

Development of automated vehicles in the Netherlands: scenarios for 2030 and 2050

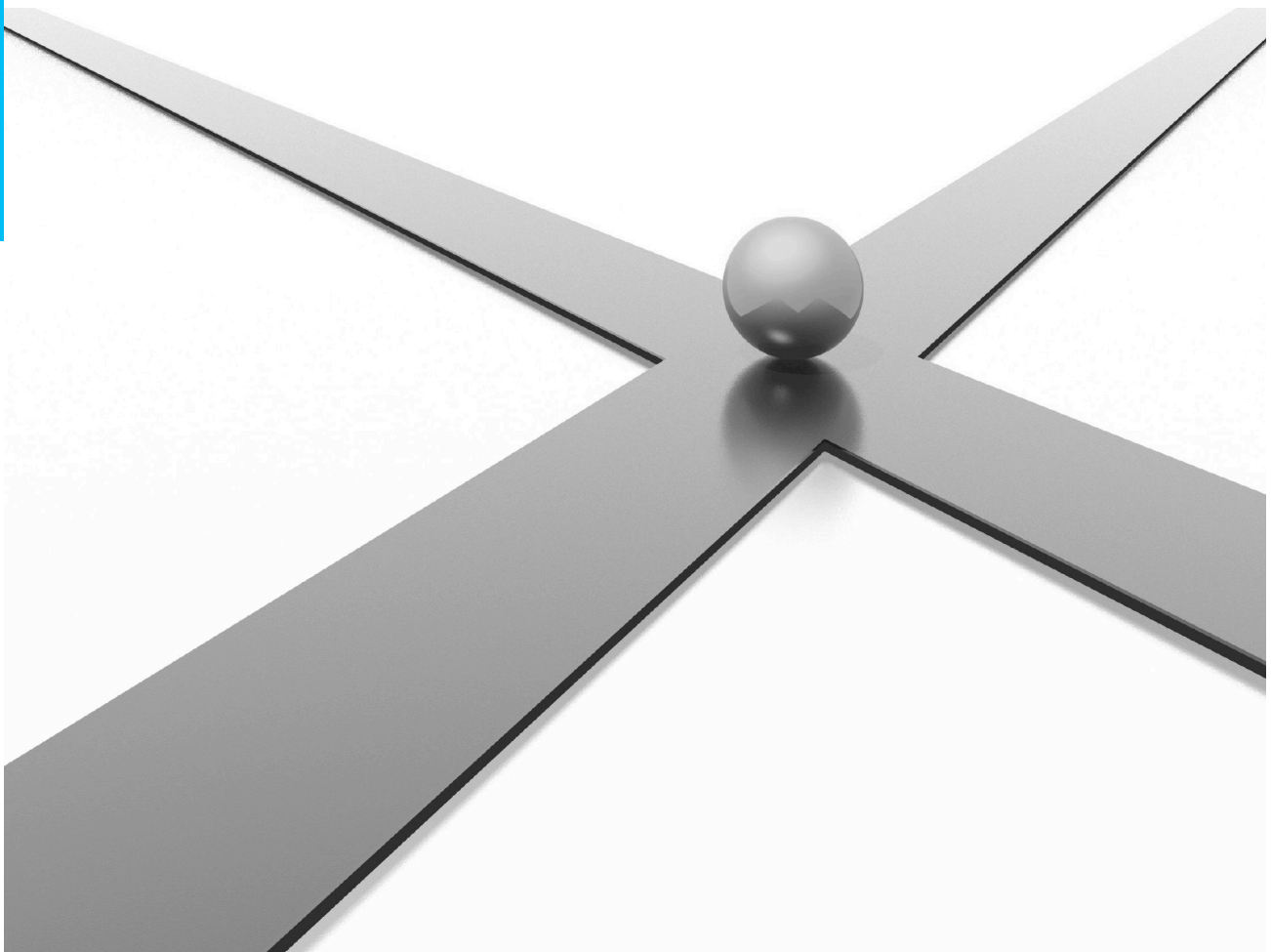
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10. Abstract

This study identified through scenario analysis plausible future development paths of automated vehicles in the Netherlands and estimated potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. Four scenarios were constructed assuming combinations of high or low technological development and restrictive or supportive policies for automated vehicles (*AV ...in standby*, *AV ...in bloom*, *AV ...in demand*, *AV ...in doubt*). According to the scenarios, fully automated vehicles are expected to be commercially available between 2025 and 2045, and to penetrate market rapidly after their introduction. Complexity of urban environment and unexpected incidents may influence development path of automated vehicles. Development of automated vehicles is expected to have implications on mobility in all scenarios. Hence, the Dutch government is expected to take measures (e.g., travel demand management) to curb growth of travel and subsequent externalities in three out of the four scenarios.

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Summary

Automated vehicles are expected to be part of the transportation system within coming years. Certain impacts are possible on transportation demand and planning. The aim of this project is to provide input to PBL – Netherlands Environmental Assessment Agency on whether to include automated vehicles in the forthcoming long-term foresight study 'Prosperity and Environment' (WLO). Therefore, we identify plausible future development paths of automated vehicles in the Netherlands and estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. The research questions of the project are the following:

- ✓ What are the possible developments for automated vehicles and which factors will determine these developments on a time horizon up to 2030 and 2050? What stages in this development can be distinguished?
- ✓ What are the implications for road capacity, and traffic flow efficiency? Does this differ between urban roads, regional roads and motorways?
- ✓ What are the implications for users (value of time) and consequently for travel behaviour?
- ✓ To what extent might automated vehicles affect transportation planning?

We conducted a scenario analysis that involved experts from various planning, technology, and research organizations in the Netherlands and was completed in three workshops. Four scenarios about development and implications of automated vehicles in the Netherlands was constructed through a structured deliberative process that comprised five sequential steps: (a) identification of key factors and driving forces of development of automated vehicles, (b) assessment of impact and uncertainty of driving forces, (c) construction of the scenario matrix, (d) estimation of penetration rates and potential implications of automated vehicles in each scenario, and (e) assessment of the likelihood and overall impact of each scenario.

Sixteen key factors and five driving forces behind them were identified as critical in determining future development of automated vehicles in the Netherlands. Technology and policies were selected as the most relevant (influential and unpredictable) driving forces to build our scenario matrix. The four scenarios were constructed assuming combinations of high or low technological development and restrictive or supportive policies for automated vehicles. Although scenarios were built around permutations of those two driving forces, we also incorporated all remaining driving forces (customers' attitude, economy, environment) aiming to capture as much as possible of the complexity surrounding this exercise. The four scenarios are:

- ✓ *AV ...in standby*
- ✓ *AV ...in bloom*
- ✓ *AV ...in demand*
- ✓ *AV ...in doubt*

The first scenario (*AV ...in stand by*) describes a path where although automated vehicles technology develops rapidly (fully automated vehicle are commercially available in 2030), the Dutch government is reluctant to invest on it because they see a lot of risks surrounding this technology. Thus, development of automated vehicles is industry driven, succeeding to overcome initial customers' skepticism and achieving high penetration rates, especially after 2030 when fully automated vehicles become available. Initial fears of the Dutch government about potential

negative implications, like strong induced travel demand, sprawling trends and a pressure to conventional public transportation services are confirmed.

The second scenario (*AV ...in bloom*) describes a path where both technology and policies of the Dutch government offer a positive context for the development of automated vehicles. Fully automated vehicles become available in 2025 and a progressive regulatory framework, involving also high subsidies, is adopted. The positive economic context, the supportive governmental policies, but also the wider societal changes of this period push the demand for automated vehicles high. Also, the growth of fully automated taxis operating 24/7 is enormous. The Dutch government soon realizes that demand management and further regulatory measures should be taken to curb fast growing vehicle travel because of the introduction of automated vehicles.

The third scenario (*AV ...in demand*) describes a path where the Dutch government promotes automated vehicles through several measures because they are very optimistic about potential societal benefits (e.g., congestion relief and reduction of accidents). However, technological evolution is very slow (fully automated vehicles become available only in 2040) for several reasons including some fatal accidents during initial introduction of automated vehicles. Thus, demand incrementally increases up to 2040 and significantly expands thereafter, when the psychological barriers for this technology are removed. The combination of a decrease in value of time and an increase in capacity results in more VKT, which urges the Dutch government to take travel demand management measures.

The fourth scenario (*AV ...in doubt*) describes a path where none of the basic forces (high technological development, supportive policies and positive customers' attitudes) for the development of automated vehicles exist. The Dutch government estimates that vehicle automation could have counter-effective results for the transportation system. They expect that the system will not evolve enough to become fully automated. Also, several incidents in the auto and high tech industry slowdown technological growth in this field. Fully automated vehicles hit the market only in 2045. Automated vehicles evolve as a technology for the upper class that could pay a premium to have it. Fully automated taxis offering premium services (work and rest spaces on the move) become also available after 2045.

According to our scenario analysis:

- ✓ fully automated vehicles are expected to be commercially available within a time window of twenty years (between 2025 and 2045), while the respective time-window for conditional automation is smaller (ten years) and more immediate (between 2018 and 2028),
- ✓ full vehicle automation will likely be a game changer, driving the demand for automated vehicles high. Penetration rates of automated vehicles are expected to vary among different scenarios between 1% and 11% (mainly conditionally automated vehicles) in 2030 and between 7% and 61% (mainly fully automated vehicles) in 2050,
- ✓ vehicle automation and cooperation are expected to follow converging evolution paths. The type of cooperation (V2I, V2V) will likely vary though among different scenarios according to the main drivers (policies, technological development),
- ✓ complexity of urban environment is expected to influence development path of automated vehicles either by inducing regulation allowing automated vehicles to travel only in motorways or by complicating and subsequently delaying technological development in this field,

- ✓ unexpected incidents like fatal accidents; bankruptcy or change in strategic priorities of major industry players could significantly influence the development path for automated vehicles not only in the Netherlands, but also in any country,
- ✓ development of automated vehicles is expected to have implications on mobility in all scenarios. These implications vary from very important in the 'AV ...*in bloom*' scenario to minimal in the 'AV ...*in doubt*' scenario,
- ✓ the Dutch government is expected to take measures (e.g. travel demand management) to curb growth of travel and subsequent externalities in three out of the four scenarios.
- ✓ scenario 2 (AV ...*in bloom*) and scenario 3 (AV ...*in demand*) were perceived as the most likely to happen in the future, while likelihood of scenario 1 (AV ...*in standby*) and scenario 4 (AV ...*in doubt*) was assessed lower.

In conclusion, our study suggests that fully automated vehicles will likely be a reality between 2025 and 2045 and are expected to have significant implications for mobility and planning policies in the Netherlands. The pace of development and subsequent implications largely depend on technological evolution, policies and customers' attitude.

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1

Introduction

Automated vehicles are expected to be part of the transportation system within coming years. Certain impacts are possible on transportation demand and planning. The aim of this project is to provide input to PBL – Netherlands Environmental Assessment Agency on whether to include automated vehicles in the forthcoming long-term foresight study 'Prosperity and Environment' (WLO). Therefore, we identify plausible future development paths of automated vehicles in the Netherlands and estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. The research questions of the project are the following:

- ✓ What are the possible developments for automated vehicles and which factors will determine these developments on a time horizon up to 2030 and 2050? What stages in this development can be distinguished?
- ✓ What are the implications for road capacity, and traffic flow efficiency? Does this differ between urban roads, regional roads and motorways?
- ✓ What are the implications for users (value of time) and consequently for travel behaviour?
- ✓ To what extent might automated vehicles affect transportation planning?

The rest of this report is structured as follows. Section 2 presents the results of a literature review¹ about the development and potential implications of automated vehicles. In section 3, we describe our methodology for the construction of the scenarios and in section 4 we present four scenarios about the development and possible effects of automated vehicles in the Netherlands. We close this report with our conclusions in section 5.

¹ The literature review section is partly reproduced with permission from the following research report: Snelder, M., van Arem, B., Hoogendoorn, R., van Nes, R. (2015), Methodische Verkenning Zelfrijdende Auto's en Bereikbaarheid, TU Delft T&P 1501, ISSN: 2212-0491.

2

Literature review

This section provides an overview of the literature related to the research questions of this project. Thus, it first focuses on studies exploring potential development paths of automated vehicles and then it reviews research about effects of automated vehicles on road capacity, traffic flow, value of time, travel behaviour, travel time, safety, energy and the environment, and transport infrastructures. The aim is to provide adequate background information for the scenario workshops.

2.1 Definitions and possible development of automated vehicles

In 2014, TrafficQuest published a report on the state of art with respect to cooperative systems and automated driving (TrafficQuest, 2014 - forthcoming). This report covers the following topics:

- ✓ What are we talking about? Definitions, areas of influence (network, local, autonomous), cooperative systems and services, goals of automated driving, roadside-vehicle transition and integration, autonomous versus cooperative – manual versus automatic, communication technologies, data exchange, fusion and algorithms, and enablers for accelerated implementation.
- ✓ How much progress has been made in the Netherlands? Policy context, projects in the Netherlands, demonstrations of cooperative systems, test facilities and tools, and partnerships and networks.
- ✓ How much progress has been made elsewhere? Europe, USA, Japan, other countries and international co-operation.
- ✓ What are the expected benefits? Expected impact of cooperative systems and automated driving and effects in figures.
- ✓ Where are we headed?

To a large extent, the TrafficQuest report answers the question of what is known in the literature regarding plausible scenarios for automated vehicles. In this section, we summarise some (though not all) of the elements related to the above-mentioned scenarios, including some sources on this subject.

Two main taxonomies of vehicle automation is distinguished internationally (NHTSA, 2013; SAE International, 2014). These are displayed in figure 1. A plausible scenario is that more and more vehicles will be launched on the road where an increasingly larger share of the driving task will be taken over by the vehicle itself.

Summary of SAE International's Draft Levels of Automation for On-Road Vehicles (July 2013)

SAE's draft levels of automation are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or automated driving system, as appropriate. NHTSA's levels of automation are provided to indicate approximate correspondence.

NHTSA level	SAE level	SAE name	SAE narrative definition	Execution of steering and acceleration/deceleration	Monitoring of driving environment	Backup performance of dynamic driving task	System capability (driving modes)
<i>Human driver monitors the driving environment</i>							
0	0	Non-Automated	the full-time performance by the <i>human driver</i> of all aspects of the <i>dynamic driving task</i> , even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	1	Assisted	the <i>driving mode</i> -specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	Human driver and system	Human driver	Human driver	Some driving modes
2	2	Partial Automation	the <i>driving mode</i> -specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the <i>human driver</i> perform all remaining aspects of the <i>dynamic driving task</i>	System	Human driver	Human driver	Some driving modes
<i>Automated driving system ("system") monitors the driving environment</i>							
3	3	Conditional Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> with the expectation that the <i>human driver</i> will respond appropriately to a <i>request to intervene</i>	System	System	Human driver	Some driving modes
4	4	High Automation	the <i>driving mode</i> -specific performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> , even if a <i>human driver</i> does not respond appropriately to a <i>request to intervene</i>	System	System	System	Some driving modes
	5	Full Automation	the full-time performance by an <i>automated driving system</i> of all aspects of the <i>dynamic driving task</i> under all roadway and environmental conditions that can be managed by a <i>human driver</i>	System	System	System	All driving modes

Figure 1: Levels of automated driving (SAE International, 2014)

The question is: to what extent can the systems, which are taking over the driving task, be considered cooperative? Bhat (2014) describes two conceivable scenarios: a 'capitalistic self-driving' scenario and a 'socialistic connected vehicle' scenario. The characteristics of these two scenarios are outlined in figure 2. In Timmer and Kool (2014), two similar scenarios are outlined: the autonomous robotic car and the cooperative self-steered vehicle. They indicate that Dutch policy in recent years has focused on improving traffic management and the development of cooperative systems because of the positive contribution made by these systems to government objectives, such as fewer traffic jams and safer and more sustainable traffic. Hence, they see the development track towards robotic cars (that do not communicate) as a disruptive innovation for the Netherlands and Europe. Since robotic cars are unable to drive in 'convoys', they contribute to a lesser extent in terms of reducing traffic jams and creating environmental savings. According to Timmer and Kool (2014), there is a growing awareness of the fact that cooperative and autonomous systems will have to complement one another in order to develop a sufficiently reliable and cost-effective self-steered car.

Self-Driving Vehicle (e.g., Google)	Connected Vehicle
AI located within the vehicle	AI wirelessly connected to an external communications network
"Outward-facing" in that sensors blast outward from the vehicle to collect information without receiving data inward from other sources	"Inward-facing" with the vehicle receiving external environment information through wireless connectivity, and operational commands from an external entity
AI used to make autonomous decisions on what is best for the individual driver	Used in cooperation with other pieces of information to make decisions on what is "best" from a system optimal standpoint
AI not shared with other entities beyond the vehicle	AI shared across multiple vehicles
A more "Capitalistic" set-up	A more "Socialistic" set-up

Figure 2: Self-driving and connected vehicle scenarios (Bhat, 2014)

In line with this, TrafficQuest, (2014) indicates that developments can take place along two axes (autonomous to cooperative and manual to automated). In this context, they identify two game changers²: "The first is the transition from autonomous to cooperative driving. Initially, this will mainly involve advisory systems, which can lead to a great deal of benefits (e.g. advanced information and navigation systems and communicative eco-driving support systems). Extensive automation of the driving task (also in an autonomous form) is still somewhat in the future. The 'human factor' is very important here, especially in the transition from automation level 2 to automation level 3 (game changer 2). However, the transition from level 2 to 3 may offer even greater benefits (based on the assumption that this will help avoid human inefficiency)."

The follow-up question is: how quickly can the different levels of automated driving be achieved? A survey was held during the Automated Vehicles Symposium 2014, where experts were asked about when they expected (SAE) levels 3, 4 and 5 of automated driving to be introduced (Underwood, 2014). The results of this survey are summarised in figure 3. The start and end points of the lines in the figure indicate the minimum and maximum expectations. The labels indicate the expected (median) year of introduction.

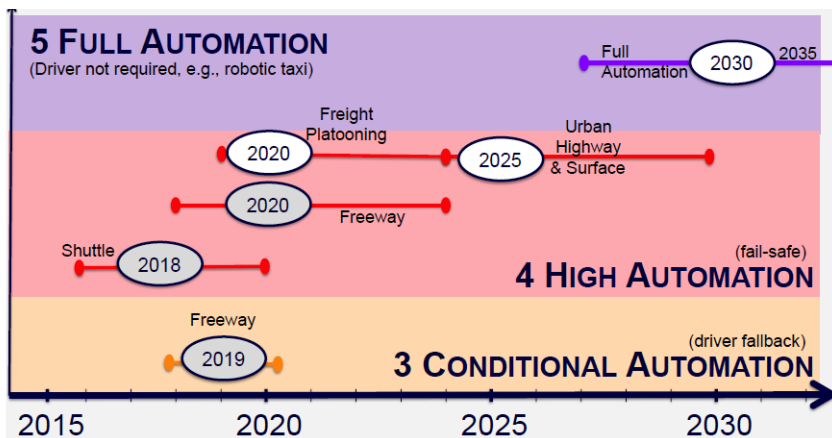


Figure 3: Expected market launch of automated vehicles (Underwood, 2014).

Figure 3 does not indicate anything about the penetration rates of the various levels of automated driving. Figure 4 displays the sales percentage in 2012 of various driver assistance systems in the Netherlands, according to van Calker and Flemming (2013). Here, R1 is the penetration rate calculated based on the data, R2 is the estimated lower limit, R4 is the estimated upper limit and R3 is an adjusted estimated penetration rate. The adjusted estimated penetration rate (R3) for 2011 is shown on the right-hand side, for the sake of comparison. Moreover, Kyriakidis et al. (2014) reported that 69% of the respondents in their internet-based questionnaire survey expected fully automated vehicles to reach 50% penetration rate up to 2050.

² Game changers: major steps in the development process, which can have a great impact on traffic operation and hence on traffic safety and the environment.

System	System Name	Deployment Rates				Correction Factor	Data Coverage	R3
		R2	R1	R3	R4			
PS 1	Blind Spot Monitoring [summary]	2,231%	3,203%	2,611%	22,452%	1,4698	69,669%	0,197%
PS 1.1	Lane Change Assist with Intervention into Steering	0,000%	0,000%	0,000%	0,000%	1,0000	99,703%	0,000%
PS 1.2	Lane Change Assist with Intervention into Braking	0,061%	0,063%	0,063%	0,783%	0,2791	97,836%	0,022%
PS 1.3	Lane Change Assist without Intervention into Driving Dynamics	2,170%	3,033%	2,485%	14,155%	1,4768	71,536%	0,167%
PS 2	Adaptive Headlights [summary]	3,444%	8,414%	5,479%	62,510%	0,3540	40,935%	5,129%
PS 2.1	Adaptive Headlights	1,863%	1,953%	1,869%	6,258%	0,4252	95,405%	0,671%
PS 2.2	Bending Light	3,444%	8,414%	5,479%	62,510%	0,3540	40,935%	3,814%
PS 3	Obstacle & Collision Warning [summary]	2,459%	4,171%	3,908%	27,090%	0,7358	58,949%	0,685%
PS 3.1	Adaptive Cruise Control	2,444%	4,062%	3,678%	26,344%	0,7436	60,168%	0,527%
PS 3.2	Precrash System	1,947%	2,303%	2,800%	9,744%	1,2331	84,543%	0,244%
PS 3.3	Automatic Emergency Brake	2,264%	3,127%	3,532%	11,467%	0,9703	72,389%	0,167%
PS 4	Lane Keeping Support [summary]	2,302%	3,956%	3,193%	30,177%	1,0092	58,187%	0,221%
PS 4.1	Lane Keeping Assist with Intervention into Braking	0,061%	0,063%	0,063%	0,783%	0,2791	97,836%	0,022%
PS 4.2	Lane Keeping Assist with Intervention into Steering	0,175%	0,232%	0,217%	1,232%	0,1877	75,587%	0,078%
PS 4.3	Lane Departure Warning	2,235%	3,071%	2,711%	12,624%	1,0315	72,774%	0,140%
PS 5	Automatic Emergency Brake [summary]	2,264%	3,127%	3,532%	7,675%	0,9703	72,389%	0,167%
PS 6	Eco Driving Support [summary]	21,274%	56,388%	34,002%	83,546%	2,1582	37,727%	9,992%
PS 6.1	Start-Stop Assistant	21,211%	56,223%	33,913%	83,484%	2,1622	37,727%	8,652%
PS 6.2	Gear Shift Indicator	0,167%	0,407%	0,246%	59,076%	3,0206	41,091%	0,216%
PS 6.3	Eco Driving Monitoring	0,002%	0,003%	0,002%	8,836%	0,1766	56,589%	0,000%
Registrations							502.527	

Figure 4: Sales percentage of various driver assistance systems in 2012 (left) and 2011 (right) (van Calker & Flemming, 2013)

How fast the automated vehicle can be launched depends on many different factors, such as the speed of technological developments, speed with which various obstacles are eliminated, government incentives, vehicle life span, vehicle purchase prices, and subscription costs for services necessary for using an automated vehicle. Litman (2014) has estimated the penetration rate of fully automated vehicles based on how fast air bags, automatic transmission, navigation systems, GPS services and hybrid vehicles are introduced and based on assumptions regarding the evolution of the purchase price and the time by which the vehicles will be developed by default as automated vehicles. He concludes that, in the United States, it may take 10 to 30 years from the time of launch before the automated vehicle dominates the car sales market and another 10 to 20 years before the majority of travel is done using automated vehicles (see Figure 5).

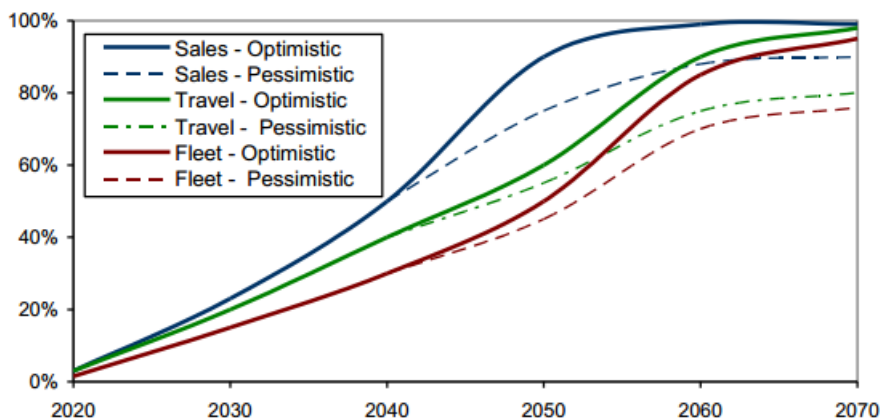


Figure 5: Sales percentage and penetration rate of automated vehicles (Litman, 2014).

2.2 Effect of automated vehicles on road capacity

Figure 6 displays the relationship between ITS systems (automated and cooperative) and capacity according to Hoogendoorn, van Arem, and Hoogendoorn (2014). The figure shows that ITS systems can provide recommendations on time gaps³, choice of speed and/or lane (including lane changes), or even help determine these aspects. In this way, they influence the free flow capacity, distribution of vehicles across lanes, stability of the traffic flow and therefore, the drop in capacity. The free flow capacity and capacity drop determine the effective capacity. The effective capacity and demand together determine the total number of lost vehicle hours on a road. The way in which ITS systems influence demand is not shown in this figure.

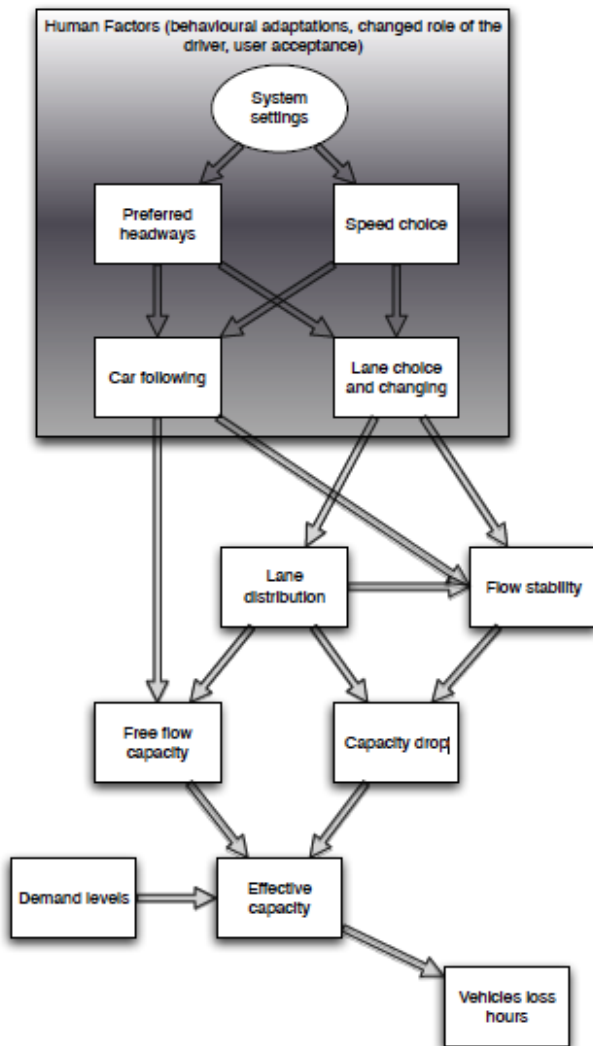


Figure 6: Relationship between ITS systems (automated and cooperative) and capacity and flow (Hoogendoorn, van Arem, & Hoogendoorn, 2014).

In the literature, there are various studies describing the influence of automated driving on, for example, free flow capacity, saturation flow, capacity drop and flow stability. These studies focus primarily on the influence of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) on the above-mentioned aspects of traffic flow efficiency. The number of field tests carried out in this area is limited. Hence, most of the studies rely on micro-simulations. The studies are sometimes difficult to compare because of the different assumptions made with respect to the time gap, vehicle mix, and penetration rate. In addition, different network

³ Time gap is the time interval between the passage of consecutive vehicles, measured between the rear of the lead vehicle and the front of the following vehicle.

configurations are used in the simulations: number of lanes, speed limits, and size of the bottleneck. Some of these studies are described briefly below.

2.2.1 Capacity

For manually steered vehicles, the capacity of a motorway, depending on the conditions and percentage of freight traffic, is between 1800 and 2200 vehicles per hour per lane. The capacity of a lane is largely dependent on the time gap. According to Calvert, van den Broek, and van Noort (2012), the minimum time gap in normal traffic is approximately 1.5 - 2.0 seconds. They have based their estimation on multiple sources. The time gap may vary due to a variety of factors, such as the weather and the quality of the asphalt. With CACC, the time gap may decrease to 0.9 seconds⁴. If the time gap decreases even further, traffic becomes unstable. Capacity in stationary traffic can be calculated with the following formula:

$$\frac{1}{\text{capacity}} = \frac{1}{n} \sum_{i=1}^n \left(\frac{\text{vehicle length}_i}{\text{velocity}_i} + \text{time gap}_i \right) \quad (1)$$

Here, i is an index for the vehicles considered in this equation. When calculated based on an average vehicle length, speed and time gap for all vehicles, capacity can be calculated as follows:

$$\frac{1}{\text{capacity}} = \frac{\text{vehicle length}}{\text{velocity}} + \text{time gap} \quad (2)$$

For an average vehicle length, with a safety buffer of 6.67 metres and a speed of 30 m/sec (= 108 km/h), the theoretical capacity per lane for a time gap of 0.9 seconds, 1.5 seconds and 2.0 seconds is equal to 3208 vehicles per hour, 2090 vehicles per hour and 1620 vehicles per hour, respectively. This means that, as a result of CACC, lane capacity could increase by approximately 58% to 98%. However, due to traffic maneuvers, such as lane changes, driving onto and exiting the motorway, merging and weaving, this theoretical increase will not be achieved. In case of ACC, time gaps greater than 0.9 seconds must be applied, as a result of which capacity might even decrease. The simulations studies below examine this in greater detail.

2.2.1.1 Without bottlenecks

In Karaaslan, Varaiya, and Walrand (1991), it was proposed that automated driving can be considered to have a substantial influence on road capacity. Here, it was assumed that this influence would be exercised, in particular, through the formation of platoons of automated vehicles. By means of microscopic simulations, they established that, depending on the size of the platoon, automated driving has a substantial impact on free flow speed as well as the separation between vehicles. Based on this, they stated that capacity can be substantially increased in this manner.

Van Arem, Hogema, and Smulders (1996) found that, although ACC can contribute to the stability (standard deviation) of the traffic, the effect on flow may be negative. For a straight road of three lanes, they took into consideration a total of four combinations of ACC, with penetration rates of 20% and 40% and time gaps of 1.0 second and 1.5 seconds. As a result of ACC, average travel time in all four scenarios increased, which implies a decrease in free flow capacity. In three of the scenarios, there was a small increase in travel time (1% to 4%). However, in the scenario with a penetration rate of 40% and a time gap of 1.5 seconds, the increase was as high as 17%. The

⁴ This is applicable to the CACC controller taken into consideration by Calvert, van den Broek, and van Noort (2012).

standard deviation of the travel time decreased in three of the scenarios. Only in case of a penetration rate of 40% and a time gap of 1.5 seconds, did this increase.

In Ioannou (1997), studies were also conducted to find out the influence of automated driving on road capacity. This study specifically examined platoon formation with coordinated braking. In his simulations, for the purpose of estimating capacity, the maximum deceleration was based on test data. Furthermore, a distinction was made between three scenarios, i.e. autonomous platoons, platoons assisted by the infrastructure and platoons managed by the infrastructure. These simulations also distinguished between situations with or without different vehicle classes. The results revealed that platoon formation has a positive influence on capacity. For example, if one used platoons consisting of 10 vehicles, the recorded capacity was 7489 vehicles/hour (three lanes). However, the study revealed that the use of different vehicle classes had a negative effect on capacity.

Van der Werf, Schladover, Miller, and Kourjanskaia (2002) and van der Werf, Schladover, and Miller (2004) have examined the effect of different penetration rates of ACC (time gaps of 1.4 and 1.55 seconds) and CACC (time gap of 0.5 seconds). They concluded that ACC with a time gap of 1.4 seconds has a marginal effect on capacity. The effect is greatest in case of a penetration rate between 0% and 20%. Between 20% and 40%, the effect is smaller (maximum capacity gain of 7%), while between 40% and 60%, there is hardly any effect. Above 60%, capacity decreases as a result of the time gap of 1.4 seconds. In case of time gaps of 1.55 seconds, the capacity decrease starts even earlier, from above a penetration rate of 40%. Their advice is that no dedicated lanes should be created for ACC, because spreading the ACC vehicles over different lanes helps reduce shock waves. For CACC, they found a quadratic increase in capacity. Hence, in case of high penetration rates of CACC, they recommend dedicated lanes, which would cause the capacity to increase from 2200 PCU/hour to 4200 PCU/hour per lane. However, only one vehicle class was used in this study. Moreover, lane changes were not taken into account in this study.

Arnaout and Bowling (2011) found that, for a road with four lanes in scenarios with and without an entry slip road, CACC has a positive effect on capacity (up to +60% for a penetration rate of 100%) when the penetration rate is greater than 40% and the inflow is sufficiently high. For lower penetration rates, there was a small positive effect. At a low inflow (free flow), they found no effect on capacity. They presumed that CACC vehicles maintain a time gap of 0.5 seconds if they are driving behind another CACC vehicle and 0.8 to 1.0 second (uniformly distributed) if they drive behind another vehicle. However, according to them, daring to maintain such short time gaps in practice will be a major challenge.

In Shladover, Su, and Lu (2012), tests were carried out for a form of CACC that uses only V2V communication with other vehicles in the vicinity. The CACC vehicles can follow the vehicles driving in front of them without the driver having to accelerate or brake; the driver only has to keep to his lane. An over-congested highway was modelled in this test, with a length of 6.5 km, a speed limit of 105 km/h and without bottlenecks. In the simulations, four types of vehicles were present: 1) Non-equipped vehicles; 2) Vehicles equipped with ACC; 3) Vehicles that only communicated their location and speed - 'Here I am' vehicles; 4) Vehicles equipped with CACC. The time gaps are based on observations made during field tests:

- ✓ Manual: 1.5 seconds plus or minus 10% (capacity ~ 2200 vehicles/hour -> effectively 2018 vehicles/hour).
- ✓ ACC: 31.1% with 2.2 seconds, 18.5% with 1.6 seconds, 50.4% with 1.1 seconds.

- ✓ CACC: 12% with 1.1 seconds, 7% with 0.9 seconds, 24% with 0.7 seconds, 57% with 0.6 seconds.

Figure 7 (top) displays lane capacity as a function of the penetration rate of CACC vehicles (with 0% ACC). Figure 7 (bottom) shows how lane capacity is dependent on the percentage of ACC and CACC vehicles. This shows that the percentage increase in capacity varies between 0% and 64%, depending on the penetration rate of ACC and CACC vehicles.

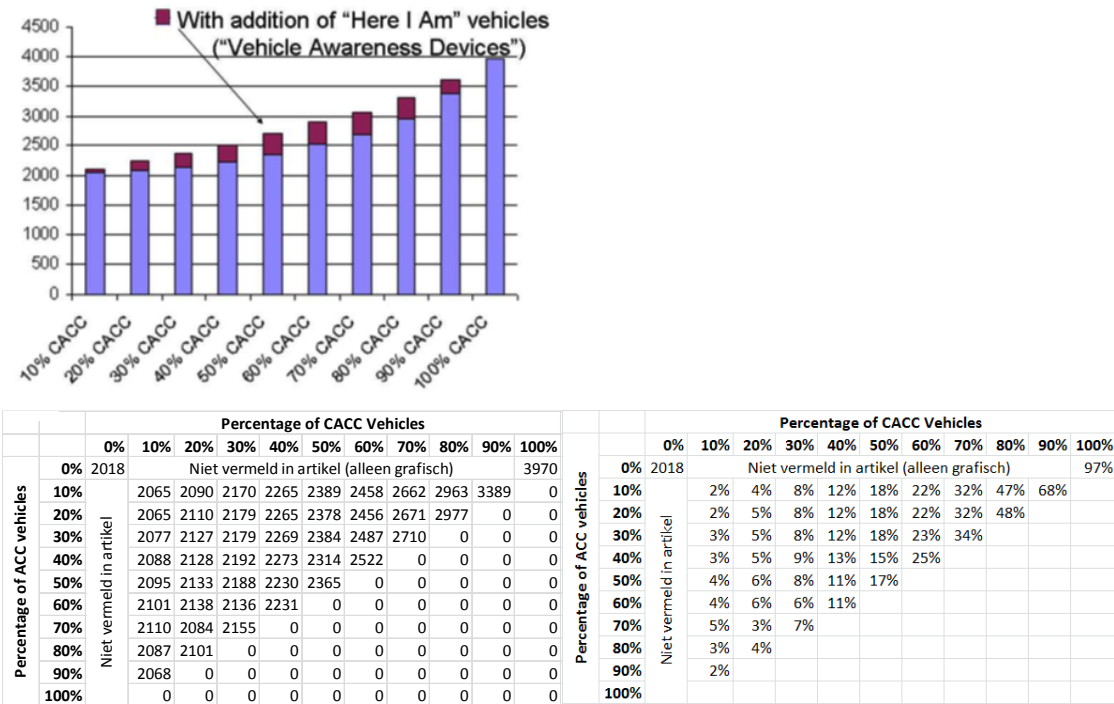


Figure 7: Lane capacity as a function of the percentage of vehicles with CACC (top). Lane capacity and percentage increase in capacity as a function of the percentage of ACC and CACC vehicles (bottom).

2.2.1.2 With bottlenecks

Van Arem, de Vos, and Vanderschuren (1997) have conducted a study for a motorway with four lanes and a narrowing of the road to three lanes, in order to examine the effect of ACC with and without a dedicated lane. They found that, in the scenario without a dedicated lane and at a penetration rate of 50%, ACC has a positive effect of approximately 4% on the capacity. With a dedicated lane, this is 6% - 8%. This larger increase is due to the assumption that a smaller time gap of 0.7 seconds can be maintained on a dedicated lane.

In van Arem, Driel, and Visser (2006), the influence of different percentages of CACC vehicles on the efficiency of traffic flow was also simulated for a motorway that reduces from four lanes to three. The CACC vehicles maintained a time gap of 0.5 seconds when following another CACC vehicle and 1.4 seconds when they were following another vehicle. The effect of a dedicated lane was also examined. The study showed that CACC has a potentially positive effect on capacity. At a penetration rate above 40%, they found small positive effects of 3% - 5%. The dedicated lane did not lead to improved capacity (rather, it led to a small decrease). They also found that, when communication between the CACC vehicles was limited to longitudinal communication, CACC can have a negative effect on safety, because other vehicles can then no longer merge into the CACC platoons. Lateral communication, allowing larger gaps to form if a CACC car wants to merge into the platoon, and restricting the length of a platoon to e.g. a maximum of five vehicles may be possible solutions for this.

Based on simulations for the A12 motorway, van Driel and van Arem (2010) have determined the effect of a Traffic Jam Assistant (a sort of ACC: active accelerator and stop-and-go) for a merging of four lanes into three. This showed that the Traffic Jam Assistant can help to significantly reduce the average travel time. In case of a penetration rate of 10% and 50%, the reduction is 30% and 60%, respectively. The reduction is largely achieved through the stop-and-go function. The active accelerator makes a limited contribution. For a penetration rate of 10% and time gap of 1.0 second, the saturation flow increased by 3%. For a penetration rate of 50% and a time gap of 0.8 seconds, they found that capacity increased by 7%.

In his dissertation, Wang (2014) has performed simulations for a 14 km motorway with two lanes. The transport demand was 1900 vehicles per lane. The bottleneck consisted of a reduced speed limit of 80 km/h, 60 km/h and 40 km/h at 11 km, 11.5 km and 12 km, respectively, for a period of two minutes. Such bottlenecks cause shock waves. For ACC penetration rates of 5%, 10%, 50% and 100%, he found an increase in the effective capacity at the bottleneck of 10%, 13%, 12% and 13%, respectively. For CACC penetration rates of 5%, 10%, 50% and 100%, he found an increase in the effective capacity at the bottleneck of 9%, 14%, 13% and 13%, respectively.

2.2.1.3 CACC overview

Based on some selected studies, Wilmink, Jonkers, Netten, and Ploeg (2013) have provided an overview of the effect of CACC on capacity for different penetration rates. This overview is displayed in figure 8. The test on the A270 motorway⁵ falls outside the range of the other studies in the figure, because this involved an informative system. Here, 'Path simulations' refers to Shladover, Su, and Lu (2012), 'Amsterdam Simulations' refers to Calvert, van den Broek, and van Noort (2011) (also see the paragraph on shock waves) and 'Arnaout Simulations' refers to Arnaout and Bowling (2011).

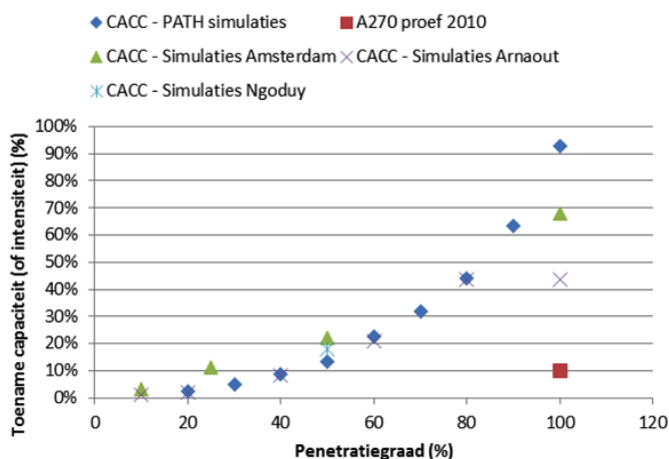


Figure 8: Capacity effects of CACC for different penetration rates (Wilmink, Jonkers, Netten, & Ploeg, 2013).

2.2.2 Capacity drop

In addition to an effect on capacity, automated driving also has an effect on capacity drop. Capacity drop implies that, when a congestion occurs, drivers maintain a greater time gap than

⁵ In February 2010, a number of large-scale experiments were carried out on the A270 motorway between Helmond and Eindhoven. The aim was to demonstrate the potential of cooperative systems for damping traffic waves. Cooperative systems offer individual advice to the driver about the extent to which he has to speed up or slow down.

they did before the congestion occurred. This leads to a decrease in road capacity. Research has shown that high intensities, in particular, lead to this phenomenon.

Studies of the influence of automated vehicles on capacity drop are scarce. However, in Kesting, Treiber, Schönhof, Kranke, and Helbing, (2007), it was demonstrated that an increase in capacity is non-linear, depending on the penetration rate. Above approximately 50% CACC vehicles, capacity increased more quickly than at lower penetration rates. This is confirmed in Kesting, Treiber, and Helbing (2010). This study once again made use of micro-simulations. Furthermore, they examined five different scenarios, such as free flow traffic and bottlenecks. These studies revealed that the capacity drop values lie between 2% and 12%. It also became clear that penetration rate is an important factor.

2.2.3 Stability and shock waves

In addition to the capacity drop, theoretically speaking, automated vehicles can also have a positive impact on traffic stability (especially important for shock waves). In general, a system is stable if, after a disruption in the system, it returns to its state of equilibrium. Based on an extensive review, Kesting and Treiber (2013) identified three types of stability: local stability, platoon stability and traffic flow stability. In Eyre et al. (1998), the influence of platoons on platoon stability was examined. In their research, they showed that, for a fixed time gap, a controller had a positive effect on stability. However, Darbha and Rahjagopal (1999) demonstrated that a constant time gap strategy has a negative influence on stability. In their study, time gaps of 1 second led to undesirable features with respect to stability. However, these findings were contradicted in Li and Shrivastava (2002). They studied traffic flow stability on a ring road, where they applied a Constant Time Headway⁶. In this study, they showed that the use of this strategy leads to stability.

Van Arem, Driel, and Visser (2006)⁷ found that the number of shock waves for the bottleneck decreased by approximately 30% to 90% in case of an increasing penetration rate of CACC vehicles. The standard deviation of the speed was also much lower.

In Schakel, van Arem, and Netten (2010), stability was examined in case of different vehicle classes. In their study, they concluded that the increase in the variability of time gaps due to the presence of the different vehicle classes only had a limited influence on stability. However, it appeared that the penetration rate of CACC vehicles has a substantial influence on the occurrence of shock waves. For higher penetration rates, the duration of the shock waves was found to be considerably shorter, but the shock wave velocity and the distance over which the shock wave travelled was greater. Based on a field test on the A270 motorway demo, it was found that AAC (acceleration advice related to CACC) help drivers to anticipate situations better, which leads to improved acceleration and deceleration. This results in less variation in time gaps and speeds, so that shock waves are stabilised. The variation in density improved by 13%.

Calvert, van den Broek, and van Noort (2011) have simulated the effect of different penetration rates of CACC vehicles on shock waves for a calibrated part of the motorway network of Amsterdam (namely, the A1 and A10 south motorways). On the A1, there was a bottleneck due to a narrowing of the road from four to three lanes. This created shock waves that had an impact

⁶ Time headway is the time interval between the passage of consecutive vehicles, measured between the front of the lead vehicle and the front of the following vehicle. Time gap is the time interval between the passage of consecutive vehicles, measured between the rear of the lead vehicle and the front of the following vehicle. Hence, it follows that: $\text{Time headway} = \text{Vehicle Length}/\text{Speed} + \text{Time gap}$.

⁷ The paragraph on free flow capacity includes an explanation of this study.

on the A10. They found that for a CACC penetration rate of 5%, 10%, 25%, 50%, 75% and 100%, the increase in the total number of arrivals (indicator for flow) was 0%, 3%, 10%, 22%, 39% and 68%, respectively. In each scenario, there was a traffic jam at the bottleneck, but above a penetration rate of 25%, the severity of the shock waves was much lower. Above a penetration rate of 50%, the shock waves do not impact the A10 and for a penetration rate of 100%, there are no shock waves at all. In a follow-up study (Calvert, van den Broek, & van Noort, 2012), they determined the optimal time gap for CACC vehicles in case of a mix of 50% ACC and 50% CACC vehicles. They concluded that the number of arrivals reaches a peak at a time gap of 0.5 seconds and the average speed in the network peaks at 0.7 seconds. According to them, in theory, a time gap below 0.9 seconds for the selected CACC controller would lead to instability (although this was not the case in practice). A comparison between time gaps of 0.9 seconds and 1.2 seconds showed that, for penetration rates of 50% and 75%, the total number of arrivals in case of a time gap of 0.9 seconds is higher than that in case of a time gap of 1.2 seconds. This is immaterial for a penetration rate of 100% since then, at a time gap of 1.2 seconds, all congestion had disappeared. In case of low penetration rates, the time gap of 0.9 seconds had a negative effect. This may be the result of stochasticity in the simulations. Another possible explanation is that, at a time gap of 1.2 seconds, the traffic is more homogeneous and hence more stable.

Finally, Wang (2014) has shown in his simulations that ACC systems improve stability upstream from the bottleneck. The resulting traffic wave has a constant speed upstream, but the speed depends on the ratio between the ACC vehicles and other vehicles. The CACC systems improve stability at both the beginning and end of a congestion and increase the effective capacity of the bottleneck in comparison to human drivers and ACC systems. A significant feature of CACC systems is that traffic waves travel more rapidly upstream as a result of vehicle-to-vehicle communication.

2.2.4 Effect of freight platooning on capacity and the PCU factor

There is a limited amount of literature available regarding the effects of freight platooning on capacity and PCU values. Capacity, expressed in vehicles per hour, is expected to increase as a result of freight platooning, provided the columns do not make it too difficult to perform weaving manoeuvres and to change lanes. The reason for this is that lorries can drive closer to one another in a platoon formation. Minderhoud and Hansen (2002) have demonstrated the effects of freight platooning via a simulation study. They have simulated a motorway with an entry and exit slip road, where the right lane is reserved as a dedicated lane for freight platoons. To allow other traffic to safely pass by the dedicated lane, they worked with stop signals issued by roadside systems for the freight traffic. In the simulation, the maximum size of the platoons was 10 lorries. The distance between the lorries in a platoon was 10 metres, the minimum distance between two platoons was 150 metres and the desired speed was 85 km/h. In theory, (without entry and exit slip roads), the capacity of the dedicated lane could potentially increase from 1400 lorries per hour to 2180 lorries per hour. However, the simulations revealed that this additional capacity could not be achieved, because the freight platoons had to stop for the stop signals. In fact, the performance of the network even declined.

Capacity expressed in passenger car units (PCU) is expected to remain approximately the same, since, due to the short time gaps, the PCU factor is expected to decrease. We could not find any literature that examines this in detail. However, the following related studies may provide some insight regarding this.

Schermers and Malone (2004) have conducted a study with a driving simulator and simulation (MIXIC) to examine the effect of freight platooning, where a lorry was fitted with a 'Driving Assistant' to control the driver's behaviour in terms of following the flow of traffic and lane keeping. Here, the calculations are based on a time gap of 1.5 seconds between platoons, 1 second within platoons and with platoons consisting of maximum 10 vehicles. The simulation has been performed for a 6 km motorway with three lanes without bottlenecks and with a freight traffic concentration of 10% and 20%. They concluded that the 'Driving Assistant' has no negative effect on flow. They found no significant effects on travel times, speeds and densities and safety indicators. However, the number of lane changes decreased, with fewer shock waves as a result. In addition, they found that the spread in the time gaps increased in the right lane, which could indicate that passenger cars make less use of the right lane or that, if they do use the right lane, they cause changes in the time gaps of the freight traffic.

Minderhoud (2011) has performed a simulation study⁸ on a 6 km motorway with two lanes, where he analysed the effect of an increasing percentage of freight traffic (0% - 40%) with increasing intensities (from 300 to 4100 vehicles/hour) on average speeds and therefore, on travel times. Based on these simulations, it could not be proved that the time to collision⁹ influences the travel time of passenger cars. This conclusion cannot be translated on a one-to-one basis to exit situations in case of platoon formation, because while exiting, there is a greater need to go towards the right and more time is required to exit in case of a platoon formation (since there are more lorries driving in succession through which you cannot pass). Despite this, the simulations provide an initial indication that freight platooning near exit slip roads might have a limited influence on flow.

Subsequently, a bottleneck was introduced to examine capacity values and PCU factors for an increasing intensity and increasing percentage of freight traffic. When maximum capacity is reached, the PCU value lies between 1.9 and 2.1, depending on the percentage of freight traffic, with an elasticity of 0.01 (i.e. if the percentage of freight traffic increases by 1%, the PCU value increases by 0.01). This has only been tested for freight traffic percentages between 0% - 20%. The capacity in PCU remains approximately constant.

2.3 Effect of automated vehicles on value of time

Gucwa (2014) indicates that automated vehicles may influence the value of time of motorists. To make a statement on the extent to which the value of time can decrease, he has made a comparison with high-quality public transport. He indicates that the advantage of travelling by car is that the car is flexible, offers personal safety and privacy and is relatively fast in comparison to public transport. On the other hand, he indicates that the advantage of travelling by public transport is that public transport is equivalent to automated driving and hence the time spent in the vehicle can be spent (more) usefully. In addition, the stress of driving a vehicle is absent, there are fewer accidents, people are less likely to become 'travel sick' and there is no personal liability. According to him, automated vehicles offer the potential to combine the advantages of both the above options into a single mode of transport. However, the question is: to what extent can this be achieved? To answer this, he has defined 4 scenarios: 1) Value of time does not

⁸ Desired speed of passenger cars used in the study: 115 km/h with a standard deviation of 4 km/h; desired speed of lorries: 88 km/h with a standard deviation of 4 km/h.

⁹ In the article by (Minderhoud, 2011), time to collision is defined as the minimum time that motorists want to be able to drive in the right lane without being hindered by slower traffic.

change; 2) Value of time is equal to the lowest time valuation of the car or public transport; 3) Value of time for the car is halved; 4) Value of time decreases to 0 euros per person per hour.

As far as we know, besides the above-mentioned study, there are no other studies available in the literature on how automated vehicles influence the value of time. However, there are (a limited number of) studies displaying the development of the value of time over a period of time. For example, the study conducted by the Netherlands Institute for Transport Policy Analysis (KiM) (2013) shows that the value of time for car traffic decreased by 19% between 1997 and 2010 for commuter and business traffic. For other traffic, this increased by 39%. This has been adjusted for inflation and revision of methods.

The real wage base increased by 30% between 1997 and 2010. According to the Addition to the Guideline on the Overview of Infrastructural Effects for Direct Effects (*aanvulling voor de Directe Effecten op de Leidraad OEI*), we should expect the real value of time to increase by approximately +15% (income elasticity of 0.5) as a result of the increase in the real wage base. A possible explanation (hypothesis) for an increase that remains below +15% could be the use of mobile phones while travelling (KiM, 2013). Since, as a result of this, a part of the travel time can be spent in a useful manner. This is also known as 'travel time enrichment'. This phenomenon was first described by Gunn (2001). He concludes that, despite a substantial increase in income, the real valuation of time savings for the change in travel time has remained approximately constant in the Netherlands in the period 1988-1997.

In case of train travel, the value of time increased by 17% for commuter traffic, 28% for business traffic and 27% for other traffic. Hence, travel time enrichment has not increased as strongly for train travel as much as for car travel, even though trains potentially offer good opportunities to work during travel. *"Perhaps the overcrowded trains – which make it difficult to find a seat – have played a role in this. It is also possible that a concept such as travel time enrichment was already applicable to trains for quite some time now, e.g. the time spent on reading newspapers or reports. As a result, the added value of ICT developments has remained limited in comparison to the car. Perhaps a slight progress can be expected on trains with the introduction of Wi-Fi."* (KiM, 2013; author's translation from the original Dutch document).

Based on the above, the question that arises is as follows: to what extent can travel time enrichment for car travel be increased further as a result of the introduction of automated vehicles? An indication for this may be that the value of time for the car passenger is 80% of that of the car driver (Guideline on the Overview of Infrastructural Effects (*OEI Leidraad*), 2000).

The literature regarding the extent to which freight platooning influences the value of time for freight traffic is beyond the scope of this literature survey.

2.4 Effects of automated vehicles on travel behaviour, travel time, safety, energy and the environment

2.4.1 Vehicle kilometers travelled, energy consumption and the environment

Litman (2014) indicates that significant effects can be expected with respect to traffic safety, fuel consumption and the environment only in case of a high penetration rate (probably between 2040 and 2060). He states that the number of kilometres travelled could then increase.

Effect	Approach	Effect estimate and reference source
(a) Platooning: close following at high speed to reduce drag	Use estimates of overall savings potential from literature	-10 % EI [5-8]
(b) Efficient driving: smooth start stop, some stop elimination	Use estimates of eco-driving potential	-15 % EI [9, 10]
(c) Efficient routing: traffic avoidance and most efficient route selection	Example cases from Buffalo, NY and from collaborative Chevy Volt project	-5 % EI [11, 12]
(d) Travel by underserved populations: (youth, disabled, and elderly)	Estimate the additional miles if all people over 16 had the VMT of the highest demographic	+40 % UI [13, 14]
(e) Efficient driving (additional): full stop elimination and trip smoothing	Use upper bound of efficiency improvement from smooth travel	-30 % EI (additional to previous estimate to give -40 % total) [9, 16]
(f) Faster travel: possible due to safe highway operation	Estimate impact on fuel economy from aerodynamic drag at 100 mph	+30 % EI [17, 18]
(g) More travel: due to faster travel and reduced traffic, people may live farther from destinations or travel more	Assume the current time spent travelling remains the same (so miles increase with speed)	+50 % UI [19]
(h) Lighter vehicles and powertrain/vehicle size optimization: Very few crashes and smoothed driving could enable light vehicles with small powertrains for many duty cycles	Assume weight could be reduced ~75 % and each 10 % reduction = 6-8 % EI reduction; Alternately compare average modern vehicle fuel economy to that of the 1994 Geo Metro	-50 % EI [20-25]
(i) Less time looking for parking: from fewer vehicles and self parking	Assume it cuts the wasted fuel in half	-4 % UI [26]
(j) Higher occupancy: facilitated by IT, automated carpooling	Use the upper bound estimates for "dynamic ridesharing"	-12 % UI [27]
(k) Electrification: deployed vehicle could be matched to user trip need	Estimate the share of vehicle trips that could be met with a 40 mi electrified range	-75 % FI (as a -100 % FI to 75 % of vehicles) [13, 28]

Figure 9: Overview of effects of automated driving on the number of vehicle kilometres (UI), energy efficiency (EI) and fuel efficiency (Brown, Gonder, & Repac, 2013).

Based on San Francisco's Metropolitan Transportation Commission's Travel Model One, (Gucwa, 2014) has calculated multiple scenarios using different values for capacity (0%, +10% and +100%) and the value of time (0%, min(car, public transport), -50%, -100%). His model runs indicate that the number of vehicle kilometres is expected to increase by 4% - 8%.

In Brown, Gonder, and Repac (2013), an overview is given of the possible effects of automated driving on the number of vehicle kilometres (UI), energy efficiency (EI) and fuel efficiency. According to them, automated vehicles can reduce CO₂ emissions and fuel consumption, as a result of higher fuel efficiency, better route choice and less congestion. On the other hand, automated vehicles could also lead to increased fuel consumption, as a result of the longer distances driven and higher speeds. The effects are summarised in figure 9.

2.4.2 Lost vehicle hours, travel time and traffic waves

Based on a literature survey, Wilmlink, Jonkers, Netten, & Ploeg (2013) provide insight into the potential effects of (speed) measures on traffic waves. The following (speed) measures have been considered:

- ✓ Roadside solutions (with intelligent algorithms, such as those used in Dynamax A12 SPECIALIST and (partly) Dynamax In Car);

- ✓ Connected vehicles (use of navigation systems for speed advice, without communication with the roadside);
- ✓ Cooperative systems (speed advice based on vehicle-roadside communication, such as in the in-car variants simulated in Dynamax In Car).
- ✓ Cooperative systems (speed advice based on information from nearby (downstream) vehicles).

The various sources studied by them examined different penetration rates and driver compliance rates for the various systems. Figure 10 indicates the penetration rates considered for each speed measure. This shows that, depending on the system, location of application, penetration rate and the driver compliance rates, the number of lost vehicle hours decreases by 0% - 60%, travel time decreases by 0% - 68% and the number of traffic waves decreases by 8% - 89%.

Maatregel/bron:	Bekeken penetratiegraden (%)															
	0	1	2	5	10	20	25	30	40	50	60	70	75	80	90	100
Dynamax SPECIALIST wegkant	x															x
Dynamax In Car	x	x		x			x									x
Connected Cruise Control (CCC)	x		x	x	x	x			x							
A270 proeven 2010	x															x
SPITS A270 2011	x				x			x								
CACC simulaties PATH					x	x		x	x	x	x	x		x	x	x
CACC - Freeway with a ramp	x					x			x		x			x		x
CACC - dynamics of cooperative flow	x				x	x		x		x				x		
Fileassistent (CACC met V2I)	x				x	x			x	x	x			x		
CACC simulaties Amsterdam	x				x		x			x			x			x

Figure 10: Penetration rates for speed measures.

2.4.3 Traffic safety

In eIMPACT (Wilmink et al., 2008), the effect on traffic safety has been determined for 12 systems. This concerns both direct effects, in the form of changes in time gaps, and indirect effects, in the form of fewer incidents and less congestion due to incidents. The following 12 systems have been considered:

1. Electronic Stability Control (ESC)
2. Full Speed Range ACC (FSR)
3. Emergency Braking (EBR)
4. Pre-Crash Protection of Vulnerable Road Users (PCV)
5. Lane Change Assistant (Warning) (LCA)
6. Lane Keeping Support (LKS)
7. NightVisionWarn (NIW)
8. Driver Drowsiness Monitoring and Warning (DDM)
9. eCall (one-way communication) (ECA)
10. Intersection Safety (INS)
11. Wireless Local Danger Warning (WLD)
12. SpeedAlert (SPE)

Of these systems, the Electronic Stability Control system is expected to contribute most towards preventing deaths and injuries: 14% fewer deaths and 5.7% fewer injuries in 2020. Significant effects are also expected from SpeedAlert (-5.2% deaths), eCall (-3.5% deaths) and Lane Keeping Support (-3.3% deaths). Litman (2014) indicates, however, that new risks may arise, such as defective systems. In addition, it is probable that more risks will be taken while driving (offsetting behaviour).

2.4.4 Other factors related to traffic operation and travel behaviour

In the literature, we find the following additional factors that could influence traffic operation and travel behaviour:

- ✓ Less stress when driving (Litman, 2014), as a result of which time can be used more usefully.
- ✓ Car use: according to Brown, Gonder, and Repac (2013), children, the elderly and the disabled, who cannot drive independently, can travel by car as a result of the introduction of automated vehicles. They do not indicate the percentage by which the number of trips made by car will increase. However, they have estimated the effect on the number of vehicle kilometres: +40% (see the following paragraph).
- ✓ Car ownership: according to Litman (2014), car ownership may decrease as a result of car-sharing, but this may also increase if cars become cheaper.
- ✓ Car occupancy rate: Brown, Gonder, and Repac (2013) they indicate that the car occupancy rate may increase as a result of the introduction of automated vehicles. Here, they are referring to car sharing systems.
- ✓ Car ownership costs: the costs of a car (purchase, maintenance and services) may increase, according to Litman (2014).
- ✓ Fuel costs: fuel costs may decrease, according to Brown, Gonder, and Repac, (2013), as a result of more cost-efficient driving. However, these costs may also increase, if the number of vehicle kilometres increase. Chapter 2.4 discusses this in detail. Gucwa (2014) indicates that fuel consumption may decrease by approximately 24% due to 'eco-driving', while to achieve high capacities, 'aggressive' driving may also be necessary at times. This is why he assumes a decrease of 15% in his simulations.
- ✓ Lower driver costs for freight traffic and taxis (Litman, 2014).
- ✓ Parking: according to Brown, Gonder, and Repac (2013), automated vehicles can help reduce the number of kilometres driven while searching for parking. Parking costs can also be reduced.
- ✓ Car design and layout: Gucwa (2014) indicates that the cars might become larger in size, in order to offer more comfort. Moreover, according to him, automated vehicles will help reduce the current problems faced by large cars in terms of parking and driving in congested traffic. Ultimately, the car layout may also change, e.g. if a steering wheel is no longer required and one does not need to look ahead through the windshield any longer.
- ✓ Information: advanced information and navigation systems. According to (Brown, Gonder, and Repac, (2013), as a result of cooperative systems, better route information can be provided, which could have a positive effect on traffic operation.
- ✓ Speed: according to Gucwa (2014), it is possible (depending on regulations) that speed limits will be strictly enforced as a result of the introduction of automated vehicles.

2.5 Effect of automated vehicles on transport infrastructures

This section discusses the potential implications of automated vehicles on transport infrastructures and reviews studies in this area. We focus on the implications for road, parking, public transport, bicycle and pedestrian infrastructures.

2.5.1 Road

The introduction of automated vehicles is estimated to reduce the need for conventional infrastructure investments (extra-wide lanes, wide shoulders, guardrails, rumble strips, stop signs) (Silberg et al., 2012). Moreover, significant improvements in traffic flow efficiency might also

increase traffic capacity and therefore reduce the need for additional road expansions (Begg, 2014). Fagnant and Kockelman (2014) note that VMT will probably increase with the introduction of automated vehicles, but new demand will likely not cause additional congestion problems since traffic capacity will probably improve as well. Therefore, these researchers estimate that existing infrastructure could smoothly accommodate new travel demand, although they recognize that the amount of additional VMT due to induced demand remains an open question. Litman (2014) offers a less optimistic view suggesting that introduction of automated vehicles could marginally affect requirements for road supply and only after a major share of vehicles will become automated (not earlier than 2040 according to his estimations).

Wagner, Baker, Goodin, and Maddox (2014) recognize that automated vehicles may allow design of narrower lanes and elimination of shoulders, thus better utilizing existing infrastructure. However, they point out that potential additional travel demand, generated by urban expansion might create the need for more roadway infrastructure and/or demand-based pricing measures to minimize the impact of decreased driving costs. Eugensson et al. (2013) describe an uncertain effect on infrastructure planning from the introduction of automated vehicles. They support that better traffic capacity is, indeed, expected to lead to lower road infrastructure requirements, but if special lanes will be necessary for deployment of automated vehicles then additional infrastructure investments will be needed to accommodate new capacity demand. Lutin, Kornhauser, and Lerner-Lam (2013) note that special lanes may be needed for platooning in particular, which might also require additional space for vehicles joining and separating from platoons.

Although, needs for conventional road infrastructure could be less in the future, additional important investments may be necessary for infrastructures suitable for automated vehicles. According to Silberg et al. (2012) the transition to automated vehicles-based infrastructure might be proven highly costly especially when it comes to connected vehicles or communications between vehicles and infrastructure. Similarly, Anderson et al. (2014) stress the point that substantial investments for the creation, maintenance, and safeguarding reliability of infrastructures (especially vehicle-to-infrastructure communication systems) for automated vehicles might be required. O' Toole (2014) suggests limited development of smart infrastructures because they might soon become obsolete if they are not constantly maintained and upgraded to meet user demands. Silberg et al. (2012) is of the opinion that part of the cost for smart infrastructures could be mitigated by applying this type of infrastructure in highly dense areas or by taking advantage of existing communications (e.g., cell) infrastructures. Moreover, Anderson et al. (2014), interestingly, note that countries with limited existing vehicle infrastructure might have the opportunity to skip development of some conventional human driver centered infrastructures. Finally, van Arem and Smits (1997) suggest that radical changes in the organizational structure and operation of the transport infrastructures may be required in the automated vehicles era. These changes might include segmentation of road network, operation and maintenance by private organizations and the emergence of transportation providers that will guarantee trip quality regardless of travel mode.

Thus far, scholarly research has focused almost exclusively on the literal relationship between automated vehicles and road infrastructure environment rather than the long-term implications of the former to the latter. Most articles have explored the issue of detection of simple lanes (Furusho & Mouri, 1999; Goldbeck, Huertgen, Ernst, & Kelch, 2000; Lee & Han, 2008; Liu, Xu, & Dai, 2012; Thomaidis et al., 2013; Li et al., 2014; Li & Fang, 2014) or multiple lanes (Huang, Moore, Antone, Olson, & Teller, 2009), road boundaries (Wijesoma et al., 2004; Han, Kim., Lee, & Sunwoo, 2012), spatial layout and multiple characteristics of road terrain (Fritsch, Kühnl, &

Kummert, 2014; Chen, Li, Li, Zhang, & Mao, 2012) and signs (de la Escalera, Armingol, & Mata, 2003) by automated vehicles. Coordination of automated vehicles in road contexts without speed lanes or unstructured environments is also explored in the literature (Ferguson, Howard, & Likhachev, 2008; Chen et al., 2014; Kala & Warwick, 2014). Implications of automated vehicles for road infrastructure are discussed for intersections in particular with both 'no modification' (Alonso et al., 2011) and 'transformation into multi-agent systems' (Dresner & Stone, 2008; Omae, Ogitsu, Honma, & Usami, 2010) approaches being presented. Also, Fishelson, Freckleton, and Heaslip (2013) explored deployment potential for different types of infrastructure for automated (primarily public transport, but also private) vehicles. He suggested that an isolated (vs an integrated with the rest of the traffic) approach would offer a faster and more beneficial deployment path for automated vehicles.

2.5.2 Parking

The introduction of automated vehicles could significantly reduce the amount of spaces dedicated to parking in urban areas (Anderson et al., 2014). Automated vehicles could drive themselves to peripheral parking lots after dropping off passengers, reducing the need for parking spaces in city center (especially in commercial and work establishments) (Begg, 2014). Moreover, potential development of automated vehicles sharing schemes may lead urban residents to live car-free or reduce the numbers of cars they own (Silberg et al., 2012). Consequently, the number of parking spaces needed in residential buildings might be reduced as well. Fagnant and Kockelman (2014) point out that parking patterns are expected to significantly change (e.g. development of automated parking in less expensive areas, or less cruising time for parking) leading to less demand for parking spaces in currently popular locations (e.g., city centers). Van Arem and Smits (1997) concluded that automated parking is, indeed, one the most possible changes that will accompany introduction of automated vehicles. These researchers noted that automated parking is expected to partly replace on street parking or to be applied at transferia.

Scholarly research has focused on the question of how vehicle automation could assist the parking process in existing parking contexts (e.g, parking lot). The aim is to offer drivers a seamless, crash-free parking experience either through parking assistance systems (Unger, Wahl, & Ilic, 2011) or with the help of local automated parking planners (Wang, Zhang, Huang, Zhang, & Mehr, 2011), path planning systems (Dolgov, Thrun, Montemerlo, & Diebel, 2010) and/or fully automatic parking systems which can guide a vehicle from the traffic lane into a parking space and perform parallel, perpendicular or angle parking (Lee, Lin, & Shiu, 2009).

2.5.3 Public transport

The introduction of automated vehicles along with the development of convenient and inexpensive taxi and car sharing services are expected to reduce the need for conventional public transport services in some areas (Litman, 2014). Anderson et al. (2014) note that automated vehicles could attract a significant portion of public transport users (e.g. those currently unable to drive) leading transit authorities to either cut services or increase fare costs, which might also lead to a further decline of public transport ridership. Moreover, O' Toole (2014) suggests that automated vehicles and subsequent development of car sharing can make public transport (rail transport in particular) obsolete especially in areas with mid and lower densities. Begg (2014) describes a potential dual role for automated vehicles with respect to bus services. First, as a substitute of bus services in lightly populated routes and second as a bus-feeder on heavily used corridors. In the second case public transport authorities might operate automated vehicles as well. However, O' Toole (2014) suggests that automated vehicles could not serve as last mile supporting service to public

transport because people would probably prefer not to transfer to another mode to reach their final destination, especially in a less congested road environment. Furthermore, Silberg et al. (2012) argues that automated vehicles could offer a more flexible and inexpensive alternative to high-speed trains if special express lanes are developed for this purpose. The paradox however is that long distance high speed public transport seems to have greater potential to operate their own automated public transport vehicles due to less number of stops and traffic conflicts (Polzin, 2014). However, this researcher concludes that introduction of private automated vehicles might influence primarily investment decisions for long distance public transport services, since traffic capacity improvements may eliminate the role for public transport in meeting future capacity needs.

Thus far, scholarly research has focused on the technical aspects (e.g., path planner) of automated public transport vehicles and on experimentation with prototypes in real world scenarios (Fernandez, Dominguez, Fernandez-Llorca, Alonso, & Miguel, 2013).

2.5.4 Bicycle and pedestrians

Part of the conventional human-driver based infrastructures could be converted to bicycle or pedestrian uses, due to significant improvements in traffic capacity from the introduction of automated vehicles (Silberg et al., 2012; Begg, 2014). However, Begg (2014) notes that it could also happen that more traffic is accommodated into the same road space, without any benefits for pedestrians and cyclists. Indeed, Litman (2014) argues that increased traffic volumes and speeds after introduction of automated vehicles may degrade walking and cycling conditions.

Most scholarly research on automated vehicles considers cyclists and pedestrians as some of the potential moving (or not) objects within the urban context that should be detected and avoided. To this end, various detection methods are proposed (see e.g., Wöhler & Anlauf, 2001; Labayrade & Aubert, 2004; Sun, Zou, Zhou, Wang, & El-Sheimy, 2013; Li et al., 2014).

2.6 Conclusions

2.6.1 Development of automated vehicles

Based on the literature, it appears that the development of automated vehicles is taking place along two axes: the axis from manual to automated and the axis from autonomous to cooperative. For the manual-to-automated axis, two main taxonomies have been identified with five (NHTSA) and six levels (SAE) of vehicle automation. The actual speed of this development and the precise nature of the transition path (mix of vehicles with different levels of automated driving and degree of cooperation) are not yet fully known. The government and the car industry have a role to play in this. The literature shows that the following factors may be influential: speed of technological developments, speed with which various obstacles are eliminated, government incentives, vehicle life span, vehicle purchase prices, and subscription costs for services necessary for using a automated vehicle.

2.6.2 Effects of automated vehicles

2.6.2.1 Road capacity

The literature focuses on the automation of longitudinal driving, with the help of ACC and CACC. Almost all the studies are based on micro-simulations, sometimes in combination with a field test. The studies are difficult to compare because of the different assumptions made with respect to the time gap, vehicle mix and penetration rate. Moreover, different network configurations are used in the simulations: number of lanes, speed limits, presence of a bottleneck, size of the bottleneck and the extent to, and location for, which the model is calibrated. The following conclusions can be drawn based on the available literature:

- ✓ ACC can either have a small negative or a small positive effect on capacity ($\sim -5\%$ to $+10\%$). This is related to the time gap used. If the time gap is greater than the time gap maintained by motorists without ACC, then capacity decreases.
- ✓ For CACC, most studies report a quadratic increase in capacity as the penetration rate increases, with a theoretical maximum increase of 100% (doubling). Here, too, the extent of increase depends on the time gaps used and the presence of bottlenecks. Most studies indicate that the increase in capacity is high ($>10\%$) only if the penetration rate is higher than 40%.
- ✓ According to (Calvert, van den Broek, & van Noort, 2012), in case of time gaps of under 0.9 seconds for CACC vehicles, traffic will become unstable (applicable to the controller considered by them). However, simulation studies often use much lower time gaps of up to 0.5 seconds in their calculations.
- ✓ Studies that examine the effect of CACC in case of a bottleneck usually focus on the narrowing of the road from four lanes to three. The studies found show that the increase in capacity for the simulated bottlenecks is usually less than 10%. One of the studies also took into consideration an acceleration lane and a dynamic speed limit.
- ✓ Research on capacity drops is scarce. A study by Kesting et al. (2010) revealed that, for high penetration rates of CACC, the capacity drop can decrease from 12% to 2%.
- ✓ ACC and CACC have a positive effect on stability. For higher penetration rates, there are fewer shock waves and the duration of the shock waves is noticeably shorter, but these shock waves travel more rapidly upstream. For very high penetration rates of CACC, no further shock waves occur.
- ✓ The effect of ACC and CACC on dedicated lanes has not been studied extensively in the literature. The available literature indicates that dedicated lanes for passenger cars with ACC and CACC can have both a negative and a positive effect on capacity. Here, the time gap, penetration rate and size of the platoons are important factors. A simulation study for freight platooning on a dedicated lane (right lane) also showed that capacity could, theoretically, increase, but that the performance of the network may still deteriorate due to other traffic merging in and out of the platoon.
- ✓ As far as we are aware, there are no studies in the literature on the effect of freight platooning on the PCU factor. The PCU factor is expected to decrease, as a result of which capacity expressed in passenger car units (PCU) is expected to remain approximately the same.

There is a limited amount of literature available regarding the automation of lateral driving. This literature relates to systems, which ensure that motorists stay within their lane. Effects of systems that focus on lane changes have not been described.

2.6.2.2 Value of time

The effect of automated vehicles on the value of time has not yet been examined in the literature. However, the available literature shows that the value of time for commuter and business traffic in

the Netherlands over the past two decades has decreased to a larger extent than might have been expected based on income changes. A possible hypothesis is that this is because of the introduction of mobile phones, so that time spent in the car can be utilised more efficiently. While this phenomenon of travel time enrichment (Gunn, 2001) offers certain clues, the question remains: how much further can travel time enrichment be increased as a result of the introduction of automated vehicles?

2.6.2.3 Travel behaviour, travel time, safety, energy and the environment

There are only a limited number of studies available that quantify the effects of automated vehicles on travel behaviour, safety, travel time reliability, energy consumption and the environment. The following effects are mentioned:

- ✓ Only at a high penetration rate (>40%) can automated vehicles be expected to have significant effects on flow, traffic safety, fuel consumption and the environment.
- ✓ Vehicle kilometres: the number of kilometres travelled is expected to increase. The rate of increase depends on the current level of congestion, penetration rate, structure of the network. An increase of 4% - 8% was found in a study in San Francisco.
- ✓ Fuel consumption: the amount of fuel consumed (CO₂ effect) may decrease as a result of higher fuel efficiency, better route choice and less congestion. On the other hand, automated vehicles could also lead to increased fuel consumption, as a result of the longer distances driven and higher speeds.
- ✓ Lost vehicle hours: depending on the system, location of application, penetration rate and driver compliance rates, the number of lost vehicle hours, travel time and the number of traffic waves have been found to decrease by 0% - 60%, 0% - 68% and 8% - 89%, respectively.
- ✓ Most systems are expected to have a positive effect on traffic safety and hence on travel time reliability.

Automated vehicles may also have an effect on the following factors that are related to traffic operation and travel behaviour: stress while driving, car use, car ownership, car occupancy rate, car ownership costs, fuel costs, driver costs, parking locations, behaviour while searching for parking, parking costs, car design and layout, safety, information and speed. At present, only hypotheses are available about how and to what extent these factors will be influenced.

2.6.2.4 Transport infrastructures

There is a general agreement in professional literature that introduction of automated vehicles is likely to reduce the requirements for road network expansion in the future. Estimations vary from substantial (Silberg et al., 2012) to only marginal though (Eugensson, 2013; Fagnant & Kockelman, 2014; Wagner et al., 2014, Litman, 2014). Increased traffic capacity because of improved traffic flow efficiency and road redesign (e.g., narrower lanes, elimination of shoulders) is the main mechanism for potential reduction of future needs for new roads. Less optimistic views point out that automated vehicles may induce new travel demand because of lower costs of travel and possible urban expansion. Therefore, additional road capacity may be required to accommodate new travel demand. Although, needs for conventional road infrastructure are likely to be less in the future, additional important investments may be necessary for creation, maintenance and securing reliability of new smart infrastructures (vehicle-to-vehicle, vehicle-to-infrastructure communication) for automated vehicles (Silberg et al., 2012; Anderson et al., 2014). Part of this cost could be mitigated by applying this type of infrastructure in highly dense areas or by taking advantage of existing communications (e.g., cell) infrastructures (Silberg et al., 2012).

New smart infrastructures may also require new management and operation structures (van Arem & Smits, 1997).

The long-term implications of automated vehicles on road infrastructure (either at the micro-scale – new road design – or at the macro-scale – road expansion –) have not been systematically explored in the academic literature yet. Thus far, research has focused almost exclusively on the road environment perception and motion planning of automated vehicles (see e.g, Furusho and Mouri, 1999; Goldbeck et al., 2000; de la Escalera et al., 2003; Wijesoma et al., 2004; Ferguson et al., 2008; Lee & Han, 2008; Huang et al., 2009; Chen et al., 2012; Han et al., 2012; Liu et al., 2012; Thomaidis et al., 2013; Chen et al., 2014; Fritsch et al., 2014; Kala and Warwick, 2014; Li & Fang, 2014; Li et al., 2014). Implications for intersections are also discussed in the literature with both 'no modification' (Alonso et al., 2011) and 'transformation into multi-agent systems' (Dresner & Stone, 2008; Omae et al., 2010) approaches being presented.

Parking demand patterns and consequently parking infrastructures are likely to be affected by automated vehicles. Most views converge that fewer parking spaces, either on-street or off-street, will be required in the automated vehicles era. Two mechanisms are identified: (a) automated vehicles will be able to drop-off passengers and park themselves in peripheral, less expensive locations (Begg, 2014; Fagnant and Kockelman, 2014) and (b) reduced car ownership levels will require less residential parking spaces (Silberg et al., 2012). However, the implications of automated vehicles on parking demand patterns and subsequently on parking infrastructure have not been examined in academic literature yet. Research has focused on the question of how vehicle automation could assist or take full control of the parking process in existing parking contexts (e.g, parking lot) (Dolgov et al., 2010; Lee et al., 2009; Unger et al., 2011; Wang et al., 2011).

A reduced need for public transport services in some areas (especially those with low and medium densities) is expected after introduction of automated vehicles. It is assumed that convenience of automated vehicles, development of vehicles sharing services and driving potential for people currently unable to drive will reduce public transport ridership (Litman, 2014). This in turn may lead public transport authorities to cut services or increase fares, which could also negatively impact ridership (Anderson et al., 2014). The paradox is that automated public transport vehicles could operate better in long distances (less number of stops and traffic conflicts), but competition with private automated vehicles along these routes is expected harder (Polzin, 2014), especially if express lanes are provided to private automated vehicles (Silberg et al., 2012). Another possibility is that automated vehicles will serve as feeder modes to public transport (Begg, 2014), but again there is doubt whether people would prefer to transfer to public transport as soon as they get into the automated vehicle (O' Toole, 2014). Academic literature has focused on the technical aspects (e.g., path planner) of automated public transport vehicles and on experimentation with prototypes in real world scenarios (Villagra et al., 2012; Fernandez et al., 2013). The implications of the introduction of private automated vehicles on public transport services have not been systematically examined yet.

Finally, pedestrians and cyclists could benefit with more space after introduction of automated vehicles (Silberg et al., 2012; Begg, 2014) as a result of traffic capacity improvements. However, most research on automated vehicles considers cyclists and pedestrians as simply some of the potential moving (or not objects) within the urban context that should be detected and avoided (see e.g., Wöhler and Anlauf, 2001; Labayrade and Aubert, 2004; Sun et al., 2013; Li et al.,

2014). The implications of automated vehicles on the infrastructure for cyclists and pedestrians have not been systematically examined yet.

In conclusion, the introduction of automated vehicles is estimated to reduce the need for road infrastructures, parking spaces, public transport services, and increase the available space for bicycle and pedestrian infrastructures. However, no clear distinction is made in professional literature among expected implications at different levels of automation. Furthermore, scholarly literature has not systematically examined any of those implications for transport infrastructures. Research with respect to automated vehicles and infrastructures has mainly focused on technical/technological issues including road environment perception, motion planning, moving obstacles detection, automatic parking, and automated public transport vehicles.

3

Methodology

This study aims to identify plausible future development paths of automated vehicles¹⁰ in the Netherlands and to estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. To this end a scenario analysis is conducted. Below, we first describe the aims and methodology of a scenario exercise based on relevant literature and then we present the steps we followed to construct the scenarios about development of automated vehicles in the Netherlands.

3.1 Scenario analysis: background

Scenario analysis is defined as *"the process of evaluation possible future events through the consideration of alternative plausible, though, not equally likely, states of the world"* (Mahmoud et al., 2009: 798). It has been used both in private and public sector to develop strategic plans (e.g., large capital investments, plans for regional development or transportation investments) that could accommodate uncertainty of the future. According to Stead and Banister (2003) scenario analysis can tell us what might happen in the future and help us acquire insights on how to avoid adverse outcomes. The history of scenario planning dates back to the 1970s, when Pierre Wack's scenarios for alternative futures helped Royal Dutch/Shell's oil enterprise to quickly and effectively adapt to the major and unpredictable challenges of that period enhancing the position of the company in the oil-industry.

Scenarios have the advantage over forecasts in that they are more flexible, creative and not necessarily probabilistic outlines of plausible futures that could assist long-term planning to broaden perspectives and identify key dynamics. Scenario analysis should be differentiated from sensitivity analysis because it challenges conventional thinking and assumptions, without focusing on the output impact of changes in one specific factor (Mahmoud et al., 2009).

Whilst methodologies for scenarios construction show great variation, there is a basic common underlying structure (Schwartz, 1991; Bood & Postma, 1997), which recently has also been suggested as a formal framework for scenario development in environmental decision-making (Mahmoud et al., 2009). The basic sequential steps of such methodology include (see Schwartz, 1991, Bood and Postma, 1997; Maack, 2001): (a) definition of the focal issue, (b) identification of key factors and driving forces, (c) classification, analysis and selection of scenario elements, and (d) construction of scenarios. The first step of the process clarifies the focus and basic features of the scenario exercise (i.e. the spatial and temporal scales of the focal issue in question). The second step identifies the most relevant factors to the focal issue (the key factors) and the driving forces behind them. The main driving forces can be categorized into five groups: social, economic, environmental, political, and technological (Maack, 2001). The key factors could be considered as the outcomes of the main driving forces. The third step classifies all driving forces according to the

¹⁰ In our scenario study we use the NHTSA taxonomy for vehicle automation. We refer to level 3 and level 4 as 'conditional' and 'full' automation respectively. In conditional automation the driver is expected to be available for occasional control of the vehicle while in full automation s/he is not. Full automation comprises both occupied and unoccupied vehicles.

magnitude of their effect (impact) and predictability of their future state (uncertainty). It also identifies the cause-and-effect relationships among driving forces. This step leads to smaller number of driving forces because only the most relevant ones to the focal issue in question are maintained. The last step of the process involves the writing of the scenario plots. These are stories that incorporate the results of the preceding analysis into narratives describing sequential interactions among driving forces and key factors (and their implications on the focal issue in question) leading towards the end state of each scenario.

According to Maack (2001) and Townsend (2014) a scenario should be plausible, distinctive (i.e. to utilize different combinations of key forces), consistent (i.e. to have a strong internal logic), relevant (i.e. to offer insights to the focal issue), creative (i.e. to reflect innovative thinking), and challenging (i.e. to challenge conventional thinking and assumptions). Moreover, Bood and Postma (1997) stress the point that scenarios should be based on current trends and conditions simply because future originates from present. Therefore, a good understanding of present trends (e.g., short-term economic forecasts, demographic data, population growth rates or sociopolitical information) is essential for a good scenario. Finally, according to Maack (2001) a diverse scenario team with respect to educational background and institutional affiliation could spark innovative approaches in scenarios.

3.2 Scenario construction: steps

The focal issue of this scenario exercise is to identify plausible future development paths of automated vehicles in the Netherlands and to estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. Four scenarios have been constructed through a structured deliberative process that involved five sequential steps (see figure 11): (a) identification of key factors and driving forces of development of automated vehicles, (b) assessment of impact and uncertainty of driving forces, (c) construction of the scenario matrix, (d) estimation of penetration rates and potential implications of automated vehicles in each scenario, and (e) assessment of the likelihood and overall impact of each scenario. The process has been completed in three workshops. The first two workshops involved five experts from Delft University of Technology. In the first workshop, the experts identified the key factors of development of automated vehicles in the Netherlands and the driving forces behind them. They also assessed driving forces with respect to the magnitude of their potential effect on development of automated vehicles (impact) and the predictability of their future state (uncertainty). A scenario matrix was subsequently drafted based on the results of the first workshop. In the second workshop the experts were asked to estimate penetration rates of automated vehicles in 2030/2050 and potential implications for road capacity, value of time and VKT in each of the four scenarios. In the last workshop, the draft scenarios were evaluated in terms of likelihood and overall impact (i.e., value of time, road capacity, and total VKT) by twenty experts from planning, technology, and research organizations in the Netherlands (e.g., I&M - Ministry of Infrastructure and the Environment, RWS - Ministry of Transport, Public Works, and Water Management, Connekt, KiM - Netherlands Institute for Transport Policy Analysis, RDW - National road traffic agency, Spring Innovation, Eindhoven University of Technology). In the next section we present the results of each step of this process, ending with the final scenarios about development and implications of automated vehicles in the Netherlands.

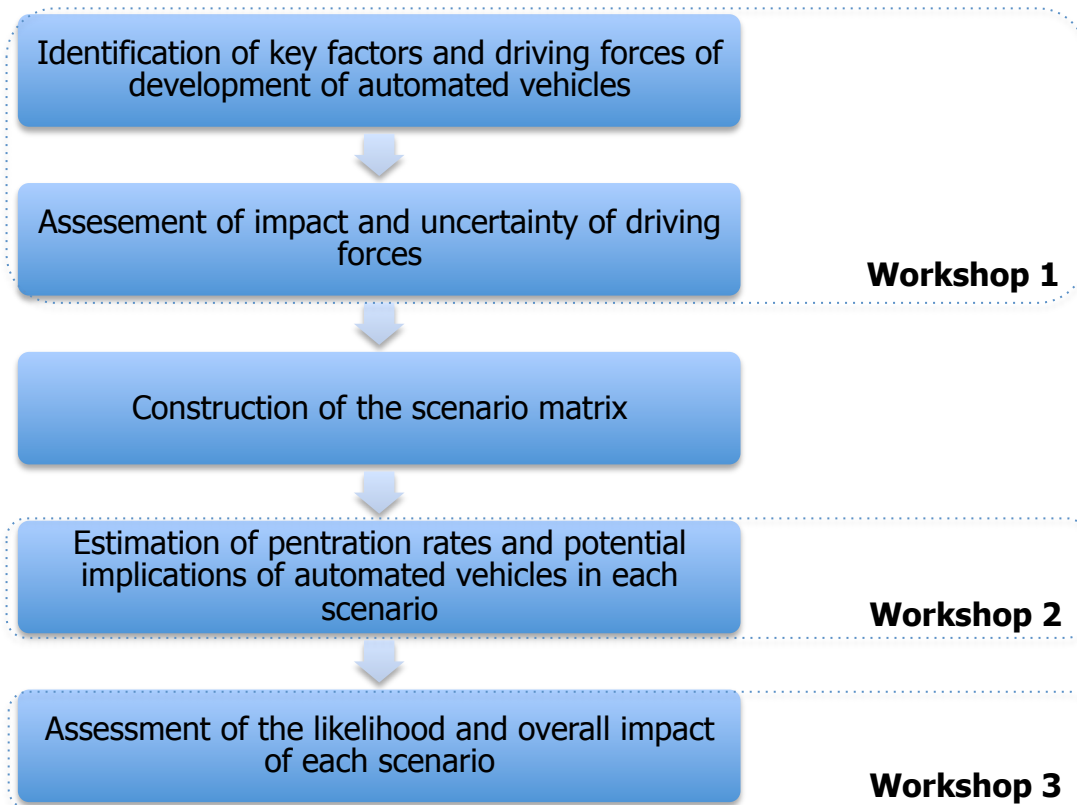


Figure 11: The five steps for the construction and assessment of scenarios about development of automated vehicles in the Netherlands.

4

Scenarios about development and implications of automated vehicles in the Netherlands

4.1 Key factors and driving forces

Sixteen key factors were identified as critical in determining future development of automated vehicles in the Netherlands (see table 1). Each factor is assumed to have a direct and an indirect (through interaction with other factors) effect on the development of automated vehicles. For example, automated vehicle trials could help advance this technology, thus accelerating transition steps towards full automation, but could also positively affect the image of automated vehicles to the public. Also, the formulation (or lack) of a progressive legal/institutional framework (both in the Netherlands and in the European Union) for automated vehicles could affect automated vehicles trials, the development of automated vehicles in neighbouring countries and in the European context in general, the evolution of shared mobility schemes and subsequently automated vehicles ownership structures, and finally the perceived psychological barriers for using this technology. On the other hand, unintended incidents (e.g., fatal accidents during initial introduction of automated vehicles) could affect direction and speed of regulations for automated vehicles.

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,
Income	Environment Economy

Table 1: The key factors and drivers of automated vehicles development in the Netherlands as identified in the workshops.

Five driving forces were identified behind key factors in the workshops. These are policies, technology, customers' attitude, economy and the environment (see table 1). Policies and technology appear as the driver for twelve and eleven key factors respectively. Customers' attitude

and economy were identified as drivers for five key factors. Finally, the environment was identified as a driver of only two key factors.

4.2 Impact and uncertainty of driving forces

In the second step of our methodology, we assessed driving forces with respect to the magnitude of their potential effect on development of automated vehicles (impact) and the predictability of their future state (uncertainty). The assessment was completed in one workshop with five participants. Each participant was asked to rank the driving forces based on their impact and uncertainty. According to the results, technology is expected to have the strongest impact on the development path of automated vehicles, but it is also highly unpredictable (see table 2). Policies were found to be quite influential, but uncertain as well. Customers' attitude was also indicated as a highly unpredictable factor, but the expected impact was assumed to be lower than technology and policies. Finally, economy and the environment were assumed to be fairly predictable and to have relatively lower impact on the development of automated vehicles.

Based on those results, technology and policies appeared to be the most influential driving forces. Both were also highly unpredictable although customers' attitude appeared as equally uncertain driving force. Therefore, technology and policies were selected as the most relevant driving forces to build our scenario matrix.

	Impact	Uncertainty
Technology	5.0	4.0
Policies	4.0	4.0
Customers' attitudes	3.0	4.0
Economy	2.0	2.0
Environment	1.0	1.0

Table 2: The median value of driving forces rank according to their impact and uncertainty (1-lowest, 5-highest). Results from five expert participants' responses collected in Delft University of Technology workshops.

4.3 Scenario matrix

Four scenarios were constructed assuming combinations of high or low technological development and restrictive or supportive policies for automated vehicles (see figure 12). Although scenarios were built around permutations of those two driving forces, we have also incorporated all remaining driving forces (customers' attitude, economy, environment) aiming to capture as much as possible of the complexity surrounding this exercise (see figure 13). Moreover, the key factors and possible interactions among them (see section 4.1) offered input into the development of detailed, dynamic and coherent scenario plots.

AV ...in standby

High technological development

AV ...in bloom

- Fully automated & cooperative vehicles (V2V) in 2030.
- Legislation inflexibility for AV. Transport policies restraining use of AV. High regulation of AV trials.
- Modest economic growth.
- "Wait and see..." customers attitude, mid-low demand for AVs.
- No major environmental problems, but still low penetration of electric vehicles.

- Fully automated & cooperative vehicles (V2V & V2I) in 2025.
- Laws allowing AV traffic. Limited regulation of AV trials. Public investments on AV research and on smart infrastructure.
- High economic growth.
- Positive customers attitudes, strong demand for AVs.
- Limited environmental problems. Clean technologies prevail.

Restrictive AV policies

Supportive AV policies

- Fully automated vehicles in 2045.
- Limited legislation for AV integration. No AV trials allowed.
- Recessive economy, high unemployment.
- Negative customers attitude, almost no demand for AVs.
- Important environmental problems. Very slow transition to low-carbon economy.

- Fully automated & cooperative (V2I) vehicles in 2040.
- Progressive legislation for AV integration. No regulation of AV trials. Promotional campaigns.
- Slow economic growth.
- "Not really interested..." customers attitude, low demand for AVs.
- Increased environmental problems. Transport sector still among major polluters.

AV ...in doubt

Low technological development

AV ...in demand

Figure 12: Scenario matrix about development of automated vehicles in the Netherlands.

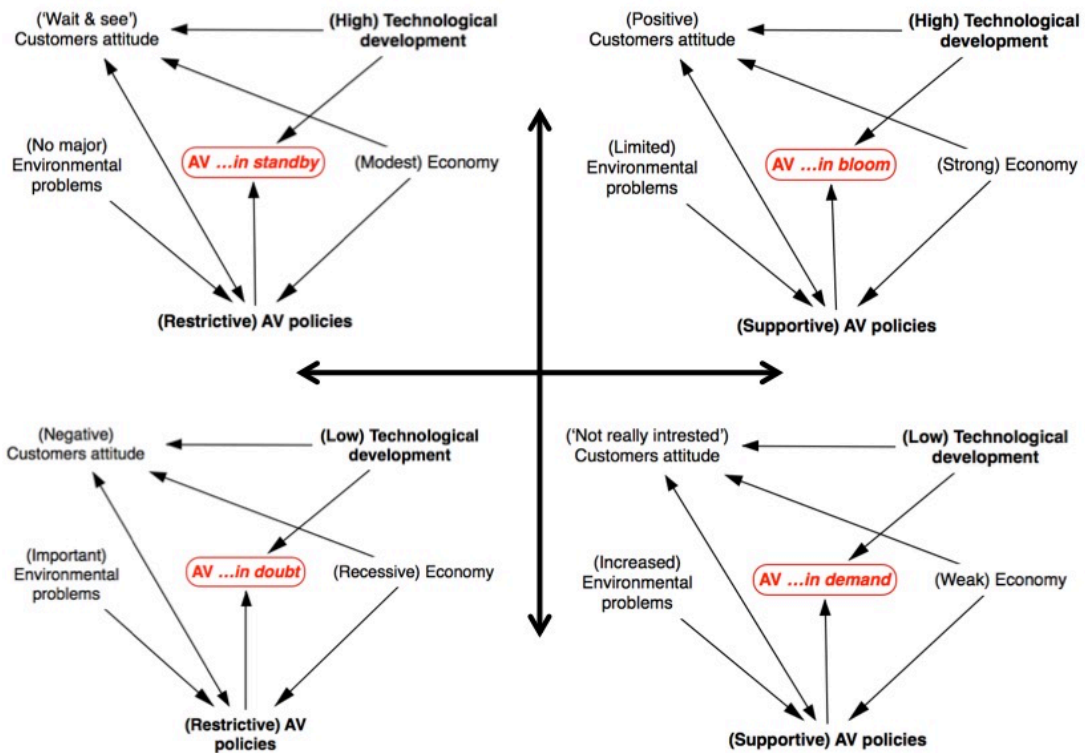


Figure 13: Possible interactions among drivers of development of automated vehicles in the Netherlands.

4.3.1 Scenario 1: Automated vehicles ...in stand by

Although discussion about the potential of having fully automated vehicles on public roads by 2030 had been intensified already since 2015 and conditional automation was a reality since 2020, the Dutch government decided not to heavily invest on integration of this mobility technology in the transportation system of the Netherlands. In fact the government did not see any major benefits stemming from a rapid development of automated vehicles, while they did foresee a lot of risks associated with this technology. It is true that the Dutch transportation system was really efficient in the early 2020's with a multimodal character, which was translated into a modal split where almost half of the trips were being undertaken by bicycle, foot or public transportation. Moreover, transport safety was steadily improving and no major environmental problems were expected in following years. The consistent strategy towards low-carbon economy had already started paying-off. Also, the modest economic growth did not allow allocation of more resources on infrastructures related to this emerging technology (V2I).

The combination of Dutch government's skepticism about automated vehicles and the weak income growth had possibly played a role on customers' moderate to low demand for automated vehicles. Customers' demand did not significantly change even when conditionally automated vehicles were made commercially available in 2020. The fact that the Dutch government allowed conditionally automated vehicles to travel only in motorways until 2025 might have deterred demand. Moreover, the attitude towards vehicles in general and automated vehicles in particular was not very positive at that time, with most customers adopting a 'wait and see' position. In fact vehicles use had already reached its peak a decade earlier (during 2010's) mainly because of the generation Y reluctance to live an automobile oriented -20th century like- life. This attitude did not change dramatically in the following years until the advent of fully automated cars in 2030. At that point automated vehicles (conditional automation) represented a small fraction of total vehicles fleet (4%) and a slightly higher percentage (7%) of total vehicle kilometers traveled (VKT) (see figure 14).

The advent of fully automated vehicles in 2030 signaled a change in customers' attitude. Auto manufacturers adopted an aggressive promotion strategy, which among other actions allowed everyone to experience first hand a fully automated vehicle for a week. They knew that 'hands on' experiences could remove psychological barriers of automated driving from both customers and citizens, even if eventually they would not buy the car. Moreover, seamless communication between automated vehicles (V2V) and safe operation in urban environments signaled a huge progress. Operation first of conditional and then of fully automated vehicles in urban environments was indeed proven a real challenge especially with respect to urban intersections and uncontrolled pedestrian movements. Customers' attitudes about automated vehicles became progressively more positive after 2030, which was translated into stronger demand for this kind of vehicles. Twenty years later (2050) automated vehicles represented 26% of vehicles fleet and 33% of total VKT (see figure 14). During the same period (2030-2050) the Dutch government regulated several areas related to fully automated vehicles (e.g., automated-taxis, liability, safety). However, no proactive actions were taken to further promote this mobility technology because initial fears about potential negative implications, like strong induced travel demand, sprawling trends and a modal shift from conventional public transportation to automated vehicles were confirmed. In fact, the decrease of value of time for automated vehicles users by 21% (see figure 15) and the increase of motorways capacity by 7% (mainly because of the development of cooperative systems) (see figure 16) could easily explain the increase of total VKT by 7% in 2050 (see figure 17).

4.3.2 Scenario 2: Automated vehicles ...in bloom

The CEO of Audi predicted in his interview on Automotive News in 2015 that *"a vehicle capable of driving itself with no need for any interaction from the driver, even in critical situations, is probably 10 years away"*. He was right. Technological development between 2015 and 2025 was really rapid. First vehicles with conditional automation were already launched in the market in 2018 and fully automated vehicles hit the market in 2025. Governments in the Netherlands, Sweden, UK, Japan and California helped research community, high technology industry and auto manufacturers to rapidly push the boundaries of vehicle cooperation (V2V) and automation. In the Dutch context, a progressive regulatory framework for automated vehicles trials was adopted as early as 2016, while significant investments in research and development followed in coming years, supported by R&D funds of the European Commission. Important investments on infrastructure communication with vehicles (V2I) were decided in mid-2010's and implemented within the next ten years, allowing for seamless operation of automated vehicles in motorways and urban streets but also for easy system upgrades thereafter. Moreover, an aggressive subsidy policy was adopted. During first five years after launch, fully automated vehicles were exempted from the registration fee, while electric automated vehicles were exempted from road taxes as well. In the case of shared electric automated vehicles (automated taxis) the government decided to provide an additional subsidy of 3000€ on the purchase, which had been proved a successful measure for electric-taxis about a decade earlier. It was clear that the Dutch government was seeing automated vehicles as the solution to many long-standing mobility-related societal problems originated in 20th century, like congestion and traffic fatalities. They were also considering the introduction of automated vehicles as an opportunity for developing a more efficient multimodal transportation system. The healthy macro-economic environment in Europe and the high economic growth in the Netherlands supported the decisions for adopting such aggressive promotional policies for automated vehicles. Moreover, most policy reports from governmental organizations at that time were suggesting that investments on automated vehicles were highly likely to pay-off soon by addressing many of the inefficiencies of the conventional transportation system. An important prerequisite, as all reports clearly noted, was user acceptance.

Customers' attitude about automated vehicles evolved quite positively during the 2010's. It was the disruptive change in the mobility experience that attracted the attention of most people at that point. More productive use of travel time and safe driving conditions were among the changes that customers valued more. They were also frequently referring to wider positive societal implications such as lower energy consumption, environmental protection, economic, and social equity benefits (e.g., mobility for elderly and disabled persons). The positive economic context, the supportive governmental policies, but also the wider societal changes of that period such as the growth of digital and shared economy and the environmental awareness movement played also a key role in having strong demand for automated vehicles. The share of automated vehicles reached 11% in 2030 and rocketed to 61% in 2050 (see figure 14). The share of VKT by automated vehicles in total travel followed a similar path (23% in 2030 and 71% in 2050). As expected, automated vehicles users (especially early adopters) were inclined to drive, on average, more kilometers than users of conventional vehicles because of the opportunity they had to relax or do other useful things during their trip. Indeed the value of time for automated vehicles users had dropped 18% already by 2030 and 31% by 2050 (see figure 15). New models of fully automated vehicles after 2030 offered a highly flexible interior design that allowed all kind of activities to be undertaken during travel including sleeping, working, tele-conferencing and many more. Moreover, the combination of automated and cooperative systems (V2V and V2I) allowed capacity to increase on

both motorways and urban streets by 25% and 6% respectively in 2050 (see figure 16). All these benefits did not come without a cost. Total vehicle kilometers had significantly increased by 3% already in 2030 and by 27% in 2050 (see figure 17). The Dutch government quickly realized that congestion relief would not come simply by introducing automated vehicles. In fact, they realized that congestion could get worse in the future because of induced travel demand and sprawling trends, if they would not take action. Therefore, stricter land use policies inspired by the compact city paradigm (which had been abandoned decades earlier) and transportation demand policies, such as road pricing, had been introduced during the 2040s to curb growth in travel and urban expansion. Furthermore, automated taxis had been highly regulated after 2030 with respect to total number of taxis per capita, and hours of operation. Automated taxis were responsible for a significant part of VKT increase and thus congestion, mainly because of their 24/7 non-stop operation. Dynamic policy adaptation, such as in the case of automated taxis (from heavily subsidized to highly regulated), was clearly the right way to go in a new transportation ecosystem where asymmetric changes were more likely than ever.

4.3.3 Scenario 3: Automated vehicles ...*in demand*

The optimism for seamless mobility by fully automated vehicles in the near future was high in the mid 2010's. The countless discussions in popular media were centered on possible changes that this technology could bring to daily mobility and subsequently to our societies. These discussions were fueled by frequent announcements of auto manufacturers' plans for fully automated mobility until 2025. Many governments around the world, including the Netherlands, were foreseeing major societal benefits from this technology, like congestion relief and significant reduction of accidents. Therefore, they rapidly formed progressive legislative frameworks allowing automated vehicles trials and supporting cooperation between automobile and high tech industry. They also invested on research and development of this technology and asked governmental organizations to adapt their plans to possible development of vehicle automation in coming years. Moreover, they secured important resources to fund smart infrastructures that would allow communication with automated vehicles both in motorways and in urban environments (V2I). These investments were partly funded by European Commission R&D funds, which in the meantime had decided to allocate more resources in developing vehicle automation in Europe mainly because of the expected traffic safety benefits.

However, the technological path to full automation was proved more difficult than assumed. It took ten years (2025) for auto manufacturers in collaboration with high technology companies only to make conditional automation commercially available. The variability of road infrastructure and weather conditions, but also the complexity of urban environment especially with respect to interaction with other road users (conventional cars, cyclists and pedestrians) and to unexpected events (e.g., road flooding) required exhaustive tests and continuous adaptation of technology to meet high safety standards. Moreover, the first fatal accidents in European urban roads between conditionally automated vehicles and pedestrians in 2026 proved that this technology was not entirely ready (at least for urban environments). The European Union and many governments around the world responded with a mandate that conditionally automated vehicles will only be allowed on motorways until the technology would evolve enough according to even higher safety standards. The Dutch government also announced a new round of funding for research and development in this area. Fifteen years later (2040) fully automated vehicles were hitting the market.

Customer's demand for automated vehicles incrementally increased up to 2040 and significantly expanded thereafter. Only 3% of total vehicle fleet was (conditionally) automated in 2030

representing 5% of total VKT (see figure 14). The first fatal accidents in 2026 further prevented customers from buying automated vehicles. It was only in 2040 with the advent of fully automated vehicles when the psychological barriers for this technology were truly removed and sales subsequently increased. In coming years people realized that this was a safe technology with significant benefits especially with respect to comfort and to various activities someone could undertake during a trip. The value of time was decreased by 16% for automated vehicle users in 2050 (see figure 15), while penetration was quite high at that time with 17% of all vehicles being automated (see figure 14). Moreover capacity increased by 5% in motorways and by 2% in urban streets in 2050 (see figure 16). The combination of a decrease in value of time and an increase in capacity resulted in more VKT in 2050 (3%) (see figure 17). In fact the Dutch government was expecting a stronger increase of VKT in coming years after 2050, because penetration of automated vehicles was expected to become even higher. Therefore, they were already planning to introduce travel demand management measures from the beginning of 2050s to prevent major increase of VKT. Unfortunately, a significant portion of automated vehicles was still carrying internal combustion engines. Thus, increased VKT were associated with more energy consumption and more emissions.

4.3.4 Scenario 4: Automated vehicles ...*in doubt*

Automated vehicles were one of the most appealing concepts of mobility technology during the 20th century. No accidents, no driving effort, more personal time, less congestion and almost no parking problems were the basic elements of vehicle automation imprinted in the collective imaginary. In the early 21st century, the discussion about the prospects of a fully automated mobility world resurfaced because of some technological progress of auto manufacturers and high technology companies in this area. However, fully automation was still way too far from reality and cities and transportation systems were more complex than ever. Thus, such a socio-technical transition seemed quite difficult even if the technology was available.

In fact, it turned out that none of the basic forces (high technological development, supportive policies and positive customers' attitudes) for such a transition were existent. In a recessive global economic context during late 2010's, most governments (the Dutch included) did not intend to spend their valuable resources on research and on infrastructures for automated vehicles. Neither did they develop a supportive institutional framework for testing and developing this technology. They thought that vehicle automation might in fact lead to counter-effective results for the transportation system. Their deepest fear was that the system would not evolve enough to become fully automated. Thus, it was likely to stuck in transition where semi-automated, fully automated and conventional cars would co-exist, causing major safety and congestion problems especially in urban environments. Their fears were absolutely justified. The technology evolved quite slowly after 2015 with first conditional automation vehicles hitting the market only in 2028 and subsequently allowed to travel only in Dutch motorways. The bankruptcy of a major automotive company (due to a sharp decrease in sales of conventional cars in China) and the shift of attention of a high tech giant from automated vehicles to other emerging technologies could partly explain the slow technological development in this field. Technical difficulties associated with the detection of obstacles and navigation in various road and weather conditions and in complex urban environments inhibited rapid technological development as well.

As a result only 1% of total vehicles fleet was (conditionally) automated in 2030. Customers' were reluctant to buy this technology since neither the government supported it through, for example, subsidizing policies, nor middle-class income could afford to pay for such a premium technology. When fully automated vehicles were launched in 2045, customers' interest became stronger since

the benefits were clearer than and the Dutch government allowed these vehicles to travel in urban environments as well. However, the price for this technology was still too high, thus fully automated vehicles continued to represent a marginal share of the vehicles' fleet in 2050 (7%). Moreover, fully automated taxis offering premium services became available after 2045. These companies have invested in transforming the interior of these taxis into fully functional work and rest spaces. The marginal share of automated vehicles affected neither capacity nor total VKT in 2050 (see figures 16 and 17 respectively).

Unlike 20th century, vehicle automation did make it through to the market in 21st century. However, until 2050 automated vehicles were still a technology for the upper class that could afford to have it. The rest of the people could have an experience with an automated vehicle by hiring an automated taxi or by just taking automated buses, which in the meantime had grown rapidly.

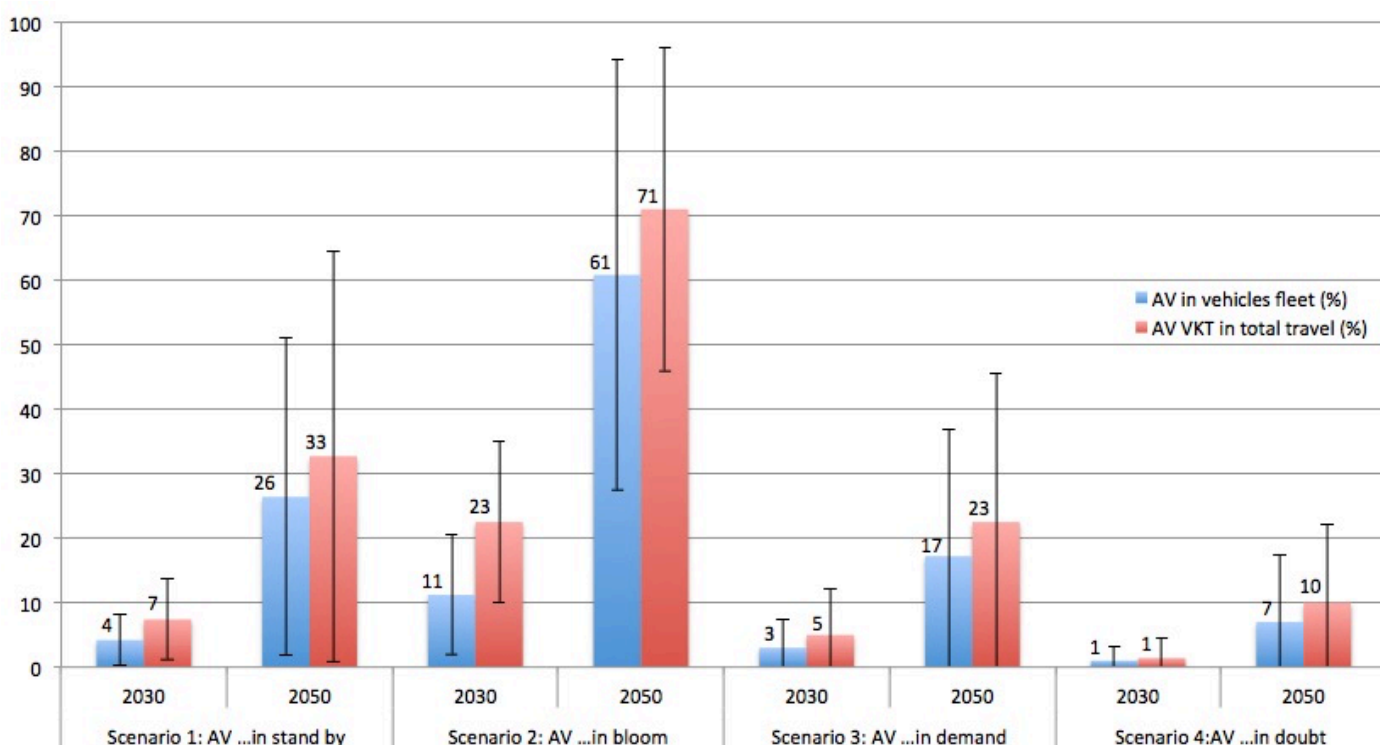


Figure 14: Estimation of (a) percentage of (conditionally and fully) automated vehicles in vehicles fleet and (b) percentage of VKT by (conditionally and fully) automated vehicles in total VKT, in 2030 and 2050. Each bar represents average value of 5 experts responses collected in Delft University of Technology workshops and error bar depicts standard deviation.

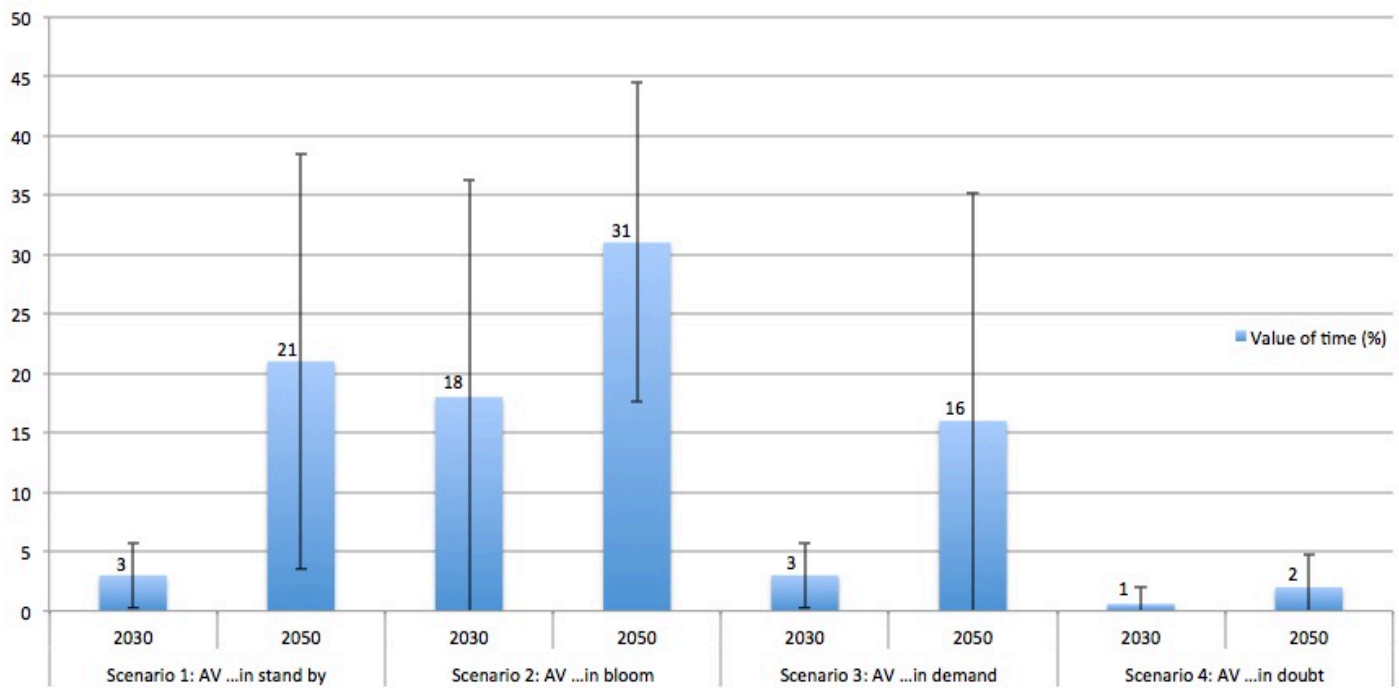


Figure 15: Estimation of decrease in value of time of automated vehicle users in different scenarios. Each bar represents average value of five experts responses collected in Delft University of Technology workshops and error bar depicts standard deviation.

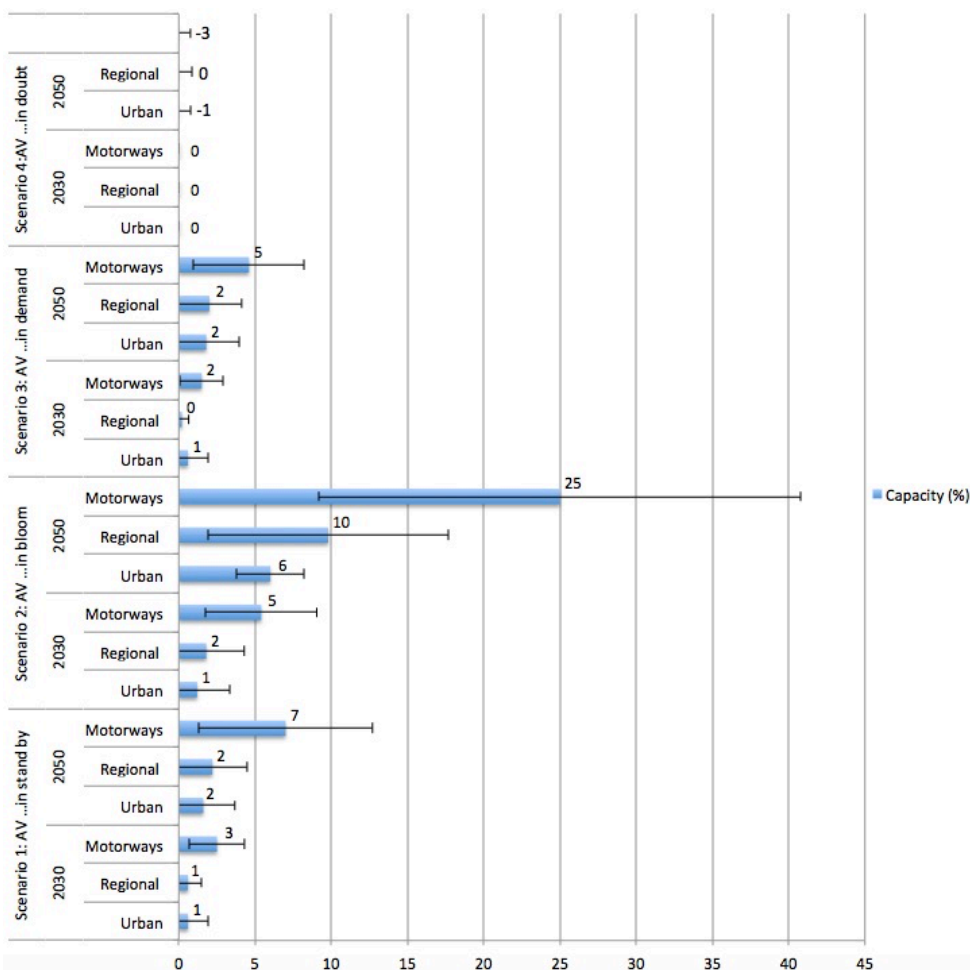


Figure 16: Estimation of capacity changes in different scenarios. Each bar represents average value of five experts responses collected in Delft University of Technology workshops and error bar depicts standard deviation.

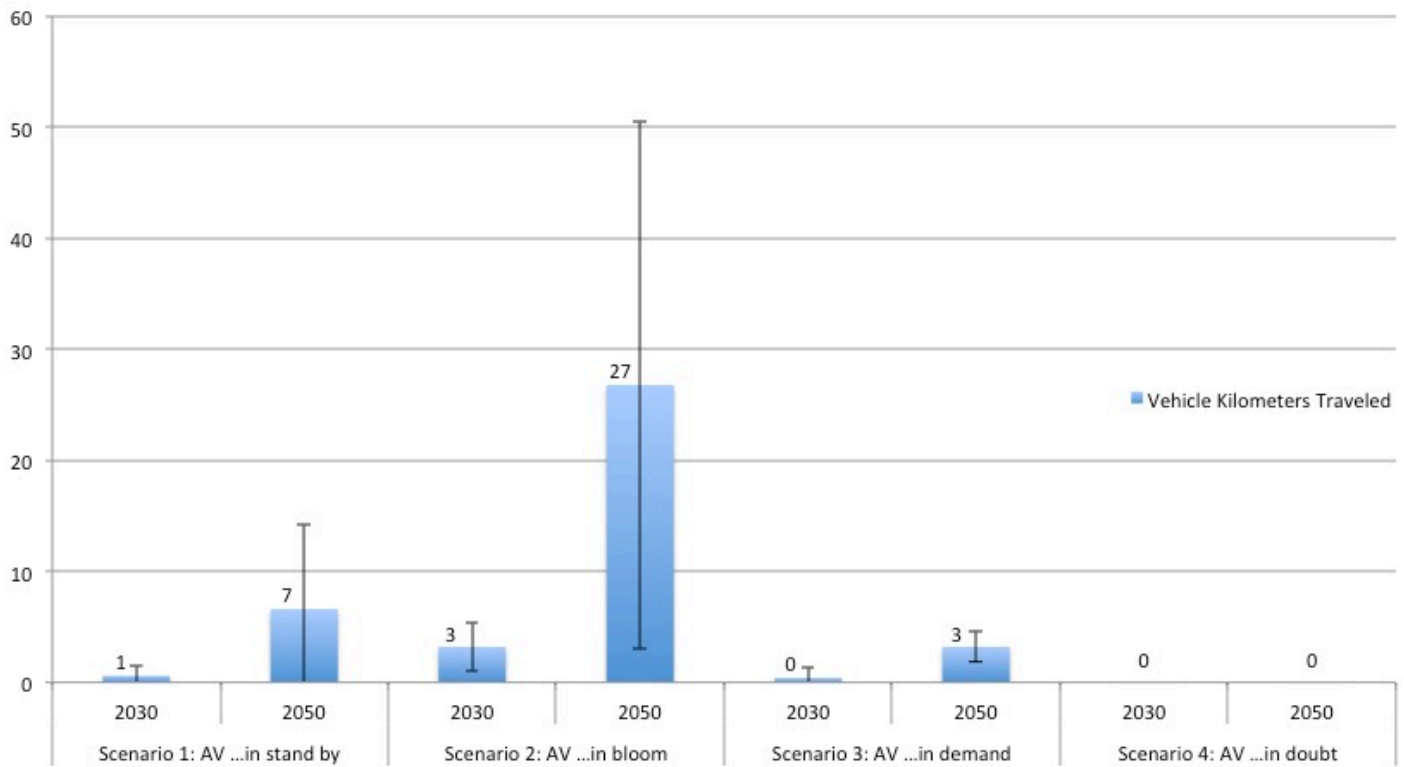


Figure 17: Estimation of change in total vehicle kilometres traveled in different scenarios. Each bar represents average value of five experts responses collected in Delft University of Technology workshops and error bar depicts standard deviation.

4.3.5 The four scenarios ...in brief

This section summarizes the main characteristics of the scenario plots. We focus on the market launch of conditionally and fully automated vehicles, penetration rates and mobility impacts in 2030 and 2050.

Conditionally automated vehicles are expected from our scenarios to be commercially available within a time window of ten years (between 2018 in the 'AV ...in bloom' scenario and 2028 in the 'AV ...in doubt' scenario). The respective time-window for fully automated vehicles is larger (twenty years) and more distant (between 2025 in the 'AV ...in bloom' scenario and 2045 in the 'AV ...in doubt' scenario) (see table 3). Penetration rates of automated vehicles vary among different scenarios between 1% and 11% in 2030 (see table 4). These rates regard only conditionally automated vehicles except for the 'AV ...in bloom' scenario, which anticipates fully automated vehicles to be commercially available well before 2030. Penetration rates are expected to vary between 7% and 61% in 2050. These rates represent penetration of both conditionally and fully automated vehicles. The balance between them in the market has not been quantitatively identified in this study. However a first rough estimation is available in the scenario plots. The share of automated vehicles VKT in total travel varies along similar ranges (between 1% and 23% in 2030 and between 10% and 71% in 2050).

Expected impacts of automated vehicles on mobility show great variation among the four scenarios as well. For example, the decrease of value of time for automated vehicle users varies between 1% and 18% in 2030 and between 2% and 31% in 2050. Similarly, motorways capacity changes vary between 0% and 5% in 2030 and between -3% and 25% in 2050. Moreover, expected changes in the capacity of urban roads vary between 0% and 1% in 2030 and -1% and 6% in 2050. Finally, total VKT varies between 0% and 3% in 2030 and between 0% and 27% in

2050. The highest impacts appear in the 'AV ...in bloom' scenario and the lowest in the 'AV ...in doubt' scenario.

	First vehicle in the market	
	Conditionally automated	Fully automated
AV ...in stand by	2020	2030
AV ...in bloom	2018	2025
AV ...in demand	2025	2040
AV ...in doubt	2028	2045

Table 3: Market introduction year for conditionally and fully automated vehicles according to different scenarios.

	2030		2050	
	Min	Max	Min	Max
AV in vehicles fleet (%)	1	11	7	61
AV VKT in total travel (%)	1	23	10	71
Value of time - AV users (%)	1	18	2	31
Capacity (%)				
<i>Motorways</i>	0	5	-3	25
<i>Regional roads</i>	0	2	0	10
<i>Urban roads</i>	0	1	-1	6
Total VKT (%)	0	3	0	27

Table 4: Range of penetration rates and impacts of automated vehicles in the four scenarios.

4.4 Likelihood and overall impact of the scenarios

All scenarios were assessed with respect to their likelihood and overall impact during the last workshop. In this workshop, the draft scenarios were presented to twenty experts from twelve different planning, technology, and research organizations in the Netherlands. After two rounds of discussion about the four scenarios of development and implications of automated vehicles in the Netherlands, the participants were asked to evaluate each scenario with respect to (a) its likelihood on a scale ranging from 0% (impossible) to 100% (certain), and (b) its overall impact (i.e., value of time, road capacity, and total VKT) on a scale ranging from 0 (no impact) to 5 (highest impact). The participants were also asked to respond about their confidence with the estimations on a scale ranging from 0 (not at all confident) to 5 (very confident).

According to the results, scenario 2 (AV ...in bloom) and scenario 3 (AV ...in demand) were perceived as the most likely to happen in the future (41.8% and 38.3% respectively; see figure 18). The likelihood of scenario 1 (AV ...in standby) and of scenario 4 (AV ...in doubt) was assessed lower (31.8% and 25.8% respectively). The average sum of probabilities per person was 137.5%, while only one person estimated a sum of probabilities below 100%. Moreover, the participants were quite confident about their responses (average level of confidence: 3.1). The results did not change significantly when responses were weighted based on the level of confidence.

The scenario 2 (AV ...in bloom) was also expected to have the highest overall impact (4.6), with scenario 1 (AV ...in standby) and scenario 3 (AV ...in demand) having similar but lower effects (2.4 and 2.3 respectively) (see figure 19). The scenario 4 (AV ...in doubt) was not expected to have significant impacts on mobility (1.1).

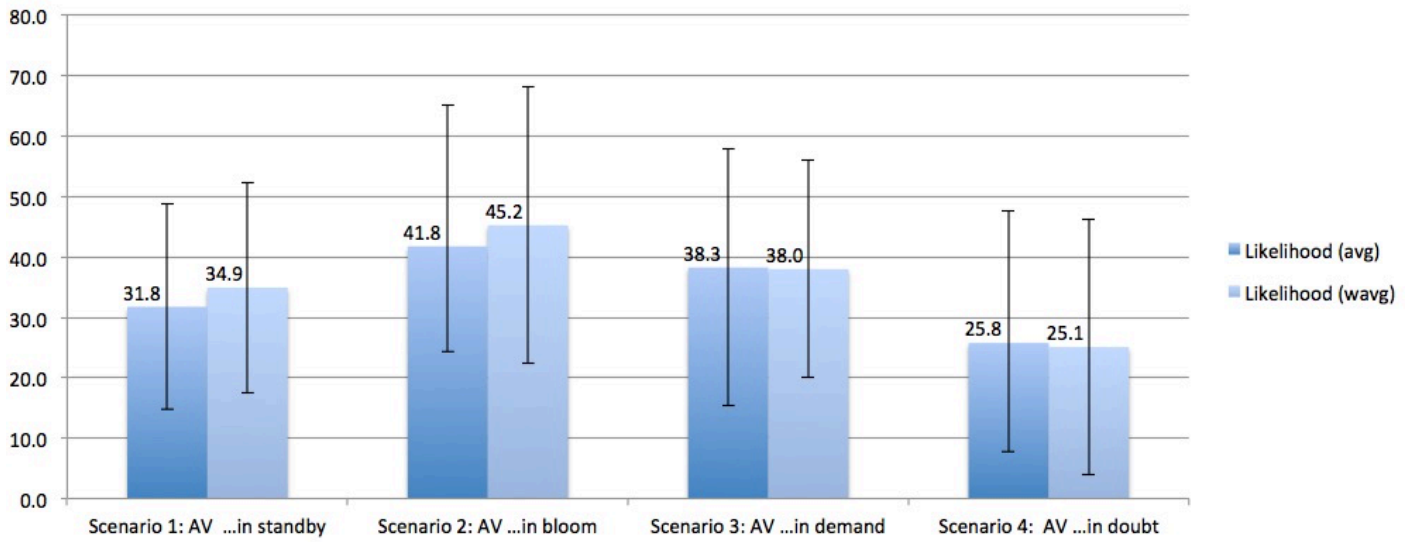


Figure 18: The perception of likelihood of the four scenarios about development of automated vehicles in the Netherlands. Weighted average values are based on the participants' level of confidence. Error bars depict standard deviation.

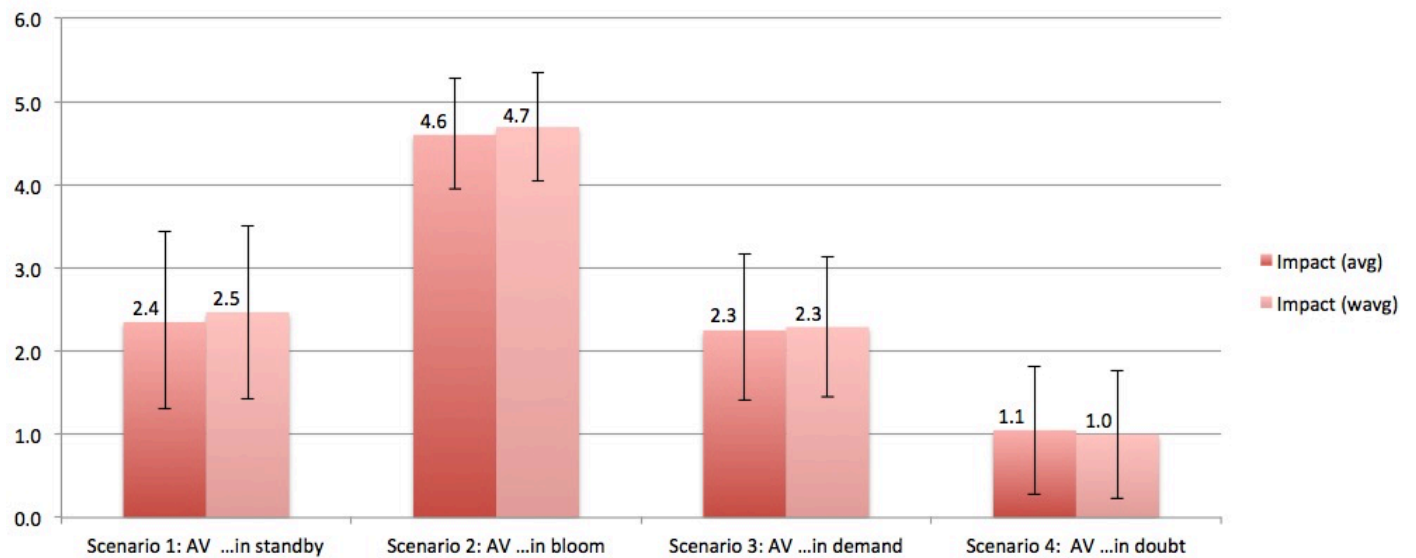


Figure 19: The perception of overall impact (i.e., value of time, road capacity, and total VKT) of the four scenarios about development of automated vehicles in the Netherlands. Weighted average values are based on the participants' level of confidence. Error bars depict standard deviation.

5

Conclusions

The aim of this study was to identify plausible future development paths of automated vehicles in the Netherlands and to estimate potential implications for traffic, travel behaviour and transport planning on a time horizon up to 2030 and 2050. A scenario analysis was conducted involving five sequential steps: (a) identification of key factors and driving forces of development of automated vehicles, (b) assessment of impact and uncertainty of driving forces, (c) construction of the scenario matrix, (d) estimation of potential implications of automated driving in each scenario, and (e) assessment of the likelihood and overall impact of each scenario. The process was completed in three workshops and resulted in four scenarios about development and implications of automated vehicles in the Netherlands.

Sixteen factors and five driving forces behind them were identified as critical in determining future development of automated vehicles in the Netherlands. The driving forces are technology, policies, customers' attitude, economy and the environment. Technology and policies were assessed to be the most influential and unpredictable driving forces; hence the scenario matrix was built around them. Four scenarios were constructed assuming combinations of high or low technological development and restrictive or supportive policies for automated vehicles. All remaining driving forces have been incorporated in our scenarios as well. Moreover the relationships among different key factors have also been reflected in our scenario plots.

The first scenario (*AV ...in stand by*) describes a path where although automated vehicles technology develops rapidly (fully automated vehicles are commercially available in 2030), the Dutch government is reluctant to invest on it because they see a lot of risks surrounding this technology. Thus, development of automated vehicles is industry driven, succeeding to overcome initial customers' skepticism and achieving high penetration rates, especially after 2030 when fully automated vehicles become available. Initial fears of the Dutch government about potential negative implications, like strong induced travel demand, sprawling trends and a pressure to conventional public transportation services are confirmed.

The second scenario (*AV ...in bloom*) describes a path where both technology and policies of the Dutch government offer a positive context for the development of automated vehicles. Fully automated vehicles become available in 2025 and a progressive regulatory framework, involving also high subsidies, is adopted. The positive economic context, the supportive governmental policies, but also the wider societal changes of this period push the demand for automated vehicles high. Also, the growth of fully automated taxis operating 24/7 is enormous. The Dutch government soon realizes that demand management and further regulatory measures should be taken to curb fast growing vehicle travel because of the introduction of automated vehicles.

The third scenario (*AV ...in demand*) describes a path where the Dutch government promotes automated vehicles through several measures because they are very optimistic about potential societal benefits (e.g., congestion relief and reduction of accidents). However, technological evolution is very slow (fully automated vehicles become available only in 2040) for several reasons including some fatal accidents during initial introduction of automated vehicles. Thus, demand

incrementally increases up to 2040 and significantly expands thereafter, when the psychological barriers for this technology are removed. The combination of a decrease in value of time and an increase in capacity results in more VKT, which urges the Dutch government to take travel demand management measures.

The fourth scenario (*AV ...in doubt*) describes a path where none of the basic forces (high technological development, supportive policies and positive customers' attitudes) for the development of automated vehicles exist. The Dutch government estimates that vehicle automation could have counter-effective results for the transportation system. They expect that the system will not evolve enough to become fully automated. Also, several incidents in the auto and high tech industry slowdown technological growth in this field. Fully automated vehicles hit the market only in 2045. Automated vehicles evolve as a technology for the upper class that could pay a premium to have it. Fully automated taxis offering premium services (work and rest spaces on the move) become also available after 2045.

There are some interesting points that we could make based on the four scenario plots: (a) fully automated vehicles are expected to be commercially available within a time window of twenty years (between 2025 and 2045), while the respective time-window for conditional automation is smaller (ten years) and more immediate (between 2018 and 2028), (b) in all scenarios full vehicle automation are expected to be a game changer, driving the demand for automated vehicles high. Penetration rates of automated vehicles are expected to vary among different scenarios between 1% and 11% (mainly conditionally automated vehicles) in 2030 and between 7% and 61% (mainly fully automated vehicles) in 2050. Recall that fully automated vehicles are expected no earlier than 2025, (c) vehicle automation and cooperation will likely follow converging evolution paths. The type of cooperation (V2I, V2V) will likely vary though among different scenarios according to the main drivers (policies, technological development), (d) complexity of urban environment is expected to influence development path of automated vehicles either by inducing regulation allowing automated vehicles to travel only in motorways or by complicating and subsequently delaying technological development in this field, (e) unexpected incidents like fatal accidents; bankruptcy or change in strategic priorities of major industry players could significantly influence the development path for automated vehicles not only in the Netherlands, but also in any country, (f) development of automated vehicles is expected to have implications on mobility in all scenarios. These implications vary from very important in the '*AV ...in bloom*' scenario to minimal in the '*AV ...in doubt*' scenario, (g) because of the above-mentioned implications, the Dutch government is expected to take measures (e.g. travel demand management) to curb growth of travel and subsequent externalities in three out of the four scenarios.

In the last step of our study twenty experts assessed the likelihood of all scenarios and overall impact (i.e., value of time, road capacity, and total VKT). Scenario 2 (*AV ...in bloom*) and scenario 3 (*AV ...in demand*) were perceived as the most likely to happen in the future, while likelihood of scenario 1 (*AV ...in standby*) and scenario 4 (*AV ...in doubt*) was assessed lower. These results show that the experts who participated in our workshop expect policies in the Netherlands to be generally supportive of automated vehicles (scenarios 2 and 3 exhibited the highest likelihood) and thus it is probably technology that will mainly influence development path of automated vehicles. In fact, participants seem also to believe as well that technology has good chances to develop rapidly and full automation to be a reality within the next ten years, if we take into account that '*AV ...in bloom*' was ranked as the most likely scenario. It should be noted that the average sum of probabilities per participant was 137.5%, while only one person estimated a sum of probabilities below 100%. This indicates that the participants were quite confident that the four scenarios can

adequately describe potential development paths of automated vehicles in the Netherlands or at least they did not consider a fifth scenario as more likely than the scenarios presented to them. Finally, the experts expect the 'AV ...*in bloom*' scenario to have the highest and the 'AV ...*in doubt*' scenario the lowest overall impact. This estimation coincides with the results of our earlier workshops about more detailed assessment of mobility impacts in different scenarios.

In conclusion, our study suggests that fully automated vehicles will likely be a reality between 2025 and 2045 and are expected to have significant implications for mobility and planning policies in the Netherlands. The pace of development and subsequent implications largely depend on technological evolution, policies and customers' attitude.

6

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