.

Step 1: Identifying factors and driving forces for automated driving

In the previous collaboration with PBL (Milakis et al., 2017), a group of 5 experts jointly determined through a group discussion which factors have the greatest influence on the introduction of automatic vehicles in the Netherlands. These factors are shown in Table 1. Subsequently, the underlying driving forces that influence the various factors were determined for these factors. This may concern, for example, technological developments, policy, the attitude of travellers towards automated driving, economic developments or environmental factors. After, these driving forces were scored by all individual experts on the impact they have on the effect of automated driving and the degree of uncertainty of these factors.

Table 1: Key factors and driving forces previous study (Milakis et al., 2017)

Key factors	Driving forces
AV technology trials	Technology, Policies
Interoperability among AV technologies	Technology, Policies
Costs/benefits of AV technology	Technology, Policies, Customers' attitude
Development of AV in EU	Technology, Policies, Customers' attitude
AV ownership structure (public vs private)	Technology, Economy
Transition steps	Technology, Policies
Incidences	Technology
Energy, emissions	Technology, Policies, Economy, Environment
Legal/institutional context (national and European)	Policies
Public/private expenditures on infrastructure	Policies, Economy
Stability of policies	Policies
Accessibility, social equity	Technology, Policies
Psychological barriers (Citizens and customers)	Technology, Customers' attitude
Marketing/image of AV	Policies, Customers' attitude
Attitudes towards AV	Technology, Policies, Customers' attitude, Economy, Environment
Income	Economy

This approach was changed on a number of points in order to make better use of insights from the literature and to make use of insights from a larger group of experts. A group of 20-30 experts were asked to complete a short online survey to indicate what they believe are the most important factors influencing the development of automated driving, including a brief explanation of each factor and a score that reflects the importance of the factor. The survey can be viewed at: [PBL Automated driving (google.com)]

TU Delft collected this input and brought it together into 1 list during a workshop with experts from TU Delft and PBL. This list was supplemented on the basis of the literature search that was being carried out in a parallel project (Correia et al., 2023). During this workshop, the underlying driving forces were also determined. The final list of factors and driving forces are depicted in Table 2.

Table 2: Key factors and driving forces

Key factors	Driving forces
Affordability/cost Good business case and societal value case Industry investements in automated driving Large scale investments Ownership Public vs private vehicles Utility	Business case
Automated vehicle sensor capability (camera, radar, lidar, etc.) Capabilities and limitations of the vehicle Distributed ODD awareness Performance of algorithms used in ADS software Technological developments Electrification To what extent AV can drive in mixed mode areas	Vehicle Technology
C-ITS services Developing the physical and digital infrastructure Digital infrastructure support Digital infrastructure to support (safe) automated driving Infrastructure adjustments Infrastructure quality To what extent AV can drive in mixed mode areas Will it work under (virtually) all conditions? (slippery roads, behaviour of pedestri	Infrastructure Technology
Automated vehicles as part of a multimodal traffic and transport system Safety Waiting time for car ride Multi-disciplinary cooperation System approach	System
Comfort Driver training and testing Affects other road users? Human Behaviour and human acceptance Human centered design of automated driving functions Other road user acceptance Public acceptance of risks of AVs Public trust and interest in automated driving Role transition Social status of driving AV Societal acceptance THe role of the user Vehicle user acceptance Willingness to use AV	Human factor/Acceptance
Explicit reference to AD in policy priorities (EU, national, regional, local) Innovative (Virtual, scenario based) testing methods on safe behavior of CAVs Regulations Stepwize introduction of automated driving	Policy

Step 2: Determining the impact of the driving forces

The key factors and driving forces are used in the first workshop to determine which factors are most important for the development of automated driving and therefore should be included in the scenarios. It was decided to cluster them into actions that different stakeholders can take. This resulted in the switchboard that 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.

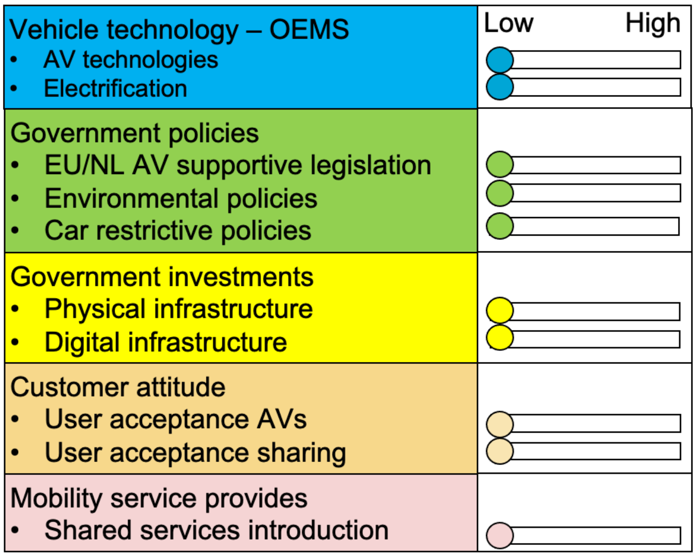

Figure 2: Switchboard of driving forces

Step 3: Constructing scenarios

In this step, four scenarios are constructed and for each scenario a description is then drawn up of what the mobility system with automated vehicles (AVs) would look like in 2040 and 2060 in the relevant scenario.

The switchboard in Figure 2 offers the possibility of creating many different scenarios. If only the low and high options are chosen, 1024 (=2^{10}) scenarios can already be constructed. If intermediate steps are also considered, this number increases even more. Therefore, the actions of different stakeholders have been prioritised. The investments of OEMS are a prerequisite for the development of automated driving. If they do not invest, nothing will happen. It is assumed that they will invest only if they expect high user acceptance of AV. 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. Based on this logic, the scenarios were drawn up as summarised in the decision tree in Figure 3 and the description in Table 3. In the remainder of this chapter the scenarios are described in more detail

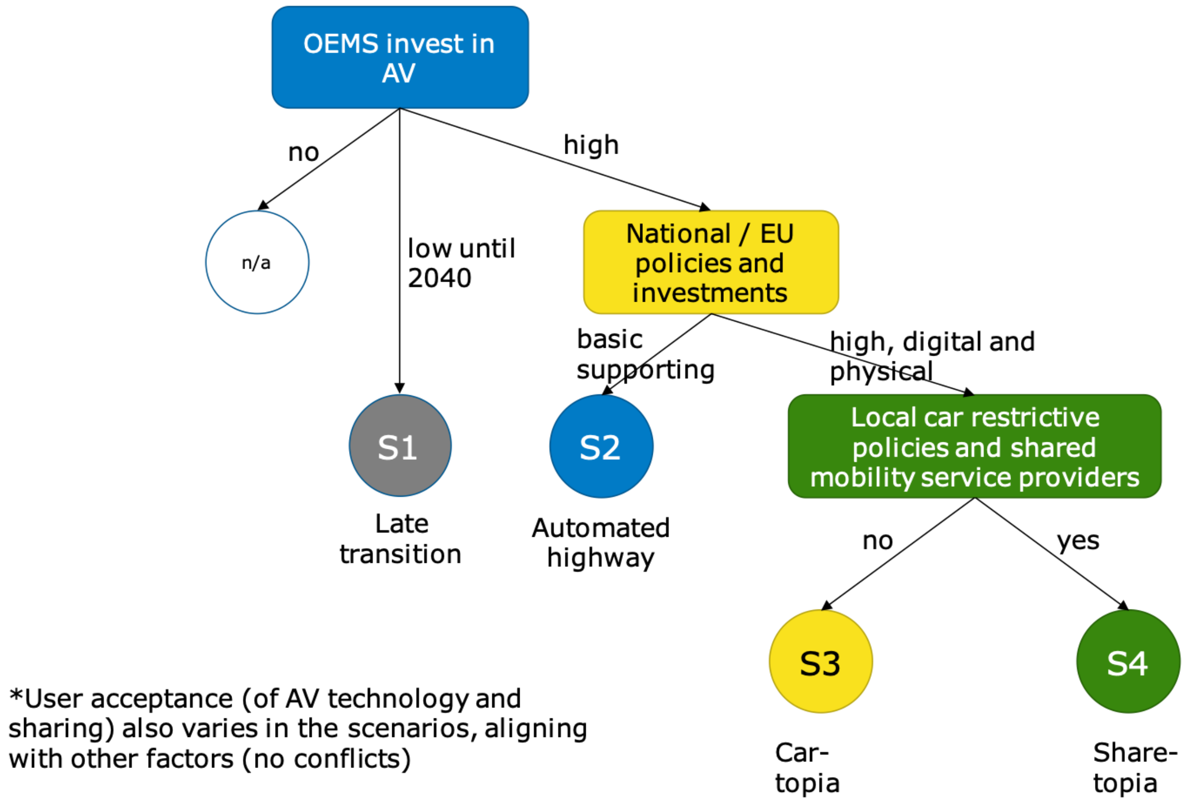

Figure 3: Scenario tree

Table 3: Scenario overview

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

*AV= (autonomous) automated vehicle; CAV = connected automated vehicle

Scenario 1– late transition

Figure 4 shows the switchboards for the first scenario “late transition”

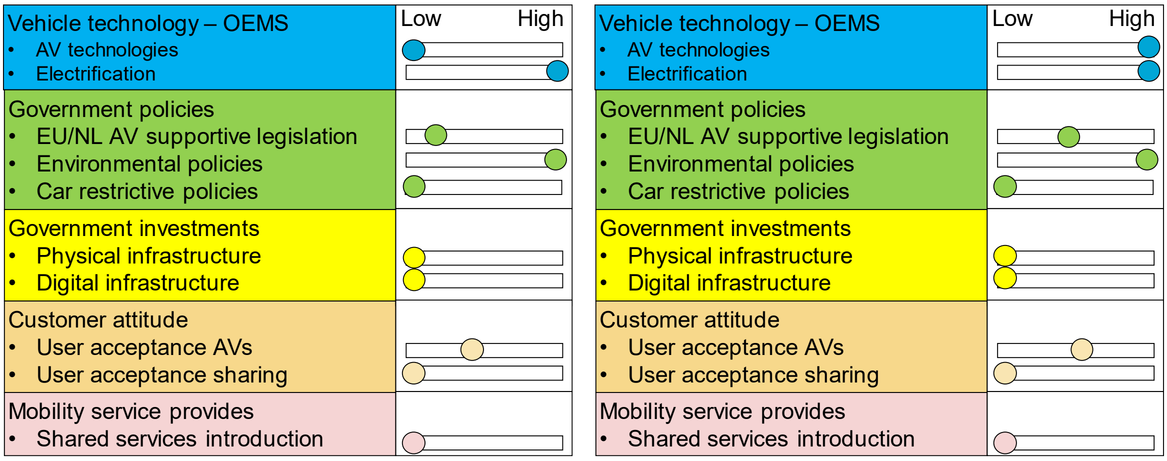

Figure 4: Switchboards scenario 1– late transition (left 2040, right 2060)

Description 2040

To meet the climate goals, all effort of OEMs goes 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 AV developments slow down and penetration rates will not increase much. Governments decide not to invest in physical and digital infrastructures for AVs. Therefore, only the penetration rates of autonomous L2 vehicles increase over time. Since electrification is believed to solve all environmental problems, no further car restrictive policies are taken leaving hardly any market opportunities for shared vehicles.

Result: L2 autonomous vehicles on motorways and N-roads

Description 2060

In this scenario OEMS invest in AV technology because they see benefits for their customers and want to increase their market share. EU and the Dutch national and regional governments decide not to invest in physical and digital infrastructure, but they do allow automated vehicles and trucks on motorways because of safety benefits. 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 N-road and embrace the AVs. However, like governments, they are sceptical for driving on local 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.

Result: L4 private autonomous vehicles on motorways and N-roads.

Scenario 2– automated highway

Figure 5 shows the switchboards for the second scenario "automated highway"

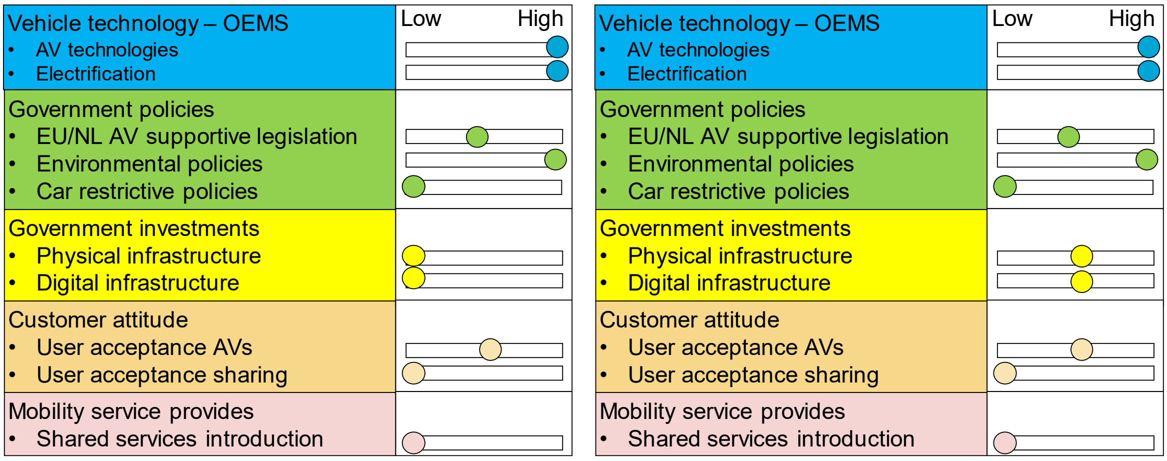

Figure 5: Switchboards scenario 2– automated highway (left 2040, right 2060)

Description 2040

In this scenario OEMS invest in AV technology because they see benefits for their customers and want to increase their market share. EU and the Dutch national and regional governments decide not to invest in physical and digital infrastructure, but they do allow automated vehicles and trucks on motorways because of safety benefits. Only low critical connected applications like road works and incidents warning are developing further. Local governments believe that AVs will only lead to a reverse modal-shift from active modes and PT 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 N-road and embrace the AVs. However, like governments, they are sceptical for driving on local 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.

Result: L4 private autonomous vehicles on motorways and N-roads (only low critical connected applications)

Note: 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.

Description 2060

In this scenario OEMS invest in AV technology because they see benefits for their customers and want to increase their market share. EU and the Dutch national and regional governments allow automated vehicles and trucks on motorways because of safety benefits and decide to invest in digital infrastructure for private connected automated vehicles (CAVs) to increase the capacity of roads and avoid extra congestion. However, 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. However, for safer implementation and cost-saving strategies, governments invest in physical and digital infrastructure for L4 public transport automation. Customers see the added value of driving in automated mode on motorways and N-road and embrace the AVs. However, like governments, they are sceptical for driving on local 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.

Result: L4 private CAVs on motorways and N-roads + L4 dedicated infrastructure for public transport automation

Scenario 3– car-topia

Figure 6 shows the switchboards for the third scenario "car-topia"

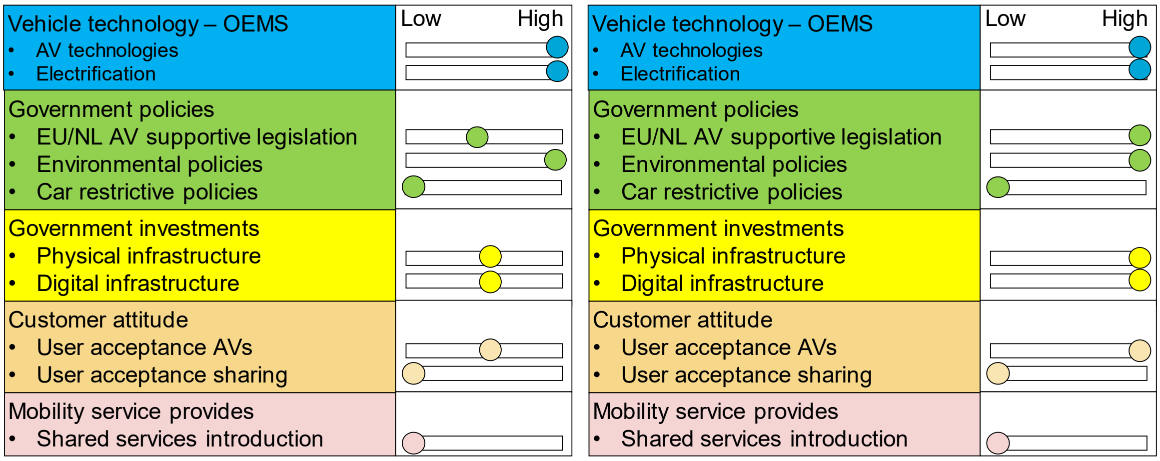

Figure 6: Switchboards scenario 3– car-topia (left 2040, right 2060)

Description 2040

In this scenario OEMS invest in AV technology because they see benefits for their customers and want to increase their market share. EU and the Dutch national and regional governments allow automated vehicles and trucks on motorways because of safety benefits and decide to invest in digital infrastructure for private connected automated vehicles (CAVs) to increase the capacity of roads and avoid extra congestion. However, local governments believe that AVs will only lead to a reverse modal-shift from active modes and PT 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. However, for safer implementation and cost-saving strategies, governments invest in physical and digital infrastructure for L4 public transport automation. Customers see the added value of driving in automated mode on motorways and N-road and embrace the AVs. However, like governments, they are sceptical for driving on local 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.

Result: L4 private CAVs on motorways and N-roads + L4 dedicated infrastructure for public transport automation

Note: this scenario is almost identical to scenario 2 2060 – automated highway. The difference is that the developments go faster, and the same situation is reached as early as 2040.

Description 2060

In this scenario OEMS, governments and customers are all very supportive of 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. Electrification is proving to be a catalyst for the introduction and adoption of AVs and vehicles are built in such a way that all hardware for AVs is in place or can be installed via a retrofit. Software can be continuedly 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 unpopular car restrictive interventions, sharing doesn't become popular. Why share if you can still drive to your destination? Public transport is fully automated to reduce the operating costs.

Result: L5 private CAVs and public transport

Scenario 4– share-topia

Figure 7 shows the switchboards for the fourth scenario "share-topia"

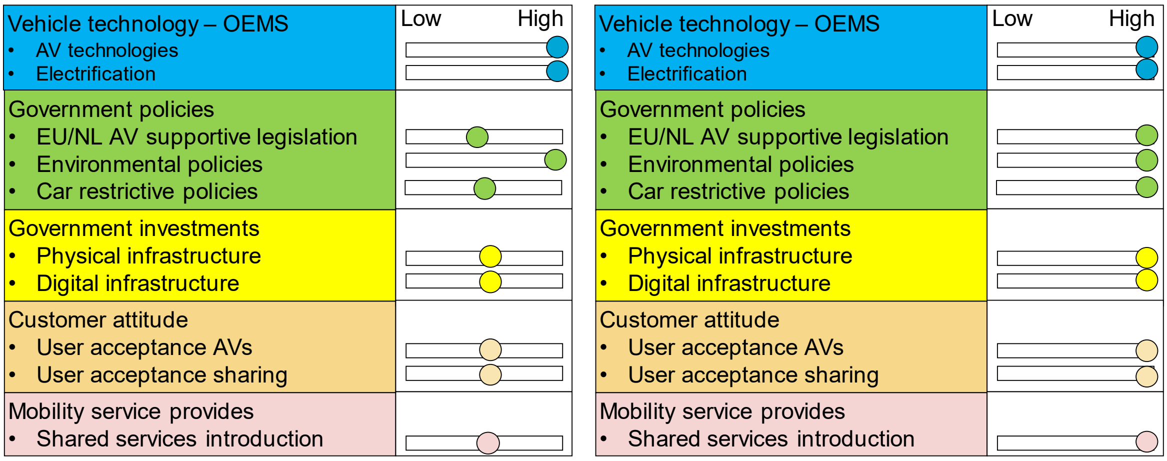

Figure 7: Switchboards scenario 4– share-topia (left 2040, right 2060)

Description 2040

In this scenario OEMS invest in AV technology because they see benefits for their customers and want to increase their market share. EU and the Dutch national and regional governments decide to invest in physical and digital infrastructure for private and shared CAVs, because of safety and capacity benefits. For safer implementation and cost-saving strategies, governments invest in physical and digital infrastructure for L4 public transport automation and decided to use private car-low zones to stimulate active modes and shared motorized modes and to increase the liveability in urban areas.

Customers see the added value of driving in automated mode on motorways and N-road and embrace the AVs. Their attitude towards sharing is improving because they see the added value and it helps them to reach their destinations. However, like governments, they are sceptical for driving on local roads, so L5 automation remains out of scope.

Result: L4 private CAVs on motorways and N-roads + L4 dedicated infrastructure for public transport automation, private car-low zones

Description 2060

In this scenario OEMS, governments and customers are all very supportive of 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. Electrification is proving to be a catalyst for the introduction and adoption of AVs and vehicles are built in such a way that all hardware for AVs is in place or can be installed via a retrofit. Software can be continuedly updated. Governments invest in physical and digital infrastructure for automated driving and allow vehicles on all roads. They require implementation of automated driving functions in all vehicles. However, 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 shared AVs on their roads to facilitate a specific set of trips (e.g. disabled people, large groceries etc.), but prohibit private CAVs in 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. Customers fully trust automated vehicles and a large group is intrinsically motived to share vehicles.

Result: L5 private CAVs, L5 public transport, private car-free zones, new shared services complement public transport (shuttles, shared rides)

Step 4: Estimating the impact of automated driving for each scenario

The group of experts who provided input regarding factors influencing the development of automated driving were asked in this step to estimate the penetration rate 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 value of travel time (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 chapter in Figure 8 to Figure 17. Since only 5 experts responded, the results are supplemented on the basis of the literature search that was carried out in a parallel project (Correia et al., 2023).

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 is 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 scenarios some experts still expect a small percentage of L5 vehicles scenario 3 (car-topia) and scenario 4 (share-topia). In 2060 the penetration rate of L3/L4 automated vehicles is expected to increase to 38%-64% depending on the scenario. In scenario 3 and 4 the penetration rates for level 5 vehicles in 2060 is expected to be 27% and 31% respectively. Note that the bandwidths for all these numbers are quite large, indicating that the estimates of the different expert 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.

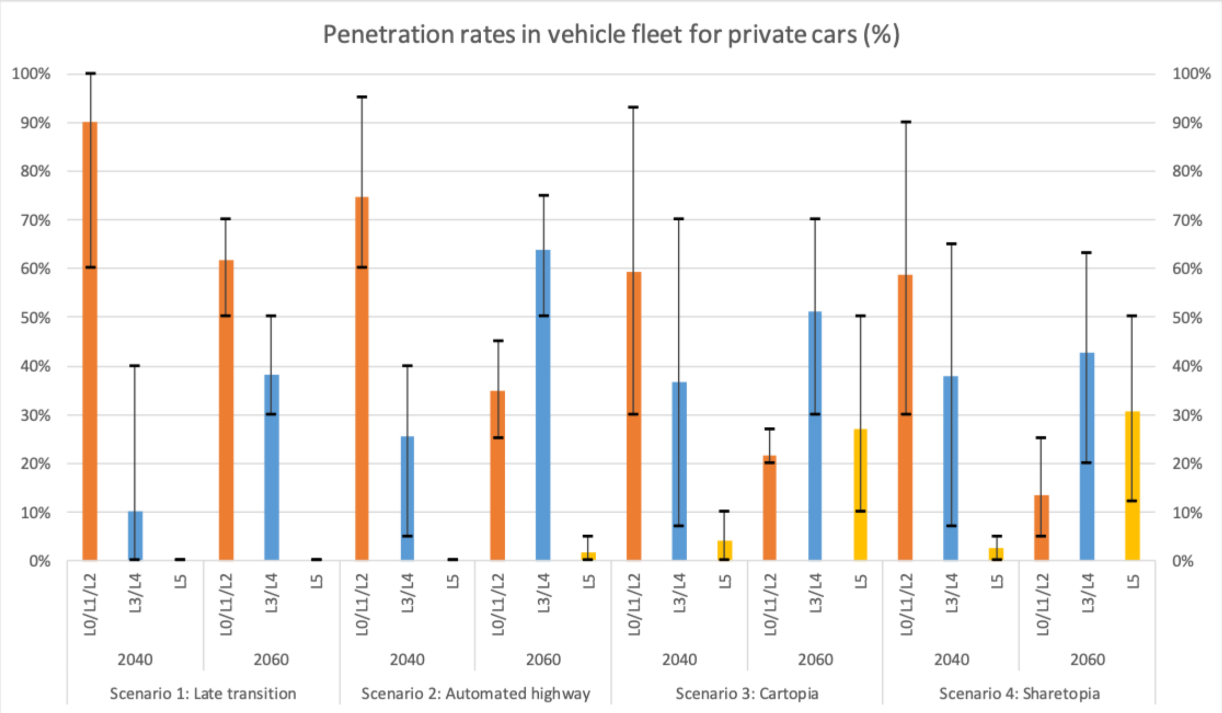

Figure 8: Penetration rates in vehicle fleet for private cars

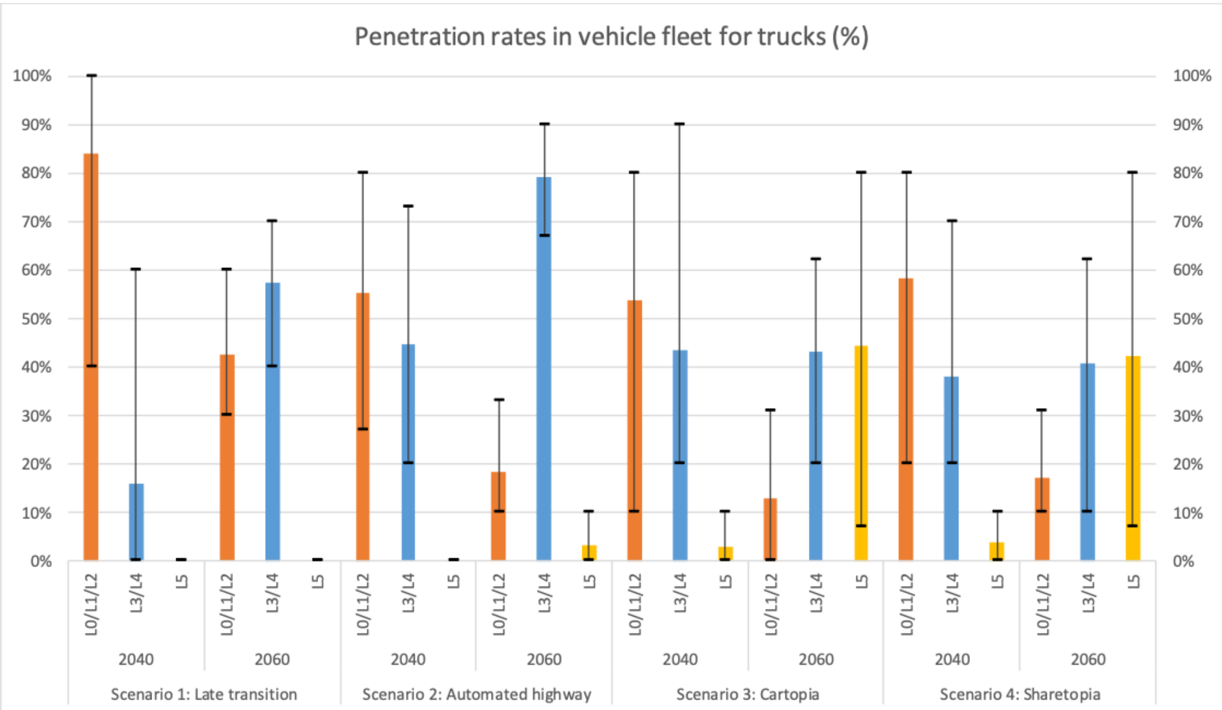

Figure 9: Penetration rates in vehicle fleet for trucks

The literature highlights that the share 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 bandwidths in the surveys, which are filled in by experts with possibly varying points of view and expectations of development and adoption paths and speeds. In literature, penetration rates between 37%-57% are expected for L3/L4 vehicles in 2035 (McKinsey, 2023). Penetration rates of 18% and 43% are expected for L5 vehicles in 2040 and 2060 respectively by Litman (2023) and of 19,8% (1,5%-38%) and 43% (5%-74%) by Nieuwenhuijsen et al. (2018). This shows that the consulted experts in our survey have lower expectations of automated driving than can be expected based on the literature.

Value of time

When looking at value of time (Figure 10), L5 is expected have the biggest impact. For private cars it is expect that the value of time reduces with 14% on average. However, the bandwidth is quite large. One expert expects a decrease in value of time of 40%. For L3/L4 an average decrease of 9% is expected. Private cars show a larger reduction than shared cars. For shared AVs one expert even expects an increase in value of time, which might be explained by the fact that the vehicle is shared with others.

In literature a reduction of 26%-32% in the value of time is expected for private AVs (Steck et al. 2018; Correia et al., 2019; Zhong et al., 2020). For shared 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.

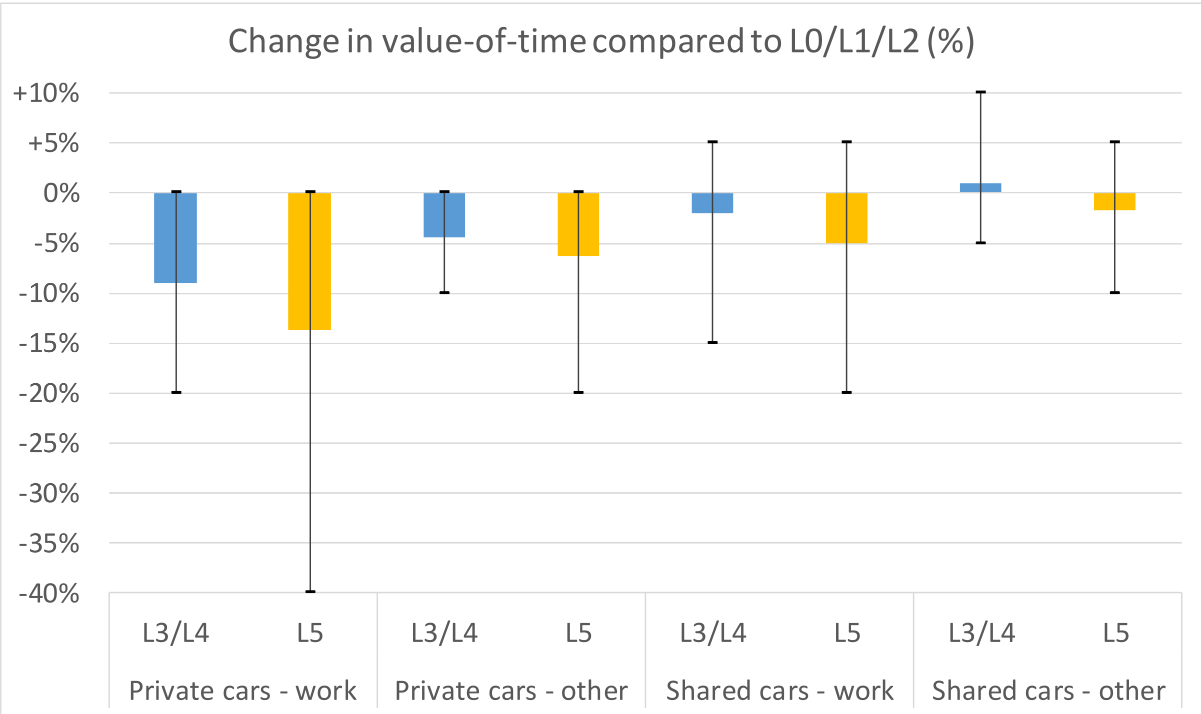

Figure 10: Change in value-of-time compared to L0/L1/L2

Time-headway

Figure 11 shows the expected impact on time headway between an AV and its predecessor. This is an approximation for the impact on capacity. If the time headways decrease, vehicle can drive closer to each other which has a positive impact on the capacity. However, besides time headways other factors like the response time, acceleration and deceleration possibilities, lane change behaviour etc. also affect the capacity.

Figure 11 shows that a decrease of time headways (read: increase in capacity) is expected for AVs (-16%) and CAVs (-22%), where the decrease is bigger for CAVs. Note that 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. Figure 12 shows the results excluding outliers. In that case, a small increase of time headways (= decrease in capacity) is expected for autonomous automated vehicles and a decrease for CAVs.

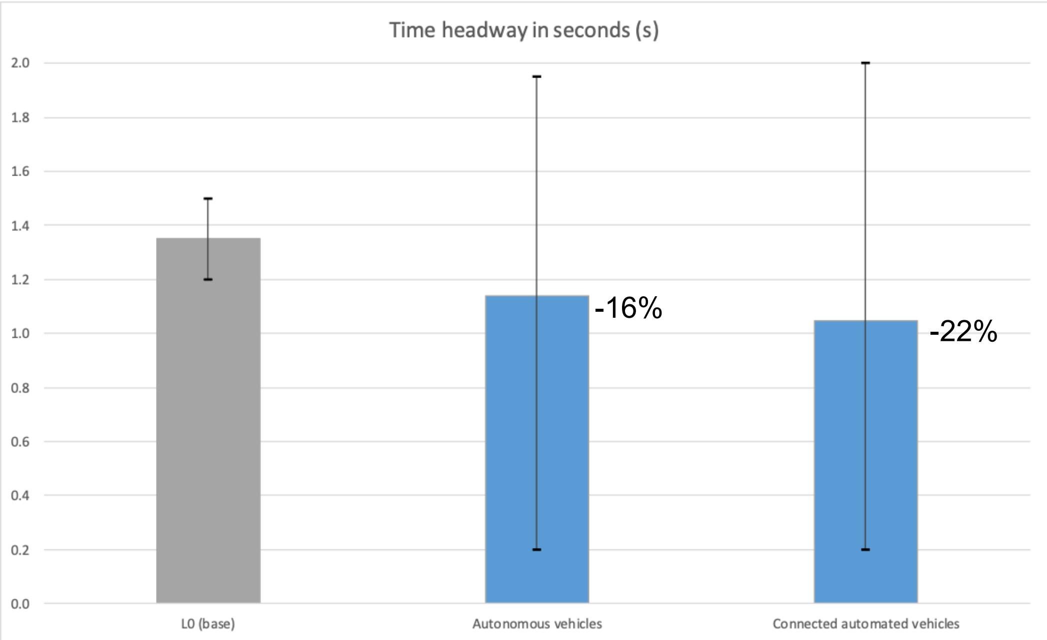

Figure 11: Time headway

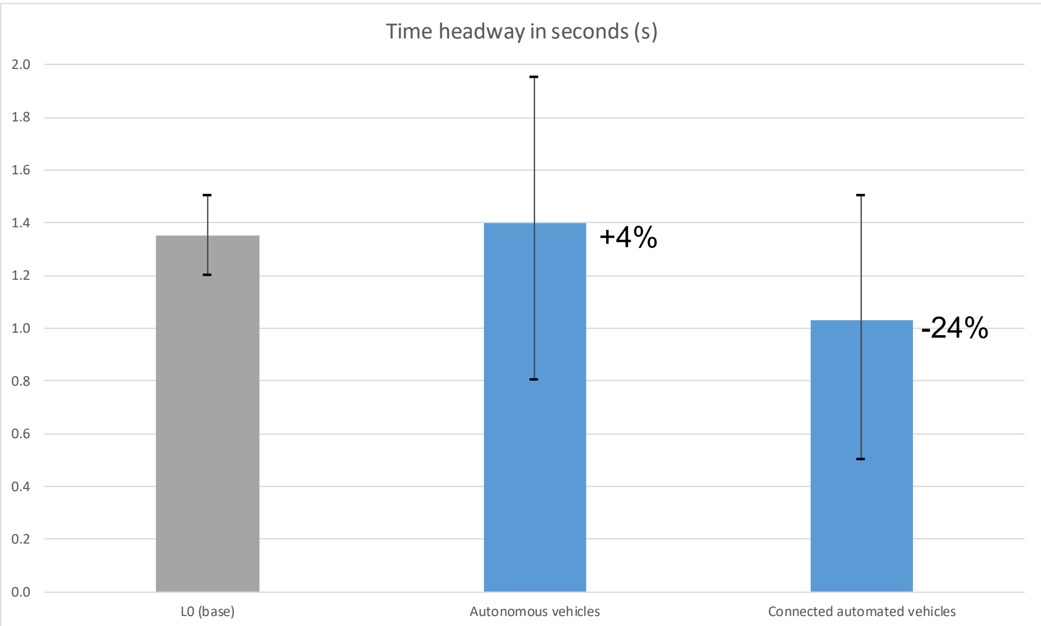

Figure 12: Time headway excluding outliers

The above is in line with the literature. Calvert et al. (2017) expect that a lengthy transitional period where only low vehicle automation (i.e. ACC) is present leading 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 by Gorter (2015). The experimental results suggested that only penetration rates exceeding 70% will improve traffic flow. In literature there are also some uncertainties. Punzo et al. (2021) and Shi and Li (2021) found that ACC can lead to a reduction or an increase in the time headway depending on the settings (capacity -32% - +36%).

Traffic and transport indicators

Figure 13 till Figure 16 show the change in number of car trips, average trip length, vehicle kilometres, and total travel times. In all these figures, all scenarios besides share-topia show an increase in number of car trips, average trip length, vehicle kilometres and total travel times. For share-topia, all results indicate, as expected, that private cars will be used less, but this will be more than compensated by the use of shared cars, still increasing the total number of trips.

For scenario 1 2040 en 2060 "late transition", scenario 2 2040 en 2060 "automated highway" and scenario 3 2040 "car-topia" the increases are: number of trips (+2% - +11%), average trip length (+1% - +12%), vehicle kilometres (+2% - +19%) and travel times (+1% - +9%). For scenario 3 2060 "car-topia", the average expected increases are much bigger: number of trips (+26%), average trip length (+39%), vehicle kilometres (+58%) and travel times (+42%).

Of course, the above-mentioned indicators are difficult to estimate by experts, because normally models are used to assess the traffic and transport impacts of developments and interventions. A quick analysis shows that for most of the above-mentioned scenarios the experts estimates are a bit higher than can be expected based on the elasticities found in literature. According to literature, the direct elasticity of the vehicles kilometres travelled for changes in travel time is -0.3 to -0.7, indicating that an average decrease in value of time of 14% results in an increase in vehicle kilometres travelled of 4% to 10%. If it is assumed that the expected increase in trips, are new trips not caused by a modal-shift then the results of the experts are even in line with literature. If they are caused by a modal-shift, then they are overestimated. For scenario 3 2060 "car-topia" the estimates of the experts clearly exceed the bandwidths of the literature.

The fact that the experts expect that the travel times increase less than the vehicle kilometres travelled suggests that the capacity increases or a longer part of the trips take place on motorways, whereas they also expect that in te scenarios without connectivity the capacity decrease.

Figure 17 depicts the share of vehicle kilometres per road type. Here we can observe that indeed for all scenarios in 2040 a small shift towards motorways is expected to occur. In 2060 for the first 2 scenarios a small shift towards motorways occurs as well, whereas for "car-topia" (scenario 3) a shift towards regional roads and cities is expected and for "share-topia" (scenario 4) an increase in vehicle kilometres of shared vehicles in cities is expected. This makes sense since private cars are not allowed in the cities in this scenario. It must be noted that in all graphs we observe large uncertainty bandwidths, which indicates that even within the considered scenarios, outcomes might vary substantially.

The literature study concludes that in scenarios with high automated driving functionalities in cars, VOTT (Value of Travel Time) is likely to decrease and the number of trips will increase, whereas the capacity of the roads will likely not be sufficient to absorb the higher future demand. This is in line with the survey. Furthermore, the literature study emphasizes that mode choice will play a large role in adoption and development of automated vehicles as well. Research is pointing in shared and non-shared directions, which can roughly be compared to scenario 3 and 4 in our study.

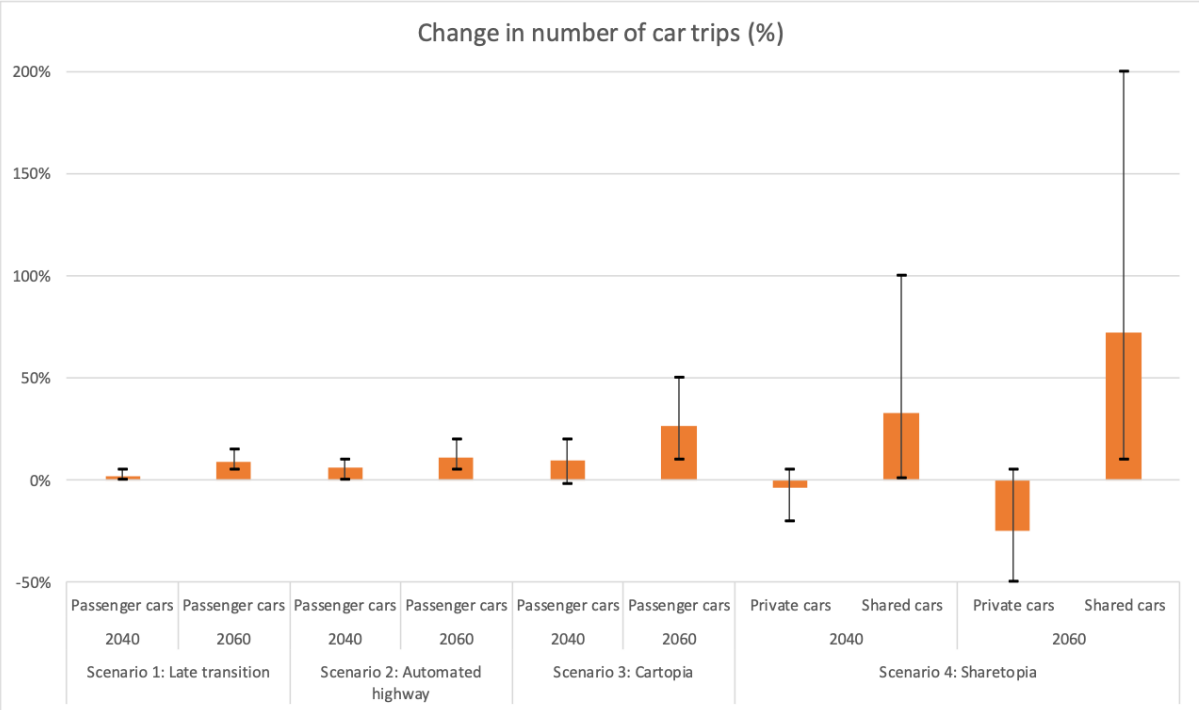

Figure 13: Change in number of car trips

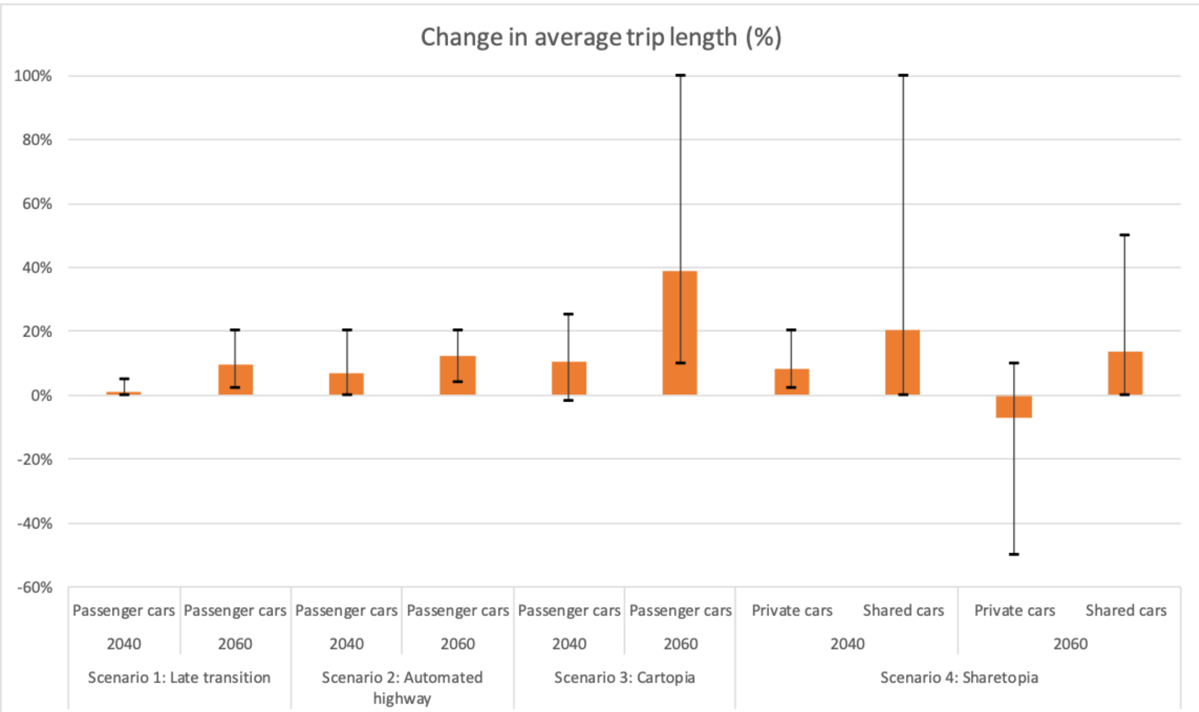

Figure 14: Change in average trip length

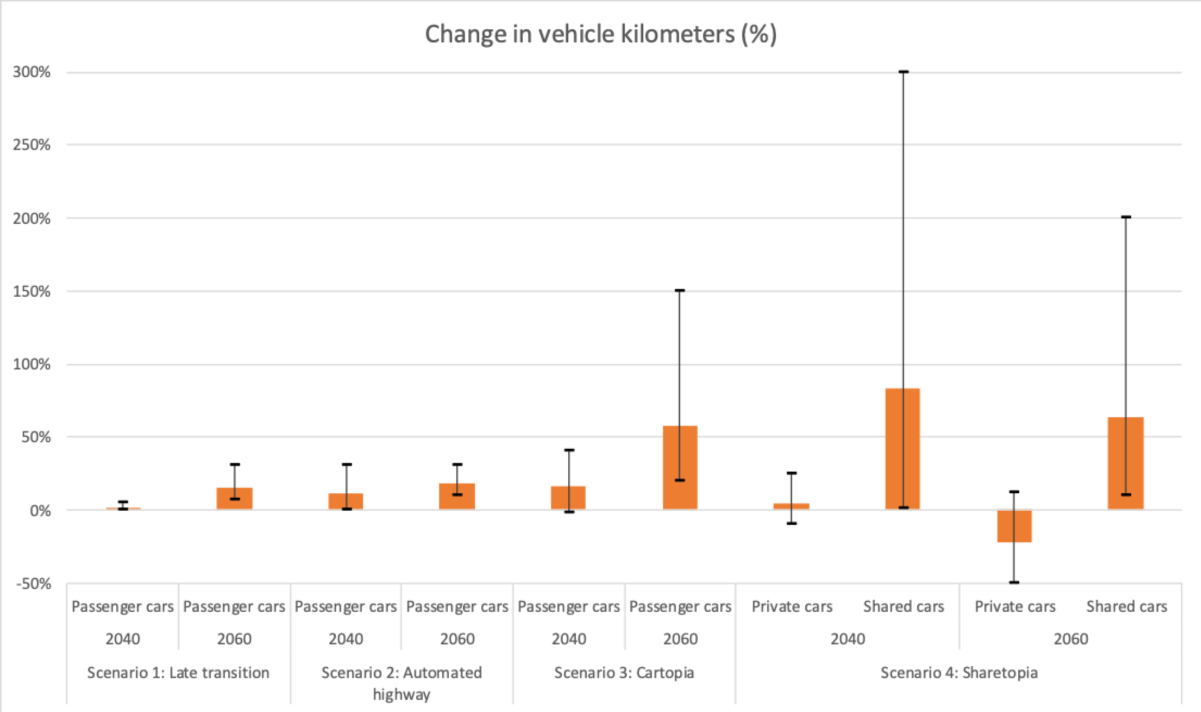

Figure 15: Change in vehicle kilometres

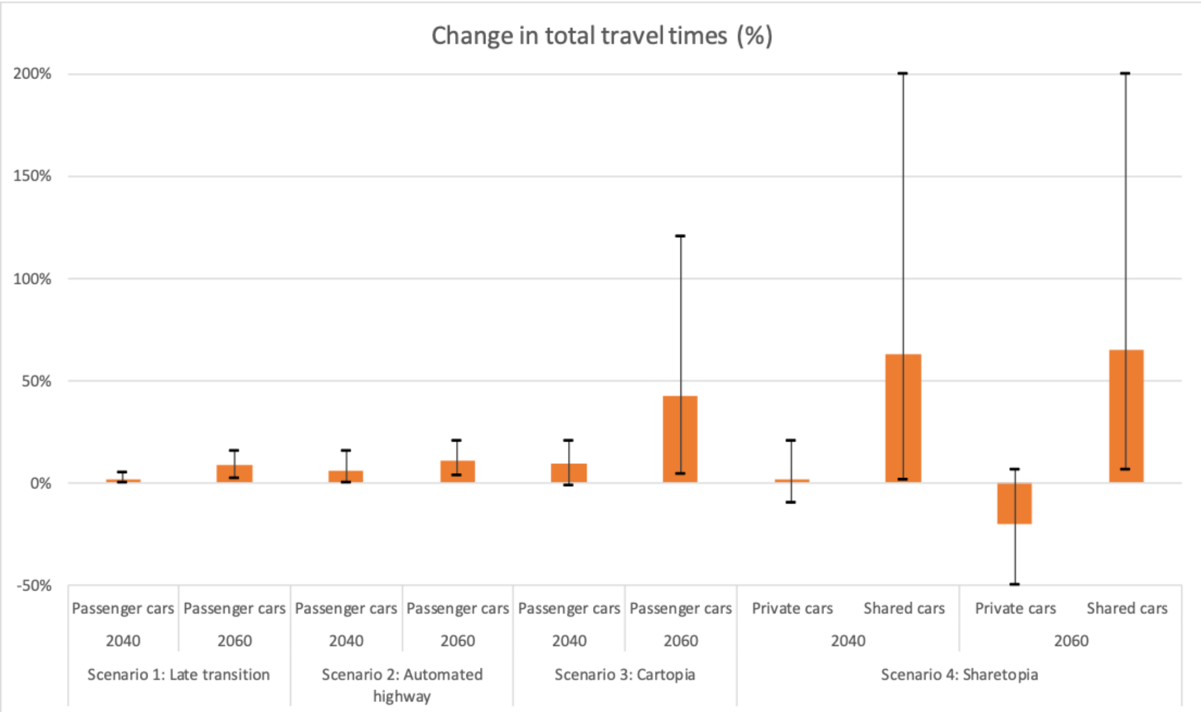

Figure 16: Change in total travel times

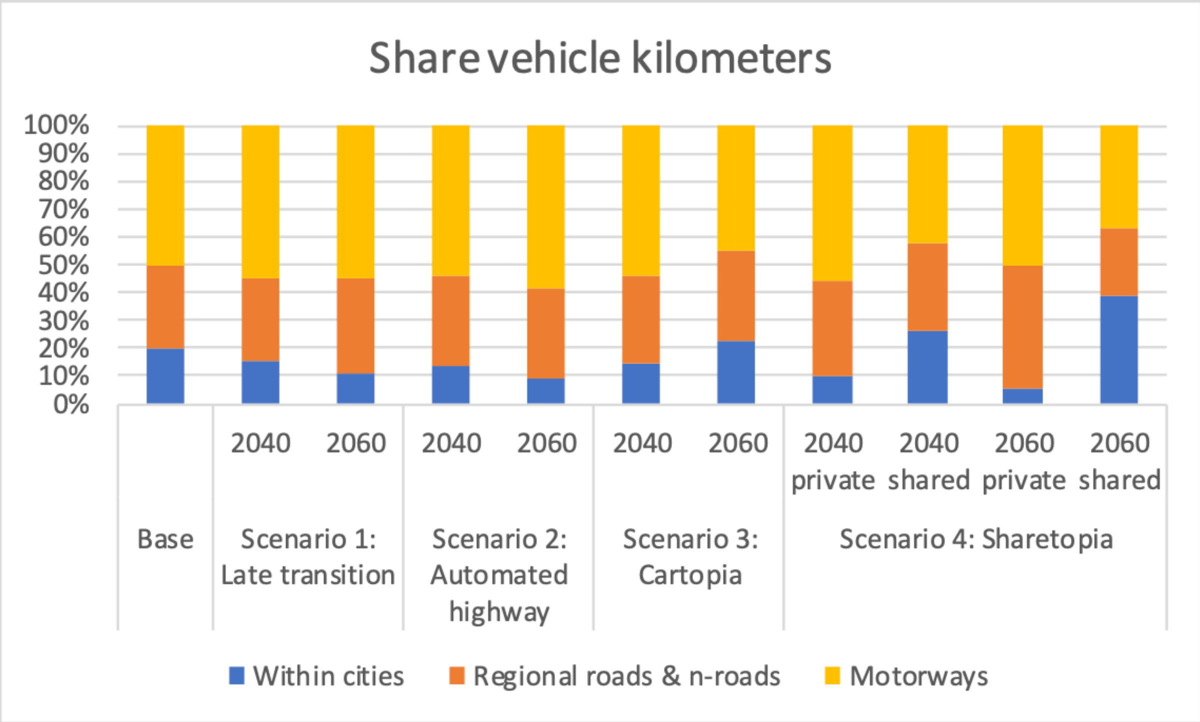

Figure 17: Share vehicle kilometres

Step 5: Review of the scenarios

During a third workshop, 4 external experts were invited to discuss and possibly supplement the scenarios together with PBL, 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. It is important to consider the introduction of connectivity, 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. Connected automated vehicles 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 the 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 and there are more confident policy makers, this may change.
- L5 automation: the fact that level 5 automation is considered 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. There is no difference between L4 and L5 once everybody can serve their needs with L4.
- Share-topia may be more likely given the current political climate.
- 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. Even if OEMS don't like it, they will adapt.

Impact of automated vehicles

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.

Value of time: the fact that people can do other things in AVs can indeed reduce the value of time significantly. The results from the survey seem a bit low, but this may be explained that some people might not be able to do other things in the car because of motion sickness. Researchers and OEMS are focussing on developments that minimize motion sickness. The fact that the decrease in value of time 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 (HVs). 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). You need more redundancy at low headways (higher cost). Therefore, the step from 1s to 0.8s is cheaper than for 0.8s to 0.6s. So, 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 1s when there are still HVs on the road, because that would require different legislation for AVs than for HVs. 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.

Side note: because manufacturers are not primarily interested in the capacity, but more in a safe and conformable road, the question is of the government can demand lower headways. The question is then also who should invest? Investments in shorter headways may reduce the need for investments in extra physical road infrastructure.

Change in number of car trips, average trip length, impact on vehicle kilometres and travel times.

The conclusion that automation leads to more trips and more vehicle kilometres is shared by the experts. A 10% increase in trips and average trips lengths may not sound much, but still has a big impact on vehicle kilometres and travel times.

Conclusions and recommendations

In this report four scenarios for automated driving have been constructed for 2040 and 2060:

- Scenario 1 "late transition". In this scenario automated driving developments go slow resulting in L2 AVs on motorways and N-roads in 2040 and L4 AVs on motorways and N-roads in 2060.
- Scenario 2 "Automated highway": In this scenario developments go a bit faster. L4 AVs on motorways and N-roads are already expected to reach higher penetration rates in 2040 and there will be some low critical connected applications like road works and accidents warnings. In 2060 there will be L4 CAVs on motorways and N-road and L4 dedicated infrastructure for public transport.
- Scenario 3 "Car-topia": In this scenario the developments go even faster. L4 CAVs on motorways and N-roads and L4 dedicated infrastructure for public transport is already expected in 2040. In 2060 L5 CAVs and public transport is expected.
- Scenario 4 "Share-topia": In this scenario also L4 CAVs on motorways and N-roads and L4 dedicated infrastructure for public transport is expected in 2040. However, to keep urban areas liveable also private car-low zones are introduced and sharing will become more popular. In 2060, technology has developed further resulting in L5 CAVs and public transport. In urban areas there are private car-low zones. Automated shuttles and other shared vehicles are introduced in these areas to keep them accessible for all.

For these scenarios, the expected traffic and transport impacts have been analysed. Based on this analysis, the following conclusions can be drawn for the three research questions:

What are possible future scenarios, how likely are these scenarios and what factors determine in which scenario we will end up?
Four possible future scenarios have been defined as briefly summarized above. The external experts think that the scenarios with CAVs are most likely (i.e. scenario 2 2060 and scenario 3 and 4 2040 and 2060), because it has been recognized by the government that connectivity is very important to avoid capacity reductions and to increase safety. Governments and OEMS are already investing in connectivity. On the other, it remains quite challenging to introduce connectivity because it requires European standards. Therefore, scenarios without CAVs cannot yet be ruled out.

Since sharing and car-low zones are high on the political agenda, scenario 4 2040 "share-topia" is considered very likely. L5 automation is considered unlikely in 2060. However, if this is replaced by L4+ automation (in some areas, vehicles can drive in automated mode on all road within this area) this scenario becomes likely after all.

The factors that determine in which scenario we will end up are:
- the investments of OEMS in AV-technology and electrification;
- the policies of the European and national, regional and local governments regarding AV supportive legislation, environment and car restrictions;
- investments of the government in physical and digital infrastructure;
- customer attitude towards automation and sharing; and
- the introduction of shared mobility services by mobility service providers.

What is the bandwidth of possible impacts of automated driving on the value of time, capacity and traffic conditions considering the development of market penetration rates over time?
The expected impacts are summarized below:

- Penetration rates: for cars, it is expected that in 2040 penetration rates of L0/1/2 vehicles is still higher than 59% in all scenarios, for L3/4 the penetration rates vary between 10% – 38%. In 2060, the penetration rate of L3/L4 automated vehicles is expected to increase to 38%-64% depending on the scenario. In scenario 3 and 4 in 2060, the penetration rate for level 5 vehicles is expected to be 27% and 31% respectively. 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, because they have a higher renovation rate and the economic benefits are higher
- Value of time: It is expected that the value of time will reduce with about 14% according to the survey results and 26%-32% according to literature. The difference can possibly be explained by the fact that some experts believe that some people might not be able to do other things in the car because of motion sickness. Researchers and OEMS are focussing on developments that minimize motion sickness.
- The time headways (approximation for capacity) are expected to increase with 4% for AVs (= capacity reduction) and decrease with 24% for CAVs to 1.0-1.3s. This is in line with literature, although in literature it is also suggested that only penetration rates exceeding 70% will improve traffic flow. These penetration rates may be reached by 2060. This is also in line with the fact that experts believe that it will be difficult to have time headways <1s because of (European) legislation.
- Automated driving will make cars more attractive leading to more trips and an increase in average trip length, vehicle kilometres travelled and total travel times. By 2040, this impact is limited to a 2%-16% increase in vehicle kilometres and 1%-9% in total travel times. By 2060 impacts are still limited in the first two scenarios to an 15%-19% increase in vehicle kilometres and an 9%-11% increase in travel times. In the third scenario "car-topia" an average increase of 58% in vehicle kilometres is expected as well as an increase of 42% in total travel times. In the fourth scenario the restriction of the usage of private cars in cities will lead to fewer private car kilometres in cities and an increase in shared vehicle kilometres.

Note that the bandwidths for all these numbers are not explicitly reported above, but they are quite large, indicating that the estimates of the different expert differ quite a bit.

What are the implications of the scenarios for infrastructure policies and investments in the next 8 years?
The results indicate that investments in digital infrastructure are needed to avoid a capacity reduction that may be caused by autonomous (= not connected) vehicles. Since automation is expected to lead to an increase in vehicle kilometres travelled and travel times (despite the increase in capacity), it can be beneficial to invest in extra infrastructure. However, the reduction in value of time reduces these extra benefits again. Especially, the third and fourth scenario may require extra physical infrastructure on motorways and N-roads, but potentially also on local roads to make vehicle automation on these roads possible.

Governments play an important role in the implementation of automated driving. To a large extent, they can determine in which scenario we will end up. Therefore, they can also decide themselves if scenario 3 and 4 are desirable future scenarios and, if so, they can invest extra in physical infrastructure.

Recommendations

Since it is difficult for experts to estimate the traffic and transport effects of automated driving, it is recommended to use the national model system (LMS) to assess these effects. The experts estimates of the penetration rates, value of time and time headways can be used as input. The time headways can be converted to passenger car equivalents (PCU factors) for automated vehicles. It is also possible to specify on which roads AVs or CAVs are allowed to drive in automated mode. Based on these inputs, the LMS computes the destination choice, mode choice, route choice and congestion effects and therewith the impact on number of car trips, vehicle kilometres and travel times.

Furthermore, the focus of this study was on regular conditions. However, about 20%-25% (Snelder et al., 2013) of all the delays on motorways is caused by accidents. It is expected that AVs are safer than human driven vehicles and that a subset of these accidents can be avoided by AVs. These benefits also need to be considered when making infrastructure investment. It is therefore recommended to analyse in more detail what the expected impact is of AVs on accidents and delays caused by accidents.

Finally, certain weather conditions like fog, snow and heavy rain can make driving in automated mode difficult, if not impossible. 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.

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