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MANTRA

MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business

Impacts of automation functions on NRA policy targets

Deliverable D3.2

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MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business

Deliverable D3.2 – D3.2 Impacts of automation functions on NRA policy targets

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Executive summary

The development of various types of automated vehicles is progressing slowly towards higher levels of automated driving. Introduction of automation will impact the mobility and travel behaviour, driving behaviour and traffic flow, traffic safety and energy and environment. This impacts the core business of National Road Authorities (NRAs), including operational processes and maintenance. Therefore, this report assesses the implications of connected and automated driving using simulation studies, followed by the impact of automation on operational processes and the overall impacts of automation on NRA key policy targets.

We analysed the effects of four different automation functions: highway autopilot including highway convoy, highly automated freight vehicles on open roads, commercial driverless taxi services, and driverless maintenance and road works vehicles.

Simulation studies indicated that the introduction of highway autopilot will lead to an increase of kms driven on motorways – the roads where automated driving is allowed according to the ODD specification. However, due to more efficient traffic flow caused by automated driving (and thereby an increase in road capacity), the experienced delays are expected to decrease. The traffic flow efficiency and safety were analysed in another simulation study involving microsimulation of a motorway segment. The results show that indeed decreasing travel times are to be expected as the penetration rate (the percentage of AVs on the road) increases. However, these results highly depend on the way conventional vehicles are modelled. If conventional vehicles drive more aggressively (e.g. as captured by helicopter data in peak hours in the Netherlands) the introduction of highly automated vehicles (keeping shorter time headways) will not have any negative effects, whereas mixing them with “normal” conventional vehicles will lead to an increase in travel time with small penetration rates.

The simulation study examining the impact of highly automated freight vehicles on a major motorway corridor indicated that the impacts on travel time and speed were positive. The benefits generally increased in line with penetration of the automated vehicles, with the most substantial benefits being in congested conditions. In free flow conditions, the benefits accrued mainly to the automated vehicles. Shorter inter-vehicle gaps and a maximum platoon length of four instead of three vehicles both increased the benefits, but only in congested stretches of motorway.

Commercial driverless taxi services were added to a simulation model of the city of Delft, the Netherlands. It was shown that the introduction of robotaxis hardly results in any changes in public transport and bicycle usage – only trips performed by private cars are affected. The relocation of empty robotaxis – getting back to the origin or a new trip – results in many additional kms driven and thereby also leading to additional delays for all road users. We only looked into private taxi trips, the use of (partly) shared trips might overcome this problem by decreasing the required number of trips.

We tested the impact of two different types of automated maintenance: a safety trailer in front of a slow moving work zone (15 km/h), and a winter maintenance truck for snow ploughing (45 km/h) and preventative salting (60 km/h). The position of the automated maintenance vehicle was communicated to other automated vehicles only, combined with an advice to move to the other lane. What to communicate and how highly automated vehicles should respond is a point of attention: during our simulations it was shown that communication leads to delays for all types of vehicles, mainly caused by hindering non-automated vehicles not always being able to merge into a lane due to large speed differences. No communication (i.e. only using sensors to detect that the speed of the vehicle(s) in front is low) results in the smoothest traffic flow. The results indicate that communication should be available to either both automated and non-automated vehicles or neither rather than being given to automated vehicles only.

The impact of automated maintenance vehicles was assessed with regard to road safety, traffic efficiency, environment and customer service. The introduction of automated safety trailers to

protect work zones caused by unexpected incidents will likely provide the largest benefit to road safety. This will also result in a positive effect on traffic flow efficiency. Automated winter maintenance trucks performing preventative salting works might lead to an improvement in environment due to optimization of the required amount of salt. Last, the customer service is to be expected positively for nearly all automated maintenance operations due to the possibility of detailed information provision.

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1 Introduction

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads (CEDR). CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities (NRA) or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level.

The participating NRAs in the CEDR Call 2017: Automation are Austria, Finland, Germany, Ireland, Netherlands, Norway, Slovenia, Sweden and the United Kingdom. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered. The research budget is jointly provided by the NRAs as listed above.

MANTRA is an acronym for "Making full use of Automation for National Transport and Road Authorities – NRA Core Business". MANTRA responds to the questions posed as CEDR Automation Call 2017 Topic A: How will automation change the core business of NRA's, by answering the following questions:

- What are the influences of automation on the core business in relation to road safety, traffic efficiency, the environment, customer service, maintenance and construction processes?
- How will the current core business on operations & services, planning & building and ICT change in the future?

MANTRA work started with the analysis of vehicle penetrations and Operational Design Domain (ODD) coverage of NRA-relevant automation functions up to 2040. This part is reported in MANTRA Deliverable D2.1 (Aigner et al., 2019). Work-package 3, concentrates on the impacts of connected and automated driving, and how the impacts relate to the role and policy targets of NRAs. The following work-packages continue from that, and assess and discuss the consequences of automation functions on infrastructure, and how the deployment of automation changes the core business of road operators.

The first deliverable of Work Package 3, MANTRA Deliverable D3.1 (Penttinen et al., 2019) has been published in May 2019. It provides a comprehensive state of the art on the impacts of connected and automated driving on travel demand, travel behaviour, traffic flow, safety and energy. The review is based on ongoing and recently completed EU and national projects, and a literature review of key publications and articles on the topic. The deliverable introduces the variety of impacts and impact mechanisms in connected and automated driving (CAD), and the related key performance indicators (KPIs).

The given KPIs are used within this Deliverable 3.2. In this report we assess the implications of selected automation functions (as defined in MANTRA Deliverable 2.1) on mobility and driver behaviour. Simulation models are utilised to assess the impact of connected and automated driving. Finally, impacts of automation on efficiency in operational processes and maintenance are assessed and all the assessments are summarized as impacts of automation on NRA key policy targets, based on the literature review, models, expert interviews and expert evaluation.

The deliverable is structured as follows: first we provide a summary of the used KPIs as given in D3.1. Next, we discuss the implications on both mobility and travel behaviour (task 3.2), driver behaviour and traffic flow (task 3.3), ordered by each of the automation functions. Chapter 7 provides the results of task 3.4, analysing the impacts of automation on efficiency in operational processes and maintenance. The last chapter then summarizes the impacts of automation on NRA key policy targets.

2 Overview of Key Performance Indicators to assess the impact of automated and connected vehicles

Deliverable 3.1 (Penttinen et al., 2019) provided an overview of the state of the art literature on connected and automated driving. As a part of the deliverable, several KPIs were defined. These KPIs are used to analyse the impacts of automation functions using simulation studies as will be described in the following chapters. Some KPIs are mainly used as an input for setting the values of the parameters in simulations, and will therefore not be used to assess the output (e.g. this makes no sense as output is identical to the input). The sections below provide a brief overview of each of the KPIs, resulting in a final selection which will be analysed in each of the simulation studies on mobility and travel behaviour.

2.1 Mobility and travel behaviour

Mobility is seen as the mobility of the society, whereas travel behaviour focusses on decisions made by individuals in terms of mode and route choice. Both are analysed at a macroscopic level. It concerns which trips are made (e.g. how often, which origins and destinations), as well as mode choice (e.g. choice for car, train or bike) and route choice.

2.1.1 Value of Travel Time

Travel time is traditionally counted as a 'waste' of time or cost to the traveller during the traveller decision-making process and in travel demand modelling. This is described as the Value of Travel Time (VoTT). It is accepted that the VoTT depends on the ability to engage in other activities during travelling. In the context of automated vehicles there are three main streams concerning the effects of automation on the VoTT: assuming that automation leads to similar VoTT values as being a car passenger; assuming that time in automation will be used efficiently (resulting in a lower VoTT); and assuming that driving an automated vehicle will result in a higher VoTT due to a lack of trust in new technologies. Within simulation studies (as performed in Chapters 3 to 6), the VoTT is usually used as an input to predict the decision-making process in mode choices. Since three different streams provide three different thoughts on VoTT increase or decrease due to automation, we will use the same VoTT for car users and users of automated vehicles. This KPI will therefore not be assessed.

2.1.2 Number of trips

The number of trips might influence the usage of the infrastructure (e.g. kilometres travelled). However, it is uncertain how automation will change the number of trips. It is expected that mainly elderly and disabled persons might benefit from automation with regard to their accessibility, and they could especially increase their trips. Given the assumptions in the underlying models and the uncertainty in the share between ownership and automated on-demand mobility services in the future, the potential effects of automation on the number of car trips have a large uncertainty. Therefore, we do not consider the number of trips as a variable in our simulation studies, but we assume that it stays constant. The only additional trips in the simulation models are empty trips, for example relocating robotaxis.

2.1.3 Total kilometres travelled

The total kilometres travelled will be impacted by both penetration rates and route choices made. Automation may result in longer trips due to living further away from jobs or city centres (due to a decreasing VoTT), and also in different route choices. For example, if automation is only possible at the highway according to the ODD, a shift from local roads toward highways might happen, resulting in more kilometres travelled.

2.1.4 Share of car and public transport

The share of car and public transport directly relates to mode choices made. Mode choice depends on many factors including trip distance and travel time, trip motive, available transport alternatives and travel costs. Especially the introduction of robotaxis might result in a shift from public transport to robotaxi or from car to robotaxi.

2.1.5 Travelling on peak hour (timing)

It is expected that automated cars will increase the road capacity, possibly resulting in a higher traffic demand during peak hours without increase of travel time. On the other hand, it is expected that (work-related) activities performed during a trip in an automated vehicle might result in a better spread of peak travels (i.e., leaving at a different moment in time while working the same number of hours), and thereby reducing the number of trips performed during peak hour. However, some people might also use the travel time in automated vehicles to 'switch off' and relax, not influencing any choices in timing of trips. The total effects remain unclear, but will definitely not appear with low penetration rates. We will not consider this element as a KPI or changing factor in our simulation studies.

2.1.6 Travelling reliability

The travelling reliability is seen in two ways: the way that the system is flexible enough to stay reliable, and the delays encountered by travellers on the road. The flexibility and reliability of the offered services is hard to assess as a KPI, as this fully depends on the amount of vehicles available as well as the demand (i.e. balancing supply and demand).

The other aspect of travelling reliability – experienced delays – can be measured using simulation models. An increase in road usage (e.g. increasing total kilometres travelled or empty vehicle trips) might result in an increase in encountered delays, resulting in longer travel times. We will therefore assess the impact of delays as a KPI within the simulation studies.

2.1.7 Travelling comfort

The comfort of travel relates to underlying factors, including mental, emotional and physical. The resulting comfort of automated vehicles is highly dependent on the implementation of such vehicles. For example, smooth driving reduces motion sickness, but automation may also result in higher stress levels due to a lack of trust. It is hard to judge these factors during simulation studies, and therefore these will be left out.

2.1.8 Accessibility

Automation, especially shared on-demand mobility, may result in a larger accessibility of travellers. It may reduce the wasted value of travel time while travelling; automated vehicles may perform activities on their own overcoming temporal constraints (e.g. shop closing hours); and they may become cheaper and thereby more affordable. Despite these important aspects, the resulting accessibility of inhabitants is hard to measure in mobility simulation studies. Therefore, this aspect will not be considered.

2.2 Energy and environment

The impact area of energy and environment can be split in three categories: energy usage, carbon emissions and noise. Energy is influenced by both vehicle design and traffic flow and congestion. The vehicle design of AVs is not a topic of this deliverable. The traffic flow and congestion is a relevant aspect, as a decrease in congestion leads to a decrease in energy usage. Carbon emissions are highly influenced by the electrification of vehicles. This is a different topic which is left out of the MANTRA project. Noise levels are a direct effect of the number of vehicles on the road (i.e. mobility and travel behaviour), vehicle speeds (see 2.3.1) as well as the road properties. To conclude, only energy is of importance as a KPI to be assessed.

2.3 Driver behaviour and traffic flow

Driver behaviour and traffic flow concerns the interactions between individual vehicles at a microscopic level. This includes lane changing behaviour, following distances and speed variabilities. The selection of the KPIs for MANTRA work on driver behaviour and traffic flow has been provided in D3.1 (Penttinen et al., 2019). This section provides a brief overview of each of the KPIs, resulting in a final selection which will be analysed in each of the simulation studies.

2.3.1 Driving speed and speed variability

It is assumed that automated vehicles have a more constant speed and lower speed variability than non-automated vehicles. Additionally, AVs are expected to stick to the speed limit. This is in general not the case for (all) non-automated vehicles, which may result in a lower average speed if automated vehicles are introduced. Within simulation studies (as performed in Chapter 3 to 6), the speed and speed variability are usually used as an input to model the driver behaviour, and not as an output. Therefore, speed and speed variability, will not be assessed as a KPI.

2.3.2 Time headway

The time headway is the gap between vehicles, specified in seconds. ACC and CACC vehicles will never have lower desired time headway values than the legally prescribed value. However, non-automated vehicles do keep smaller time headways regularly. On the other hand, if communication is possible or sensors improve, it would be possible to have much shorter time headways. The preferable time headways (and their distribution) are used as input to model the driver behaviour, and will therefore not be assessed as a KPI.

2.3.3 Capacity

The capacity of a road is highly related to the time headway distribution, resulting from the time headways of AVs and the penetration rate. Additionally, acceleration and deceleration behaviour as well as desired speeds affect the capacity of a road. In general, a larger time headway is expected to result in a lower capacity than a smaller time headway. The capacity of a motorway is usually highly influenced by the capacity of the nodes in the network, i.e. the ramps and weaving sections. Merging vehicles accepting smaller gaps might result in shockwaves and thereby a reduction of capacity. On the other hand, if most of the vehicles are connected and/or automated, this might lead to a largely increased capacity due to small headways and anticipating behaviour in merging and lane-changing situations. The capacity of a road is an interesting KPI, but often hard to measure. It is usually defined as the moment just before the average traffic speed drops, resulting in lots of simulations to find the exact moment in time with accompanying flow of vehicles.

2.3.4 Travel time

Travel time is expected to reduce with the introduction of connected, automated vehicles. By reducing time headways and enabling communication between vehicles, shockwaves are reduced and thereby travel times also decrease. However, this would require a 100% penetration rate. For lower penetration rates, additional shockwaves may be formed. This is caused by AVs merging in front of a CV with a small gap, not acceptable by the CV. The CV will then presumably brake, resulting in shockwaves and thereby an increased travel time. The average travel time of vehicles on a road section is an easy to measure KPI. The travel time reflects the capacity of a road (i.e. a higher capacity leads to lower travel times) as well as the traffic stability and the impact of several driver behaviour parameters such as desired distance between vehicles, desired acceleration and deceleration. It can be used to easily see the impact of AVs on the road as the penetration rate increases.

2.4 Traffic safety

In general, it is assumed that roads get safer if all vehicles are automated, mainly caused by absorbing human errors caused by fatigue, sensing problems, inattention or inabilities (i.e. night-time visibility) and a slower reaction time. However, this is often hard to simulate. It is questionable whether behaviour modelled in microsimulation exactly corresponds with real-world behaviour.

Safety impacts can be assessed e.g. according to the number of crashes, the number of conflicts (i.e. if the time to collision is less than a certain threshold) and the number of instances with hard braking. Microsimulation software does not model accidents: they only occur if some human error occurs, which does not happen in a simulation. Therefore, only the number of conflicts which might happen in the future if drivers do not change their behaviour (i.e. brake) are relevant.

2.5 Final set of KPIs assessed

The impact areas and associated KPIs from MANTRA deliverable D3.1 have been discussed in the previous sections. This results in a list of KPIs that will be assessed to judge the impact of AVs on both macroscopic and microscopic level in the following Chapters 3 to 6.

Table 2.1. Selected KPIs for assessing the impact of automation in simulation studies

Impact area	Simulation tool	Assessed KPIs
Mobility and travel behaviour	Macro simulation	• Total kilometres travelled • Share of car and public transport • Delays (travelling reliability)
Energy and environment	Macro simulation	• Energy
Driver behaviour and traffic flow	Microsimulation	• Capacity • Travel time
Traffic safety	Microsimulation	• Number of conflicts

3 Impacts of Highway autopilot including highway convoy (L4)

This chapter concerns simulations for the highway autopilot automation function. First, the ERTRAC definition is discussed, followed by simulations assessing the impact on mobility and travel behaviour, and simulations assessing the impacts on traffic flow efficiency.

3.1 Highway autopilot including highway convoy

According to ERTRAC (2017) and Aigner et al. (2019), the highway autopilot including highway convoy provides automated driving up to 130 km/h on motorways or roads similar to motorway from entrance to exit, on all lanes, including overtaking and lane change. The driver must deliberately activate the system, but does not have to monitor the system constantly. The driver can at non-critical times override or switch off the system. There are no requests from the system to the driver to take over when the system is in normal operation area (i.e. on the motorway). When outside the normal operation area, the system will go to a reduced risk condition, i.e. bring the vehicle to a safe stop (e. g. in case of failure or malfunction). It is assumed that AVs are connected (V2V communication). Depending on the deployment of cooperative systems, ad-hoc convoys could also be created.

The ODD specifications will likely not correspond to those in 2040 as the capability and price of the sensors and software in automated vehicles will likely improve considerably during the next 20 years, expected to increase greatly the coverage of the ODDs. It is, however, impossible to predict with reasonable accuracy the ODD of 2040. Thereby, MANTRA is using the ODD specification of Aigner et al. (2019) as agreed in the CEDR CAD WG. This applies to all of the four automated driving use cases.

3.2 Impacts on mobility, travel behaviour and energy

Allowing Level 4 Automated Vehicles (AVs) to drive on highways could potentially have an impact on the road network performance. Although it might probably take a while before AVs are on the road, National Road Authorities (NRAs) are already concerned about understanding what changes would be required on their current infrastructure to make it ready for (C)AVs (Connected Automated Vehicles). In this part of the study, we simulate part of the motorway network in the Netherlands, the region of Rotterdam - The Hague, to investigate the impact of CAVs on the mobility and travel behaviour in terms of total kilometres travelled and encountered delays. We only simulate the motorway network, and therefore we are not looking into the share of public transport due to the introduction of CAVs.

3.2.1 Simulation set-up

We perform simulations using macro simulation software OmniTRANS 8.0.16 of DAT.Mobility which is the most widespread software used for transport demand modelling in the Netherlands. We use traffic model “V-MRDH 2.2” featuring Metropolitan region Rotterdam – The Hague (The Netherlands) as a basis (see Figure 3.1). This traffic model includes predictions on demand growth and network modifications for 2020, 2030 and 2040. We use the settings of the year 2040. The model consists of 3 time periods for an average working day: morning peak (7-9am), afternoon peak (4-6pm) and the rest of the day for the Rotterdam – The Hague area. It has been extensively calibrated using traffic counts and cellular data.

The model uses the four-step transport model as a basis, including trip generation (number of trips per origin and destination), trip distribution (linking origins and destinations to form trips), modal split (choice between different modes) and assignment (route choices projected on the network). For the simulation studies of the MANTRA project, we are only rerunning the assignment step. This means that we assume the same number of trips per time period, where the only difference is the percentage of CAVs on the road (replacing normal car trips). This results in different route choices made, and thereby different amount of kilometres travelled as well as encountered delays.

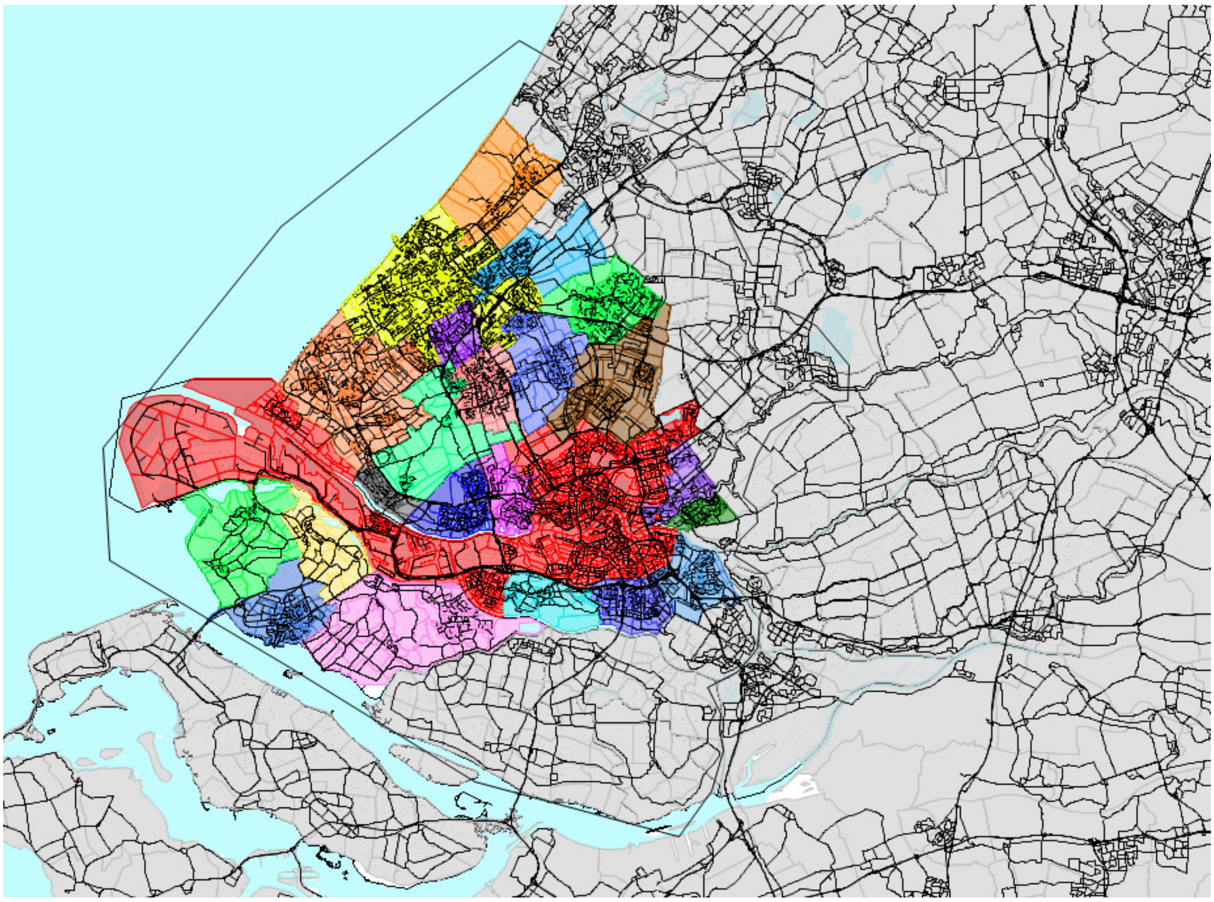

Figure 3.1 Overview of zones in the V-MRDH 2.2 model. Coloured areas are internal zones, grey areas are external zones

3.2.2 Simulating Automated vehicles

The MANTRA project defined several penetration rates for different automation types in Deliverable 2.1, based on market introduction predictions and fleet renewal statistics (Aigner et al., 2019). In this simulation study, we want to investigate the impacts on mobility and travel behaviour in the most optimistic scenario for 2040. Deliverable 2.1 defined this scenario as "2040-high", which implies that a vehicle-km penetration rate of 47.2% is expected for the highway autopilot. This scenario assumes the acceleration of automated driving via financial incentives such as reduced taxation or via regulatory actions, for instance by mandating automated driving in specific conditions. Given the predicted veh-km penetration rate, we assume that approximately 50% of the vehicles in the simulation network is a CAV.

To simulate that 50% of vehicles is a CAV, we need to adjust the behaviour of the vehicles. For simplicity reasons, we do not alter the (interaction) behaviour of vehicles but instead increase the capacity of all motorway links in the network. According to Shladover et al. (2012) a 50% CACC penetration rate implies an 8% increase of motorway capacity, assuming CACC vehicles. We do not assume any capacity benefits on other roads due to the presence of CAVs. However, we do simulate the complete network including roads inside the city and other roads.

We did not simulate any additional trips other than those incorporated by the V-MRDH2.2 traffic model. It is expected that the introduction of CAVs on motorways alone (Level 4) will not lead to new trips by elderly or disabled people, since only part of the trip can be performed automated. Additionally, increased travels due to reduced Value of Travel Time (VOTT), (e.g. due to working during a trip) or shifts from public transport to CAV are still too uncertain: we prefer not to guess at this stage, but perform a basic analysis of possible impacts on mobility due to the introduction of CAVs instead.

		Percentage of CACC Vehicles								
		10%	20%	30%	40%	50%	60%	70%	80%	90%
Percentage of ACC	10%	2065	2090	2170	2265	2389	2458	2662	2963	3389
	20%	2065	2110	2179	2265	2378	2456	2671	2977	0
	30%	2077	2127	2179	2269	2384	2487	2710	0	0
	40%	2088	2128	2192	2273	2314	2522	0	0	0
	50%	2095	2133	2188	2230	2365	0	0	0	0
	60%	2101	2138	2136	2231	0	0	0	0	0
	70%	2110	2084	2155	0	0	0	0	0	0
	80%	2087	2101	0	0	0	0	0	0	0
	90%	2068	0	0	0	0	0	0	0	0

Figure 3.2 Impact on the capacity of a 2-lane road with different percentages of (C)ACC vehicles (Shladover et al., 2012)

3.2.3 Results

We adjusted our network such that motorways have higher capacities, according to Shladover et al. (2012) and thereby model a 50% penetration rate of CAVs (having CACC abilities). In this section, the results of simulations performed at the V-MRDH model 2.2 are presented.

Total kilometres travelled

Due to the introduction of CAVs on motorways, a slight shift of 1% from other roads to motorways can be noticed, as can be seen in Figure 3.3. This generally implies driving a bit longer routes. Accordingly, the total vehicle-kms driven in the network during the afternoon peak (about 9 million kilometres) increases with 0.438%.

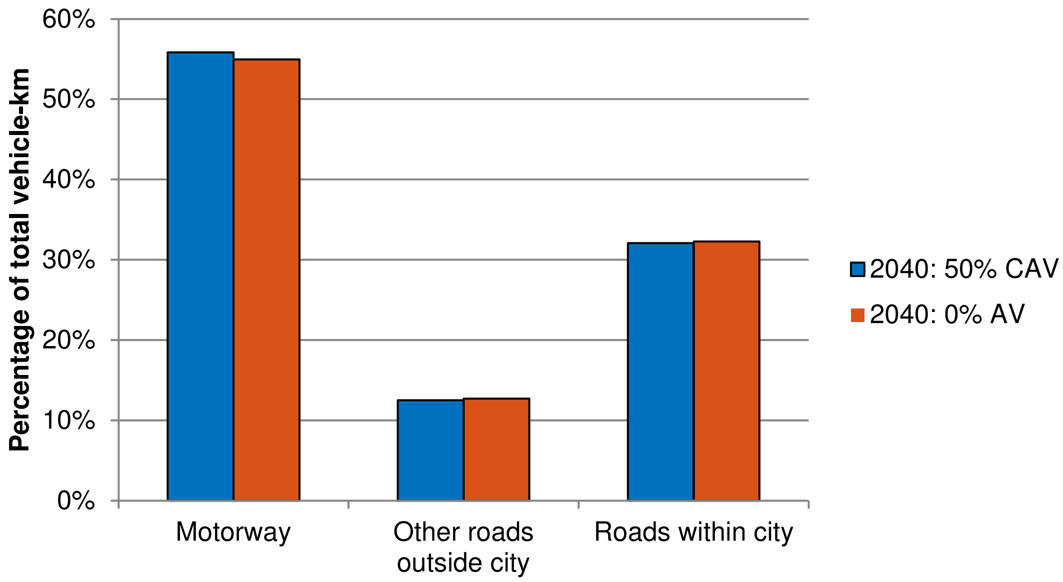

Figure 3.3 Percentage of vehicle-km per road type in the afternoon peak, relative to 0% AV.

The total results of distances travelled split per road category are shown in Table 3.1. Equal trends can be seen for each of the time periods, where CAVs shift toward motorways resulting in higher amounts of total kilometres travelled in the network.

Table 3.1. Total kilometres travelled per road category (in km x 1000)

	Morning peak		**Afternoon peak**		**Rest of Day**	
	50% CAV	**0% AV**	**50% CAV**	**0% AV**	**50% CAV**	**0% AV**
Motorway	4567 [57.8%]	4505 [57.3%]	5074 [55.6%]	4995 [55.0%]	20585 [54.6%]	20385 [54.2%]
Other roads outside city	935 [11.8%]	948 [12.1%]	1138 [12.5%]	1157 [12.7%]	4245 [11.3%]	4283 [11.4%]
Roads within city	2396 [30.3%]	2414 [30.7%]	2914 [31.9%]	2935 [32.3%]	12855 [34.1%]	12918 [34.4%]
Sum	7898	7867	9127	9087	37685	37586

Total travel time

Although the total distance travelled increases, the total travel time decreases due to the increased capacity of motorways. For example, the total travel time in the morning peak reduces from 44978185 (0% AV) to 44933673 hours (50%): a reduction of 44512 hours or 0.1%. It should be noted that 54% of the travel time is spent on other roads than motorways. Therefore, it is more useful to look into the changes in delay after introduction of CAVs.

Delay

The introduction of CAVs on the motorways leads to a decrease of 15-22% of delay on the motorways as can be seen in Figure 3.4. Delays are computed by comparing the driven travel times to the free flow travel times. In absolute numbers, this means a decrease from 9233 to 7639 hours during the morning peak. Also other road types slightly benefit from the introduction of CAVs, mostly due to traffic shifting towards motorways.

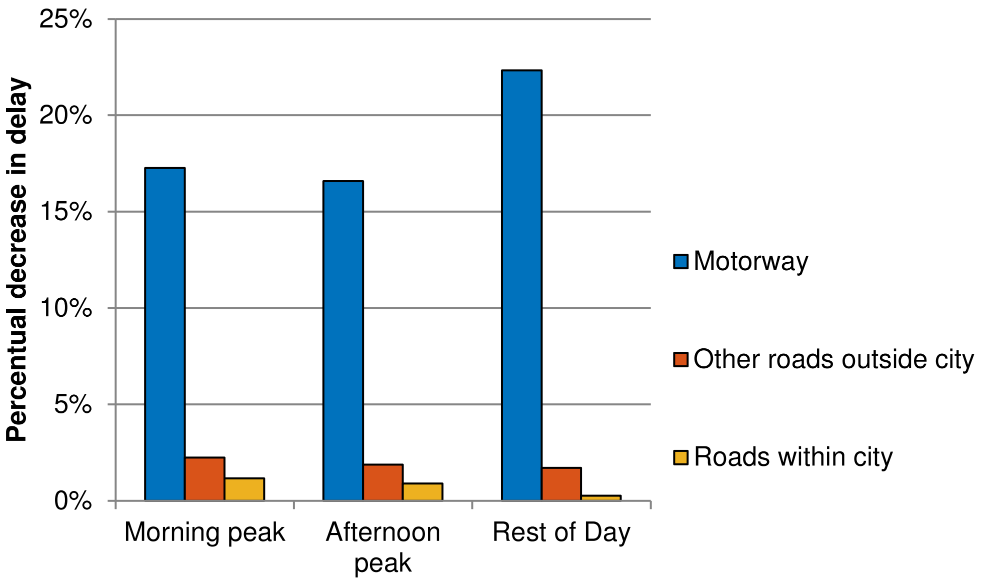

Figure 3.4 Decrease in average delays with 50% CAV, split per time period and road type

3.2.4 Discussion

The results of the macro simulation with 50% CAVs show a shift from local roads toward motorways, leading to an increase in vehicle-kms driven and a decrease in total travel time and delay (15-20%) due to the added road capacity. However, in this way it is assumed that every motorway is occupied by 50% CAVs, which might not necessarily be the case. A better implementation might be introducing a completely new mode where a CAV is modelled as a vehicle with a lower PCU-value.

We did not rerun the complete traffic model, which means that we assume a constant number of trips and an identical mode choice (albeit with cars half replaced by CAVs). Therefore, we are not able to report the share of public transport and vehicles as a result of introducing CAVs.

Additionally, no specific details on energy consumption were reported. We assume that the decrease in delays results in a decrease in energy consumption. However, the precise amount of energy saved depends on the vehicle design of the CAVs, as well as electrification and "eco-modus" options of normal cars.

In general, NRAs should take notice that allowing (C)AVs on the motorway most likely leads to increased traffic volumes on the motorway. However, due to better traffic flow caused by CAVs (increase in capacity), this will not result in additional traffic delays – assuming that AVs are connected.

3.3 *Impacts on driver behaviour, traffic flow and safety*

In the precious section we estimated the impact of CAVs on mobility for a 50% CAV scenario. We assumed that 50% CAVs lead to an 8% capacity increase. In this section we will look closer to the impact of CAVs on the motorway traffic performance using microsimulation: how will the traffic flow efficiency and safety be affected in reality? We not only discuss the 50% AV scenario, but discuss the whole range between 0% and 100% AVs on the motorway.

Introduction of AVs on the motorways are expected to result in various impacts on driver behaviour, traffic flow efficiency and safety. Especially in the introduction phase (i.e. small amounts of AVs on the road) possibly negative effects may be noticed in terms of travel time and safety due to different driving styles and anticipation of conventional vehicles and automated vehicles. The goal of this section is to make NRA's aware of possible effects of different penetration rates of AVs on motorways at a micro-level using different varieties of road designs. During the CEDR CAD WG in Tallinn (06-07.03.2019), it was concluded that straight sections of motorways do not provide the most interesting insights in traffic flow and safety. Nodes are the more interesting parts of the network concerning impacts of AVs, including ramps and weaving sections. We therefore focus on these three specific elements: entry ramps, exit ramps and weaving sections. We simulated different vehicle penetration rates of conventional vehicles and automated vehicles in the microsimulation program VISSIM 11, as will be presented in this section.

3.3.1 Simulating Conventional Vehicles

Conventional Vehicles (CVs) are normal cars that can be found on the roads nowadays. We assume that they are not equipped with intelligent functionalities such as (C)ACC. Although they exist on the road for a long time, modelling them in simulation software is not as straight forward as it seems.

The simulation software package VISSIM 11 uses the Wiedemann 99 car-following model to model the behaviour of vehicles (Wiedemann, 1991), defining the driver perception thresholds and the regimes formed by those thresholds. This includes headway times, natural variation in following distances, lane changing behaviour (e.g. acceptable merging gaps) and acceleration or deceleration behaviour.

A default set of Wiedemann 99 parameters is provided for modelling typical driver behaviour on motorways. Usually, these are used directly in microsimulations. Nevertheless, it is advised to always calibrate them to the specific situation of interest (Fellendorf & Vortisch, 2001).

One calibration study of the Wiedemann 99 parameters was performed by van Beinum et al. (2018). The parameters resulting from this study and used within the MANTRA project are based on empirical trajectory data of two weaving sections in the Netherlands. The data was gathered using cameras mounted underneath helicopters (see Figure 3.5). The parameters are different than the default Wiedemann 99 car-following model. For example, the mean time headway is changed from 0.9 seconds (VISSIM) to 0.5 seconds (empirical data according to (van Beinum et al., 2018)), as can be seen in Table 3.2.

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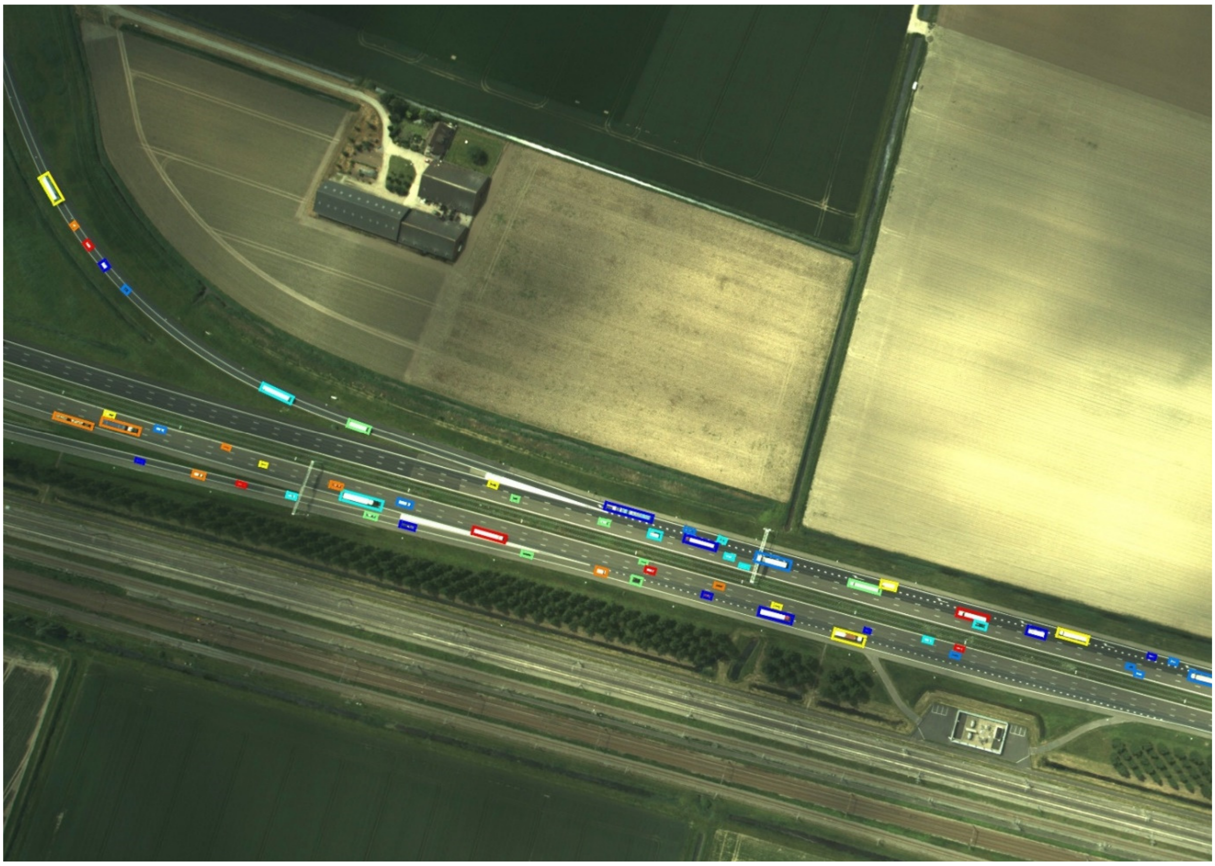


Figure 3.5 Example helicopter data gathered by van Beinum et al. (2018).

It should be noted that these parameters are calibrated according to two specific crowded situations in the Netherlands. These might not be realistic for every motorway across Europe, especially in non-crowded situations. The default VISSIM parameters are more representative of non-crowded situations. Therefore, we perform each of the simulations using two different CVs: using the default VISSIM parameters and by using the set of calibrated parameters.

Table 3.2. Driver behaviour parameters including Wiedemann 99 parameters for Conventional Vehicles: default and calibrated based on van Beinum et al. (2018)

	CV: VISSIM default	**CV: Calibrated** van Beinum et al. (2018)
Number of interaction objects	2	8
Number of interaction vehicles	99	99
Look ahead distance (min – max, m)	0-250	0-250
Look back distance (min – max, m)	0-150	0-26.16
Enforce absolute braking distance	No	No
Use implicit stochastic	Yes	Yes
Cooperative lane change	No	No
CC0 – Standstill distance (m)	1.5	2.33
CC1 – Headway time (s)	0.9	0.5
CC2 – Following variation (m)	4	3.91
CC3 – Threshold for entering "following" (s)	-8	-9.87
CC4 – Negative "following" threshold (m/s)	-0.35	-1.21
CC5 – Positive "following" threshold (m/s)	0.35	1
CC6 – Speed dependency of oscillation	11.44	11.44
CC7 – Oscillation acceleration (m/s^2)	0.25	0.24
CC8 – Standstill acceleration (m/s^2)	3.50	3.50
CC9 – Acceleration with 80 km/h (m/s^2)	1.50	1.50

3.3.2 Simulating Automated Vehicles

For modelling AVs the recommended numerical values as proposed by the CoEXist project (CoEXist, 2018) were used. The CoEXist project is a European H2020 project which aims at preparing the transition phase during which automated and conventional vehicles will co-exist on the roads. As a part of the project, simulation guidelines for AVs were published. The CoEXist project defined three different driving logics: cautious, normal and all knowing. The cautious driving logic represents AVs that always adopt a safe behaviour. For example, the vehicle will always make sure that it could brake without a collision, even if the leading vehicle comes to an immediate stop ("turns into a brick wall"). The normal driving logic is quite similar to a human driver, albeit with additional capacity of measuring distances and speeds of surrounding vehicles thanks to its sensor suite. The all-knowing driving logic is expected to have a perfect perception and prediction of its environment, resulting in the possibility of smaller time gaps between vehicles during all manoeuvres and situations. Additionally, a kind of cooperative behaviour is expected.

The main Wiedemann 99 parameters for each of the driving logics are shown in Table 3.3 and compared to the CVs. As can be seen in Table 3.3, the main differences are: smaller time headways (0.6 seconds for all-knowing, compared to 0.9 seconds for a CV), an increased desired acceleration (110%) and cooperative lane change functionality.

AVs also use the functionality of "number of interaction vehicles". The "number of interaction objects" refers to all vehicles and objects (including stop signs, priority rules, speed limits), whereas the "number of interaction vehicles" only refers to real vehicles, providing an upper bound for the observed leading vehicles. For example, this value is set to 1 for automated vehicles with sensor equipment that cannot see through the leading vehicle. An example is shown in Figure 3.6. In this case, the red car can only detect the vehicle in front of him and the traffic light. The red car cannot detect the car between the car in front and the traffic light. A value of 99 (as shown in the CV specification) means that there is no distinction between interaction objects and vehicles: the amount of objects also includes the maximum amount of vehicles visible.

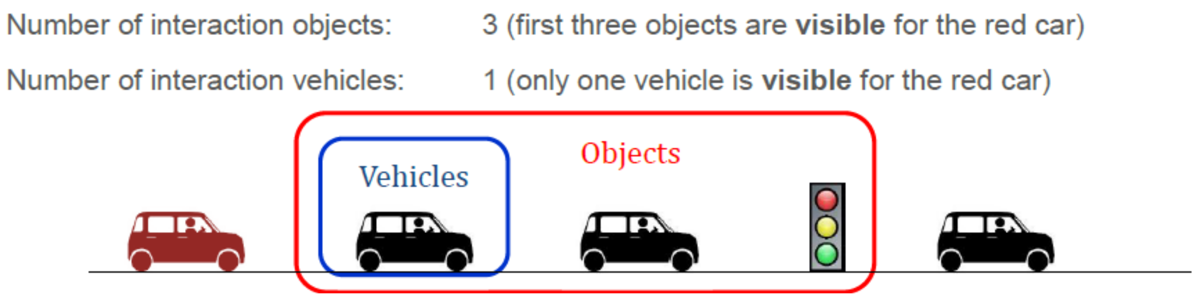


Figure 3.6 Example VISSIM number of interaction objects vs number of interaction vehicles (CoEXist, 2018).

Table 3.3. Driver behaviour parameters including Wiedemann 99 parameters for Automated Vehicles: cautious, normal and all-knowing based on the Co-EXist European project (CoEXist, 2018).

	Cautious AV	Normal AV	All-knowing AV
Number of interaction objects	2	2	10
Number of interaction vehicles	1	1	8
Look ahead distance (min – max, m)	0-250	0-250	0-300
Look back distance (min – max, m)	0-150	0-150	0-150
Enforce absolute braking distance	Yes	No	No
Use implicit stochastic	No	No	No
Cooperative lane change	No	Yes	Yes
CC0 – Standstill distance (m)	1.5	1.5	1
CC1 – Headway time (s)	1.5	0.9	0.6
CC2 – Following variation (m)	0	0	0
CC3 – Threshold for entering “following” (s)	-10	-8	-6
CC4 – Negative “following” threshold (m/s)	-0.1	-0.1	-0.1
CC5 – Positive “following” threshold (m/s)	0.1	0.1	0.1
CC6 – Oscillation acceleration (m/s^2)	0.0	0.0	0.0
CC7 – Oscillation acceleration (m/s^2)	0.1	0.1	0.1
CC8 – Standstill acceleration (m/s^2)	3.0	3.5	4.0
CC9 – Acceleration with 80 km/h (m/s^2)	1.2	1.5	2.0

Additionally, the CoEXist project, as well as literature (Viti et al., 2008), assumes that AVs have less dispersion around the mean speed. The desired speed value for a road having a 120km/h speed limit is therefore set to 118-122 km/h, as opposed to the default of 85-155 km/h, as can be seen in Figure 3.7.

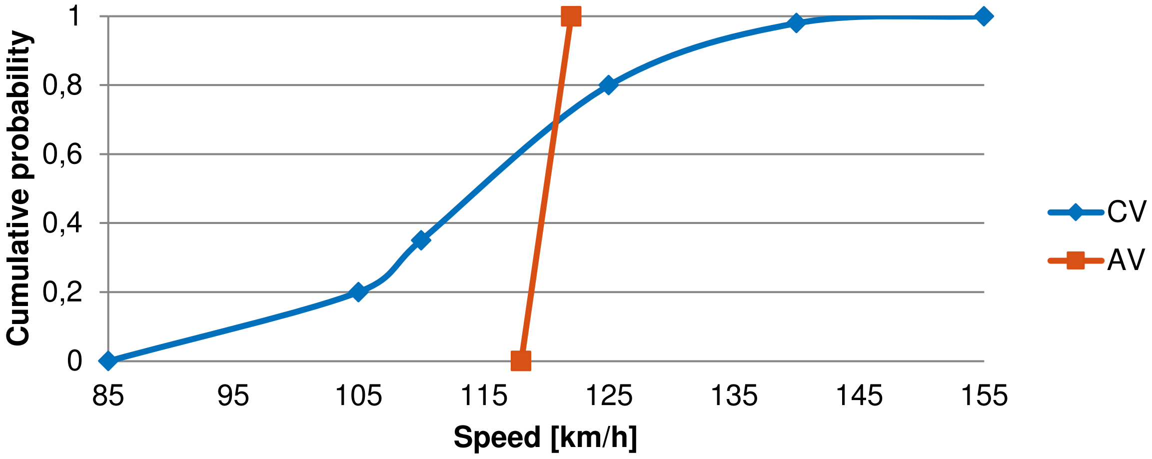


Figure 3.7 Speed distribution in VISSIM for a motorway with a 120 km/h speed limit

Within the MANTRA project, we are interested in the impact of highway autopilots including highway convoys. Therefore, we assume that AVs have a perfect perception and prediction of the traffic situation, including cooperative behaviour and connectivity (i.e. CAV). This corresponds to the driving logic class "All-knowing" as defined by CoEXist. We carry out a sensitivity analysis of our results by also modelling the other driving logics in Section 3.3.8.

3.3.3 Simulation set-up

In order to get an idea of the impacts of highway autopilot on traffic efficiency and safety that NRA's may expect in the future, we simulate a stretch of a motorway with a weaving section, an entry ramp and an exit ramp. In the simulation, we also test the impact of different taper lengths.

Network set-up

Traffic simulations are performed using microsimulation software VISSIM 11. We model a motorway with 2 lanes on each carriageway and a speed limit of 120 km/h. We model 3 nodes of a motorway: a weaving section, an entry ramp, and an exit ramp.

The modelled weaving section is of the "Ex-Ex type" according to AASHTO (2018), meaning that the entry and exit ramps are on the same side (i.e. right side) of the road. According to empirical trajectory data collected from a video camera mounted underneath a hovering helicopter above weaving sections in the Netherlands (van Beinum et al., 2018), we assume that merging vehicles (i.e. vehicles that enter the motorway) have a speed of 80 km/h, and only start accelerating to the maximum speed limit (120 km/h) once they enter the taper lane (see Figure 3.7).

We use the demand data from the Dutch A59 Klaverpolder-north (51.696689, 4.645896) (van Beinum et al., 2018), which entails that 15% of traffic is merging and 7% of traffic is diverging. To assess possible interventions taken by NRAs to increase future traffic throughput, we model two different lengths of taper lanes: 300m (being the minimum design length in the Netherlands (Rijkswaterstaat, 2017)) and 600m (being the minimum design length according to AASHTO (2018)).

The simulated entry ramp has a taper lane of 0m, 300m or 600m. As a basis, the entry ramp at the A13 Delft (52.014498, 4.374516) has been used, which was modified accordingly. We assume 12% of traffic uses the entry ramp.

The simulated exit ramp also has a taper lane of 0m, 300m or 600m. Again, we used an exit ramp of Delft as a basis (52.014718, 4.373768). According to the Delft exit ramp, we assume that 11% of traffic uses the exit ramp.

The complete overview of the network for an example weaving section is shown in Figure 3.8. The entry ramp and exit ramp sections look similar.

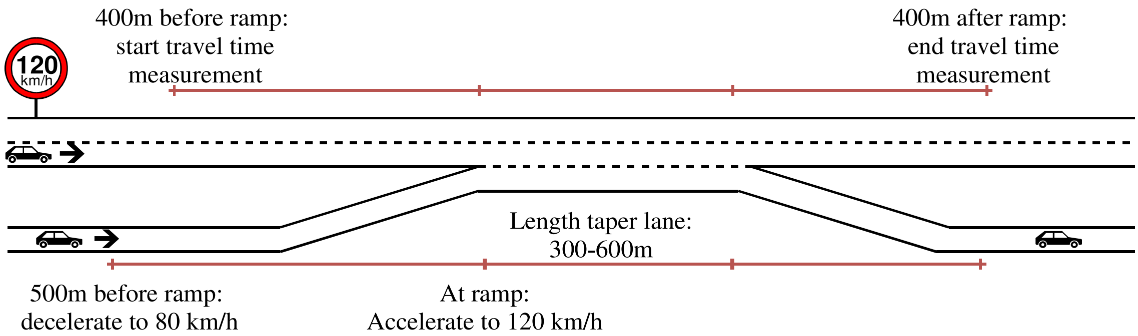


Figure 3.8 Overview of simulated weaving section

Simulation scenarios

We model 11 different levels of penetration rates of AVs (from 0 to 100%, in steps of 10%). Additionally, we simulate two levels of demand: a free flow situation and a near traffic jam situation. This corresponds to Flow/Capacity ratios of 0.55 and 0.80, respectively. We assume a static capacity of 4200 vehicles/hour.

We only model AVs and CVs: no trucks are assumed. Leaving out trucks is not assumed to be a critical assumption because the main purpose is to compare different scenarios. As explained before, we simulate 2 (300m, 600m) and 3 (0m, 300m, 600m) different lengths of taper lanes for the weaving section and entry and exit ramps, respectively. Additionally, we model 2 different types of CVs using the default VISSIM parameters and the calibrated parameters.

In total, this implies running 88 different configurations for the weaving section and 132 for the entry and exit ramps, i.e., in total 352 simulation configurations. Every configuration is run 11 times with different random seeds. For every simulation, we record the average travel time of all vehicles (split per vehicle type, AV vs. CV) over a segment between 400m before the ramp and 400m after the ramp, split in through-going, merging (coming from the entry ramp) and diverging (taking the exit ramp) traffic.

Safety analysis

Besides analysing the traffic flow, we also estimate the safety aspect of the road. We consider this aspect using the SSAM software (Surrogate Safety Assessment Model) developed by the Federal Highway Administration of the US Department of Transport (Gettman et al., 2008). Vehicle trajectories from VISSIM are extracted and possible conflicts are identified. Conflicts are identified by considering the maximum Post Encroachment Time (PET) value as 5 seconds and the Time To Collision (TTC) as 1.5 seconds, the default values used by the SSAM model. One may argue that AVs may respond earlier if necessary, but for safety considerations, this would only matter if there are no CVs on the road, that is, at the 100% penetration level only. For simplification purposes, we, therefore, assume one value (i.e. 1.5 seconds for TTC, 5 seconds for PET) for analysing all results.

The SSAM model has not been verified for usage with AVs, and it is unsure whether the SSAM model makes any sense with AVs. However, there are no better tools available currently to assess the safety impact of AVs.

3.3.4 Results - weaving section

The simulation of the weaving section was performed according to the description provided in Section 3.3.3. The results of average travel times for a weaving section with a 0.55 Flow/Capacity ratio are shown in Figure 3.9. Differences between the default VISSIM parameters (a,b) and the calibrated parameters (c,d) for CVs are large: the default parameters show an increase in travel time for small penetration rates, only decreasing after about 40% AVs, resulting in actual travel time gains after 80-90%. On the other hand, the calibrated car-following model' parameters show a constant decrease in travel time as the number of AVs grows. A negative effect is only slightly noticeable with a penetration rate of 10%.

Differences between a taper lane with length 300m (a,c) or 600m (b,d) are marginal. Additionally, travel times of AVs and CVs do not differ much from each other and therefore are not reported.

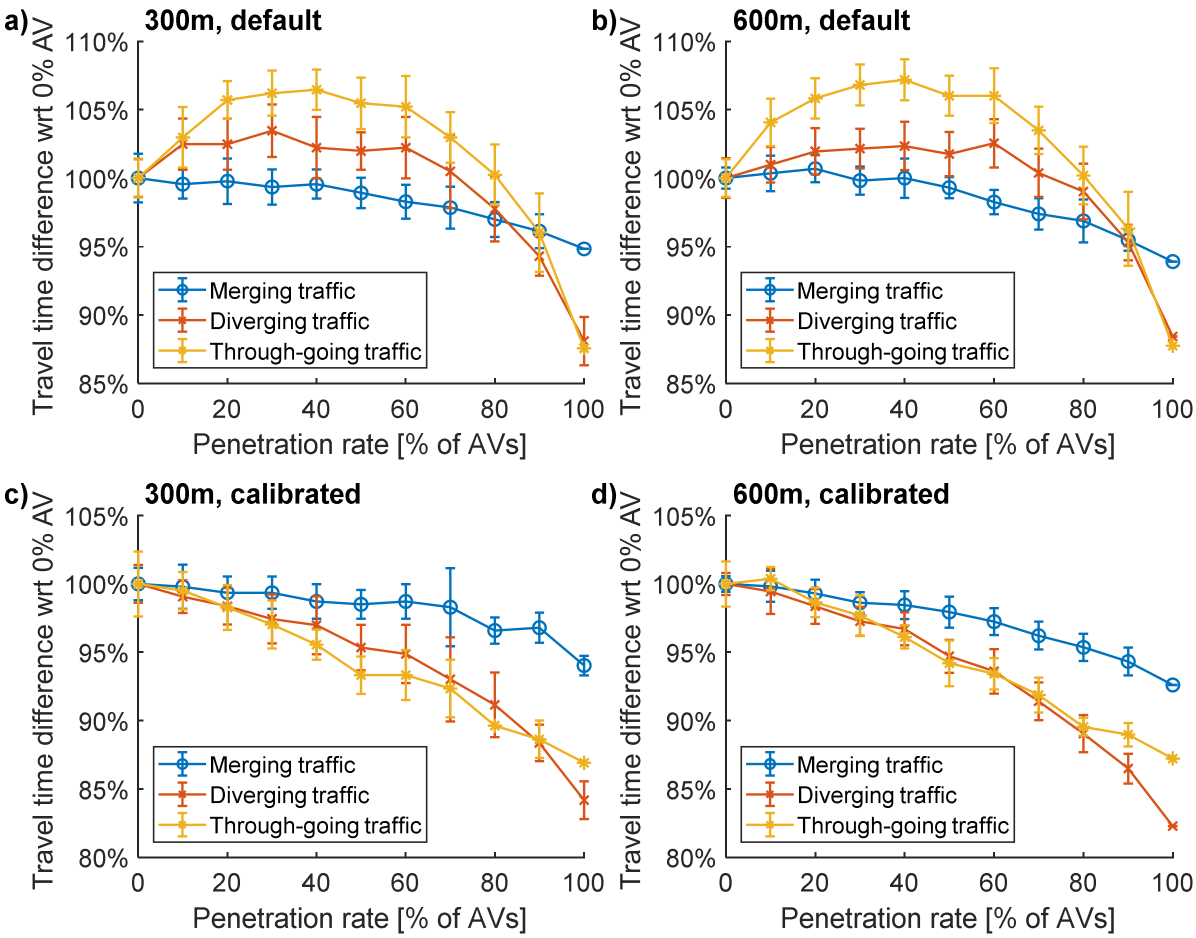


Figure 3.9 Percentage of travel times w.r.t the 0% AV scenario for a weaving section with a 0.55 Flow/Capacity ratio, with a 300m (a/c) or 600m (b/d) taper lane and using the default (a/b) or calibrated (c/d) parameters for conventional vehicles

An increased traffic flow with Flow/Capacity ratio of 0.80 shows the same pattern (see Figure 3.10), with at first increasing travel times if CVs are modelled according to the default parameters and decreasing travel times if CVs are modelled using the calibrated parameters. In general, the standard deviation (as shown by the error bars) decreases as the number of AVs increases. This is a logical result of decreasing in speed variations for AVs. Again, differences between 300m (a, c) and 600m (b, d) are marginal.

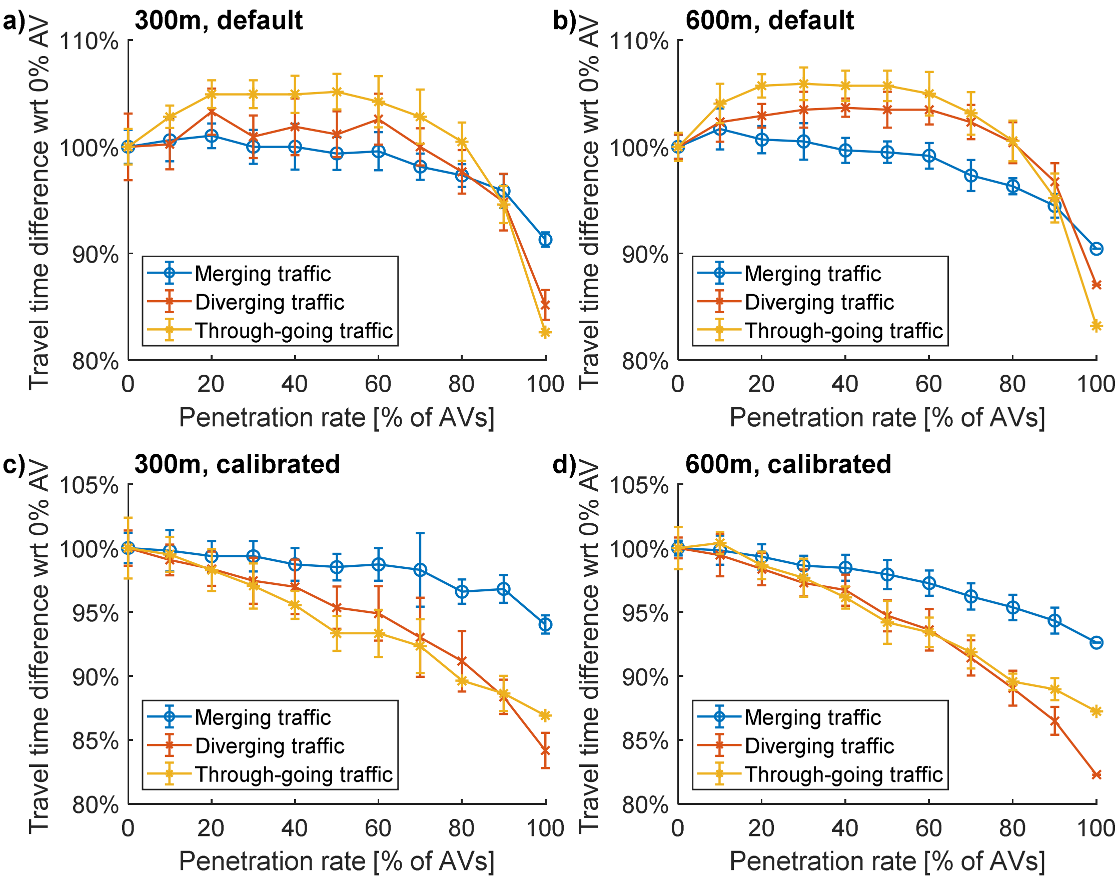


Figure 3.10 Percentage of travel times w.r.t the 0% AV scenario for a weaving section with a 0.80 Flow/Capacity ratio, with a 300m (a,c) or 600m (b,d) taper lane and using the default (a,b) or calibrated (c,d) parameters for conventional vehicles

3.3.5 Results - entry ramp

The results for the entry ramp simulation (0.80 f/c ratio) are shown in Figure 3.11. These results correspond with the weaving section results: at first increasing travel times as the penetration rates increase if CVs are modelled according to the default parameters, after that followed by a decrease. If CVs are modelled using calibrated parameters, the results show a near constant decreasing travel time for both merging and through-going traffic.

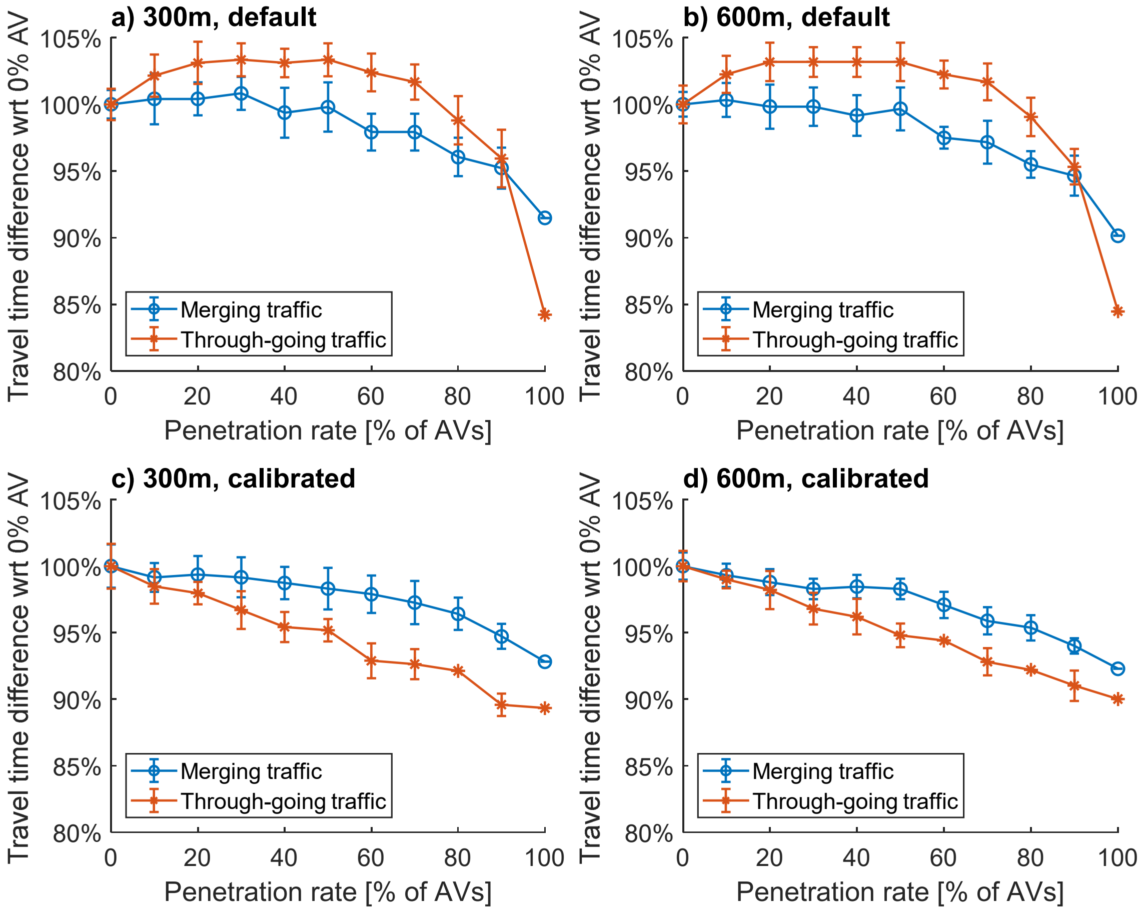


Figure 3.11 Percentage of travel times w.r.t. the 0% AV scenario, for an entry ramp with a 0.80 Flow/Capacity ratio. The simulated entry ramps have 300m (a,c) or 600m (b,d) taper lane and are run using default (a,b) or calibrated (c,d) parameters for conventional vehicles

It is a different story if we look at the taper lanes of 0m, i.e. no space to speed up as shown in Figure 3.12. In these cases, it often happens that vehicles simply cannot find a gap to merge (and speed-up at the same time). Therefore, we tested different flow/capacity ratios (10%, 40% and 80%). The results are shown in Figure 3.13.

It can be seen that for the default parameters in VISSIM, a 10% flow/capacity ratio doesn't result in much different travel times as the penetration rate grows. The 40% scenario shows equal results, with only a slight increase in travel times for penetration rates higher than 70%. The 80% flow/capacity ratio scenario seems to have a positive influence on the travel times for merging traffic in the default scenario for penetration rates up to 70%. The calibrated parameters show equal trends for the 10% scenario. However, the 40% f/c scenario results in large differences between the different random seeds (showed by the error bars). This is likely to be caused by smaller gaps between CVs, resulting in more difficulty to merge in. The 80% f/c scenario results again in large differences between random seeds, as well as substantial negative effects on travel times. However, it is important to consider that not every vehicle reached his destination in this simulation.

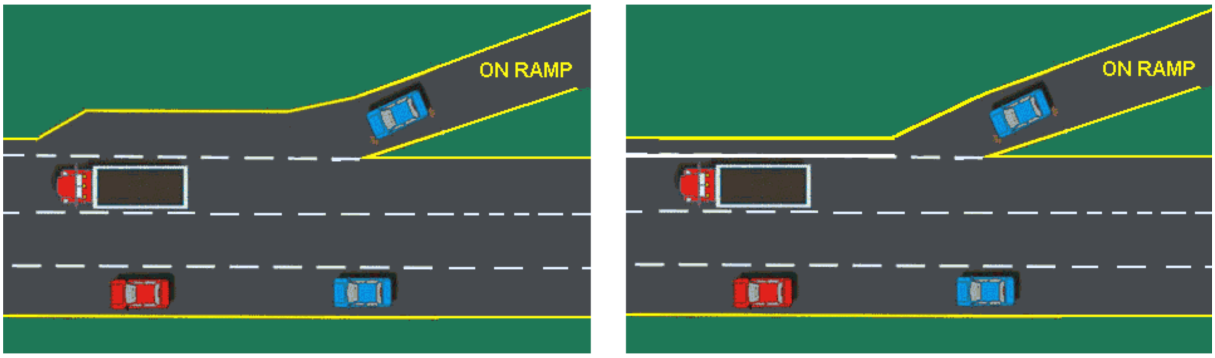


Figure 3.12 Two entry ramps, the left one having a taper lane, the right one not.

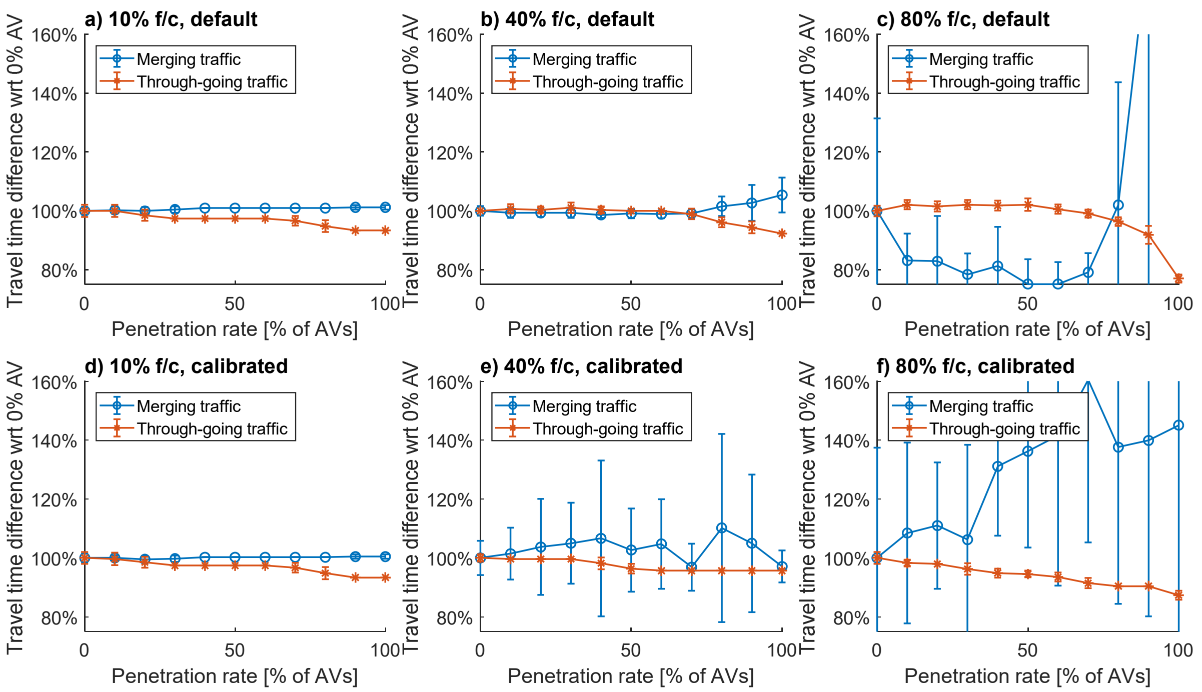


Figure 3.13 Percentage of travel times w.r.t the 0% AV scenario for an entry ramp with a taper lane of 0m, with 0.10 Flow/Capacity ratio (a,d), a 0.40 Flow/Capacity ratio (b,e) or a 0.80 Flow/Capacity ratio (c,f). Simulations used the default (a,b,c) or calibrated (d,e,f) parameters for conventional vehicles.

The problem of vehicles not reaching their destination is visualised in Figure 3.14. The top figures (a,b) show the merging vehicles that actually reach their destination. For the 10% and 40% scenarios, no problems are really visible: a 90% ratio of vehicles reaching their destination is seen during every simulation. Not all vehicles are reaching their destination because they are still driving on the road when the simulation is stopped. The bottom figures (c,d) show the amount of vehicles that were removed during simulation. A vehicle is automatically removed if it is standing still for more than 1 minute. It can be seen that the 80% f/c scenario has lots of vehicles not reaching their destination, indicating severe problems. In reality, this would lead to a situation with long traffic jams in front of the entry ramps.

It can be concluded that a 0% taper lane situation is only advisable in situations with less traffic, for example 10 to 40% f/c ratio. During higher amounts of traffic, severe traffic jams occur.

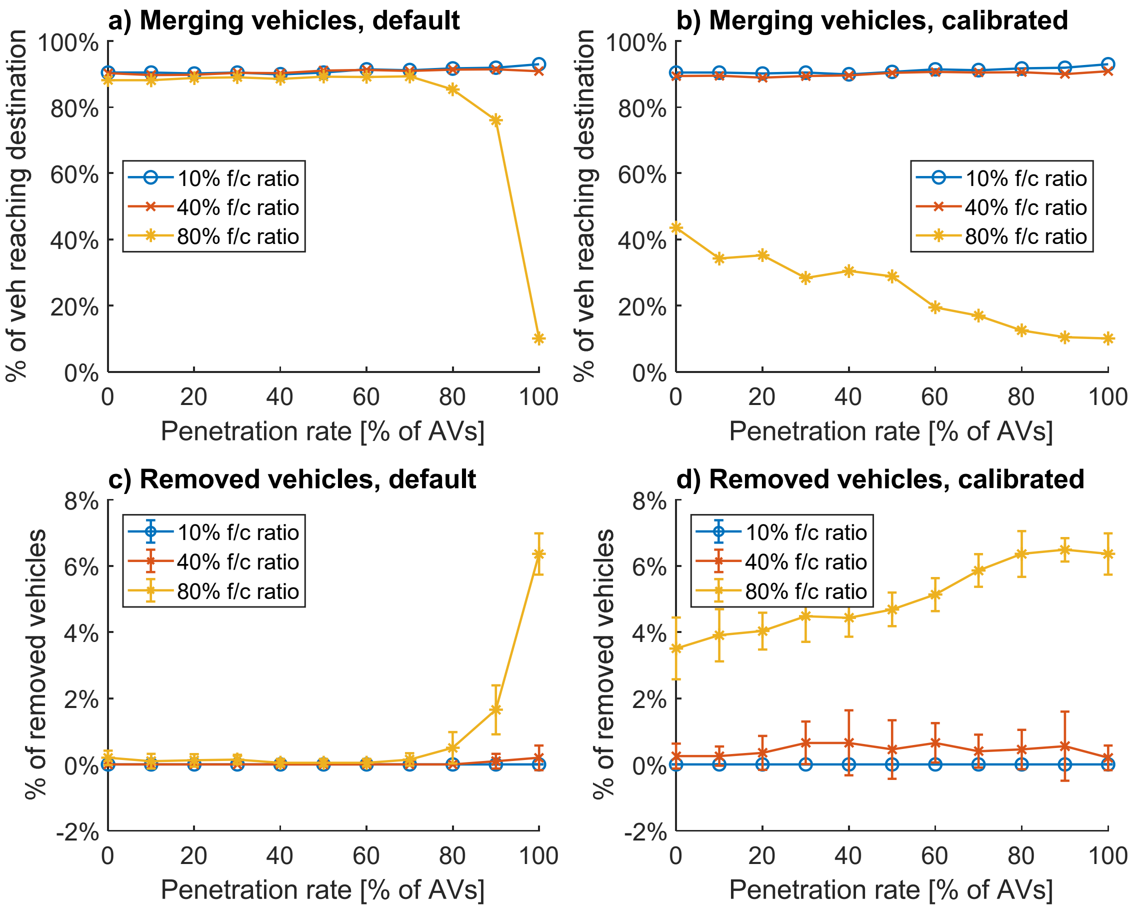


Figure 3.14 Vehicles not reaching their destination for an entry ramp with a 0m taper lane. Percentage of vehicles not reaching their destination (a,b) and vehicles standing still longer than 1 minute that have been automatically removed from simulation (c,d). Simulations used the default (a,c) and calibrated (b,d) parameters for conventional vehicles

3.3.6 Results - exit ramp

The exit ramp simulation results for a 300m and 600m taper lane are shown in Figure 3.15. In the calibrated parameter simulations (c,d) travel times stay about the same constant level. The default parameter sets show a slight increase followed by a decrease – equal to the patterns shown during the weaving section results.

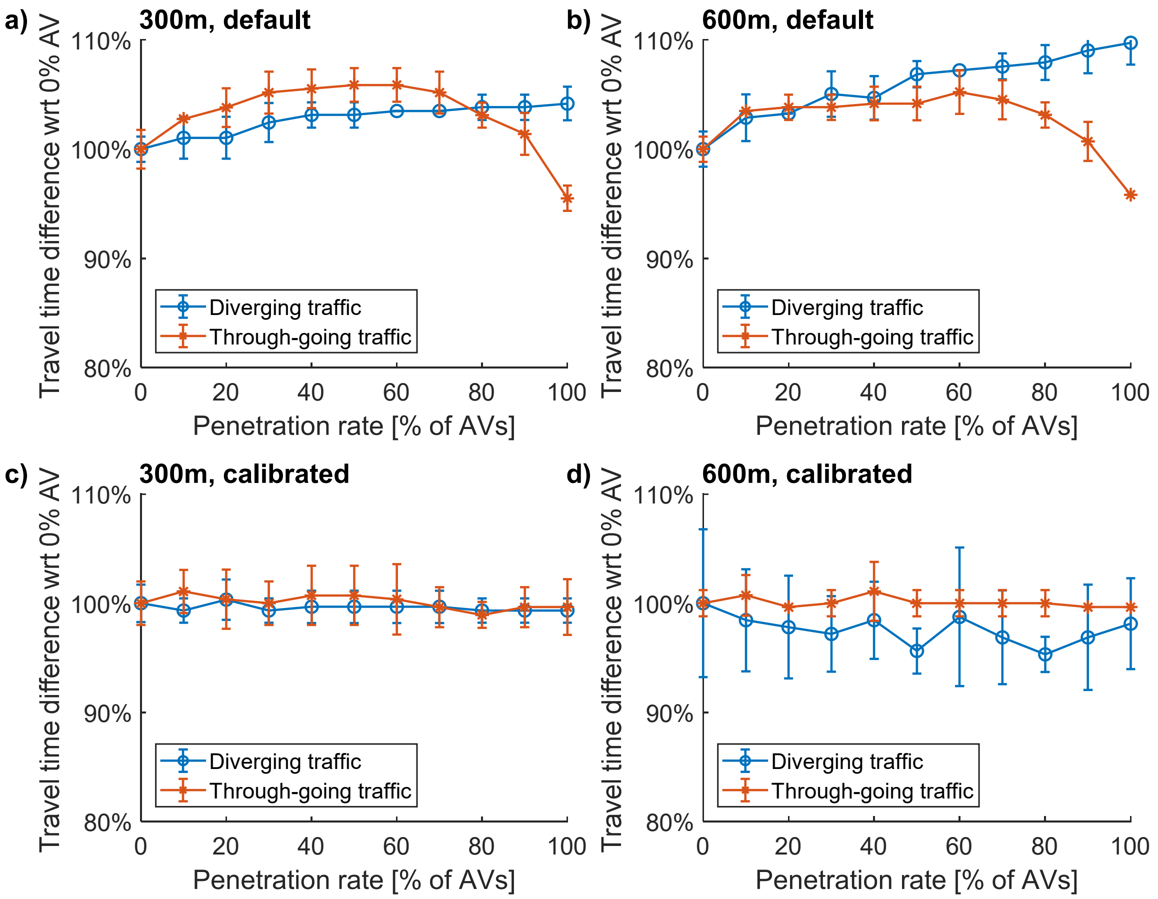


Figure 3.15 Percentage of travel times w.r.t. the 0% AV scenario, for an exit ramp with a 0.80 Flow/Capacity ratio. The simulated entry ramps have 300m (a,c) or 600m (b,d) taper lanes and are run using default (a,b) or calibrated (c,d) parameters for conventional vehicles.

As with the entry ramp simulations, we performed the simulations for different flow/capacity ratios: 10%, 40% and 80%. The results are shown in Figure 3.16. It can be seen that differences between the different scenarios are marginal. Further analysis also showed that no vehicles were removed from simulation or did not reach the correct destination. It should be noted that it is easier to diverge via an exit ramp than to merge into the traffic using an entry ramp. With an exit ramp, you don’t need to deal with other traffic and gaps between them – it’s only relevant that you are driving on the right lane before approaching the exit ramp.

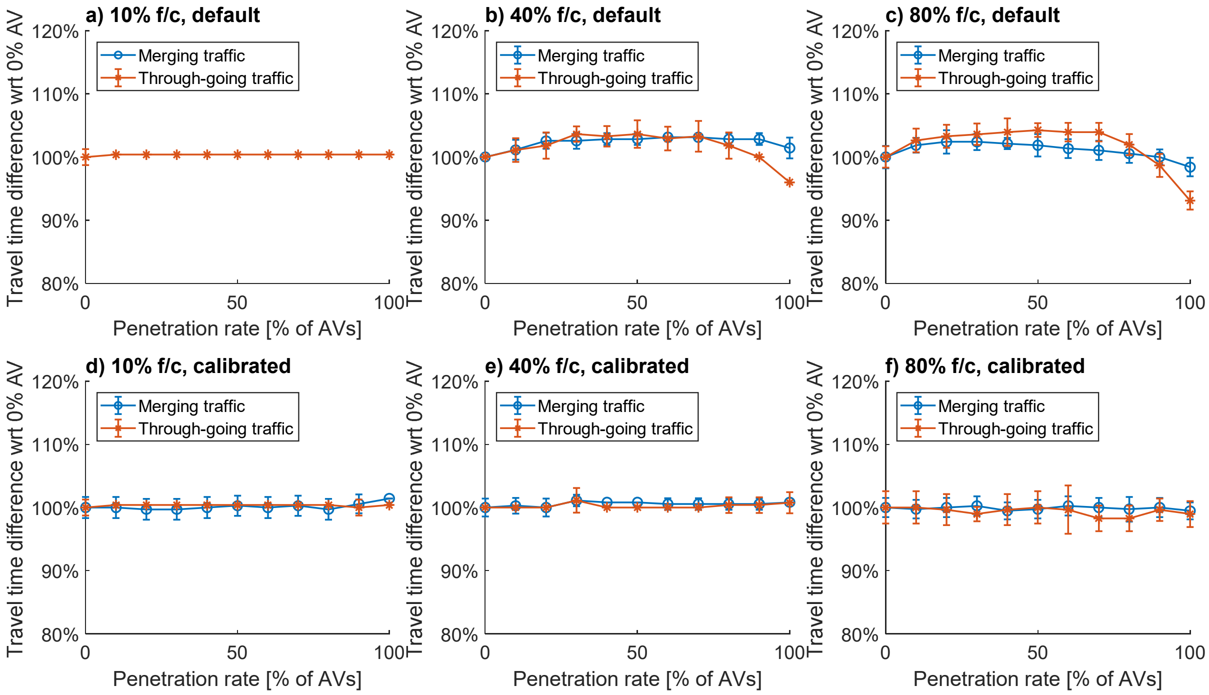


Figure 3.16 Percentage of travel times w.r.t the 0% AV scenario for an exit ramp with a taper lane of 0m, with 0.10 Flow/Capacity ratio (a,d), a 0.40 Flow/Capacity ratio (b,e) or a 0.80 Flow/Capacity ratio (c,f). Simulations used the default (a,b,c) or calibrated (d,e,f) parameters for conventional vehicles

3.3.7 Results - safety analysis

For the flow/capacity ratio of 0.80 in the weaving section scenario, we performed an SSAM analysis. We analyse the average number of conflicts happening in each of the simulation scenarios (i.e., the average of the 11 simulation runs per scenario), both using the default and calibrated parameters for modelling CVs. A conflict is defined as an observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged (Gettman et al., 2008).

The results of the SSAM conflict analysis are shown in Figure 3.17. The default parameters of CVs are recognized by a high safety (i.e. low number of conflict points), which doesn't vary much as the penetration rate grows. The calibrated set of parameters represents a more aggressive behaviour with small time headways and thereby lots of possible safety conflicts. Based on the SSAM analysis, the introduction of AVs results in a safer situation on the road with fewer conflict points. However, the SSAM model has not been validated for AVs and it is questionable whether the results are correct as they do not incorporate any other safety related issues such as a loss of control or software failure. Additionally, we did not perform a sensitivity analysis of the PET and TTC parameters used – it is unknown what the impact on number of possible conflicts is with varying numbers.

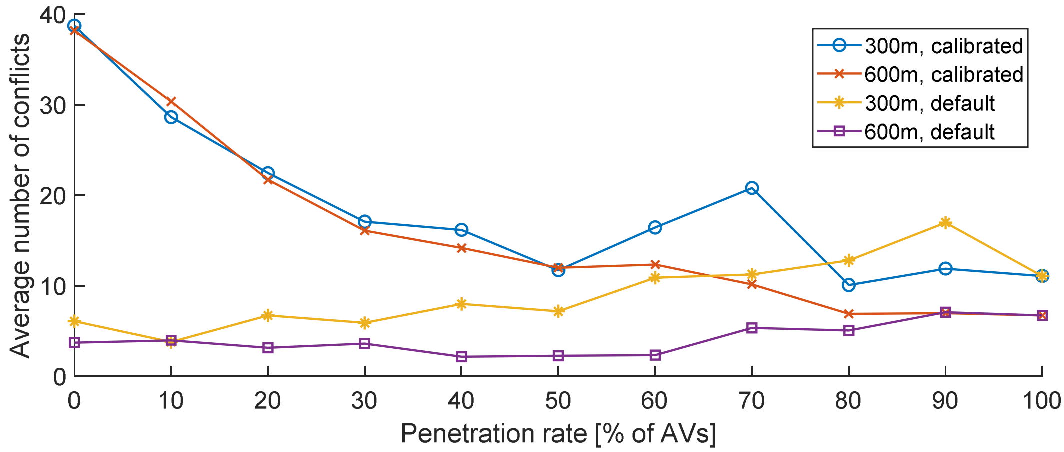


Figure 3.17 Average number of safety conflicts for a weaving section with a 0.80 Flow/Capacity ratio, with a 300m or 600m taper lane and using the default or calibrated parameters for modelling CVs.

3.3.8 Results - different driving logics

In our simulations we assumed that all AVs are of the type "all-knowing". However, to validate our results, it is interesting to see the impact of using the other driving logics as defined by the CoEXist project: cautious and normal AVs. Therefore, we modelled a weaving section with different penetration rates of AVs, for each of the three different driving logics. As with the previous simulations, we used two different types of conventional vehicles (default and calibrated) as well. Results on travel times compared to a 0% AV situation are shown in Figure 3.18.

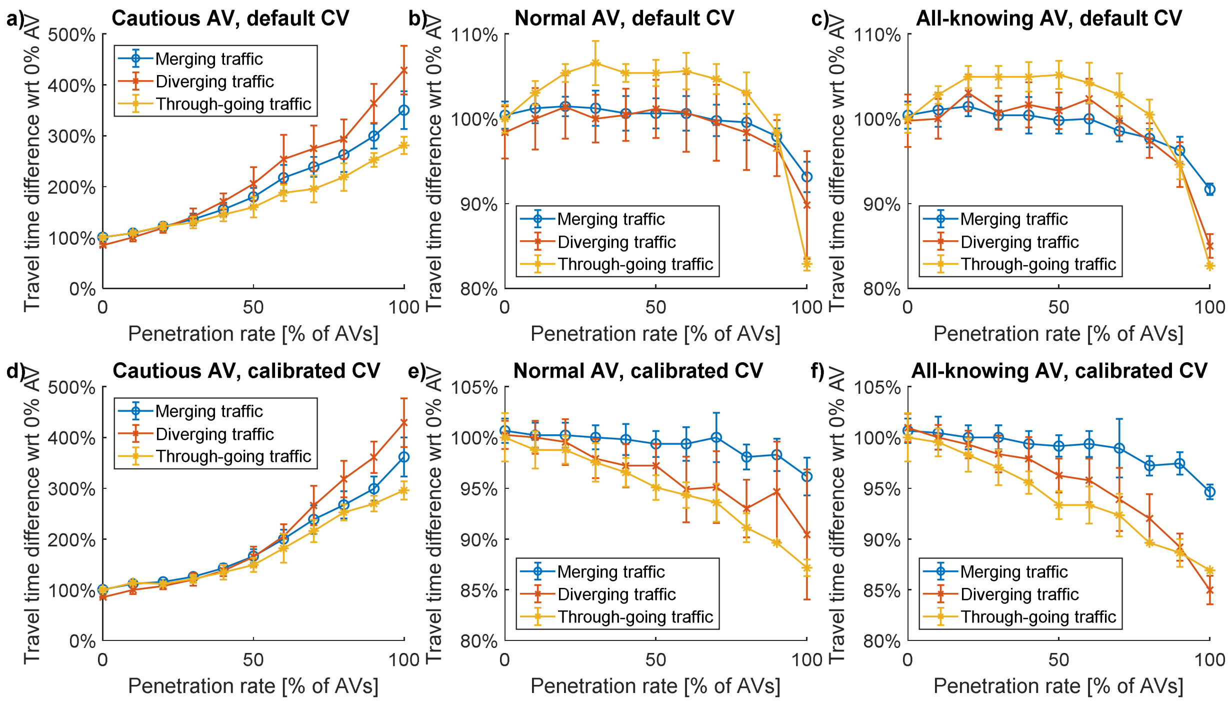


Figure 3.18 Comparison of different AV driving logics (cautious, normal, all-knowing) and different conventional vehicles (default, calibrated), modelled on a weaving section with a 300m taper lane and 0.85 flow/capacity ratio.

It can be seen that the cautious driving logic leads to an enormous increase in travel time as the amount of AVs on the road increase. The very safe behaviour of AVs leads to large gaps between vehicles and thereby a decreased level of service of the road. Differences between the normal and all-knowing driving logic are not very large – the travel times for both default and calibrated CVs are about identical. The main difference can be found in the spread of results (indicated by the error bars), which is slightly lower with all-knowing AVs than normal AVs.

We do not expect large groups of cautious AVs on the roads – they will probably mostly behave according to the normal or all-knowing driving logic. Since the normal and all-knowing driving logic result in about the same results for this weaving section simulation test, we expect that differences in our simulation results will be limited for normal AVs and all-knowing AVs, and therefore it was a valid assumption to only simulate the all-knowing AV type.

3.3.9 Discussion

In this study the results of 88 different simulation scenarios of an entry ramp, exit ramp and weaving section were presented. We varied the ramp length (0-300-600m), the Flow/Capacity ratio (0.55 or 0.80) the penetration rate (0-100% AVs), and the way a CV is modelled (using default or calibrated parameters). In general, it can be concluded that the way a CV is modelled has a high influence on the results, both in terms of average travel times and resulting safety. We discussed our results during the CEDR MANTRA Workshop for WP3 in Vienna on the 10th of September 2019, as well as during a Transport & Planning PhD meeting on the 5th of December 2019, the results are reflected in this section.

The reported travel times using default VISSIM parameters correspond with the finding of Bierstedt et al. (2014), who concluded that benefits only occur if 75% of the fleet mix consists of AVs. Results using calibrated parameters show a different result: benefits are already visible for small penetration rates (>10%). The large difference between default and calibrated car-following models might be explained by the more aggressive behaviour shown by the Dutch drivers during peak periods – in general, the following distances are lower than officially prescribed. An AV is nearly programmed with the same set of parameters as the calibrated vehicles. Commonly stated “mass-damper” effects caused by CVs braking for AVs merging with a too small headway are therefore neglected.

However, reported decreases in travel times are not as large as predicted by Rios-Torres and Malikopoulos (2016): they found that a 100% CAV penetration rate would result in a reduction of up to 60% in travel time in high traffic congestion on merging roadways. Our results only show a decrease of up to 20%, which is more in line with the findings of Aria et al. (2016) (i.e. a 9% reduction with 100% AVs during peak period). Differences might be caused by the different motorway sections used. For example, we have only analysed one weaving section and not a complete network or long stretch of motorway.

Differences between a taper lane with length 300m or 600m are marginal in all simulations performed. Longer taper lanes (for example, in Ireland these are between 1 and 1.4 km in length) therefore also do not seem to influence much. This corresponds to the empirical findings of van Beinum et al. (2018), who concluded that most of both entering and exiting drivers desire to change lanes in the first part of the weaving segment, leaving the second half unused. Therefore, longer weaving segment lengths seem to have little benefit. However, taper lanes of 0m (non-existing) at the entry ramp road show severe problems with higher flow/capacity ratios. The result is not unexpected: with high volumes of traffic, there hardly exist any gaps that are long enough for a vehicle to merge and accelerate from 0 to 120 km/h. The introduction of AVs doesn’t make it better. It should be noted that we did not consider any visibility issues (not being able to see the approaching traffic), which might not be realistic in this scenario.

Flow/Capacity ratios of 0.55 and 0.80 show similar results for all simulations. The decrease in travel time, as well as the differences between different taper lane lengths, is nearly identical. During visual inspection, it was noticed that a 0.80 F/C ratio still resulted in a quite smooth flow (i.e. no traffic jams appearing). This might be the reason for hardly any differences. It is advised to select a higher F/C ratio in this specific scenario to be able to state something about the influence of AVs in high flow traffic.

We used static Flow/Capacity ratios to describe the amount of traffic on the road, but in fact this is not fully correct. The ratios assume that the capacity stays constant as penetration rate grows, which is not the case. The capacity will increase as the amount of AVs increases. Also, using calibrated CVs results in a higher possible road capacity. However, it is hard to compute the actual capacities, so we believe that it's easier for comparison to stick with a non-changing amount of vehicles/hour instead of increasing number of vehicles as the capacity increases.

Only one type of AV was considered in our simulations, following the "All-knowing" driving logic, a quite advanced driving logic. A more realistic situation would be a mix of CVs, "smarter" CVs (e.g. L2, equipped with (C)ACC, ADAS), cautious AVs, normal AVs and advanced AVs. A comparison between the different AV driving logics (see Figure 3.18) showed that there is hardly any difference between normal and advanced ("all-knowing") AVs in terms of travel times. Possibly, CACC equipped vehicles will result in equal traffic flow efficiency. Cautious AVs add problems to the smoothness of traffic flow, severely decreasing the capacity of the road. It is advised to perform additional simulations showing the mix between CVs, cautious AVs and normal/advanced AVs.

It should be noted that in our mix of traffic we did not consider any trucks. Adding trucks, especially if being part of automated platoons, is a different research topic. This is discussed and simulated in Chapter 4.

Although AVs are expected to decrease the number of accidents on the roads, this is not fully reflected by the SSAM safety analysis. Using default CV parameters results in hardly any changes in the number of conflict points. On the other hand, AVs do increase the level of safety if CVs are modelled more aggressively (i.e. using the calibrated parameters). However, it should be noted here that in this study we did not account for potential behavioural adaptation of human drivers when sharing the road with AVs which was shown in previous studies. This should be a point of attention in future simulation studies.

Overall, it is recommended to pay attention to the calibration of parameters for CVs. Differences between calibrated and default parameters in terms of traffic flow are high. Equal effects are expected by changing the parameter settings of AVs. For example, we now simulated quite aggressive AVs, having a headway of 0.6 seconds. However, it is expected that the earliest AVs on the road will have longer headway settings compared to conventional vehicles to ensure safety. Since the adoption phase (i.e. small numbers of AVs on the road) is of special interest for NRAs, the modelling of CVs and AVs has quite some impact: it differs between slightly decreasing or increasing travel times, and thereby possibly a positive or negative advice on allowing AVs on motorways.

3.4 Conclusions

In this chapter we investigated the impacts of highway autopilot including highway convoy in two ways: using macro simulations in OmniTRANS to assess the mobility and travel behaviour impacts, and using microsimulations with VISSIM to assess the traffic flow and safety impacts.

The macro simulation provides a first insight into the impact of AVs at a network level. Since it is expected that AVs are only fully capable of driverless performance on motorways, a 50% AV scenario leads to a shift of trips from local roads toward motorways. This results in usually longer routes, causing an increase in driven vehicle-kms driven. However, due to more efficient driving of AVs this leads to a decrease in total travel time and delay (15-20%) for both AVs and CVs. However, in this way it is assumed that every motorway is occupied by 50% AVs, which might not necessarily be the case. Some routes might have higher AV ratios, and not all vehicles (CVs/AVs) might spread evenly across all road types. A better implementation might be introducing a completely new mode where an AV is modelled as a vehicle with a lower PCU value. Environmental impacts are not a default output of the simulation. However, it should be able to compute these given the vehicle-kms and speeds driven by each of the vehicle classes.

The microsimulation showed that decreasing travel times are to be expected with increasing penetration rates, also at small percentages of AVs. The influence of different taper lane lengths or demand levels seems to be marginal. Results of these simulations highly depend on parameter settings. This was shown by using two different parameter sets for modelling CVs: the commonly used default settings and the ones based on extensive calibration using real data. In general, the default parameters resulted in negative influences on travel time and a marginal influence on safety. On the other hand, calibrated parameters resulted in positive influences on travel time as well as a positive influence on the safety. Since every country or area can possibly be recognized by a different driving behaviour, reflected by different (calibrated) parameter settings, it is expected that the influence of AVs on traffic performance may highly be dependent on the country or area of interest.

In general, NRAs should take notice that the impact of AVs on the motorway is still very uncertain, especially at early adoption phases. Although only the impact of penetration rate was tested in microsimulations, the macro simulations show an increase in vehicle-kms on motorways due to the introduction of AVs. This was not considered in the microsimulation, and might have a considerable effect on the traffic flows: the traffic flows might not get improved as much as currently predicted due to an increase in traffic volumes.
Both research on how an AV should be modelled as well as how a CV should be modelled (and how they interact with each other) is required in further research. Additionally, it is recommended to research the role of NRAs in decreasing negative impacts of the deployment of motorway automation by changing road design guidelines, for example by investigating Infrastructure to Vehicle communication and traffic speed management.

In this chapter we used two different simulation software packages: OmniTRANS and VISSIM. OmniTRANS is suitable for performing macrosimulations. It is possible to add multiple vehicle types (e.g. cars, automated vehicles, connected automated vehicles), but no out-of-the-box support is present in terms of mode choice and travel time functions. This should be gained from other research, which makes it hard to set-up. Additionally, a license is required to run the model. However, once this has been set, it can be used to predict the impact of automation on a city or regional level easily. VISSIM is a microsimulation tool which can be used to simulate stretches of roads, including the interaction of vehicles. It requires a license. The H2020 CoEXist project introduced a set of parameters for modelling AVs in VISSIM which can be used as a starting point. Given this set of parameters, it is relatively easy to obtain a result if you are used to the VISSIM software environment. The CoEXist project also provided guidelines for simulating AVs in a macroscopic simulation tool called VISUM. It might be worthwhile checking their results and possibly applying for a next research project.

4 Impacts of highly automated freight vehicles (L4) on open roads

4.1 Introduction

This study addresses the impact of highly automated (SAE Level 4) trucks on the travel times and speed of traffic in motorway driving. The research literature contains numerous modelling studies on truck platooning, examining for example energy savings (e.g. Tsugawa et al., 2016), communication aspects (e.g. Gehring and Fritz, 1997), platoon control (e.g. Martinec et al., 2014), traffic impacts (e.g. Mueller, 2012; van Maarseveen, 2017) and loading on bridges (e.g. Yarnold and Weidner, 2019). There have been a number of studies investigating platoon longitudinal control with vehicle-to-vehicle communication in the form of cooperative adaptive cruise control (CACC) as opposed to simple automated control in the form of adaptive cruise control (ACC). Nowakowski et al. (2016) described the control and manoeuvring strategies for managing platoon assembly and disassembly with CACC, as well as a process for handling cut-ins by other vehicles. Bevly et al. (2016) performed a microsimulation of CACC operation of heavy trucks on a 5.3 mile section of a U.S. interstate with three exits. The CACC system was modelled with four different headway settings (1.25s, 1.00s, 0.75s and 0.50s) and penetration rates of 20%, 40%, 60%, 80% and 100%. Traffic volumes were modelled at the current situation and increases of 15% and 30%. Traffic speed increased and travel delay decreased with smaller headway, and the effects were greater with increased traffic volume.

However, there is no parallel body of literature on the impacts of highly automated (Level 4) trucks. This study uses the test case of an existing motorway corridor with substantial heavy truck usage to examine the impact of truck automation on traffic speed and travel time. Vehicle flows were kept to the current situation, and heavy trucks were progressively converted to automated operation at penetrations of 25%, 50%, 75% and 100%. The automated capability was the ability to begin a process of ad hoc coupling with other similarly automated trucks when within a closing distance of 200 metres. That coupling was via vehicle-to-vehicle communication (i.e. CACC) and was maintained through intersections, except when a coupled vehicle had to exit the motorway.

Information on fuel consumption was not collected. The main reason for omitting this aspect of performance was that the chosen software, AIMSUN, does not have the capability to calculate the savings induced by close following on air flow and hence on fuel consumption. It was therefore thought that any estimation of fuel consumption would be incorrect.

4.2 Chosen network

The selected corridor was the M62 motorway westbound from Leeds (Junction 28) towards Manchester to just beyond Junction 22 at the top of the Pennine mountain range. The motorway is one of the main UK east-west corridors and acts as a part of the wider European network linking Rotterdam (via Hull) to Dublin (via Liverpool). The motorway also covers several important urban areas in England: Hull, Leeds, Bradford, Manchester and Liverpool. It has heavy long-distance freight use.

Entrance and exit ramps were included in the network, together with short sections of the M621 and M606 motorways which merge with the M62. The motorway is relatively flat from Leeds up to Junction 25 (Brighouse), which is 73m above sea level. It then begins a steady climb to the top of the Pennines, reaching 230m at Junction 24 (Ainley Top) and a maximum elevation of 372m just east of Junction 22. The inclusion of an ascent section allowed investigation of the impact automation on traffic behaviour where trucks are slowed by road gradient.

Figure 4.1 presents the stretch of the motorway simulated: it starts before Junction 28 in the East and runs until after Junction 22 in the West. The M621 joins Leeds to M62 at Junction 27, and the M606 connects Bradford to the M62 at Junction 26. The stretch between Junctions 27 and 26 can be very congested given the close proximity of Leeds and Bradford. Features of the chosen motorway are:

- There are varying levels of congestion in the stretches chosen, allowing us to observe potential differences in traffic flow.
- Just before Junction 22 is the highest point on a motorway in England, indicating significant uphill stretch. Given the weight of trucks, speed in the uphill portions is slow, causing potential slowing of traffic following the trucks.
- Connections with two other motorways serving Leeds and Bradford ensures substantial merging and exiting traffic, with potential weaving behaviour.
- The motorway traffic has a relatively high share of trucks, up to 25% in some stretches

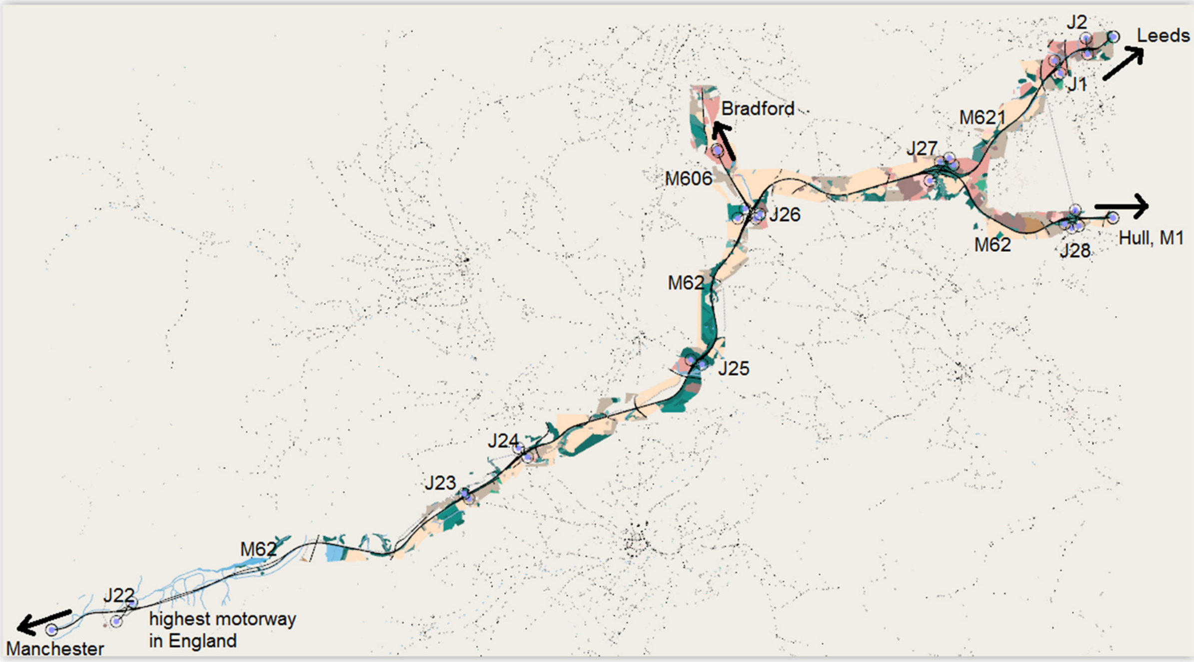


Figure 4.1: Plan view of the M62 stretch simulated, with location of junctions and other connections included

Note that unlike in the Dutch scenario above (section 3), in motorways in the UK the exit ramp appears earlier than the entry ramp; as such the potential conflict between entering and exiting traffic at the junctions is much less.

4.3 Simulation setup

A conscious decision was made to not include any potential demand implications of freight vehicle automation, i.e. any changes in the freight vehicle volume due to changes in the relative prices of freight transport due to truck automation is not included. This is done in order to disentangle the traffic flow impacts of the technology from any demand impacts.

Microsimulation software AIMSUN was used to simulate the potential impacts of truck automation on motorway travel. Given Wadud's (2017) finding that trucks will likely be one of the earliest adopters of automation for motorway travel and decision from CEDR CAD WG, only trucks are assumed to be automated in our simulation.

The entire stretch as shown in Figure 4.1 was simulated in AIMSUN, with details of the junctions, their entries and exits, sometimes including the associated roundabouts (which are fairly common). Figure 4.2 shows the merging of the M62 and the M621 at M62 Junction 27.

The simulation is carried out for one hour during the peak traffic. This falls between 0700-0800 hours in the selected motorway stretch.

The traffic flow data is collected by Highways England, which provides counts on the basis of loop data. The entry ramp and exit ramp data are not always available for every junction, and some minor manual adjustments were made for maintaining consistency of the traffic across the junctions.

Traffic flow is measured for different vehicle classes. However, the classes are described on the basis of vehicle sizes, specifically lengths. We have assumed the definitions in Table 4.1 for this experiment. The large trucks were given automation capability in the simulation.

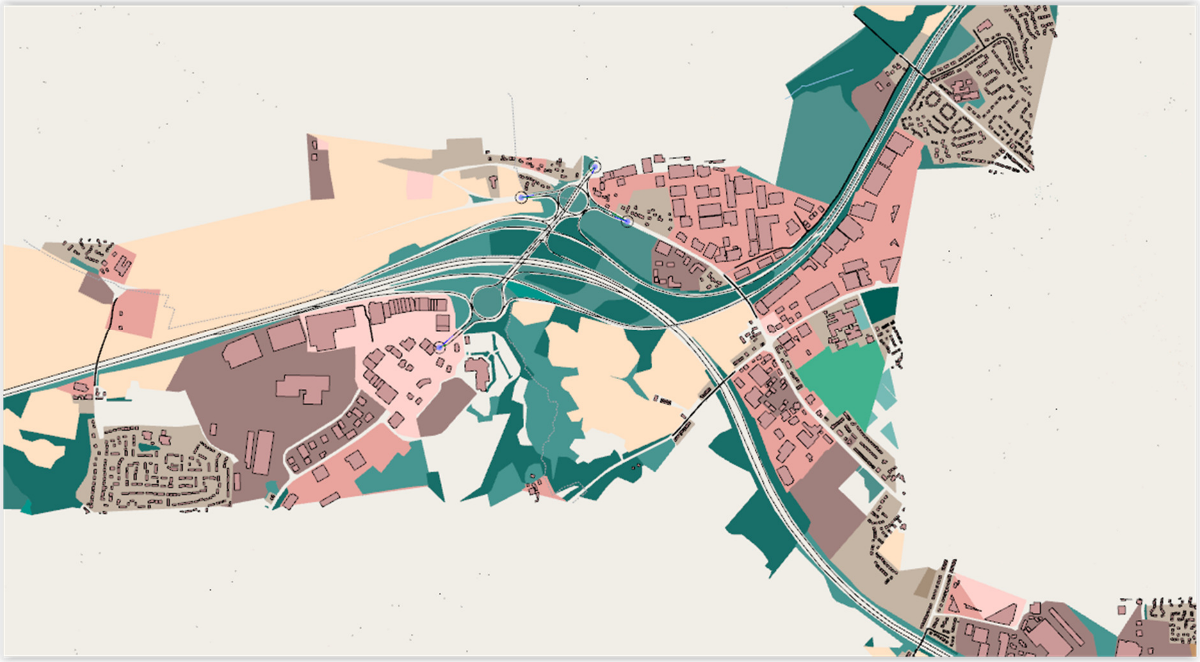


Figure 4.2: Junction 27, where the M621 merges with the M62, as represented in AIMSUN

Table 4.1: Different vehicle classes

Vehicle length as per motorway count measurement system	**Vehicle class assumed in this experiment**
<=5.2m	Cars
>5.2m and <=6.6m	Vans
>6.6m and <=11.6m	Light Commercial Vehicles (light trucks)
>11.6m	Large trucks: here split into 50% rigid and 50% articulated

AIMSUN uses the car following model of Gipps (1981). We have generally applied AIMSUN's default parameters for simulating the standard (non-automated) vehicles, with some minor adjustments in order to calibrate against the average speed for different vehicle classes at each section of the motorway and to reflect UK specific regulations. For example, truck desired speed distribution was curtailed beyond the speed limit, since trucks in the UK are fitted with mandatory maximum speed limiters. Table 4.2 presents the speed profiles for standard and automated vehicles. Table 4.3 presents the comparison of actual traffic flow and simulated flow for standard vehicles.

The desired acceleration and deceleration profiles for each vehicle type are shown in Table 4.4 and Table 4.5. The vehicles' assumed weights are shown in Table 4.6.

Table 4.2: Speed profiles for each vehicle type

Vehicle type	**Mean speed**	**Standard Deviation Speed**	**Minimum Speed**	**Maximum Speed**
Car	110 km/h	10 km/h	80 km/h	150 km/h
Van	100 km/h	10 km/h	80 km/h	120 km/h
Truck (Auto)	85 km/h	0 km/h	85 km/h	85 km/h
Truck	85 km/h	10 km/h	70 km/h	90 km/h

Table 4.3: Average simulated vs measured flows (vehicles/ hour) between junctions on the M62

Vehicle type	**Simulated Flow Junction 28 - 27**	**Measured Flow Junction 28 - 27**	**Simulated Flow Junction 27 - 26**	**Measured Flow Junction 27 - 26**
Car	2415	2408	2748	2743
Van	1204	1203	1380	1371
Truck	858	852	1045	1045
	Simulated Flow Junction 26 - 25	**Measured Flow Junction 26 - 25**	**Simulated Flow Junction 25 - 24**	**Measured Flow Junction 25 - 24**
Car	2076	2038	1869	1842
Van	1014	1012	916	921
Truck	809	809	659	655
	Simulated Flow Junction 24 - 23	**Measured Flow Junction 24 - 23**	**Simulated Flow Junction 23 - 22**	**Measured Flow Junction 23 - 22**
Car	1439	1414	1763	1737
Van	708	707	784	784
Truck	755	746	852	834

Table 4.4: Maximum acceleration

Vehicle type	Mean	Standard Deviation	Minimum	Maximum
Car	3 m/s2	0.2 m/s2	2.6 m/s2	3.4 m/s2
Van	2.5 m/s2	0.2 m/s2	2.0 m/s2	3.0 m/s2
Truck	1 m/s2	0.5 m/s2	0.6 m/s2	1.8 m/s2

Table 4.5 Normal deceleration

Vehicle type	Mean	Standard Deviation	Minimum	Maximum
Car	4 m/s2	0.25 m/s2	3.5 m/s2	4.5 m/s2
Van	3.5 m/s2	0.2 m/s2	3 m/s2	4 m/s2
Truck	3.5 m/s2	1 m/s2	2.5 m/s2	4.8 m/s2

Table 4.6 Vehicle weight

Vehicle type	Mean	Standard Deviation	Minimum	Maximum
Car	1202 kg	454 kg	839 kg	2291 kg
Van	13608 kg	9072 kg	4536 kg	40823 kg
Light Truck	13608 kg	22680 kg	4536 kg	36287 kg
Heavy Truck	13608 kg	22680 kg	4536 kg	36287 kg
Articulated Truck	17608 kg	22680 kg	8536 kg	40000 kg

Some parameters, which related to the desired speeds of the vehicles across the network, were altered. The desired speeds would change depending on the speed limit of the road and in theory the vehicles could travel faster as is seen on a real motorway. For the automated trucks this parameter was modified so that they would always obey the speed limit as shown in Table 4.7. The CACC behaviour was only used by the automated trucks.

Table 4.7 Speed acceptance

Vehicle type	Mean	Standard Deviation	Minimum	Maximum
Car	1.1	0.1	0.9	1.3
Van	1	0.1	0.9	1.15
Truck	1.05	0.1	1	1.1
Automated truck	1	0	1	1

Each simulation was run with a step interval of 0.4s. The reaction times for each vehicle type were set to a multiple of this value as seen in Table 4.8.

Table 4.8 Simulation reaction time.

Vehicle type	Reaction Time	Probability
Car	0.8 s	0.8
Car	1.2 s	0.2
Van	0.8 s	1.0
Truck	0.8 s	1.0
Automated truck	0.4 s	1.0

4.4 Modelled scenarios

Table 4.9 summarises the various modelled scenarios. The overall assumption was the trucks could couple to a maximum length of three vehicles with an inter-vehicle gap, once coupled, of 4 metres. Two variants were assessed for 100% penetration of automated vehicles into the freight fleet:

1. A maximum length of four coupled vehicles with an inter-vehicle gap of 4 metres
2. A maximum length of three vehicles with an inter-vehicle gap of 10 metres

Table 4.9: Modelled scenarios

Behaviour of Automated Trucks	Penetration of Automated Trucks in the truck fleet				
	0%	25%	50%	75%	100%
Maximum platoon size of 3 vehicles and inter-vehicle gap of 4 metres	✓	✓	✓	✓	✓
Maximum platoon size of 4 vehicles and inter-vehicle gap of 4 metres					✓
Maximum platoon size of 3 vehicles and inter-vehicle gap of 10 metres					✓

In the following section, we present the results of the different simulation scenarios. We investigate first the effects of automation penetration in the freight transport fleet. This is done by comparing the 0% baseline with penetration of automation into the large truck fleet at 25%, 50%, 75% and 100% of the vehicles (note that this penetration rate is for automation of truck, and not penetration of convoy formed). Although we have three truck types (as mentioned earlier), automation is assumed to penetrate at a similar rate in all three groups. In this primary scenario test case, we investigate a maximum convoy length of 3 freight vehicles and a gap of 4m between the automated vehicles. In addition, we conduct two separate simulation runs for a gap of 4m and convoy length of 4 vehicles and a gap of 10m and convoy length of 3 vehicles.

4.5 Effects of freight automation on traffic speed and travel time on motorways

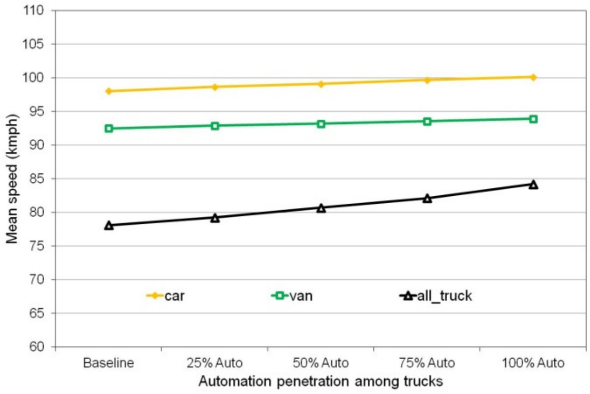
4.5.1 Effects on overall traffic

Although we have run one continuous simulation for the whole segment of the motorway, the results below are presented for smaller stretches — between the two junctions. This allows us to identify the differences in the behaviour in different stretches and where possible to draw inferences on the impact of automation in different road geometry (uphill or not) or traffic conditions (congested or not).

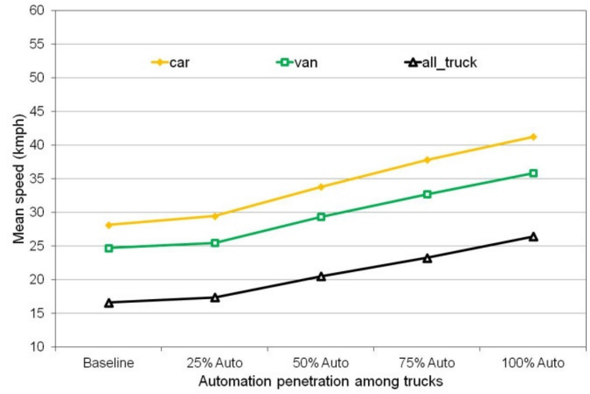
Figure 4.3 presents the effects of different levels of penetration of automation in freight vehicles on traffic speed. Cars and vans remain non-automated throughout, while the results for the freight vehicles are average speeds over all freight vehicles at each stretch of the motorway. Clearly in every segment of the motorway, the average speed for freight vehicles increase progressively as more and more of the freight vehicles are automated. Speed for other non-automated vehicles also increase as freight vehicles become automated, although this increase is negligible. Overall, freight vehicle automation increases travel speed of freight vehicles and does not have any adverse impacts on speeds of other vehicles.

There is some hint of non-linearity in the increases in average speed of the freight vehicles with respect to penetration. In normal conditions, the increases at higher penetration level are larger than those at lower penetration. In congested situations, as in J27-J26 (Figure 4.3b), the non-linearity becomes more prominent at an earlier level of penetration.

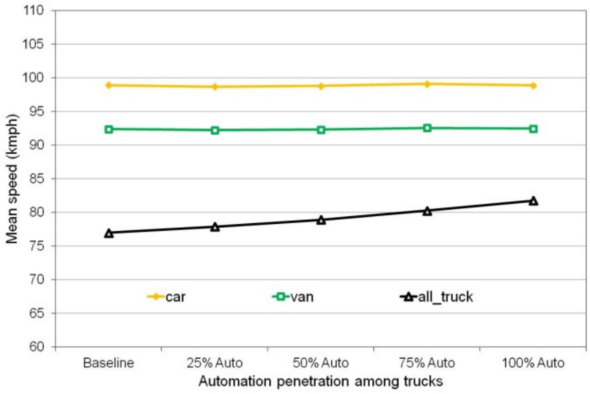
As can possibly be expected, the benefits (in terms of higher speeds) are the largest in congested situations, which is between J27 and J26 in this case study, just after the merging of the M621 with the M62 and before the merging of the M606 with the M62 (Figure 4.3b). The average speed of the freight vehicles increases by almost 60% when all of them become automated compared to when none are automated, which is a very substantial improvement. Importantly, the non-automated car and van fleets also experience the largest increases in speed in this congested situation — 46.5% and 45% respectively. In comparison, the speed increase is less than 1% for cars and vans in normal stretches. Note that this stretch of the motorway also has substantial weaving traffic, given that it lies between motorway merges at both ends.



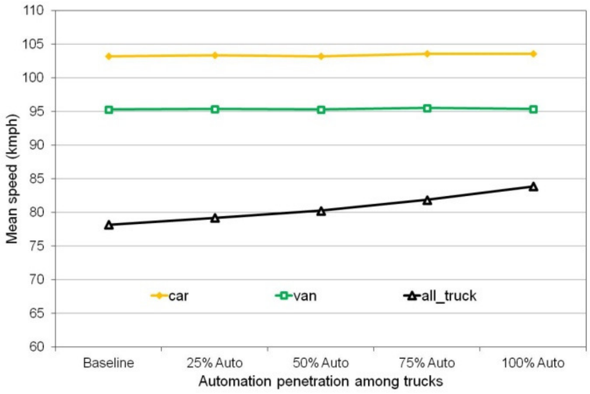
(a) J28-J27



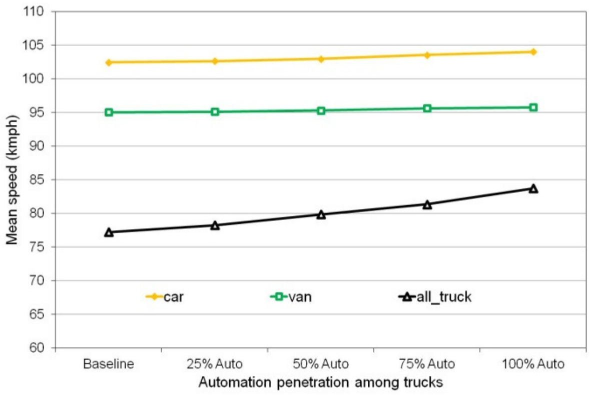
(b) J27-J26, congested



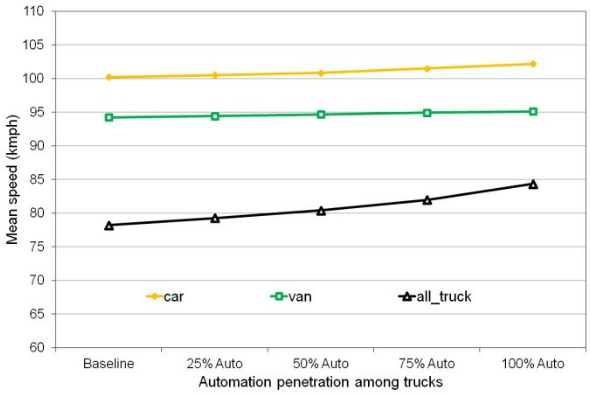
(c) J26-J25



(d) J25-J24



(e) J24-23, uphill

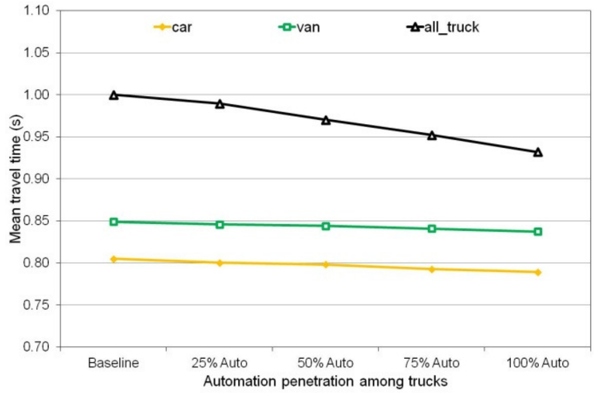


(f) J23-J22, milder uphill

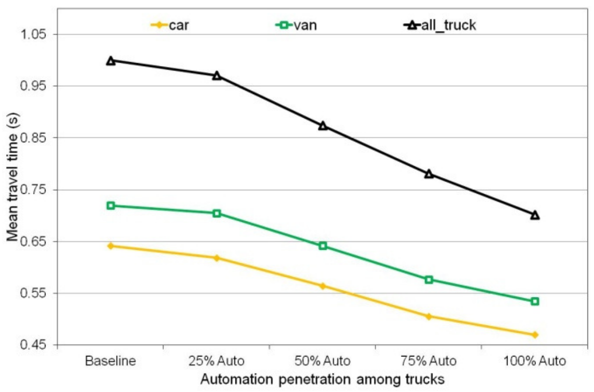
Figure 4.3: Effects of freight vehicle automation on average speed of different vehicles types in different stretches of the motorway

Average speed of the freight vehicles improves slightly more if the road segment has an uphill slope compared to when there are no such slopes. Average speed of freight vehicles increases by 8.4% at 100% penetration rate in between J24 andJ23 — which is the steepest section of the motorway (Figure 4.3e) — compared to an increase of 6.2% in between J26-J25 (Figure 4.3c). Average increase in speed between J23 and J22, which has a milder slope than J24-J23, is slightly less at 7.2%. The cars and vans also benefit slightly from freight vehicle automation in uphill stretches.

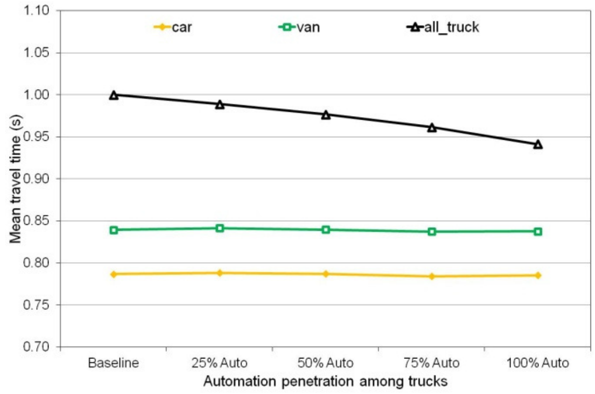
Figure 4.4 presents the time to travel the specific stretches of the motorways. However, since these stretches are of different lengths the travel times are normalized with respect to average travel time by all freight vehicles with no automation. As can be expected the results point toward similar conclusions as in Figure 4.3: automation reduces the time to travel through a stretch, and the reduction in travel time is the most pronounced for congested stretches of the motorway.



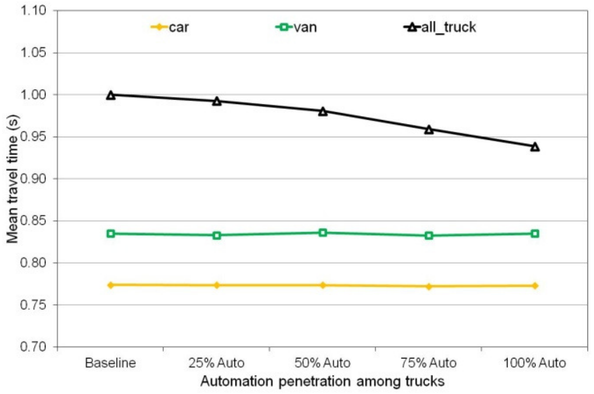
(a) J28-J27



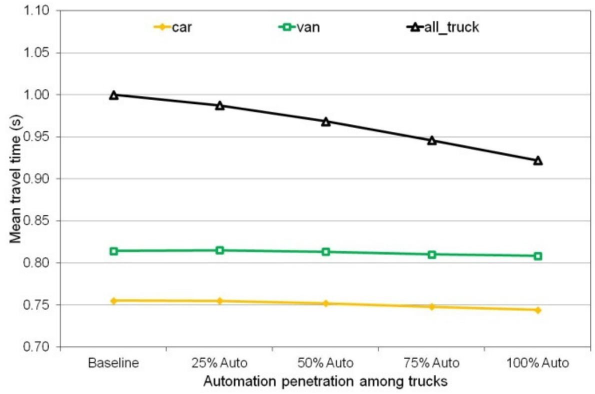
(b) J27-J26, congested



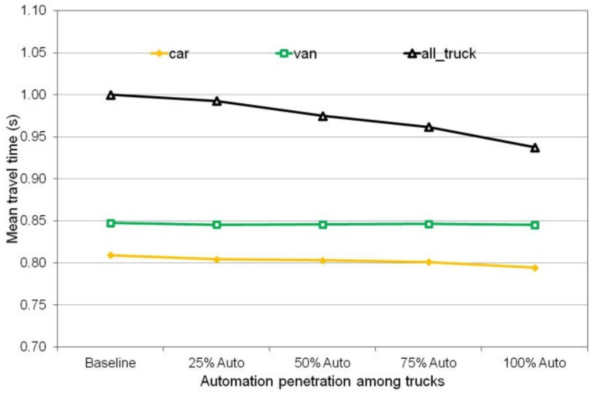
(c) J26-J25



(d) J25-J24



(e) J24-23, uphill



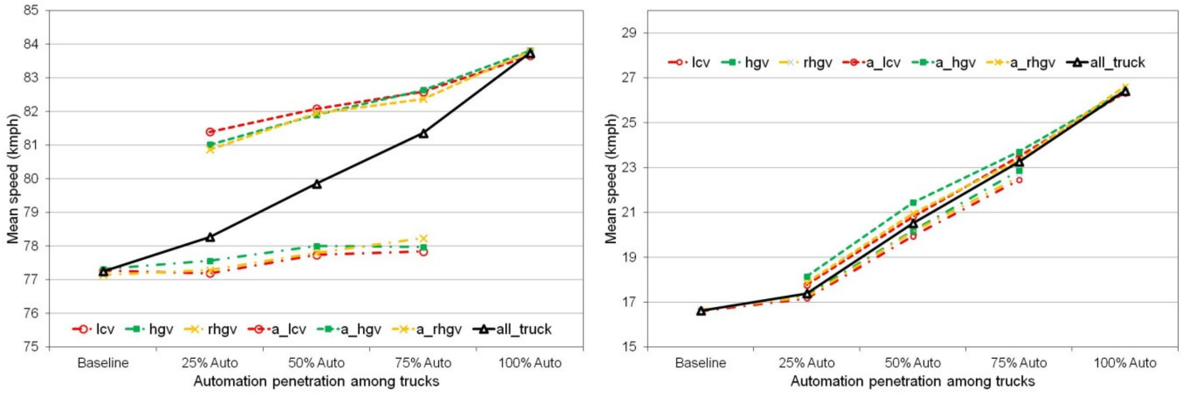
(f) J23-J22, milder uphill

Figure 4.4: Effects of freight vehicle automation on normalized travel time of different vehicles types in different stretches of the motorway

4.5.2 Effects on automated and non-automated trucks

Figure 4.5a presents the effects of automation on the speed of automated and non-automated freight vehicles of different types, as well as the average speed of all types of freight vehicles for the stretch J24-J23. For automated vehicles (dashed), the data starts only at 25% penetration since there are no automated vehicles at 0% penetration. Similarly, there are no non-automated vehicles at 100% penetration of automation. As Figure 4.5 shows, average speed improves substantially at higher levels of penetration. However, this increase is primarily due to increased speeds of the automated versions compared to their non-automated counterparts. While the average speed of non-automated freight vehicles appear to increase with higher penetration, this increase is quite modest.

For the congested stretch of the motorway (J27-J26), however, both the automated and non-automated freight vehicles experience a substantial increase in speed (Figure 4.5b). Note that this is a special case and in all other stretches the difference is more similar to Figure 4.5a, rather than Figure 4.5b. In Figure 4.3b also we can observe similar findings for cars and vans.

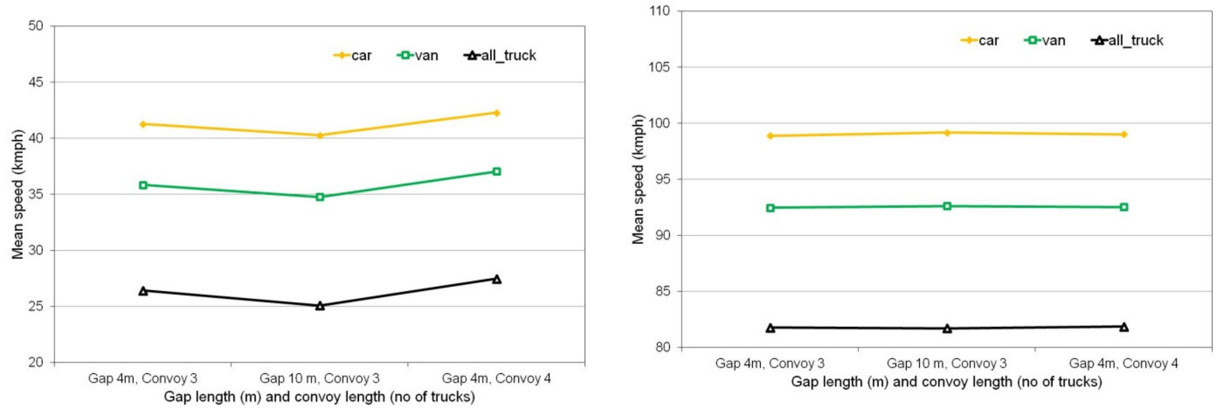


(a) J24-J23, uphill (b) J27-J26, congested

Figure 4.5: Effects of automation penetration on the speed of automated and non-automated freight vehicles

4.5.3 Effects of gap distance and convoy length on motorway speed

Figure 4.6 presents the effects of distance between the vehicles and the size of convoys on average speed in a regular segment and a congested segment. There does not appear to be any discernible effect of either gap distance (from 4m to 10m) or the size of convoy (from 3 vehicle to 4 vehicle) on average speed of the freight vehicles for normal motorway stretches. However, once again there are observable effects in a congested stretch, e.g. between J27 and J26. If gap length increases, overall speed of the freight vehicles decreases slightly — this is possibly due to the taking up of extra road space, leaving less space for vehicles to roam about. If convoy size is increased from 3 to 4, average speed of the freight vehicles increases a little. This possibly results from the vehicles driving more closely to each other, making more space available for other vehicles.



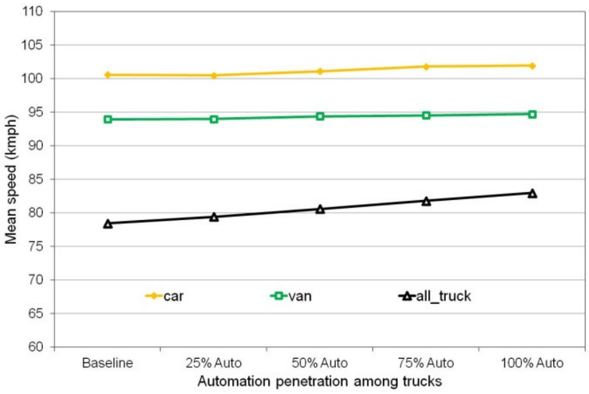
(a) J27-J26, congested (b) J26-J25

Figure 4.6: Effects of automation penetration on the speed of automated and non-automated freight vehicles

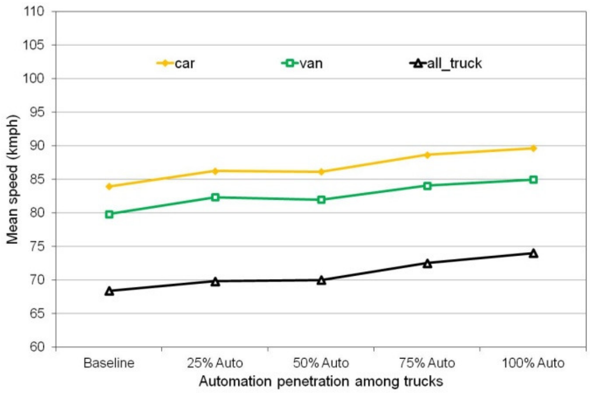
4.5.4 Effects of automation on exit and entry speed

Figure 4.7 presents the traffic speed on the motorway exit and entry ramps for 2 junctions, with respect to different rate of automation of the freight vehicles. There is always some improvements in speeds — both for entry and for exit ramps — for all vehicle types, although the magnitude of improvement can vary depending on junction characteristics.

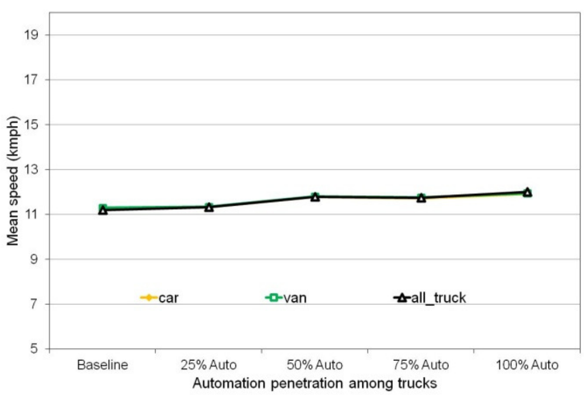
The exit ramp of J26 is the most congested of all, as reflected by the slow average speed on this ramp and there are two observations here: the improvement in flow due to freight vehicle automation is the least and there is little difference in the speeds between different vehicle types reflected the congested situation. Note that J26 exit is always congested during the peak hours (exit to Bradford). The largest gain in speed occurs in J27 entry ramp, which connects to the most congested part of the motorway. Non-automated vehicles also benefit significantly on this entry ramp — possibly a more uniform speed distribution of the freight vehicles on the merging lane helps vehicles merge better. Such large gains are not observed on J26 entry, which merges with a relatively free-flowing traffic.



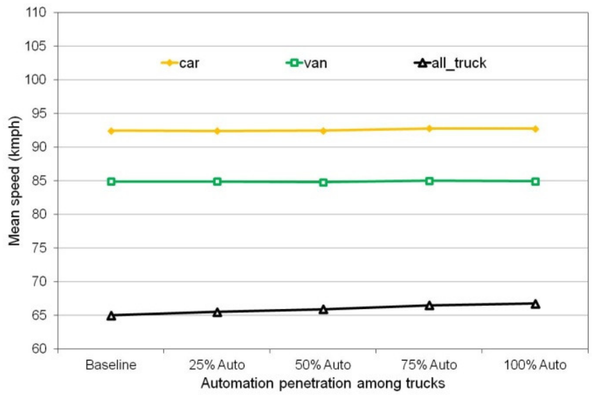
(a) J27 exit ramp



(b) J27 entry ramp



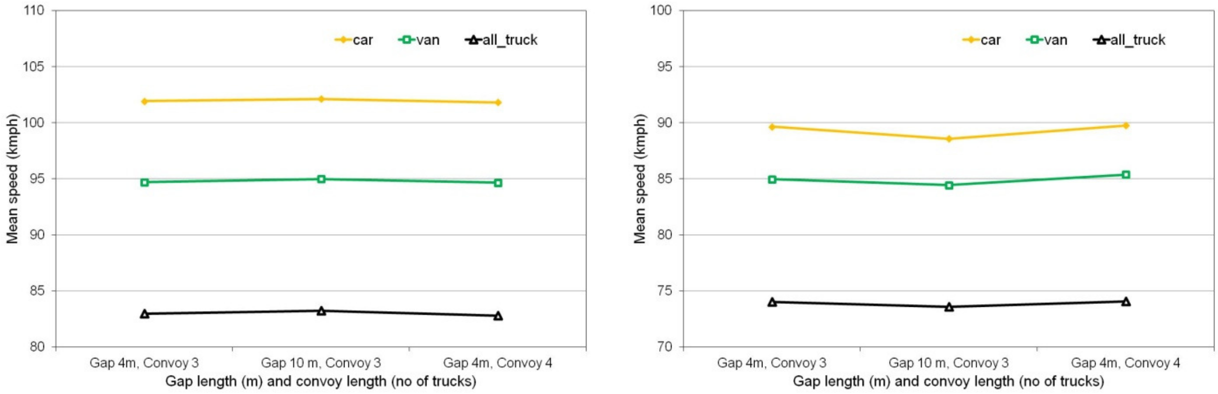
(c) J26 exit ramp



(d) J26 entry ramp

Figure 4.7: Effects of automation penetration on average travel speed on exit and entry ramps at two junctions

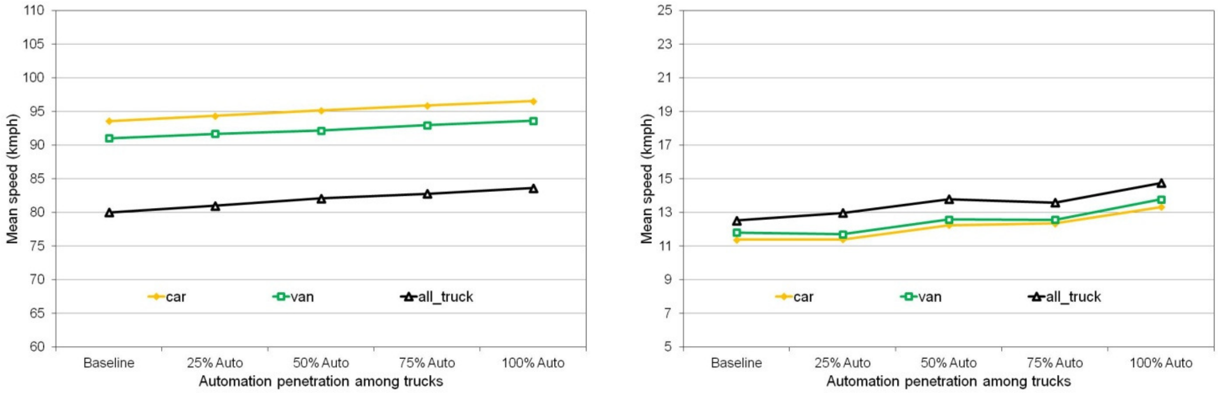
The effect of gap length or convoy size on the average speeds do not appear very significant, as seen in Figure 4.8. This reflects the current condition of freight vehicle density in the network, and we hypothesize that a higher density of freight vehicles may affect the speed and time to enter the motorway. Indeed, the entry speed for cars (which are more frequent and have a higher probability to encounter an automated convoy) falls marginally as the gap between trucks increases to 10m from 4m, which would tend to support our hypothesis.



(a) J27 exit ramp (b) J27 entry ramp

Figure 4.8: Effects of automation penetration on average travel speed on exit and entry ramps at J27

We have also measured the average speed of the 2nd left-most lane near the exits to test whether exit is hindered by the presence of potential convoys to the left. No discernible pattern could be observed (Figure 4.9), as the speed tend to increase for all vehicle types.



(a) near J27 exit (b) near J26 exit

Figure 4.9: Effects of automation of freight vehicles on mean speed at the second left lane, before exit

4.6 Conclusions

Following are the major conclusions from the simulation work on automated freight vehicles:

- Flow improves as more and more freight vehicles get automated
- There is some non-linearity in the speed and travel time benefits with respect to the share of vehicles automated
- The speed and time benefits are the largest when the motorway is congested
- In a congested situation, the benefits are more egalitarian, i.e. they accrue to all types of vehicles — automated or non-automated; in free-flow conditions, it is the automated freight vehicles which benefit the most, for other vehicles benefits are marginal
- Smaller inter-vehicle gaps allow a slight increase in average freight vehicle speed, but only in congested stretches, with no effect in other stretches
- A larger number of vehicles in the convoy increases average freight vehicle speed, but only in congested stretches, with no effect in other stretches

The simulation software used for this study was found to be highly usable, particularly since an API to handle the vehicle-to-vehicle communication was available. The principal shortcoming in the version that was used was that it was not possible to visualise the coupling process and thus to see in visual output which vehicles were coupled and which were not. It is not possible to ascertain whether the results obtained would have been different with another software suite, such as VISSIM.

5 Impacts on Commercial driverless vehicles (L4) as taxi services

This chapter concerns simulations for the commercial driverless vehicles, also referred to as robotaxis. First, the ERTRAC definition is discussed, followed by simulations assessing the impact on mobility and travel behaviour. According to discussions during the CEDR CAD WG in Tallinn (06./07.03.2019) we did not assess the impacts of robotaxis on traffic flow and driver behaviour.

5.1 Commercial driverless vehicles (L4) as taxi services

The commercial driverless vehicles as taxi services, also referred to as robotaxis, include automated taxi services operating without a human driver. The robotaxis transport passengers within the boundaries of a specific geographical area. The ODD specification of commercial driverless taxis is based on Waymo's self-driving car concept (Waymo 2017). The Waymo ODD covers city streets in good as well as inclement weather, such as light to moderate rain, in both daytime and at night. (Waymo 2017).

In the MANTRA project we focus on robotaxis as being private services. They can be ordered with an app, and operate as a normal taxi nowadays, bringing passengers from origin to destination without detours. These can be regarded as future Uber type systems (ridehailing) also being designated in the literature as shared automated vehicles (SAVs) even though they may not be used in ridesharing mode (several clients at the same time in the vehicle).

One of the important aspects for modelling the impact on mobility is the relocating of taxis, by bringing taxis back to their origin or positioning them where demand is going to be generated next. These so called empty taxi trips result in additional vehicle kilometres driven by the robotaxis but they are hard to determine as they will depend on complex relocation algorithms and strategies (Jorge et al., 2014).

5.2 Impacts on mobility, travel behaviour and energy

Allowing Level 4 robotaxis in the cities could potentially have an impact on the road network performance. Although it might probably take a while before robotaxis are on the road, National Road Authorities (NRAs) are already concerned about understanding what changes would be required on their current infrastructure to make it ready for AVs. In this part of the study, we simulate the city of Delft in the Netherlands to investigate the impact of AVs on the mobility and travel behaviour in terms of total kilometres travelled and encountered delays. We rerun the mode choice models to estimate how many people would possibly switch from car and/or public transport toward robotaxis. We also include empty taxi trips: trips that are necessary to get the taxis back to their origin.

5.2.1 Traffic model

Simulations of the impact of robotaxis are performed using macro simulation software OmniTRANS 8.0.16 of DAT.Mobility which is the most widespread software used for transport demand modelling in the Netherlands. We use traffic model "Delft" featuring the city of Delft (The Netherlands).

This traffic model models the morning peak in Delft for work and education trip purposes. The four most commonly used transport modes in Delft are modelled: private cars, bicycles, public transport (train, bus, tram) and walking. The network contains 25 zones, 692 links and 473 nodes. It has 19 public transport lines (with 43 stops in total) and roads classified in 16 different types, ranging from cycle tracks to 4-lane motorways to bus lanes. The zones are categorized in internal ("inside Delft") and external ("outside Delft"). An overview of the network is shown in Figure 5.1.

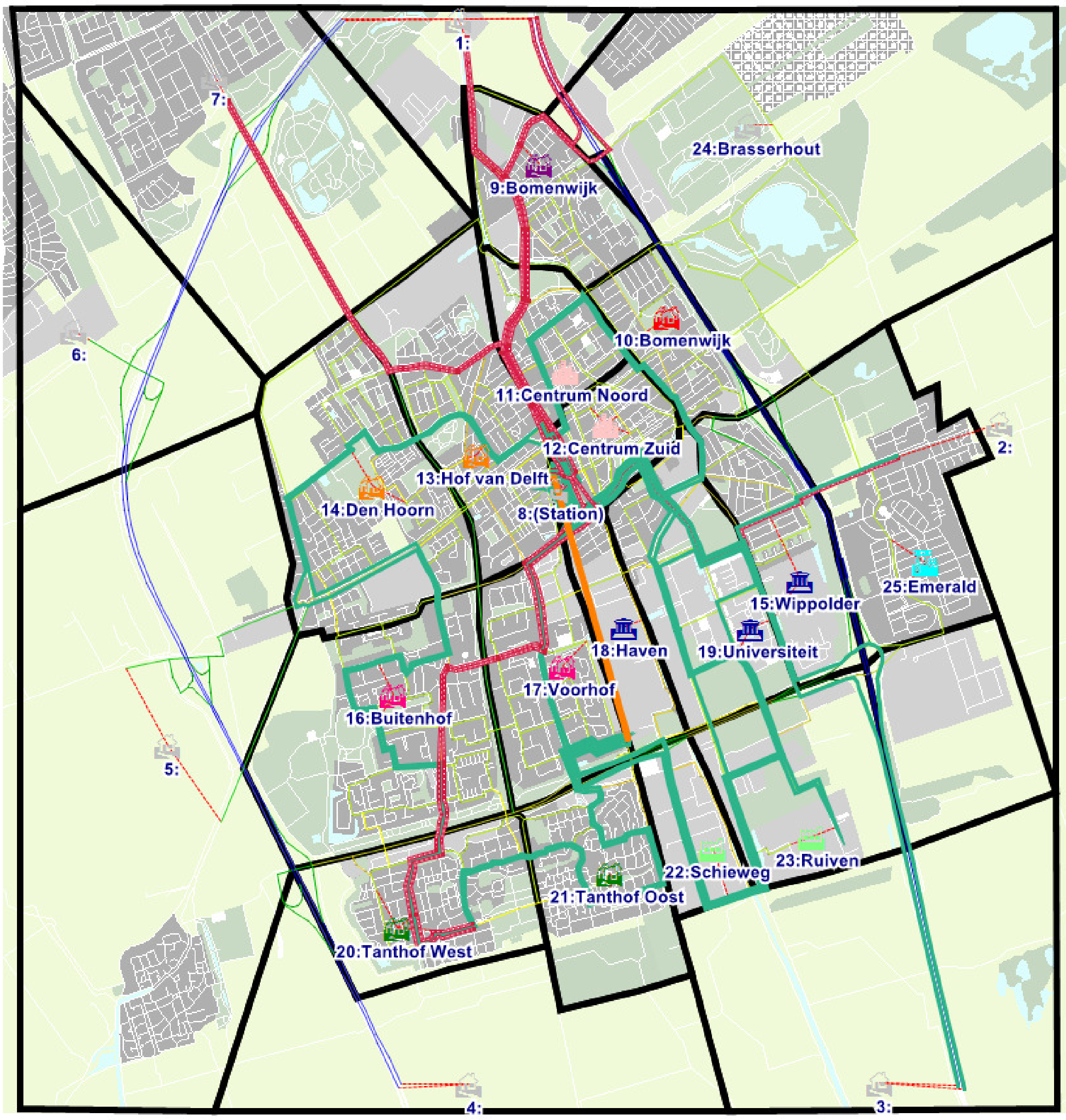


Figure 5.1 Overview of traffic model Delft, showing the 25 zones (1-8 external, 9-25 internal).

The demand data is specified for the years 2015 and 2025. Within the MANTRA project, we are only analysing the 2025-variant. Several scripts are defined for modelling traffic. Trip generation produces the number of trips produced and attracted by a zone based on zonal data. Skim generation computes generalised costs, distances and times for all modes, assuming no other traffic. Trip distribution then produces Origin-Destination matrices for all modes, where destination choice and mode choice is computed simultaneously. To compute mode choices, a deterrence function is used. This deterrence function is a top-lognormal function, as shown in Equation (1).

$$f(c_{ij}) = \alpha * e^{-\beta * \ln^2(\frac{c_{ij}}{\gamma})} \quad (1)$$

Generalised costs (c_{ij}) are specified as the travel time plus costs. Travel time includes possible waiting or transfer time. Costs are only included for public transport. Car and bike are considered free of charge in this model. The following parameters are used in the model: car: α=0.35, β=0.30, γ=5.00; bike: α=1.40, β=0.40, γ=2.00; public transport: α=0.25, β=1.50, γ=15.00. The deterrence functions for computing mode choices in the Delft traffic model using the previous parameters are visualised in Figure 5.2.

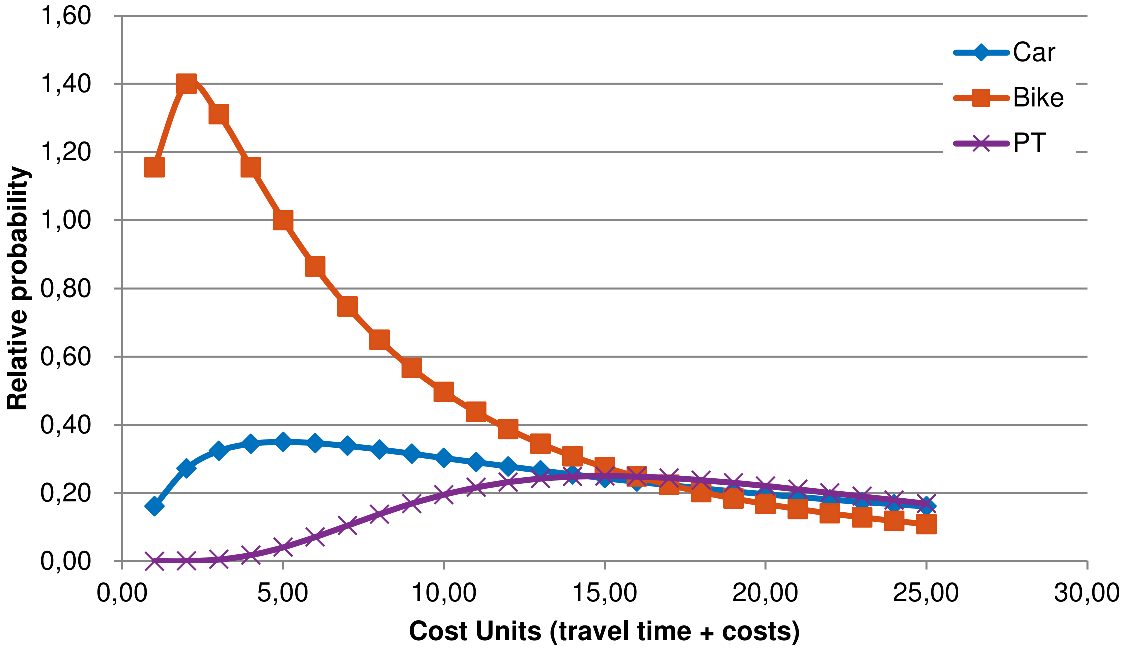


Figure 5.2 Deterrence functions for computing mode choices in the Delft traffic model.

This leads to a modal split of 70% car trips, 22% bike trips and 7% public transport trips during the morning peak period, as computed by the OmniTRANS model and presented deterrence function. If we only look into internal traffic (traffic between zones 9-25, i.e. not leaving the city), the modal split is 48% car, 47% bike and 4% public transport.

After mode and destination choice, traffic is assigned to the network using a static traffic assignment, establishing a deterministic user equilibrium using 20 iterations. Cycle lanes and public transport lines are assumed to have unlimited capacities. The results of the traffic assignment are shown in Figure 5.3 (car), Figure 5.4 (bike) and Figure 5.5 (public transport). Several crowded parts can be identified. Some key figures of the final assignment are shown in Table 5.1. The travel time delay only has been computed for cars, since cycle lanes and public transport are assumed to have unlimited capacity and no delays (given the frequency of lines).

Table 5.1. Key performance indicators of the Delft traffic model during the morning peak

	Car	**Bike**	**Public transport**
Number of trips	46976	14836	4894
Kms driven	715730 km	46097 km	22038 km
Total travel time [hours]	18764 h	3692 h	651 h
Total delay	4392 h	-	-

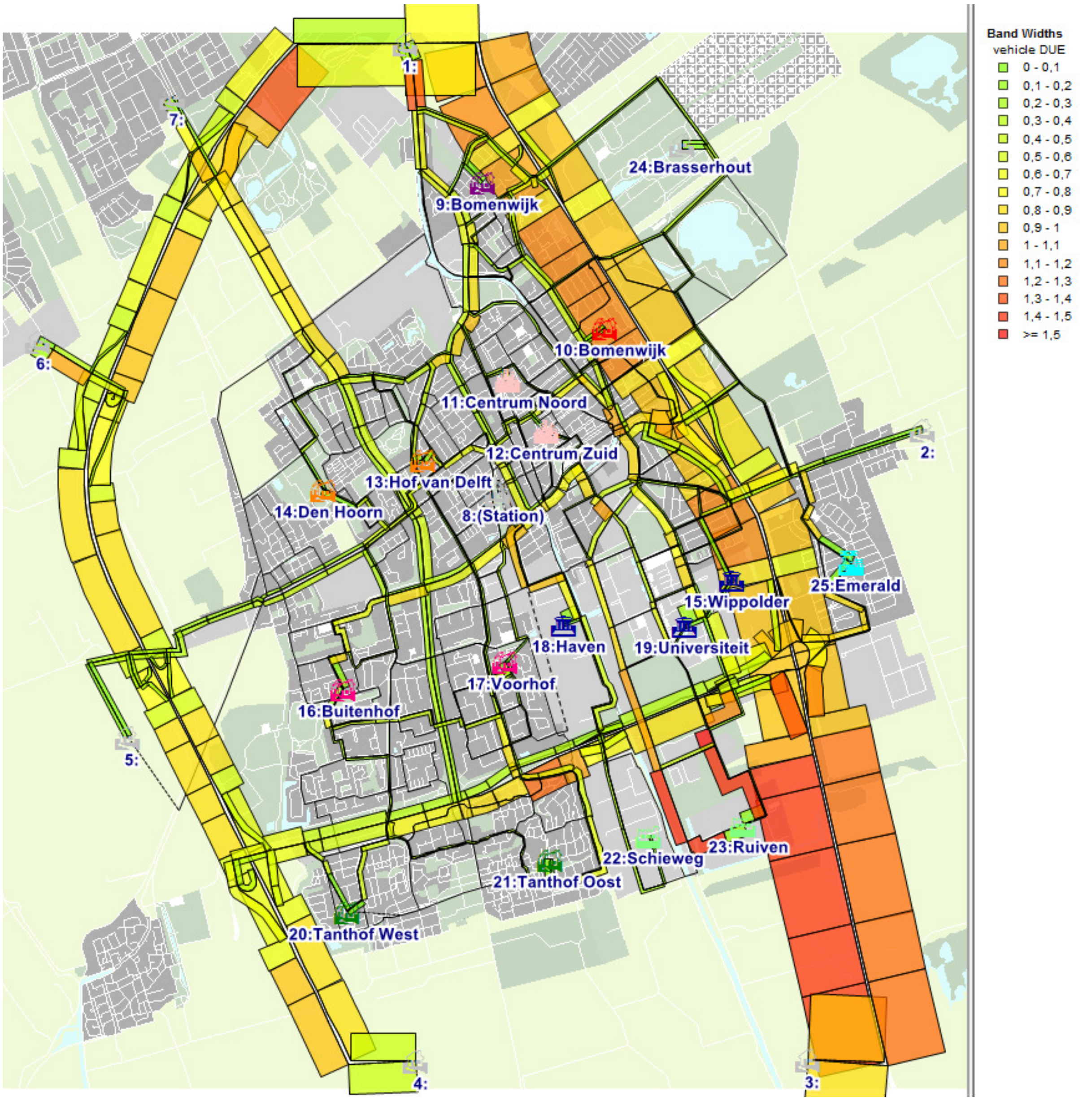


Figure 5.3 Car traffic assignment.

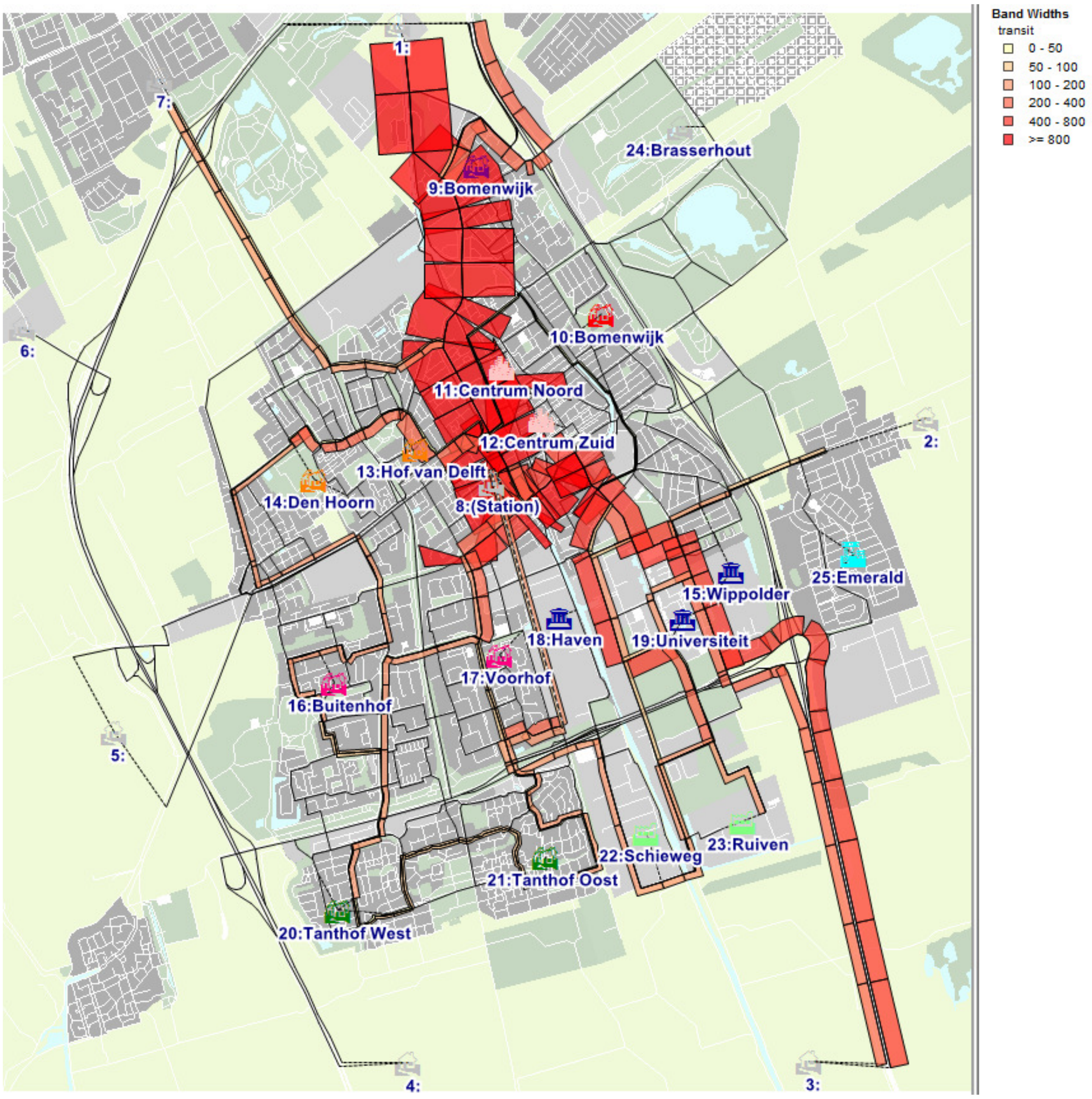


Figure 5.4 Public transport traffic assignment.

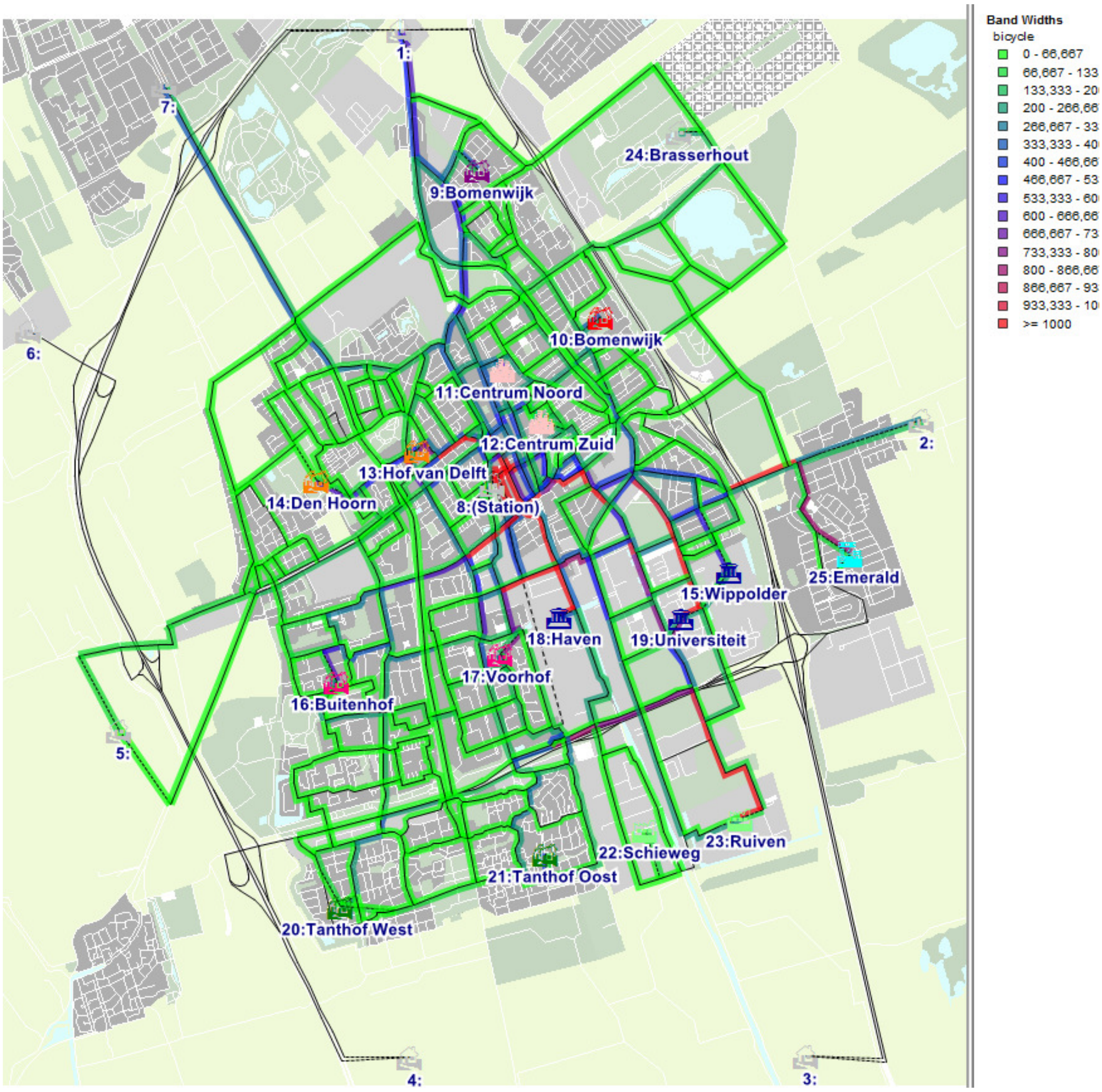


Figure 5.5 Bicycle traffic assignment.

5.2.2 Simulation set-up

We simulate robotaxis by adding them as a new mode to the OmniTRANS Delft traffic model. We assume that no additional trips take place due to the introduction of robotaxis: they only replace trips being driven by existing modes. Therefore, we do not rerun the trip generation module.

As stated before, we assume the robotaxis to be private taxis, i.e. no sharing of rides. The pick-up and drop-off points are the exact origins and destinations of passengers – no additional walking time is required. We assume that a robotaxi drives on the normal roads, following same speed limits and travel time functions as private cars. However, a robotaxi is not identical to a private car. Differences can be found in four aspects: waiting time, price, probability for mode choice, and empty taxi trips. Each of these aspects is explained in the following subsections.

Waiting time

The waiting time is defined as the time between ordering a robotaxi and the actual arrival time of the taxi. The waiting time highly depends on the amount of robotaxis available (supply) as well as the number of people requesting for a robotaxi (demand).

To estimate possible waiting times, we assume that there are enough robotaxis available in the city of Delft. We then only need to consider the travel time from their current location to the location of the passenger that wants to use the robotaxi. If we assume that all taxis are waiting together near the central station in the centre of Delft, the maximum travel time to all other zones in Delft is 10 minutes. If taxis are more spread throughout the city, the travel time may of course decrease. We will therefore model waiting times varying between 2 minutes and 10 minutes (with steps of 2 minutes, i.e. 2, 4, 6, 8 and 10 minutes).

Waiting times are modelled by considering additional travel times to the connectors for robotaxi traffic only. Connectors connect the centroids of the zones to the network, representing average travel times within the zone, shown in Figure 5.6. Adding an additional travel time as waiting time to this link means that the total trip travel time will become higher.

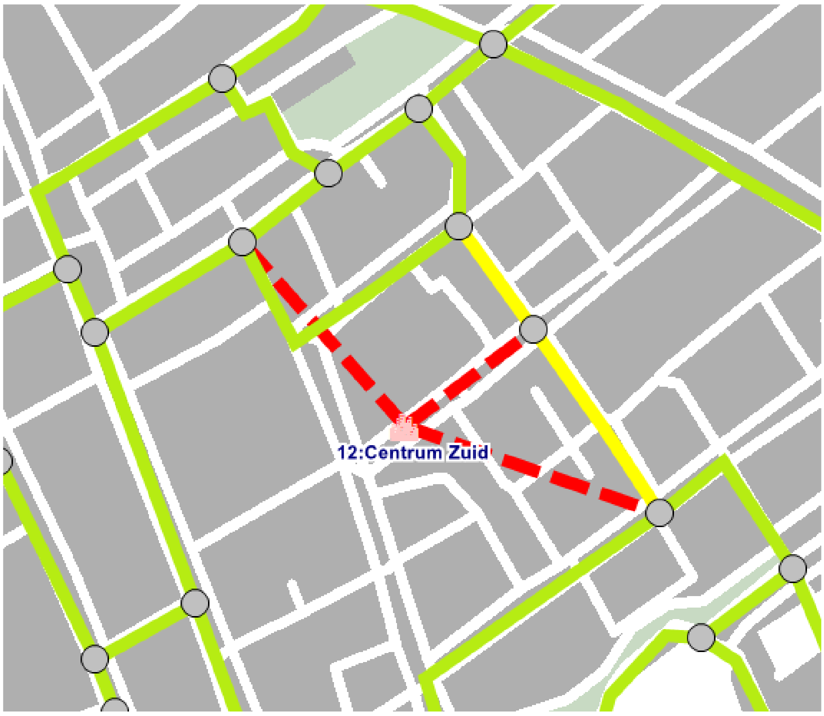


Figure 5.6 Connectors (red dashed) connecting a zone centre ("12: Centrum Zuid") to the network.

Price

The price is modelled as a price per km for taxi trips. We do not assume any fixed or start-up cost. We assume prices between €0.10 and €0.60 per km.

Probability for choosing for a robotaxi instead of another mode

Mode choices are determined in the traffic model using the deterrence function (see Figure 5.2 and Equation (1)). We do not have any studies available for estimating the deterrence function values for robotaxis in Delft. The best knowledge we have are the (calibrated) deterrence functions in the current model.

We therefore assume that robotaxis are being judged by people as a replacement for private cars, or as a replacement for public transport. We then use the parameters for both car and public transport mode to simulate robotaxis (i.e., two different sets of simulations). These values are given in Table 5.2.

Using the same parameters does not lead to a 50% probability of choosing for both car and robotaxi (or public transport and robotaxi). There is only a 50% probability if the generalised costs for both modes between two destinations are equal. This will often not be the case due to additional costs and different travel times (additional waiting time and of course completely different in case of public transport).

Besides these values, we also simulate varying values for α, β and γ to test the sensitivity to changes in parameters.

Table 5.2. Values for deterrence functions mode choice

	Car	Bike	Public transport	Robotaxi "car"	Robotaxi "PT"
α	0.35	1.40	0.25	0.35	0.25
β	0.30	0.40	1.50	0.30	1.50
γ	5.00	2.00	15.00	5.00	15.00

Empty taxi trips

Empty taxi trips are trips where taxis are relocated to another place, such that the amount of taxis in each zone stays equal. We assume a perfect situation where all one-way trips can be combined if possible. This means that if there are 5 trips going from A to B in the morning peak, and 8 trips going from B to A, only 3 empty trips are required (i.e., from A to B), as can be seen in the example OD-matrix in Table 5.3. Empty taxi trips of course do not encounter waiting time.

Table 5.3. Example robotaxi OD-matrix (a) with accompanying empty taxi trip matrix (b)

a)	A	B	C
A	0	5	6
B	8	0	4
C	2	4	0

b)	A	B	C
A	0	3	0
B	0	0	0
C	4	0	0

5.2.3 Results

We added robotaxis as a new mode to our OmniTRANS Delft model as described in the previous section. Next, we simulated the robotaxis by rerunning the modal split and assignment functionalities. We used two sets of deterrence function parameters ("car-like" and "public transport"-like), varying waiting times (2,4,6,8 and 10 minutes) and varying prices per km (€0.10, €0.20, €0.30, €0.40, €0.50 and €0.60) to check the resulting modal split. In the remainder of the analysis, we only looked into the two minimum and maximum scenarios, that is, 2 minutes waiting time with a price per km of €0.10; and 10 minutes waiting time with a price per km of €0.60.

Additionally, we performed a sensitivity analysis to check the effect of choosing parameters for mode choice (the deterrence function).

Share of cars, robotaxis, public transport and bikes

We first simulated the robotaxis as having the same mode choice parameters as cars. The resulting modal split is shown in Figure 5.7. Please note that these modal splits do not include any empty trips. The "no taxi" base scenario is added for comparison. It can be seen that public transport keeps an equal share for each of the simulations: 7% of trips. Transport by bikes decreases a bit from 22% (no robotaxis) to 20% (with robotaxis). The main influence of robotaxis can be found in the decrease of car usage. With shorter waiting times, more people switch to robotaxis. Also cheaper prices result in a higher share of robotaxi usage. This leads to a share between 32% (waiting time 2 minutes, €0.10 per km) and 15% (waiting time of 10 minutes, €0.60 per km).

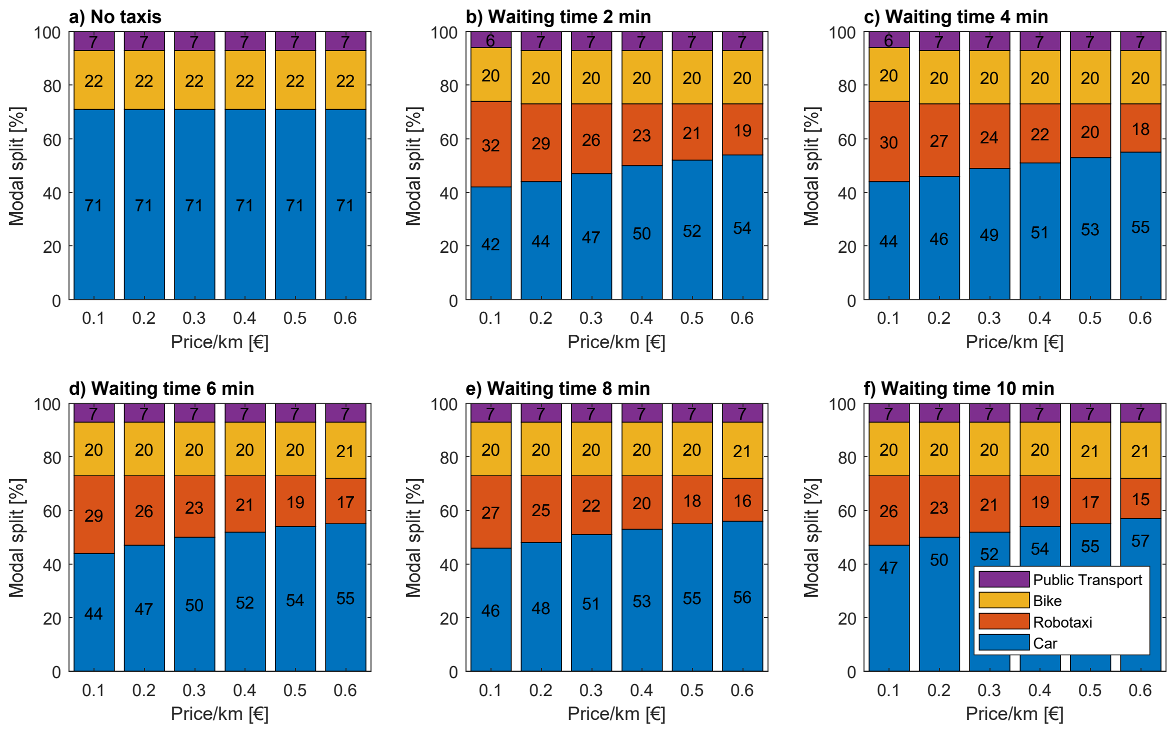


Figure 5.7 Same parameters for robotaxi and car, only varying price/km and waiting time.

Equal patterns in modal split can be found when using the „public transport parameters“ for robotaxis: public transport usage stays equal, bike decreases slightly (see Figure 5.8). Again, please note that numbers do not include any empty trips. Both shorter waiting times and cheaper prices result in a higher share of robotaxis, ranging between 31% (waiting time 2 minutes, €0.10 per km) and 10% (waiting time of 10 minutes, €0.60 per km). In general, results between the two sets of parameters (car and public transport) do not differ much: waiting time and price per km has larger effects on the total share of robotaxis during the morning peak in the city of Delft.

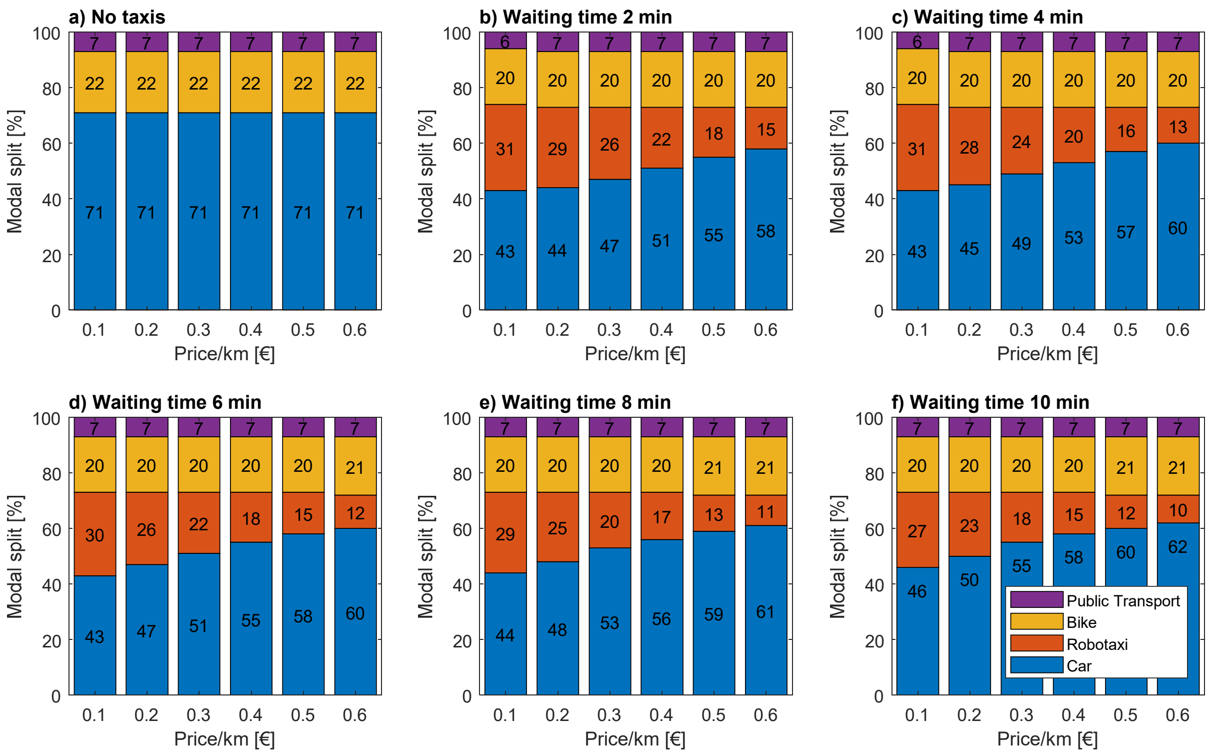


Figure 5.8 Same parameters for robotaxi and public transport, only varying price/km and waiting time

In the remainder of this section we will only present the results of the minimum and maximum scenarios, i.e. 2 minutes waiting time + €0.10 per km and 10 minutes waiting time + €0.60 per km, combined with the two sets of parameters (car and PT). In this way, it becomes clear what the range of possible outcomes will be.

Total trips

The total amount of trips is one of the KPIs described in Chapter 2. However, we do not assume any additional trips due to the introduction of robotaxis. The future is too uncertain to tell something concrete about induced demand. Therefore, the amount of total trips by passengers does not substantially vary between each of the simulations as can be seen in Table 5.4. However, there is a slight shift from bike and public transport to robotaxi usage, leading to an increase in total number of trips performed by all vehicles (private cars and robotaxis). Additionally, the relocation of empty robotaxis results in additional trips. About 26 to 29% of the taxi trips are without any passengers (assuming optimal scheduling). Of course, more empty trips occur as the robotaxi becomes a more favourable mode (i.e. in the 2 minutes / €0.10 scenarios).

Table 5.4. Number of trips for different robotaxi simulations

Number of trips	Car	Robo -taxi	Bike	Public transport	Total	Total vehicle	Empty robotaxis
No robotaxis	46976 (70%)	0 (0%)	14836 (22%)	4894 (7%)	**66706**	46976	0
Car-parameters waiting time 2 min, price/km €0.10	27968 (42%)	21407 (32%)	13026 (20%)	4305 (6%)	**66706**	55039	5664
PT-parameters waiting time 2 min, price/km €0.10	28404 (43%)	20736 (31%)	13254 (20%)	4311 (6%)	**66705**	54542	5402
Car-parameters waiting time 10 min, price/km €0.60	37964 (57%)	10312 (15%)	13805 (21%)	4624 (7%)	**66705**	51061	2785
PT-parameters waiting time 10 min, price/km €0.60	41596 (62%)	6444 (10%)	13932 (21%)	4735 (7%)	**66707**	49950	1910

Vehicle km

The resulting vehicle-kms (i.e. the sum of kms driven by all vehicles) are shown in Figure 5.9. It can be seen that the introduction of robotaxis lead to an increase in vehicle-kms, even at the minimum scenarios (i.e. waiting time of 10 minutes). This is mainly caused by the empty robotaxis being relocated. The total distances travelled by robotaxis and cars do not differ much. This is expected, as not many people switch from bike or public transport to robotaxi and both private cars and robotaxis drive the same routes with same speeds.

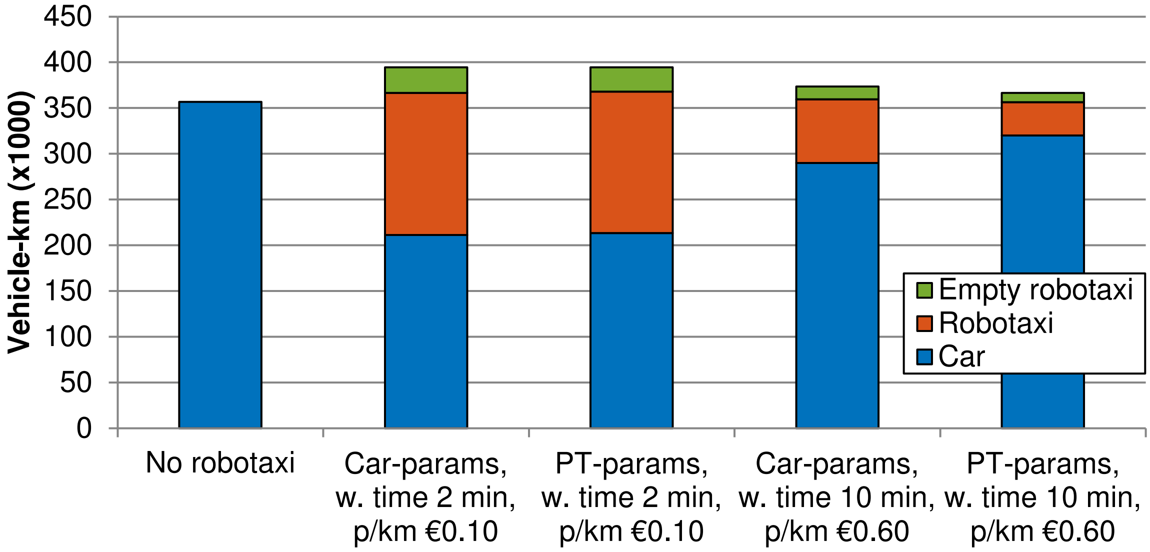


Figure 5.9 Vehicle-kms for different robotaxi simulations.

The vehicle-kms per mode and the number of trips can be combined to compute average trip lengths. These are visualised in Figure 5.10. It can be seen that robotaxis are mainly used for shorter distance trips, whereas the average trip length of car trips increases as the share of robotaxis increases. This can be explained by the costs of robotaxis per km: being charged for every driven km might get more expensive than for example using public transport.

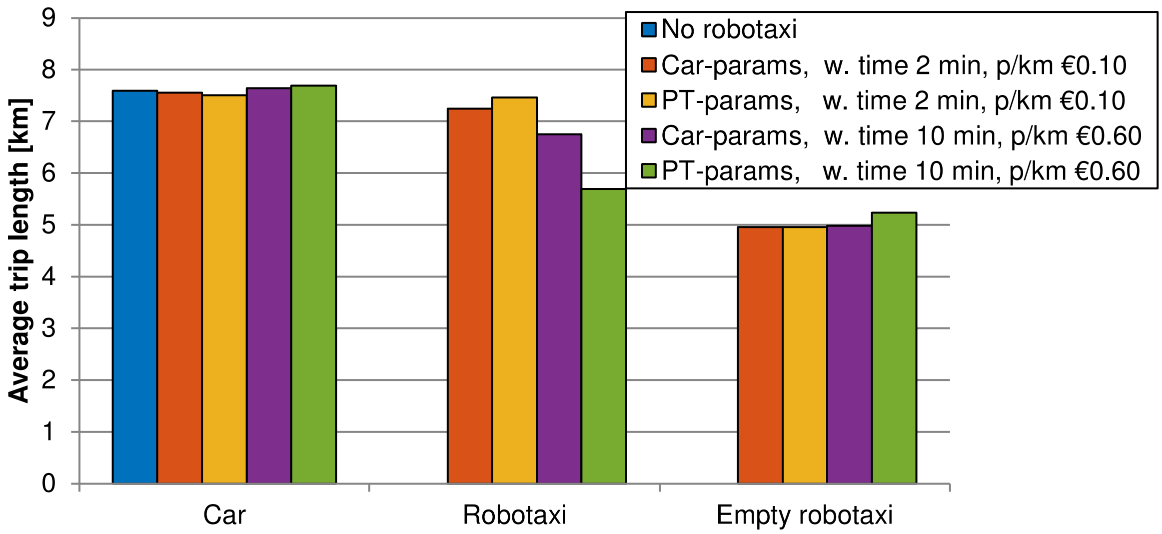


Figure 5.10 Average trip lengths for different robotaxi simulations

Travel time delay

The total travel time (i.e. the sum of travel time of all people/vehicles in the network) for each of the scenarios is shown in Figure 5.11. It can be seen that the total travel time increases for each of the scenarios.

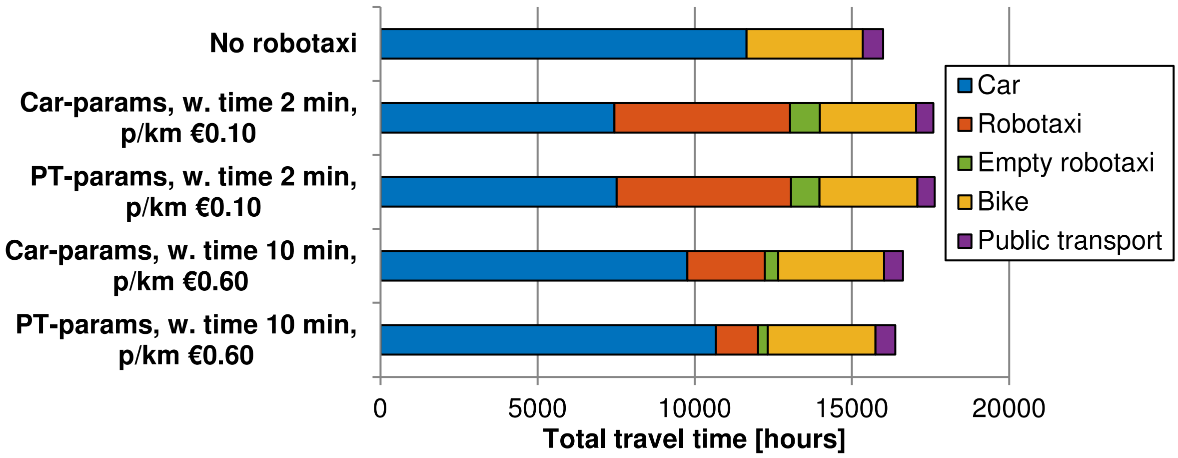


Figure 5.11 Total travel time for different robotaxi simulations

Accordingly, the delays also increase as can be seen in *Figure 5.12*. The delays are computed by subtracting the actual travel times experienced in the model by the free flow travel times (i.e. the travel times experienced when there is no one else on the road). Since the model assumes that cycle lanes and public transport have unlimited capacity, delays can only be computed for car modes (private cars, robotaxis and empty robotaxis).

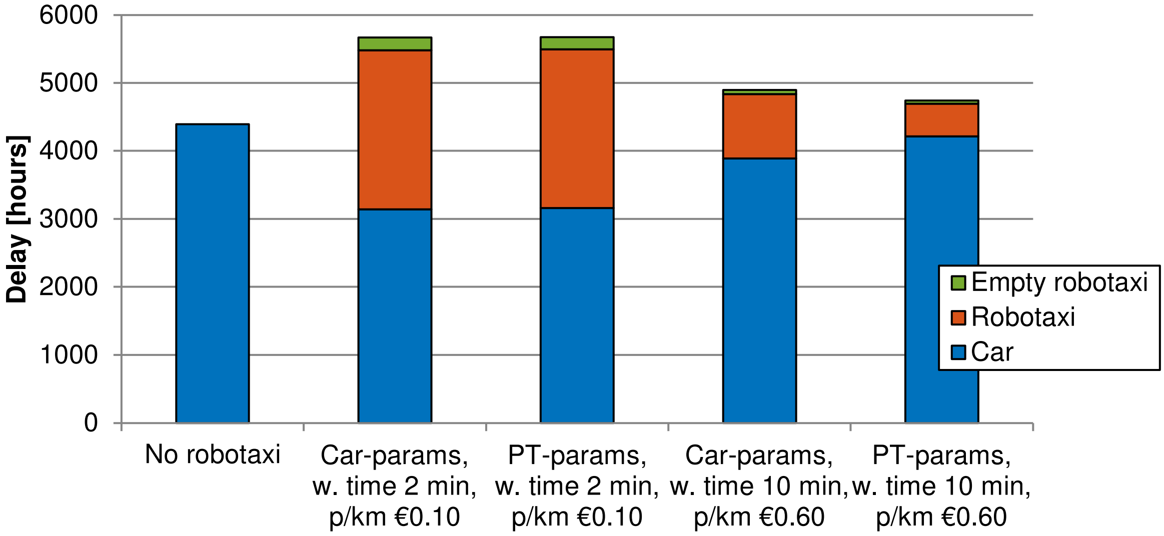


Figure 5.12 Travel time delay for different robotaxi simulations

It is interesting to see that the delays increase quite a lot due to the introduction of robotaxis. This is again mainly influenced by the amount of additional empty taxi trips. As a test, we performed another set of simulations where we did not assume any relocation of robotaxis. The results showed that with robotaxis in use, up to 12% of the delays encountered by all vehicles in the road network are caused by empty taxi trips, as can be seen in Table 5.5.

Table 5.5. Travel time delays, comparing with and without addition of empty taxi trips to the model

Travel time delay	Without empty trips	With empty trips	Difference
No robotaxis	4392 hours	4392 hours	0%
Car-params, w. time 2 min, p/km €0.10	5041 hours	5667 hours	12.4%
PT-params, w. time 2 min, p/km €0.10	5088 hours	5671 hours	11.5%
Car-params, w. time 10 min, p/km €0.60	4638 hours	4898 hours	5.6%
PT-params, w. time 10 min, p/km €0.60	4505 hours	4742 hours	5.2%

Sensitivity analysis

Until now we have looked at the effects of varying waiting times and prices per km, assuming that the parameters, α, β, and γ of the deterrence function for cars or public transport. To check the sensitivity of these selected values of the parameters, we varied them.

In Figure 5.13 the modal splits are shown with α values varying between 0.20 and 0.40. Figure 5.14 shows varying β values (between -0.5 and -0.2) and Figure 5.15 shows the result of varying γ values (between 2 and 7). It can be seen that in most cases the share of bike transport and public transport stays equal. Variances can only be found in the share between robotaxis and cars. In our previous analysis, we looked at robotaxi shares between 32% and 10% (i.e. our maximum and minimum scenarios). Nearly all observations lay between those numbers, with only a few results being higher (i.e. 35% robotaxi share).

We thereby assume that our minimum and maximum values as analysed in the previous sections provide a valid overview of possibilities after introducing robotaxis in the city of Delft.

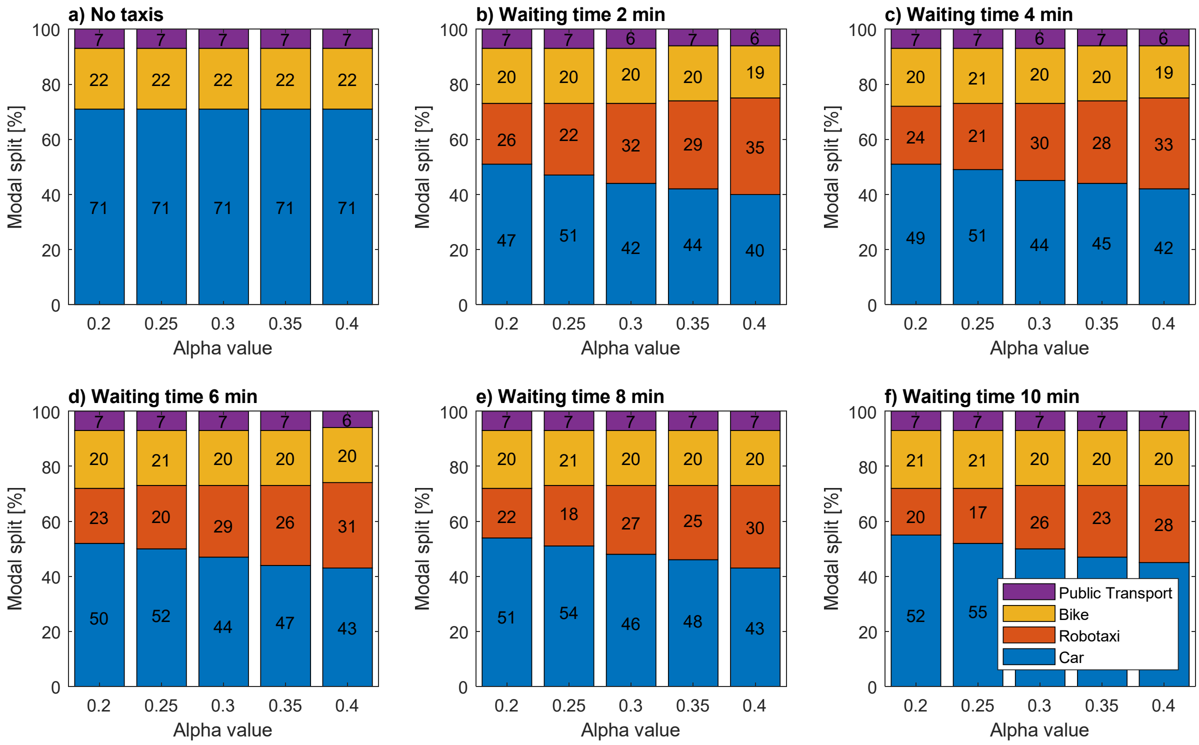


Figure 5.13 Varying alpha values, with beta=-0.3, gamma=5, price/km = 0.10

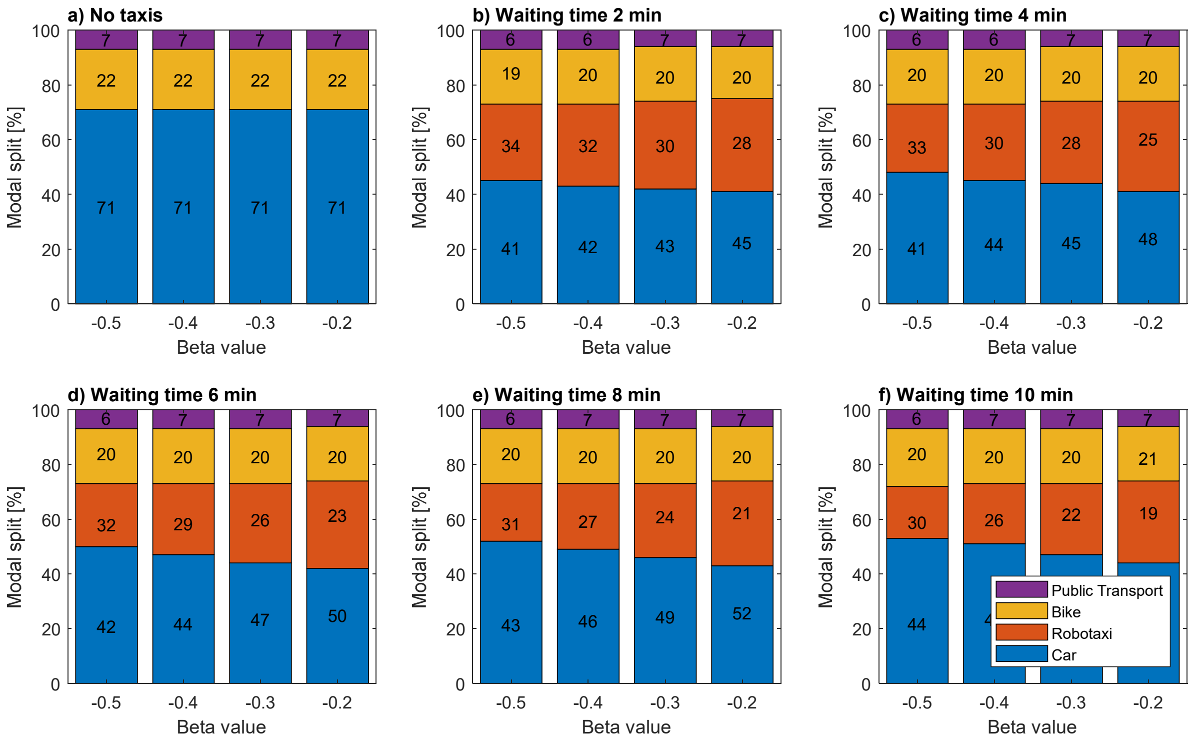


Figure 5.14 Varying beta values, with alpha=0.35, gamma=5 and price/km=0.10

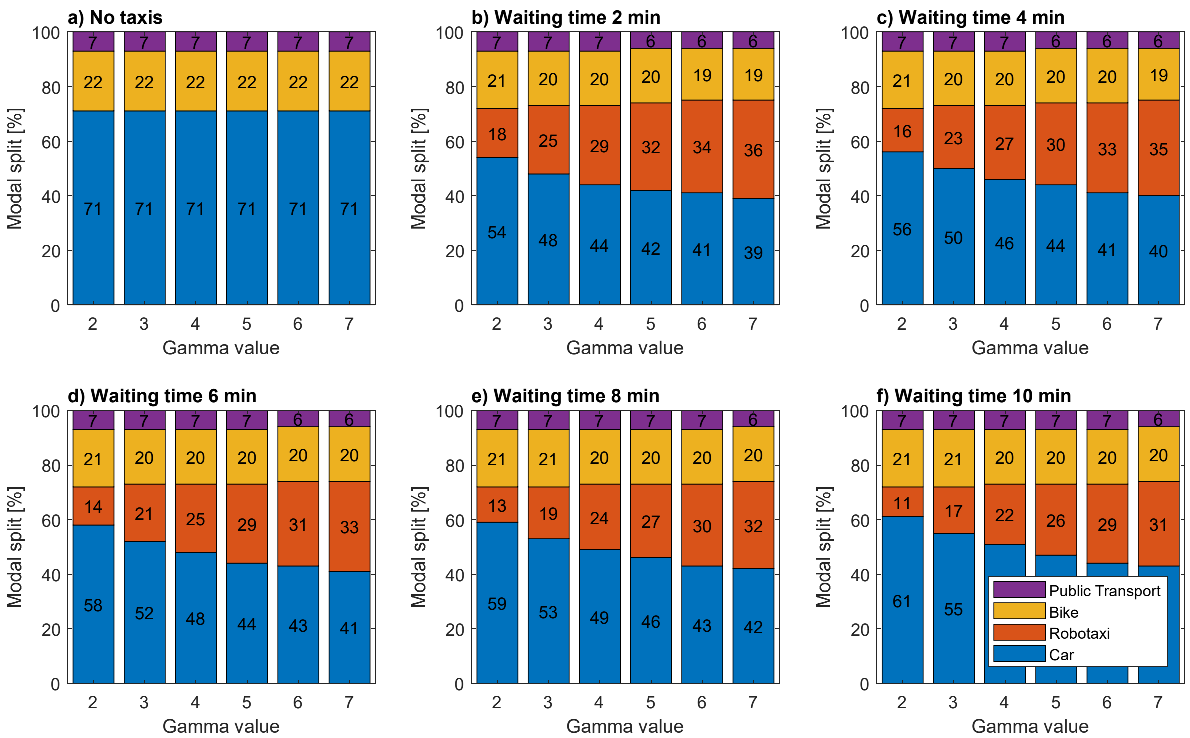


Figure 5.15 Varying gamma values, with alpha=-0.30 and price/km = 0.10

5.2.4 Discussion

The results of the macro simulation with robotaxis in the city of Delft showed a shift from car usage toward robotaxis. Public transport and bicycle usage were not influenced a lot. It was shown that mainly the addition of empty taxi trips (caused by relocation of taxis) resulted in additional vehicle-kms driven as well as additional delays experienced by all users in the network.

As a basic traffic model we used the Delft city within the OmniTRANS software. Although it has external centroids representing trips leaving or entering Delft, it does not precisely model intercity trips. However, it is expected that robotaxis will be used on the motorways (if allowed), for example for commuter traffic or (one-way) traffic to the airport. A larger network would be required to assess the impact of these kinds of trips. However, it might be necessary to adjust prices for longer trips, as the empty-trip kms might increase a lot with longer trips.

In our model we assumed that the taxi price was only influenced by the kilometres driven (i.e. a price per km). However, current taxi services in the Netherlands also charge a fixed start-up price. The addition of these costs might lead to a decrease of robotaxi share. However, it is possible to model start-up costs indirectly by adjusting the waiting time. For example, if we assume a Value of Travel Time of €10 per hour, and a start-up cost of €1, this corresponds to an "additional waiting time" of 6 minutes. If the actual waiting time is normally 4 minutes, one can look at the 10 minute results to include a start-up cost of €1.

We modelled the empty taxi trips in a basic manner, balancing trips along the modelled period. However, this might be too optimistic (less vehicles available leads to more driving around empty), or too pessimistic (not necessary to move because in the next time period people need to move the other way around). Scheduling empty trips may be performed in a smart way using trip scheduling and planning software. For example, robotaxis may form chains of trips, picking up passengers near their current location instead of immediately travelling back to their origin. However, relocation of taxis will still be required. In our study it has been shown that empty taxi trips result in additional vehicle-kms and additional delays. The aspect of taxi relocation should therefore not be neglected when introducing robotaxis in a city.

A study in the Boston area performed a similar study analysing the impact of introducing mobility-on-demand (such as robotaxis) (World Economic Forum, 2018). They assume that distances travelled in the Boston area increase by 16%, which is more than our model predicts. On the other hand, they conclude that the average travel time will decrease with 4% in an AV-scenario, while our model predicts an increase in travel time, mainly caused by relocating of taxis (empty trips). This is most likely caused by the nature of the city. Delft is more crowded than the Boston area, but also much smaller. Cycling is a frequently used mode, and some parts of the city are not very well accessible in other ways than cycling or walking. Other than that, it might be caused by the addition of other mobility-on-demand services besides robotaxis in the Boston model, such as shared modes of transport. Sharing modes of transport might result in less vehicles on the road and thereby a decrease in encountered delays. It is advisable to also incorporate other (new) mobility-on-demand services and their interaction between them.

Additionally, the Boston study looked into a longer time period than just the morning peak period as we did for the Delft case study. This might influence the results on delays: we only expect an increase in congestion during the morning and evening peak, not during the relatively silent periods during the rest of the day.

5.3 Impacts on driver behaviour, traffic flow and safety

The impacts on driver behaviour, traffic flow and safety of robotaxis have already been partly discussed in the simulations on the highway autopilot (Section 3.3). However, robotaxis are not only driving on motorways, but mostly on urban roads. Not much is known on the driving behaviour of automated vehicles in urban situations. This highly depends on the design and implementation of the robotaxis. On the other hand, the main concern of the CEDR and NRAs are motorways. It would be not very relevant for them to precisely research driving behaviours in urban situations. Therefore, we are not analysing the driver behaviour and impacts on traffic flow and safety of robotaxis in urban areas, as agreed upon during the CEDR Mini-workshop for WP3 in Tallinn, 7th of March 2019.

5.4 Conclusion

In this chapter we investigated the impacts of commercial driverless vehicles (robotaxis) using macro simulations in OmniTRANS to assess the mobility and travel behaviour impacts in the city of Delft.

The simulation results show that the introduction of robotaxis hardly results in any changes in public transport and bicycle usage. Only private car trips are being replaced by robotaxi trips. Because robotaxis need to be relocated after they perform a trip (the so-called empty taxi trips), this results in additional kilometres driven and thereby also additional delays. These delays are also experienced by people not using the robotaxi service.

We only tested one city and one new mode. It might be valuable to look into other cities as well, for example in cities where public transport is of more importance for the average modal split. In these cities, robotaxis might be more beneficial. Additionally, shared trips might result in a decrease of delays as was shown in the Boston case study (World Economic Forum, 2018).

We did not analyse the impact of robotaxis on motorways, but we expect that NRAs can be confronted with the same direction of outcomes: increase in vehicle-kms and increase in delay, mainly caused by the addition of empty taxi trips.

6 Impacts on Driverless maintenance and road works vehicles (L4)

This chapter concerns simulations for the driverless maintenance and road works vehicles. Within the MANTRA project, two case studies were defined: the safety trailer and the winter maintenance truck. Both are discussed in the next sections, followed by the results on simulations assessing the impact on traffic flow. We mainly focus on the impact on traffic flow as experienced by other road users, not necessarily the road works themselves. According to discussions during the CEDR CAD WG in Tallinn (06./07.03.2019) we did not assess the impacts of maintenance vehicles on mobility and travel behaviour.

6.1 Driverless maintenance and road works vehicles (L4)

Two types of maintenance use cases were defined in MANTRA WP2 (Aigner et al., 2019): the safety trailer and the winter maintenance truck. Both use cases are expected to increase the safety of the road workers by automating the vehicle.

6.1.1 Safety trailer

A safety trailer is defined as a protective vehicle that is used to protect temporary or slow-moving mobile road works as well as clearing works after accidents from moving traffic. The crew of the protective vehicle which safeguards such works against moving traffic bears an increased accident risk.

The operation of a driverless (connected) automated protective vehicle which follows the actual maintenance vehicle, will reduce this risk. This sub-use case implies a structured operational environment and the number of situations which have to be perceived and considered for driving decisions are limited.

6.1.2 Winter maintenance truck

In countries with snowy/icy winters, the operational works around winter maintenance belong to most crucial task when it comes to providing safe roads. During the winter months, road operators in such countries require a high number of vehicles and drivers on stand-by, ready to start work 24/7. Winter maintenance works on highways are generally divided into preventive salting works performed at speeds of up to 60 km/h independent of snowfall and snow ploughing works performed at speeds of up to 45 km/h during and after snowfall.

Preventive winter maintenance is not much different from snow ploughing works besides the slightly different operational speeds. However, for obvious reasons snow ploughing works cause a lot more challenges for an automated or even driverless vehicle as road markings are not visible and vehicle sensors are easily covered and malfunctioning. In terms of complexity, this is a very advanced sub-use case.

6.2 Impacts on mobility, travel behaviour and energy

The impact on mobility and travel behaviour due to driverless maintenance has not been researched during the MANTRA project. Whether (automated) vehicles will choose different routes due to maintenance vehicles probably depends on the predictability and precise communication of the location of maintenance vehicles, as well as whether this information is provided to all road users or only to automated vehicles. This effect will both be visible and equal for non-automated and automated maintenance vehicles, and is therefore not interesting to simulate, as agreed upon during the CEDR Mini-workshop for WP3 in Tallinn, 7th of March 2019.

It should be noted that the introduction of fully automated maintenance (i.e. no need for road workers) might result in a shift toward only performing maintenance projects at night, which of course has a positive effect on the impact on mobility due to maintenance. However, during the MANTRA project we assume that road workers will not be (fully) replaced by robots yet, and therefore we do not consider this aspect to be relevant for the MANTRA project.

6.3 Impacts on driver behaviour, traffic flow and safety

The safety trailer and winter maintenance truck will mainly increase the safety of the road workers who will be protected or replaced by the automated maintenance vehicles. In general, it is expected that a conventional maintenance vehicle and an automated maintenance vehicle have identical operating speeds and vehicle lengths as the currently used maintenance vehicles. The impact on traffic flows of conventional vehicles is therefore expected to be low.

However, we do expect that the automated maintenance vehicles can communicate their presence to automated vehicles, such that these automated vehicles can anticipate their driving behaviour accordingly. For example, AVs can switch lanes at an early stage, making sure that the traffic flow runs smoothly.

In this section we simulated a stretch of a motorway with a safety trailer or winter maintenance truck, with increasing penetration rates of automated vehicles (compared to conventional vehicles). The results show the expected impact of communicating maintenance vehicles to AVs on traffic flow efficiency.

6.3.1 Simulating a safety trailer

According to MANTRA D2.1 (Aigner et al., 2019) and a discussion during the CEDR Workshop for WP3 in Vienna on 10th of September 2019, we agreed on the use of the following parameters for simulating the safety trailer and associated work zone:

- The total length of the work zone is 150m
- The safety trailer is the last vehicle within this work zone
- The operational speed of the complete work zone is 15 km/h
- The work zone is always on the right lane (given right-hand traffic)

Additionally, we assume that the other traffic has to adhere to a speed limit of 80km/h. The length of the reduced speed area is dependent on the amount of gantries and the distance between them. For now, we assume that there are no gantries present and the reduced speed limit is active during the complete simulation time.

6.3.2 Simulating a winter maintenance truck

According to in MANTRA D2.1 (Aigner et al., 2019) and a discussion during the CEDR Workshop for WP3 in Vienna on 10th of September 2019, we agreed on the following parameters for simulating the winter maintenance truck:

- The total length of a winter maintenance truck is 10m
- There are two types of winter maintenance trucks: a preventive salting vehicle and a snow ploughing vehicle
- The operational speed of the preventive salting vehicle is 60km/h
- The operational speed of the snow ploughing vehicle is 45 km/h

We assume that only one lane is blocked by the winter maintenance vehicle at the same time, that is, snow ploughing vehicles do not block the complete road as shown in Figure 6.1. In this situation, no overtaking is possible and there is no need for communicating anything to AVs:

all vehicles will be “stuck” behind the winter maintenance trucks regardless of their abilities to switch to adjacent lanes at an early stage. Therefore, it is not an interesting use case to simulate.

Figure 6.1 Snow ploughing vehicles blocking the complete road (no overtaking possible).

6.3.3 Simulating maintenance vehicles communicating with AVs

We assume that maintenance vehicles can communicate their position to automated vehicles, that is, a Vehicle-to-Vehicle type of communication. The message with their position is broadcasted every second. AVs within 500m distance have a certain probability of actually receiving the message, where the probability increases as the distance to the maintenance vehicle decreases. The distance of 500m was discussed during the Workshop for WP3 in Vienna on 10th of September 2019 and selected according to the usual distances between gantries showing messages for conventional vehicles (CVs), as well as the minimum time required to switch to different lanes. It was suggested that AVs should not have distinct advantages over CVs due to the additional communication. Additionally, it was set that all AVs have received the position of the maintenance vehicle at 10m distance.

In our simulations we first applied a relatively simple strategy for AVs once they received the message: they directly have a desire to move to the lane where the maintenance vehicle does not drive. Once they passed the maintenance vehicle, the message is removed and the vehicle moves back to its original desired lane.

Early tests show that this might lead to CVs getting stuck behind a slow moving maintenance truck: they simply cannot move to the correct (left) lane anymore due to high speed differences on the left and right lane and relatively small gaps (see Figure 6.2).

Figure 6.2 AVs (red colour) and CVs (black colour) manoeuvring around a winter maintenance truck (green colour). While the AVs already move early to the left lane, the CVs tend to get stuck behind the maintenance vehicle due to high speed differences between the left and right lanes. Screenshot of VISSIM during a 0.85 f/c ratio scenario.

Therefore, it was decided during the CEDR Workshop for WP3 in Vienna on 10th of September 2019 that another lane switching strategy needs to be added. This policy does not only entail an advice for moving early to another lane, but also to keep a larger (gap) distance between AVs. The time headway of AVs that received the maintenance truck message was set to 5 seconds, giving CVs the possibility to merge in and switch to the correct lane.

For comparison, we have also implemented a scenario where communication between maintenance vehicles and AVs is disabled, i.e. a ”no communication“ scenario. AVs will move to the other lane, but only after they have noticed themselves that the speed on the lane where the maintenance vehicle is driving is low (as they would do with any slow driving vehicle on the motorway).

6.3.4 Simulation set-up

Traffic simulations were performed using microsimulation software VISSIM 11. We simulate a 6km motorway road stretch, having a speed limit of 120 km/h. The motorway has 2 lanes on each carriageway. There are no entry ramps, exit ramps or weaving sections present on this artificially created road.

For every scenario, we simulate AVs and CVs according to Section 3.2.1. This entails simulating AVs according to the “All-knowing” driving logic (CoEXist, 2018) and CVs according to the default and calibrated (van Beinum et al., 2018) parameter sets. Every scenario is simulated for increasing penetration rates ranging from 0% to 100% with steps of 10%. Again, every simulation is run 11 times with different random seeds. The randomness is reflected in the precise amount and timing of vehicles, as well as their desired speed during the simulation run.

As explained in Section 6.3.3 we adopt two strategies of AV behaviour after they have received a message from a maintenance vehicle: a basic lane switch and a lane switch combined with a larger time headway of 5 seconds. Additionally, we also model a “no communication” scenario.

Safety trailer

For the safety trailer use case, we reduce the speed limit to 80 km/h to overcome very large speed differences between the working zone (moving at 15 km/h) and the normal vehicles. The work zone is always on the right lane. The safety trailer use case will only be relevant during low traffic flows, i.e. off-peak hours. To check the impact of larger traffic flows, we simulate two different scenarios: one having a flow/capacity ratio of 0.38 (720 vehicles/hour), one having a slightly higher flow/capacity ratio of 0.55 (1080 vehicles/hour). Both correspond to otherwise free flow situations. The simulation time for each of the scenarios is 30 minutes, of which the work zone is present for 24 minutes (starting at t=0).

Winter maintenance

The winter maintenance use case is simulated for both driving on the right lane and the left lane. That is, vehicles should overtake the maintenance vehicle on the left lane (as normal) or via the right lane. Since speed differences between both maintenance vehicles are not too large (i.e. 45 km/h and 60km/h), especially compared to the safety trailer scenario (15 km/h), we only simulate one flow/capacity ratio of 0.76. This is a usually a free flow traffic scenario. The simulation time for each of the scenarios (preventive salting & snow ploughing) is 10 minutes, of which the maintenance vehicle is driving around 6 or 8 minutes (starting at t=0).

Driven speeds

It should be noted that the speed limit is not just the speed that all vehicles drive. As in normal traffic, there are different driving styles adopting lower or higher speeds than officially allowed. These speed distributions are taken from the default VISSIM driving behaviour parameters and the CoEXist project. For a speed limit of 120 km/h, the speed distributions are shown in Figure 6.3. Whereas AVs have a uniformly distributed speed between 118 and 122 km/h, the speeds for CVs differ between 85 and even 155 km/h. Around 65% of the CVs adhere to the speed limit.

The speed distributions for 80 km/h are shown in Figure 6.4. It can be seen that AVs again have a variance of 2 km/h: between 78 and 82 km/h. CVs on the other hand have a much larger spread between 75 and 110 km/h. Only 10% of the CVs actually follow the speed limit strictly.

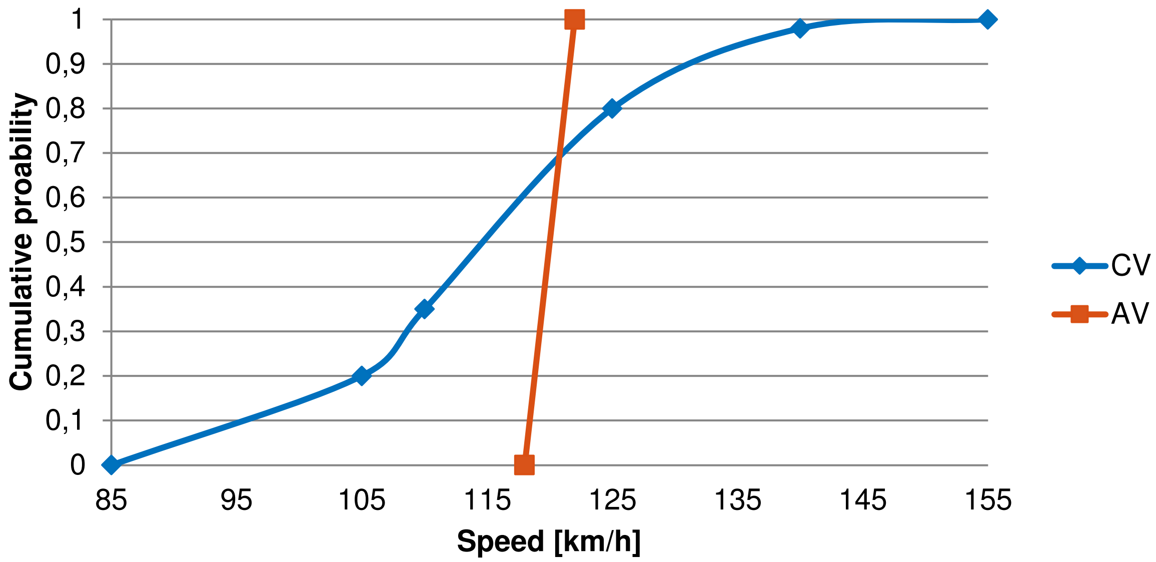


Figure 6.3 Speed distribution 120 km/h speed limit.

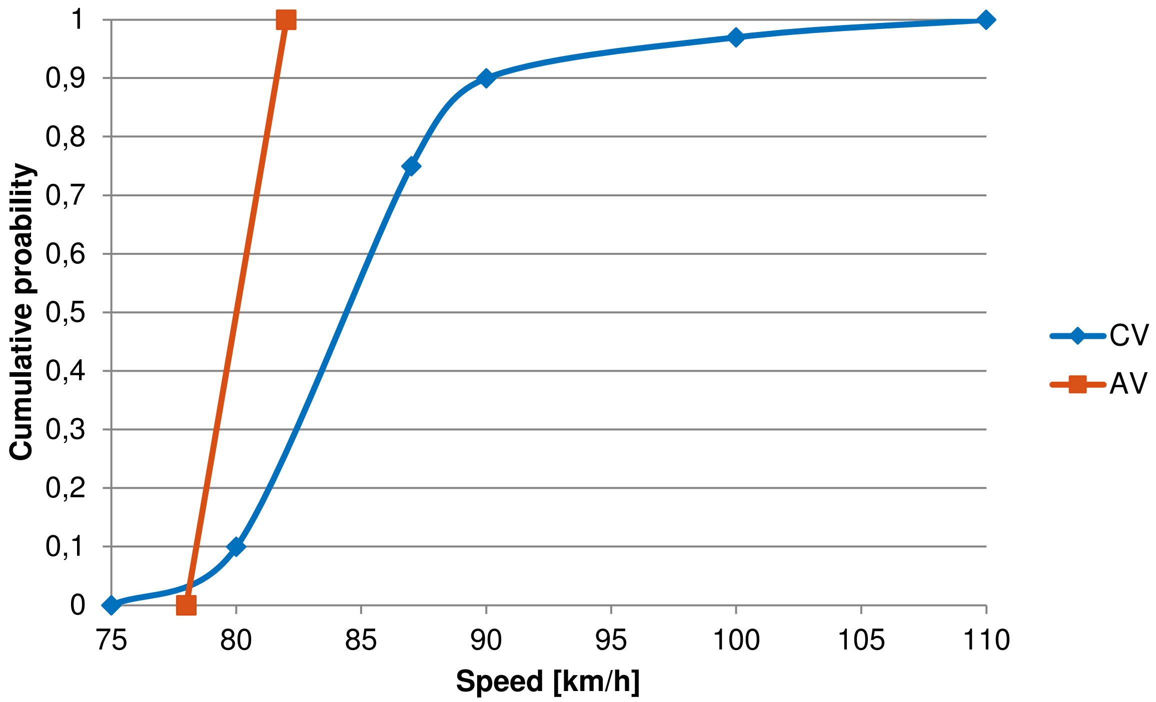


Figure 6.4 Speed distribution 80 km/h speed limit.

6.3.5 Results - safety trailer

The main simulation results of the safety trailer use case are shown in Figure 6.5. It shows the travel time for each of the different CV parameter sets (default and calibrated) and the different strategies (communication enabled and keeping a larger headway). Please notice that if no communication is enabled, headways are not changed. Therefore, the “purple” and “red” coloured lines do not differ in sub-figures a, b and c, d.

It can be seen that the travel times of AVs are usually higher than these of CVs. This is mainly due to the adherence to the speed limits. AVs are modelled in such a way that they always stick to the prescribed 80km/h, whereas CVs usually drive much faster (bandwidth between 75 and 110 km/h, see Figure 6.4).

In general it can be concluded that there is not much of a difference in travel times between the AVs having received a message ("AVs with communication") and scenarios where AVs did not receive a message ("no communication"). This probably can be explained by the low flow/capacity ratios. There are not much vehicles driving on the road and plenty of space to move to the left lane at any time and avoiding to brake for the safety trailer.

It can be seen that the difference between the default (a,b) and calibrated (c,d) parameters for CVs is limited or absent. This again can be explained by the low amount of vehicles on the road: a smaller gap acceptance ("calibrated CV") doesn't make a difference if there are no small gaps to be used.

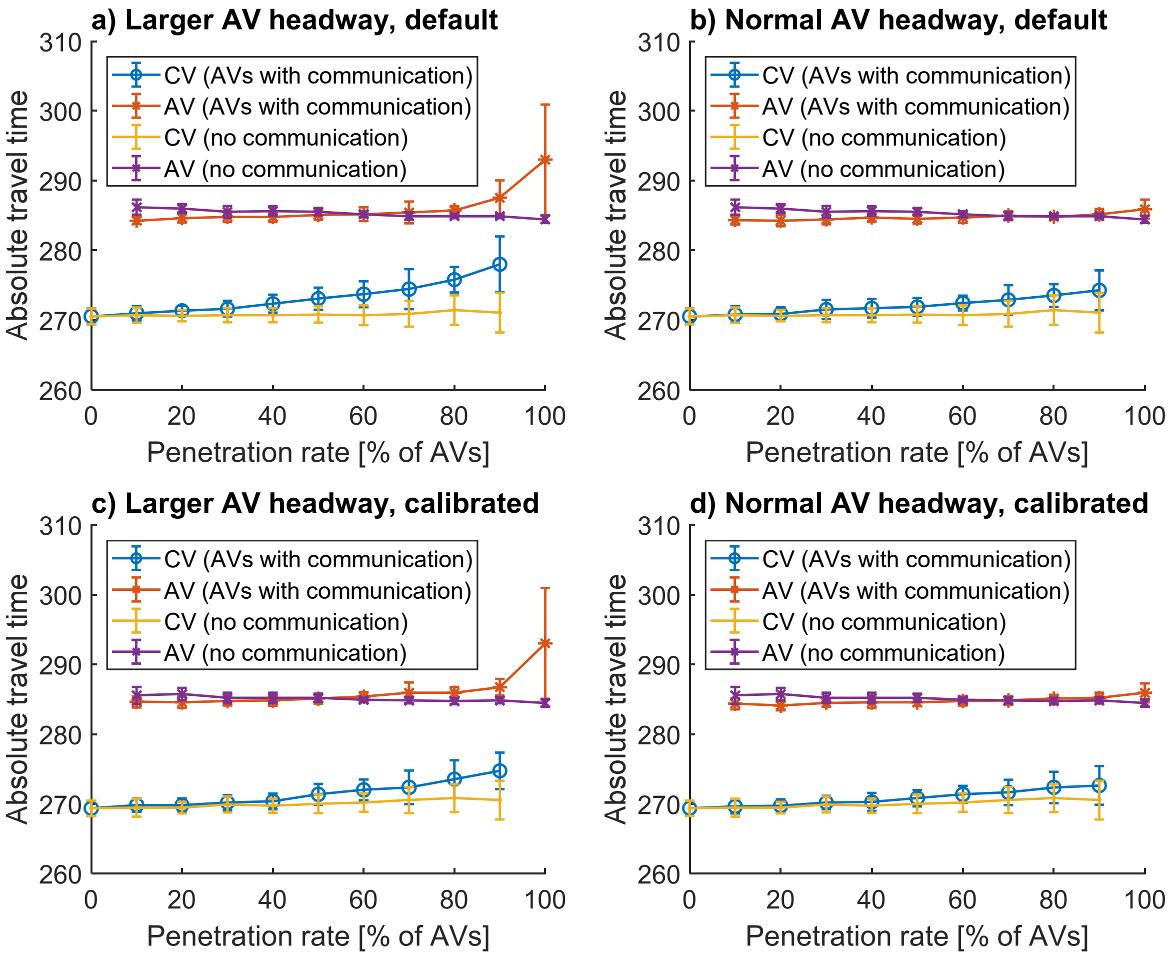


Figure 6.5 Absolute travel times for the Safety trailer use case with a 0.37 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance work zone

Results for the 0.56 flow/capacity ratio scenario are shown in Figure 6.6. Besides observations already visible in the 0.37 F/C-scenario, the most remarkable observation is the rapid growth of travel times with larger penetration rates (i.e. more than 50% AVs). The communication of the maintenance vehicle's position to AVs leads to fast changing of lanes, leaving the capacity of the right lane mostly unused long before the work zone comes insight (500m).

Contrary of what was thought as a good measure (letting AVs have larger headways), the simulation results show that keeping larger headways definitely does not help to smoothen the traffic flows in this specific scenario (sub-figures a,c). Having larger headways with a 0.56 F/C ratio leads to a decrease in capacity and thereby longer travel times.

Interesting to see is that without communication (yellow and purple graph lines), travel times tend to stay constant. It seems that the chosen AV policies do not improve the traffic flows in these scenarios due to unexpected results by not using the capacity of the road optimally.

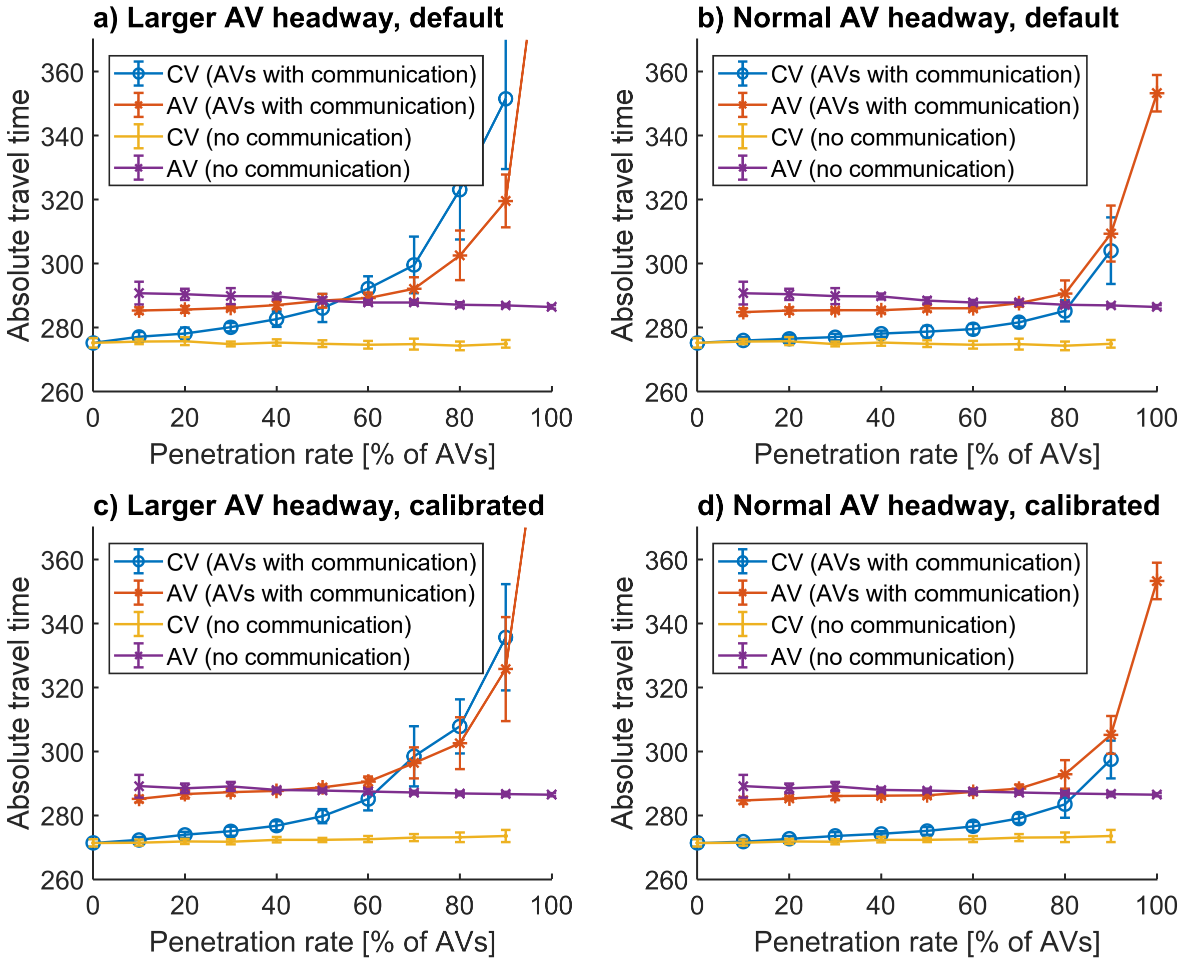


Figure 6.6 Absolute travel times for the Safety trailer use case with a 0.56 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance work zone

Some screenshots of the VISSIM simulations are shown in Figure 6.7. Sub-figure 'a' shows a typical situation during the 0.37 f/c ratio scenario, where AVs adopt a larger headway once they received the message. Although some CVs (coloured black) are waiting behind the work zone (coloured green), there is not much of a problem: there is plenty of space left to change to the left lane after waiting for a few vehicles. Notice that right after the work zone AVs adopt their normal behaviour, shown by the red coloured AV (instead of orange). Sub-figure 'b' shows the same situation, but with a larger f/c ratio of 0.56. It can be seen that the increase in the amount of vehicles leads to traffic jams and slowly driving traffic. Although speeds are not shown in this screenshot, it is clear that the distances between vehicles are much larger than the distances between AVs before the work zone. Since all AVs (orange colour) adopt a 5 second time headway, this indicates that the speeds decrease a lot before the work zone, resulting in a severe decrease in capacity (which can also be seen in Figure 6.6.a and c).

The third screenshot (c) shows a situation during the 0.56 f/c scenario, where AVs keep their normal time headways while passing the work zone. In this situation, both AVs and CVs sometimes get stuck behind the work zone – but in this example this will rapidly be solved once the vehicles on the left lanes have passed by. The reduction in capacity of the road is not clearly visible. Screenshot d) shows a situation without any communication between the work zone (safety trailer) and AVs. Therefore, all AVs are coloured red, indicating that they did not receive a message. Both AVs and CVs are waiting for a gap, but this seems to be quite evenly spread (as in sub-figure c).

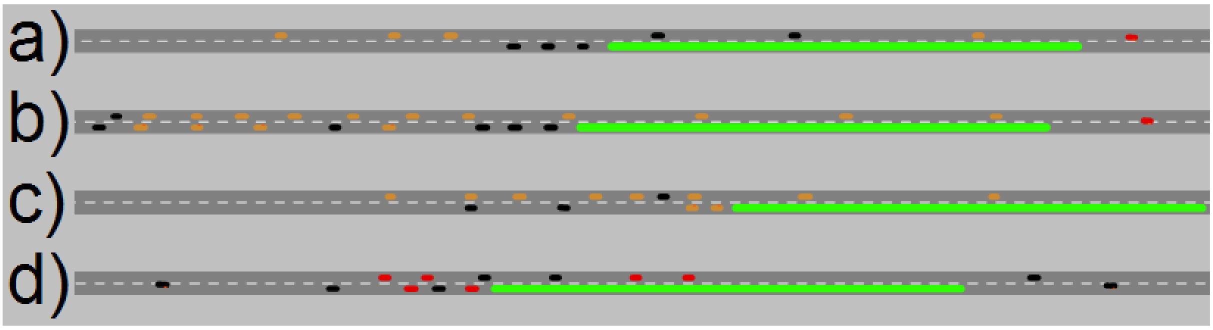


Figure 6.7 Screenshots of VISSIM, showing a situation with larger AV headways with a 0.37 f/c ratio (a), larger AV headways and a 0.56 f/c ratio (b), normal headways (c) and no communication (d). CVs are black, AVs red, AVs that received a message orange, and the work zone is coloured green.

6.3.6 Results - winter maintenance truck

The simulation results of the winter maintenance truck performing preventative salting maintenance at the right lane (60km/h) are shown in Figure 6.8. It can be seen that the travel times are in general quite stable: there is not much difference as the penetration rate increases. However, we do see that AVs have a clearly lower travel time than CVs, independent of communication. This is probably caused by AVs being able to switch to other lanes easily with smaller acceptable gaps. Additionally, AVs have more “interaction objects”, that is, they are aware of precise speeds and distances of up to 10 surrounding vehicles, which makes it easy to switch lanes if a slow driving or braking vehicle is ahead.

Besides the larger spread in travel times with increasing penetration rates (indicated by the error bars), there is no real difference observed between the default and calibrated CV parameters.

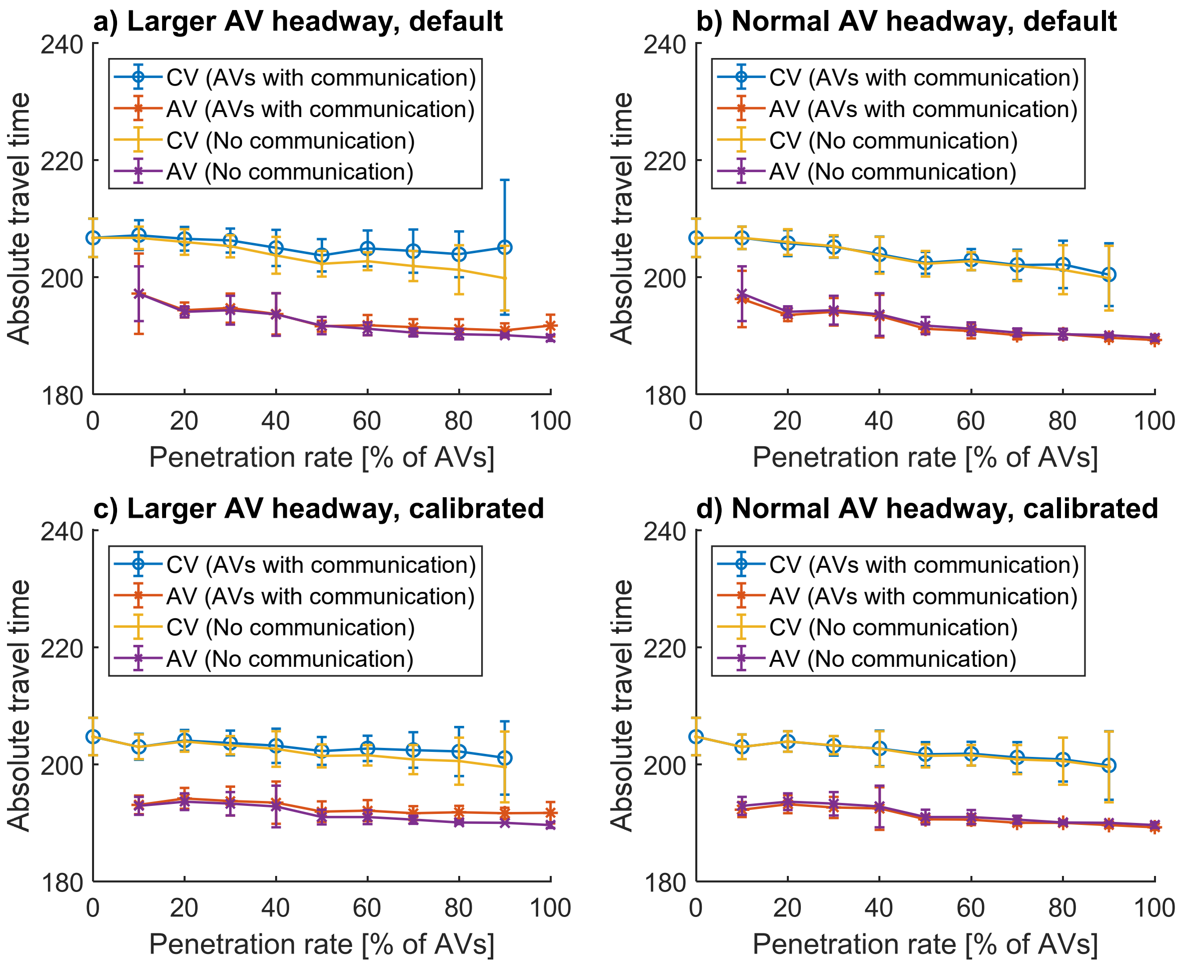


Figure 6.8 Absolute travel times for the Winter Maintenance vehicle driving 60km/h on the right lane, with a 0.76 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance vehicle

A few examples of driving behaviour shown during the simulation are shown in Figure 6.9. The first screenshot (a) shows a situation where AVs keep a larger headway once they receive the message from the maintenance vehicle. It can be seen that this sometimes leads to CVs (coloured black) sticking behind the winter maintenance vehicle. Especially with high penetration rates (e.g. 80-90%) and a default CV driving behaviour (i.e. large gaps necessary for merging), this leads to a high dispersion in results, which can also be seen by the large interval of error bars in Figure 6.8, graph a.

The second screenshot (b) shows the situation where AVs keep smaller distances. Although CVs are not able to merge into ”trains“ of AVs, the capacity does increase, creating more space for vehicles and less dispersion.

The third screenshot (c) shows the situation where no AV receives a message. Due to the high number of ”interaction objects“ this does not lead to any problems: AVs are able to switch to the other lanes in time once they observe the maintenance vehicle – just as CVs do.

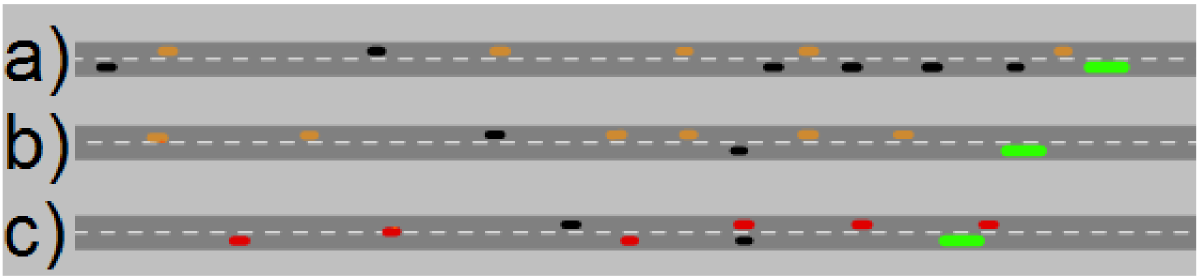


Figure 6.9 Screenshots of VISSIM, showing a situation with larger AV headways (a), normal AV headways (b) and no communication (c). CVs are black, AVs red, AVs that received a message orange, and the winter maintenance vehicle is coloured green.

Results for the snow ploughing winter maintenance vehicles (45 km/h) driving at the right lane is shown in Figure 6.10. It can be seen that the larger speed difference (45 vs 120 km/h and 60 vs 120 km/h) results in longer travel times with larger AV headways. On the other hand, no communication scenarios and normal AV headway scenarios still result in stable travel times as observed in the preventative salting use case.

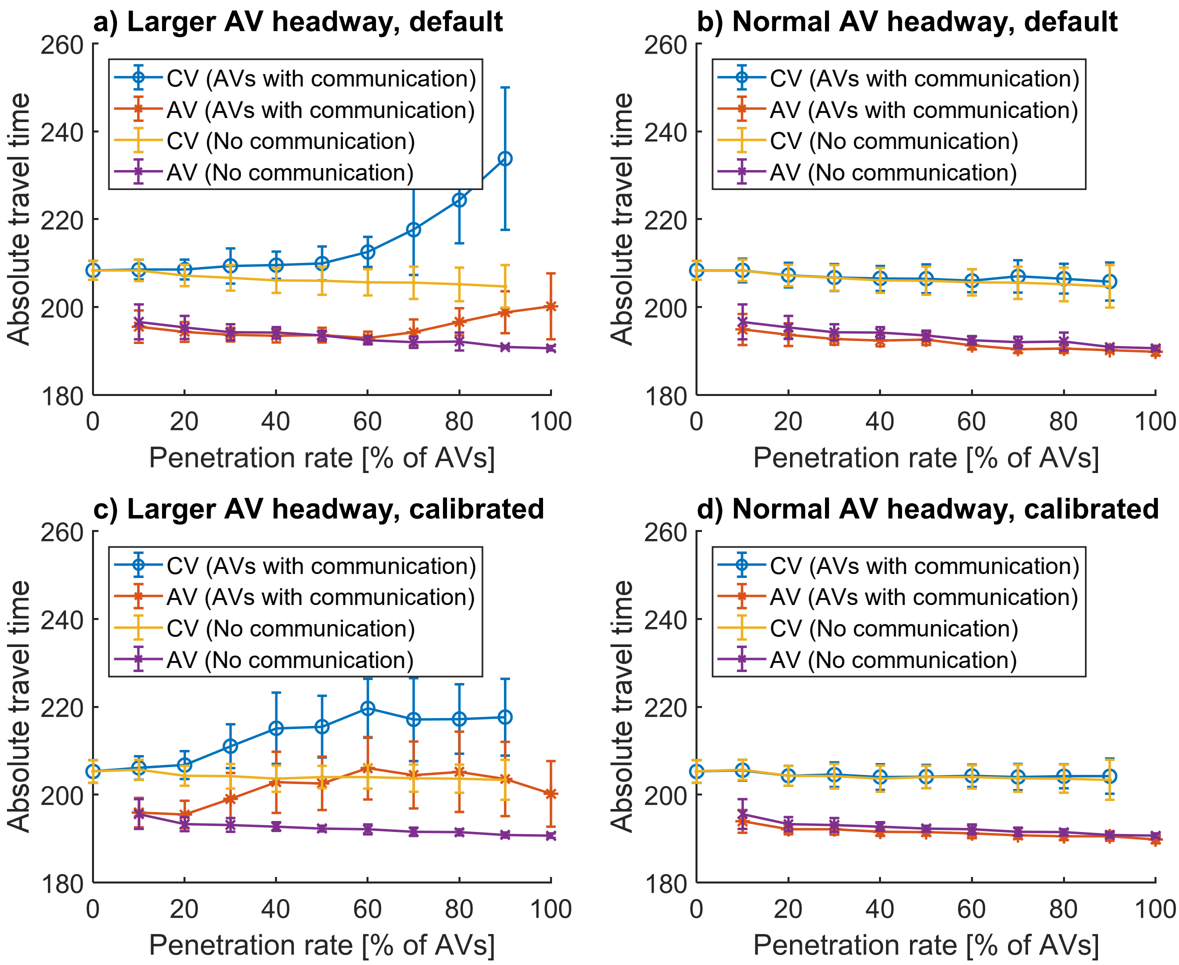


Figure 6.10 Absolute travel times for the Winter Maintenance vehicle driving 45km/h on the right lane, with a 0.76 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance vehicle

Results for driving a winter maintenance vehicle on the left lane are shown in Figure 6.11 (60 km/h) and Figure 6.12 (45 km/h), respectively. Large differences can be observed compared to the previous graphs where the winter maintenance truck was driving on the right lane.

In this left lane variant, one should overtake ”at the wrong side“ to avoid getting stuck behind the winter maintenance truck. Since this is unusual behaviour, one can spot clear advantages for AVs receiving the position of the maintenance truck. However, this communication and behaviour of AVs results in negative effects for CVs, who obviously need to wait longer before being able to merge into the right lane.

In the 45km/h scenario (Figure 6.12), CVs (blue line) are clearly obstructed by AVs if larger headways are incorporated (a,c). As was already noted before, the road capacity decreases a lot if AVs keep a 5 second time headway. Also AVs suffer from the larger headways, resulting in increasing travel times for AVs as the penetration rates increase.

Again, CVs have in general a lower average speed and thereby a higher average travel time than AVs, as was also observed in the previous graphs. Differences between default (a,b) and calibrated (c,d) CV parameter settings are limited.

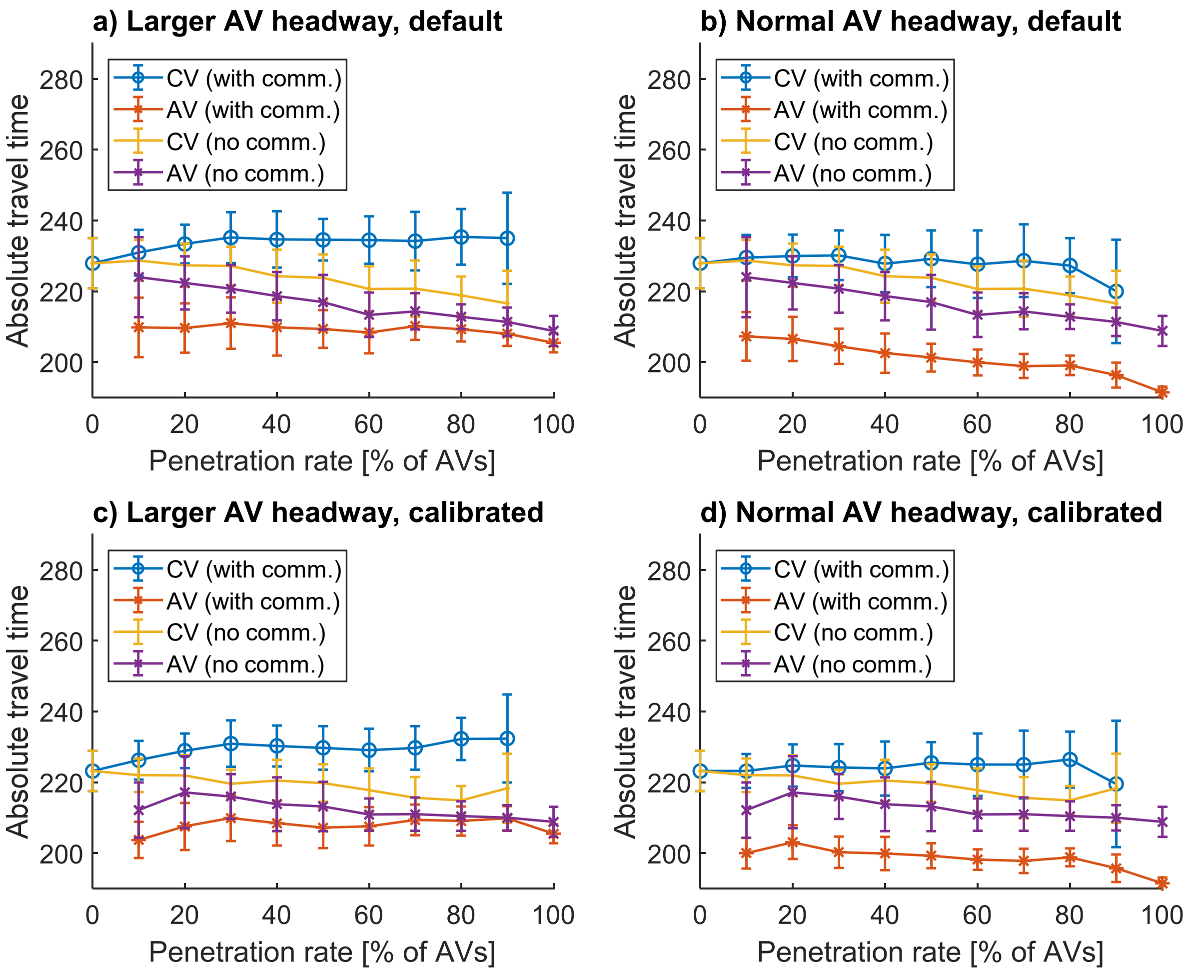


Figure 6.11 Absolute travel times for the Winter Maintenance vehicle driving 60km/h on the left lane, with a 0.76 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance vehicle

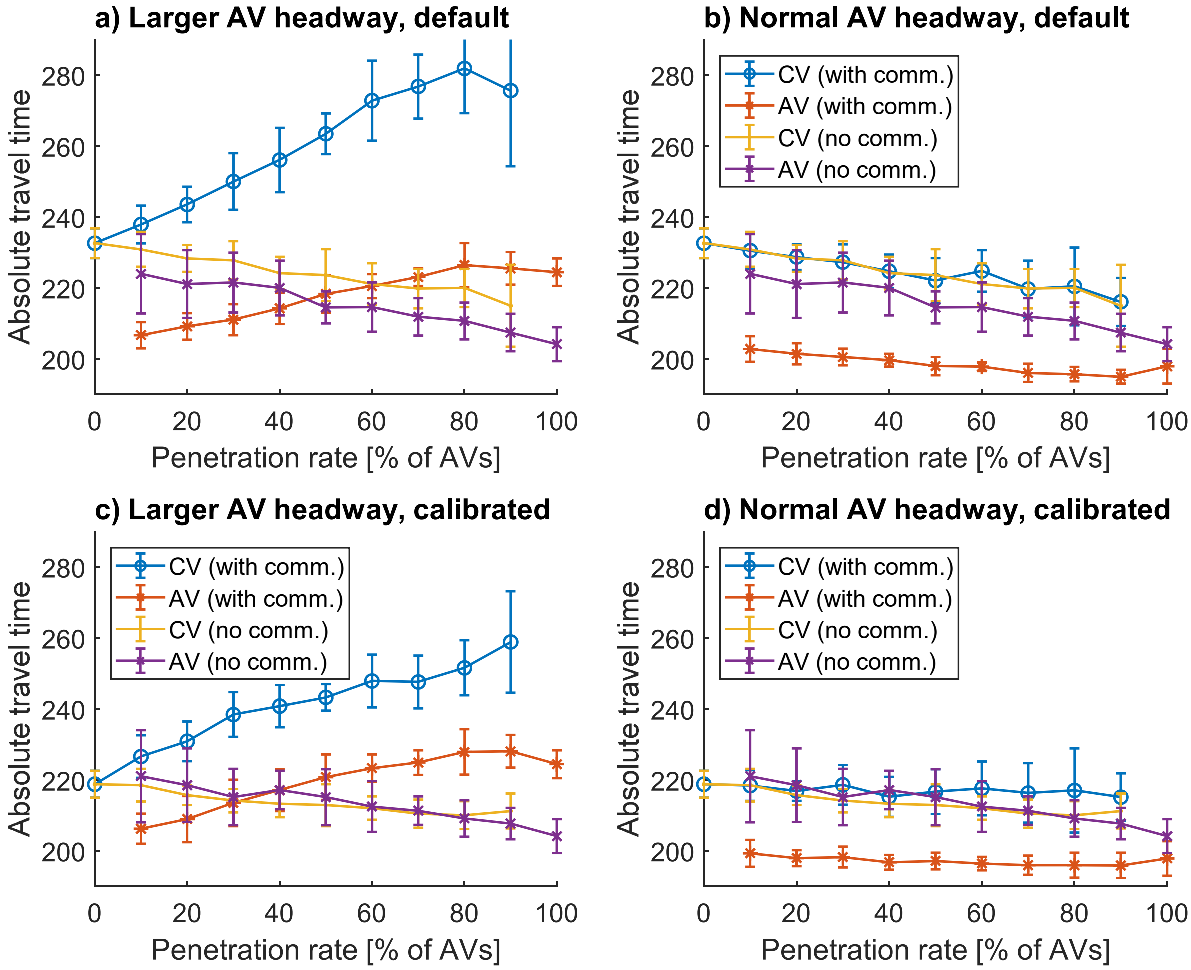


Figure 6.12 Absolute travel times for the Winter Maintenance vehicle driving 45km/h on the left lane, with a 0.76 f/c ratio, with CVs modelled using default (a,b) or calibrated (c,d) parameters and AVs adopting a larger headway (a,c) or normal headway strategy (b,d) while overtaking the maintenance vehicle

6.3.7 Results safety analysis

The safety benefits due to automated maintenance are obviously seen at the road workers themselves who do not get hit anymore by vehicles bumping into the maintenance vehicles at high speed due to not noticing the maintenance vehicles. The implications are discussed in MANTRA WP4 (Ulrich et al. 2020).

However, adding communication between AVs and maintenance vehicles might also add safety benefits to the vehicles themselves. Therefore, we performed a safety analysis for each of the simulated scenarios using the SSAM software (Surrogate Safety Assessment Model) developed by the Federal Highway Administration of the US Department of Transport (Gettman et al., 2008). Vehicle trajectories from VISSIM are extracted and possible conflicts are identified. Conflicts are identified by considering the maximum Post Encroachment Time (PET) value as 5 seconds and the Time To Collision (TTC) as 1.5 seconds, the default values used by the SSAM model.

Surprisingly, none of the scenarios resulted in any conflict – it was considered safe according to the SSAM software. In the safety trailer scenario, this might be due to low flow/capacity ratios of maximum 0.56, leaving always plenty of space to merge. However, we expect the main reason for not having any conflicts by the nature of the VISSIM simulation software: vehicles simply don't bump into each other during simulation, and as the maintenance vehicles are moving at constant speeds, no vehicle needs to deal with unexpected behaviour (i.e. unexpected braking). All vehicles are perfectly aware of the speed of the vehicle driving right in front of it, resulting in no safety conflicts.

6.3.8 Discussion

In this chapter we analysed several situations where a maintenance vehicle or work zone is interacting with AVs. Both smooth and severely hindered traffic flows were spotted. The main factor of influence seems to be the communication between the maintenance vehicle and the AVs.

Although previous test showed that CVs tend to get stuck behind a work zone if AVs already switch lanes early (see Figure 6.2), the proposed solution of adopting a larger headway of 5 seconds did not solve the problem. If we perform the calculations, this is not an unexpected conclusion. Imagine that a CV is driving behind a winter maintenance vehicle driving 45 km/h, and that it wants to merge into AVs driving on the left lane with 120 km/h. Given that the maximum acceleration of the vehicle (according to the settings in VISSIM) is 3.0 m/s^2, and the speed difference is 20.83 m/s (120-45km/h = 75km/h), this would require a time of 6.94 seconds (=20.83/3.0) to speed up. Even without considering the length of the vehicles or minimum spacing between the vehicles, this already leads to the conclusion that a gap of 5 seconds will definitely not be enough. Although CVs might not get stuck anymore if the gap headway time is increased to 10 seconds, this decreases the road capacity tremendously. It seems to be a better idea to not communicate anything to the AVs, and just let them find out themselves when to merge to another lane if they notice upcoming large speed differences between both lanes. The underlying problem is that CVs are not aware of the position of maintenance vehicles at an early stage. It might be the case that by 2040, also all CVs will get notified via V2V and V2I communication. This will resolve the problems of CVs getting stuck behind work zones, and in this way results for a 90-100% penetration rate might be representative for any 2040 case study. Additionally, no speed limits or traffic regulations were modelled. In cases where speed differences of 75 km/h occur, definitely traffic regulations will be applied to ensure safety.

However, not communicating the maintenance position might result in negative effects if the maintenance vehicle is driving on the left lane. Taking over on the right lane is a strange behaviour – even CVs will definitely struggle with that. AVs will only do so if they are told so using communication, or if the speed differences between left and right lane are very large. Possibly, this situation should be avoided or communicated to both AVs and CVs.

Additionally, communication and switching lanes of AVs nearly always seems to lead to increasing travel times as the penetration rates grow. Especially at high penetration rates (80-100%) the capacity decreases a lot if all AVs decide to switch lanes already 500m ahead of the maintenance vehicle. Possibly, the advices should be more diverse (i.e. proportions of traffic receiving different advices). One may also think of a decentralized system, where the AVs themselves decide upon what to do instead of the system.

Another remarkable simulation output are the differences in travel time for AVs and CVs during free flow situations. For example, the winter maintenance vehicle simulations (e.g. Figure 6.8) show that AVs are always faster than CVs, regardless of the communication policy used. On the other hand, in the safety trailer use case (e.g. Figure 6.5) the CVs are always faster than the AVs. This directly relates to the speed distributions used in VISSIM. According to the VISSIM default parameters, the 80km/h speed limit (adopted in the safety trailer use case) is very often exceeded by CVs (90% drives faster!). On the other hand, AVs strictly adhere to the speed limit of 80km/h. This results in higher travel times for AVs and lower travel times for CVs. At a 120 km/h speed limit (adopted in the winter maintenance use case), the speed limit is much better adhered to by CVs (only 35% drives faster), resulting in lower travel times for AVs. The speed distributions might widely vary throughout countries within Europe. It is therefore advised to not look into the absolute differences of AVs and CVs, but only to the relative differences within one vehicle type. You may also adjust the VISSIM desired speed distributions according to data obtained from real traffic situations in the country of interest.

6.4 Conclusion

In this part of the MANTRA simulation studies we looked at two use cases for automated maintenance: the safety trailer indicating a slow moving work zone (15 km/h), and a winter maintenance truck. We simulated different penetration rates (0-100%), different CV driving logics (default and a Dutch calibrated set of parameters), and different communication policies for AVs (adopt a larger headway around the maintenance work, keep the same headway, or not communicating anything). Additionally, we simulated different flow/capacity ratios and speeds driven by the winter maintenance trucks (45 km/h and 60 km/h).

Given these factors, it can be concluded that the communication policies have the largest effect on smooth traffic flows. Interestingly, a “no communication” scenario where AVs do not receive messages from the maintenance vehicles results on average in the smoothest traffic flows. Changing lanes directly after receiving the message of a work zone ahead results in decreases of capacity on a longer stretch of road, and thereby resulting in longer average travel times. Not only CVs were hindered, also AVs were not able to merge into the correct lane. It might be advised to communicate the same to AVs (e.g. broadcast messages) and CVs (e.g. signs along the road), and let them decide themselves what to do with it. A centralized approach where every AV receives the same advice (“move to the other lane”) doesn’t seem to be the best solution.

The differences between the CV driving logics (default and calibrated) were limited for each of the scenarios. The influence of the maintenance work itself seems to be much larger. This might change if you look at a motorway stretch that includes entry ramps, exit ramps or weaving sections, which was not included in the simulation conducted in this chapter.

Additionally, large differences can be spotted between the safety trailer and the winter maintenance simulations. This possibly mainly has to do with the speed of each of the work zones: 15km/h vs 45 km/h vs 60 km/h. If you get stuck behind a 15 km/h driving work zone, chances are that you have to wait for a long time before you are able to overtake. Of course, the business on the road (i.e. f/c ratios) have a high influence on this effect as well: if it gets more crowded, one might not be able to overtake (on time), and as a result it might take longer to find a gap.

7 Impact of automation on efficiency in operational processes and maintenance planning

7.1 Introduction

Highway operation and maintenance works traditionally face the challenge to be carried out right next to high-speed traffic and therefore poses enormous safety hazards for the workers. Driverless maintenance vehicles and automation of operation and maintenance processes have the potential to reduce this risk tremendously. Many tasks will always need to be done manually by experienced workers. However there are quite a few use cases where the driverless vehicles could already provide safety and efficiency benefits in the near future.

The potential use of additional available road condition data of the various assets (pavement skid resistance, rutting, tunnel wall reflectivity, etc.) combined with the potential to carry out selected operational tasks automated can provide increased efficiency also in the road operational processes and maintenance planning. The objective of this chapter is to assess the potential efficiency in operational processes and maintenance planning (task 4 of WP 3 in accordance with the project proposal). In addition these potential efficiencies are examined in terms of their impact on policy goals and potential solutions to major NRA challenges as identified by CEDR in the DoRN.

The core of this impact category forms the possibility to improve infrastructure related operations as a result of utilizing automated functions or new data provided by these functions. This involves for example improved maintenance and operation carried out by automated vehicles or new ways of data provision on assets' condition.

The impacts of automation on efficiency in operational processes and maintenance planning are based on a literature research and assessment of current challenges in operation and maintenance. These are then discussed and validated through expert interviews.
Figure 7.1 shows the overall approach and methodology to tackle this topic.

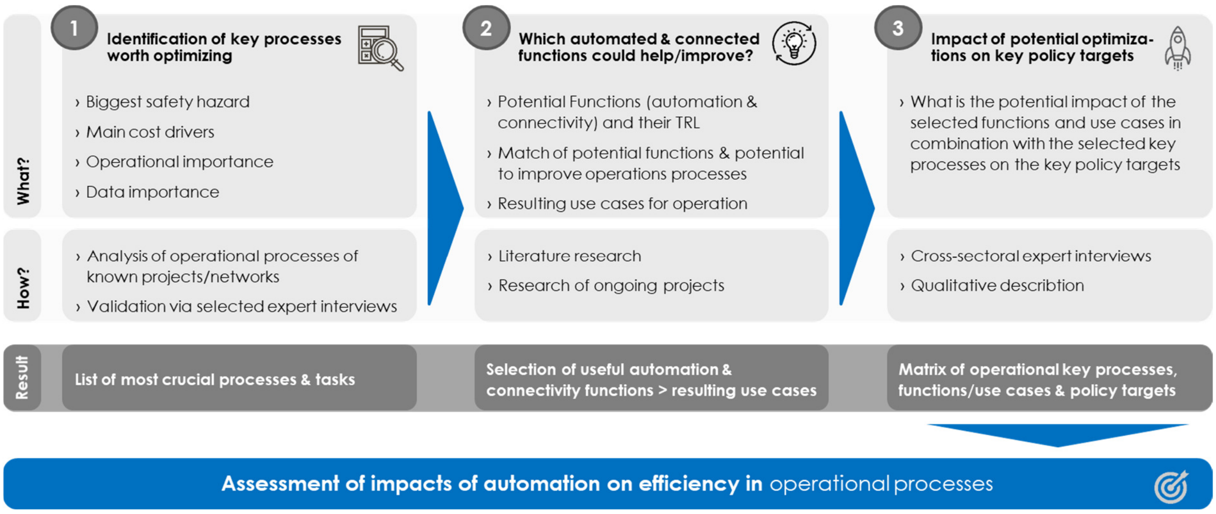


Figure 7.1 Overall methodology for assessment of impacts on the efficiency in operational processes

7.2 Identification of key processes worth optimizing

The starting point here is to identify which operational and maintenance (O&M) processes are already working perfectly in terms of safety, availability, cost, etc. and those which would benefit in either of these policy targets by some kind of optimization. For such operational and maintenance processes it needs to be evaluated whether CAD could help in improving. Significant elements of these works will still need to be carried out manually even in 2040. However, for quite a few of the tasks, CAV or even driverless vehicles could perform the actual driving task.

In order to structurally assess the potential O&M tasks to be automated and in turn their impact on efficiency, key operational tasks according to NRAs are listed below.

- Inspection of the highway condition and inventory
- Safety patrols and inspections
- Detailed visual inspections
- Maintenance and repair of the road elements and furniture
- Cleaning of road surface
- Cleaning and repair of noise barriers, signs and other road furniture
- Debris and litter collection (on highway and off highway)
- Road marking
- Maintenance and repair of road surface
- Maintenance and repair of structures
- Landscaping & grass cutting
- Incident management / Emergency responses potentially incl. rescue of broken down vehicles
- Traffic management
- Environmental / health and safety management

These works and services are commonly believed to be necessary to achieve the best possible results with regard to the availability, reliability and sustainability of a highway. They are essential to ensure the safety of the road users, for proper management and communication of all incidents as well as of all planned maintenance works and to ascertain that the condition and status of the highway is maintained.

In a next step the typical O&M works have been grouped into task groups. In each task group only tasks are listed that require transportation or a vehicle somehow, leaving out those works that are performed without any vehicles.

Table 7.1. Critical O&M tasks

Task Group	Task
Winter maintenance	Preventive salting on highway main-carriageway
	Preventive salting on highway ramps
	Snow ploughing and salting on main-carriageway
	Snow ploughing and salting on ramps
Work zone protection	Planned, stationary maintenance works on emergency lane (e.g. tree cutting)
	Planned, stationary maintenance works on first lane (e.g. pothole repair, joint sealing)
	Planned, stationary maintenance works on fast lane (e.g. pothole repair, joint sealing)
	Planned moving maintenance works on emergency lane (e.g. grass cutting shoulder)
	Planned, stationary maintenance works on first lane (e.g. road marking)
	Planned, stationary maintenance works on fast lane (e.g. grass cutting on median)
	Unplanned incidents on emergency lane (accident, litter removal)
	Unplanned incidents on first lane (accident, litter removal)
	Unplanned incidents on fast lane (accident, litter removal)

Task Group	Task
Traffic management	Incident management including removal of debris or cars
	On-highway traffic management (currently VMS, highway patrol vehicles, mobile trailers)
Inspections	General safety patrols and inspections
	Bridge inspections
	Pavement inspections
Operational highway works	Grass cutting on shoulder
	Grass cutting on median
	Maintenance and repair of road assets and furniture
	Cleaning of road surfaces
	Road marking

In a next step the key O&M tasks to date are assessed in terms of their optimization potential to identify those that are worth optimizing through automation. This list of typical operational tasks has been discussed in the expert workshop with CEDR CAD WG (Tallinn, 07.03.2019). During the workshop the participants defined those tasks of operation and maintenance that are either

- big safety hazards for operational workers or road users during road operations works ("safety hazard") or
- are very intensive on resources use and cost ("cost driver") or
- have big impact on road availability ("operational importance")

These three categories are considered to be the typical NRA policy targets that are potentially influenced by O&M works. The tasks have been rated by the participants in terms of their impact on safety, road availability and cost. The results of this rating provides the ground for the further analysis of potential improvements by automation in O&M. Each workshop participant got a set of 10 points per category and could allocate them to the tasks most relevant. The tasks with the most points are considered most promising for optimization. The results are shown below in Table 7.2.

Table 7.2. Workshop result identification of O&M tasks worth optimizing

		Safety Hazard	Cost driver	Operational importance	Total Score
Winter maintenance	Preventive salting on highway main-carriageway	8	7	6	21
	Preventive salting on highway ramps	3	3	6	12
	Snow ploughing and salting on main-carriageway	5	5	5	15
	Snow ploughing and salting on ramps	4	3	4	11
Work zone protection	Planned, stationary maintenance works on emergency lane (e.g. tree cutting)	1	0	0	1
	Planned, stationary maintenance works on first lane (e.g. pothole repair, joint sealing)	3	0	2	5
	Planned, stationary maintenance works on fast lane (e.g. pothole repair, joint sealing)	7	0	0	7
	Planned moving maintenance works on emergency lane (e.g. grass cutting shoulder)	1	3	1	5
	Planned, stationary maintenance works on first lane (e.g. road marking)	1	0	3	4
	Planned, stationary maintenance works on fast lane (e.g. grass cutting on median)	1	2	1	4
	Unplanned incidents on emergency lane (accident, litter removal)	6	2	4	12
	Unplanned incidents on first lane (accident, litter removal)	10	4	5	19
	Unplanned incidents on fast lane (accident, litter removal)	12	5	7	24
Traffic management	Incident management including removal of debris or cars	6	3	4	13
	On-highway traffic management (currently VMS, highway patrol vehicles, mobile trailers)	0	0	0	0
Inspections	General safety patrols and inspections	0	6	0	6
	Bridge inspections	1	2	5	8
	Pavement inspections	1	2	0	3
Operational highway works	Grass cutting on shoulder	4	4	2	10
	Grass cutting on median	6	3	0	9
	Maintenance and repair of road assets and furniture	7	4	5	16
	Cleaning of road surfaces	1	5	0	6
	Road marking	5	5	6	16

By consolidating these results the most promising tasks for optimization have been identified and summarized as presented below Table 7.3.

Table 7.3. Workshop result: Most promising O&M tasks

		Safety Hazard	Cost driver	Operational importance	Total Score
Winter maintenance	Preventive salting on highway main-carriageway	8	7	6	21
	Snow ploughing and salting on main-carriageway	5	5	5	15
Work zone protection	Unplanned incidents on first lane (accident, litter removal)	10	4	5	19
	Unplanned incidents on fast lane (accident, litter removal)	12	5	7	24
Operational highway works	Maintenance and repair of road assets and furniture	7	4	5	16
	Road marking	5	5	6	16

7.3 CAD functions with the potential to improve O&M

Winter maintenance and work zone protection are the operational task groups identified to have the biggest potential for improvement by CAD. This is also in line with the use cases that have been selected in work-package 2 of MANTRA as detailed use cases for driverless maintenance vehicles (Aigner et al., 2019). These use cases have been further analysed in terms of their required Operation Design Domain (ODD) and infrastructure impact in work-package 4 (Ulrich et al., 2020). For these use cases simulation studies have been performed in Chapter 6 to assess their impact on traffic flow. In addition to those use cases also standardized linear works like road marking are considered to be possible and interesting to be carried out by CAD as well as maintenance and repair works or road assets and furniture.

International research and pilot projects in these fields were assessed to find out about the benefits in terms of safety for road/maintenance workers and efficiency of maintenance works. Research and pilot projects around the globe on one hand reach for the low-hanging fruits of very limited rather simple use cases like driverless safety trailers on emergency ramps. On the other hand complex and cost-intensive tasks are tackled through step-by-step improvements like e.g. winter maintenance operations.

7.3.1 Driverless safety trailers for work zone protection

The project “Automated Unmanned Protective Vehicle for Highway Hard Shoulder Road Works”, short aFAS (Schulz et al., 2019; Stolte et al., 2015) developed and tested a self-driving safety trailer on the hard shoulder of German motorways. As also the rating in our workshops proofed mobile road works on the hard shoulder bear an increased accident risk for the crew of the protective vehicle which safeguard road works against moving traffic. The project aimed at the unmanned operation of the protective vehicle in order to reduce this risk. This was also the very first unmanned operation of a vehicle on German roads in public traffic. Besides technical deployment of the very limited use case of hard shoulder road works protection, aFAS also showed the legal adaptions necessary to enable unmanned operation of vehicles in moving traffic (Schulz et al., 2019).

So far safety trailer use has only been tested on hard shoulders and not as desirable for significant policy target improvements on the fast lane. This, however, is mainly due to legal boundaries that each country needs to work on in order to enable the safety potential of this use case. Besides the legal boundaries the good news are that the TRL of driverless safety trailers is already in the upper regions (TRL 7-9) with possible use at least on the hard shoulder as soon as 2020 or 2021 if industry is able to provide for NRAs demand.

7.3.2 ADAS for winter maintenance vehicles

In terms of highway maintenance and operation one of the more complex applications is the field of winter maintenance. As an extremely safety critical task involving a lot of manpower in rather condensed periods of time but still potentially long shifts, driverless solutions are desirable. However, technical complexity of the driving task itself due to limited visibility as well as the necessary ever-changing strategy adjustments of salting amounts, snow plough shield adjustment make this use case particularly difficult. High-level automated or even driverless snowploughs for motorways are therefore a distant vision. In the meantime the step-by-step integration of automated functions is tested with promising results in projects worldwide. Snowplough operators are often tasked with numerous monitoring and operational activities that they need to do simultaneously while removing snow and spreading de-icing agents on the road. In Minnesota (Arabzadeh et al., 2019) applications for snow ploughing convoys and lane boundary guidance were tested using DSRC and GNSS-based lane boundary guidance systems. Results showed that the positioning accuracy with DSRC was inadequate for providing the plough operator with sufficient information to maintain spacing between two vehicles. The GNSS-based lane boundary guidance system successfully supports plough operations when visibility is poor and lane boundary cues are limited. Also snow plough operators found the boundary guidance system very helpful and asked for further development in this direction (Liao et al., 2018).

In Japan pilot tests have been done on a Hokkaido expressway as well as other roads with similar goals. Highly accurate positioning data from a quasi-zenith satellite were combined with high-resolution 3D map data to provide the operator with additional guidance as well as to track the snow removal progress for the traffic management centre (Abe, 2019).

One remaining challenge for winter maintenance vehicles besides the difficult driving condition is also the appropriate portioning of the salt amount in preventive winter maintenance. While algorithms can certainly calculate appropriate average salting amounts based on weather data, the difficulty is in the detail. Black ice spots usually have the potential to form in very specific spots like on bridges, dilations, changes of pavements ahead or after tunnel portals and in micro-climate zones. While danger spots based on road assets (bridges, tunnels, etc.) can be solved with according HD maps together with high accuracy positioning which are necessary for driverless winter maintenance vehicles, micro climate zones are much more difficult. Nowadays the salting amounts follow salting patterns based on weather data but are always adapted for specific conditions by the experienced winter maintenance drivers. Such micro climate zones can change within metres and need to be taken very seriously. A lot of historic weather data together with life weather sensors on the winter maintenance vehicles will be necessary to ensure that such black ice danger zones are also tackled safely in case of driverless winter maintenance vehicles.

International research together with no findings of serious industry attempts to work on developments of actual driverless winter maintenance vehicles unfortunately prove that the TRL is only on the very low end of the scale (TRL 1-3). A step-wise support with ADAS will however still benefit the safety of operational workers and potentially also traffic flow. Actual driverless winter maintenance vehicles as simulated in this work package are however a far distant vision.

7.3.3 New data sources and driverless vehicles for operational highway works

Another important research field for maintenance improvements is the automated provision of infrastructure condition data through vehicle-to-infrastructure (V2I) communication both ways. Various C-ITS projects tested and provided solutions for communication of condition data into vehicles which provide a basis for the planning of operational highway works. The sensors of CAVs will provide a lot of data of the traffic and environmental conditions along their route. Such data would be extremely useful to the road operators and traffic managers. At the same time, the availability of such data would enable road operators to give up large parts of their monitoring infrastructure resulting possibly in cost savings. On the other hand, the vehicle and information service industry is not willing to give for free the data that they have collected via connected and/or automated vehicles. The only type of data, which also the industry needs to share according to European legislation is safety-related information. This information, detailed in eight information types, has to be shared on the basis of the delegated regulation for road safety-related minimum universal traffic information free of charge to users (European Commission, 2013).

From a maintenance perspective the possibility for vehicles providing road condition data through V2I communication to the TMC promise major improvements for predictive maintenance. One project in Germany by Mercedes Benz is testing the provision of data on snowy or icy road conditions through electronic stability control (ESC) and anti-lock braking system (ABS) to enable more efficient winter maintenance planning (Next Mobility News, 2019). While this would benefit winter maintenance rather that operational highway works it would still provide the grounds for communication protocols to enable also data provision on other road conditions. Results from Finnish tests indicate that the problem with using ESC and ABS related data is that data is obtained only for sections where the vehicles tend to accelerate of decelerate i.e. on ramps or at intersection exits or approaches. Future ambitions involve also the collection of road condition data like cracks, rutting or skid resistance facilitating sensor technology of highly-automated vehicles through V2I communication. However so far it remains unclear if CAV sensors will be suitable for the provision of condition data. Other examples of automated condition data provision include new concepts utilizing drones for difficult to access infrastructure assets like high bridges, gantries or tunnels as tested in projects like e.g. Riskmon (Bladescanner, 2019).

In terms of the provision of e.g. road marking by automated vehicles no research or industry ambitions could be found. The key for road marking will be the exact positioning and the preparation of HD maps for the road marking application itself on the respective road section as well as afterwards for the further use of this data in HD maps provided to road users and traffic management will be crucial. Other than that the actual driving task should be easily possible by a self-driving road marking vehicle at least on highways as road marking is performed on closed sections with continuous speed. Therefore the complexity of this use case would be rather straight forward. So even as there are no documentations about ongoing tests or developments it is assumed that industry will use driverless vehicles as soon as economically feasible for road markings tasks, if only for market competitiveness. The TRL for road marking vehicles is assumed to be in the high region (7-9) with the time to market introduction depending on the economic feasibility as otherwise market application is difficult.

Regarding the actual work for other operational highway works like crack repairs, etc. the main challenge actually is not the work itself. Due to its often very small scale character the actual repair work needs to be done manually by workers with small equipment rather than vehicles. The dangerous part is once again the safe guarding of the temporary maintenance side where driverless safety trailers would provide the necessary benefit.

7.4 Impact of potential O&M optimizations on key policy targets

The optimization of operational tasks is only as valuable as their actual contribution to the improvement of NRAs policy targets. The focus of MANTRA in accordance with the aim of CEDRs research programme is to investigate what transformational change automation will create for NRAs. Specifically this means potential through crosscutting automation up to 2040 that supports:-

- Road safety
- Traffic efficiency
- Environment
- Customer service

The following summary table shows how the identified O&M tasks with the biggest potential to be improved through automation can support these policy targets:

Task	Road safety	Traffic efficiency	Environment	Customer Service
Winter maintenance				
Preventive salting on highway main-carriageway TRL 1 - 3	Road safety improvements are possible due to potentially faster salting cycles and no more long shifts for operational workers. Critical black ice spots (micro climate zones) will need to be taken very seriously.	Preventive salting with driverless winter maintenance vehicles could potentially be even more performed during low-traffic times and this way affecting regular traffic less.	Automation of correct salting amounts is a challenge that needs to be solved before application. However if automation of salting amounts can be calibrated perfectly, salt consumption could be optimized and reduced to have less impact on the environment.	Customer service could be improved with life information on where winter maintenance fleets are in progress and this way feed into routing decisions and travel time.
	Impact potential: average	Impact potential: average	Impact potential: average	Impact potential: average
Snow ploughing and salting on main-carriageway TRL 1 - 3	The use of driverless winter maintenance vehicles would make intense and potential long shifts for operational workers in case of long running sever conditions unnecessary and resulting fatigue obsolete.	Traffic efficiency could be improved with life information on where winter maintenance fleets are in progress and this way feed into routing decisions and travel time.	Snow ploughing over waters will need to be specifically addressed to avoid pollution in case of driverless vehicles. Potential for improvement is considered limited.	Customer service could be improved with life information on where winter maintenance fleets are in progress and this way feed into routing decisions and travel time.
	Impact potential: average	Impact potential: minor	Impact potential: minor	Impact potential: average
Work zone protection				
Work zone protection in case of unplanned incidents on first lane (accident, litter removal) TRL 7 - 9	Safety potential for road users only in case of connected, driverless safety trailers providing warnings further ahead of protection zones. Big safety potential for operational workers.	Traffic efficiency improvements for road users only in case of connected, driverless safety trailers providing warnings further ahead of protection zones and enabling smart and flexible traffic management subject to traffic density.	No specific impact expected.	Customer service improvement through better and earlier information of unplanned work zones as part of the traffic management.

Task	Road safety	Traffic efficiency	Environment	Customer Service
	Impact potential: high	Impact potential: average	Impact potential: minor	Impact potential: average
Work zone protection in case of unplanned incidents on fast lane (accident, litter removal) TRL 7 - 9	Safety potential for road users only in case of connected, driverless safety trailers providing warnings further ahead of protection zones. Big safety potential for operational workers.	Traffic efficiency improvements for road users only in case of connected, driverless safety trailers providing warnings further ahead of protection zones and enabling smart and flexible traffic management subject to traffic density.	No specific impact expected.	Customer service improvement through better and earlier information of unplanned work zones as part of the traffic management.
	Impact potential: high	Impact potential: average	Impact potential: minor	Impact potential: average
Operational highway works				
Maintenance and repair of road assets and furniture TRL 1 - 3	Strongly depend on maintenance task. Low TRL makes valuation difficult. Safety potential for road users limited, for operational workers the safeguarding is crucial	Smart and flexible traffic management subject to traffic density, however mainly based on work zone protection rather than actual works.	No specific impact expected.	Smart and flexible traffic management subject to traffic density, however mainly based on work zone protection rather than actual works.
	Impact potential: minor	Impact potential: minor	Impact potential: minor	Impact potential: minor
Road marking TRL 7 - 9	Automated road marking in combination with exact positioning and HD maps for production can provide an accurate basis for lateral positioning data for road users.	Potentially automated road marking can be performed always in low traffic times and this way decreasing road closures.	No specific impact expected.	No specific impact expected.
	Impact potential: average	Impact potential: average	Impact potential: minor	Impact potential: minor

8 Impacts of automation on key NRA challenges

The Conference of European Directors of Roads (CEDR) study assignments have focused on crosscutting automation up to 2040 that support road safety, traffic efficiency, environment, and customer service. Different dynamics are in place concerning key NRA challenges in different regions and cultures in Europe; specifically the role of digitalisation on strengthening a country's or region's economic competitiveness in a global innovation system is easier recognised in some cultures. Some NRA haven't had any explicit mention of fostering a country's economic competitive capacity. This might change – but currently it is one element to explain a rather hesitative impacts section from the perspective of some of those NRAs who have already committed to a strong contribution onto competitiveness via automated mobility and digital infrastructures.

Automation is well on its way, both on vehicle side, as well as with various processes of road operators, NRAs and various service providers. Vehicle automation as well as the availability of various degrees of automated functions in vehicles on European roads can be regarded as longer transition processes with continuous feedback loops and adaptations. This anticipated iterative process will challenge several key NRA activities and some conceptions of a rather clear separation between research, innovation and deployment in the years to come.

Some drivers for these challenges are:

- Rather different innovation cycles / innovation speeds between digital updates in (1) telecom and software / platform providers, (2) vehicle manufacturers and vehicle software and (3) NRAs with legacy systems, intentionally / strategically unshared digital infrastructures and core processes
- Competitiveness via digitalisation and availability of vehicle automation: availability of vehicle automation is in some countries regarded as one contributing factor to economic strength, prosperity and industrial policies as a kind of ecosystem and platform prerequisite for global cooperation with Asia and the US in a highly competitive cooperation context. This has the potential to kind of request contributions from NRAs prematurely or without sufficient empiric evidence or active users. This has significant potential to increase investment risk and risk of stranded cost.
- Another kind of almost digital divide in mobility-related stakeholder groups resulting from a tendency of human resources following innovation dynamics and competences and structures in organisations: road authorities might find it increasingly challenging to attract qualified experts on automation, digitalisation and AI in an ecosystem where digital platform providers and fully digital service providers attract some of the best talent and continue with impressive growth in human resources.
- Tendency to a "the winner takes it all" kind of world in a digital platform ecosystem: digital maps, routing services, entirely new micro payment services and new forms of shared vehicle ownership or automated vehicle operation have the potential to kind of marginalize NRAs' significantly smaller, or nationally rooted activities;
- Yet unrecognized limits of providing valid centralised traffic information and recommendations for an increasing number of rather heterogeneous connected vehicles and mobility users and mobility lifestyle segments. This is partially due to cycles of rapid learning about mobility preferences with NRA's national customer bases and a potential self-selection mechanism between customers who share their data and interest rather freely with Big Tech (integrated digital platform providers in the sense as it has been used at CES2020 – Google, Facebook, Amazon, Alipay and similar commercial groups entering mobility industries); Big Tech at the same time many of these somehow uncritical data sharing customers do not want to share anything with a public authority or anybody outside the Big Tech platform ecosystem: highly specialised interest groups will continue to find international service providers

and benefits from using international platforms and user interfaces.

- Telecom networks and other networks will always have some availability issues. Therefore, vehicle manufacturers have tried to keep vehicle functions operational even with minimum network or communication availability. In this scenario decentral self-organisation-type of traffic information (e.g. smaller cells and decentralised event horizons in 5G) have at least some potential to add information quality that goes far beyond what can be effectively handled in today's traffic control centres. It is fully acknowledged that processes in traffic control centres are also being automated and equipped with sophisticated AI solutions. So prima vista the TCCs can be seen as quite effective in handling any additional information. However, from several interactions with project managers in European car manufacturers some here would rather anticipate that providing individualised quality recommendations to individual cars has at least the potential to go far beyond of at least several NRA's service concepts and concepts of their current key business. [strong car brands have capitalized on the idea, that not every car is equal]
- Entirely new perception of travel time in automation scenarios: how travel time is perceived in emerging mobility contexts, is expected to undergo significant changes. Once passengers are always connected in terms of social media and videoconferencing in combination with increasing time slots where no focus on driver functions is required. E. g. at CES2020 The Financial Times quoted an Intel study using the entirely new term "passenger economy". However, in some aspect this new term has the potential to validly capture some of the turmoil mobility might see from future assisted and automated driving functions. e.g. in Europe in combination with a focus on a new green deal, these mechanisms could provide new opportunities for mitigating peak hour traffic or provide higher acceptance for reduced travel speed in environmentally challenging areas or weather situations.
- Absorptive capacity is a key feature for NRAs: automation and digital transition know-how cannot be acquired in ways similar to new hardware. The corporate co-evolution or co-development on organisational level need significantly higher levels of absorptive capacity. Therefore, building adequate organisational cultures for digital transition and automation most probably can be seen as a rather long-time high priority activity.
- Some stakeholders e.g. in DG CONNECT have raised potential synergies and merging ideas between future low-air traffic control centres (e. g. for automated air taxis) and road-based traffic control rooms. It is not entirely clear, how this would impact key NRA activities.
- In several NRAs, automation is treated as rather preparatory activity before implementing traffic management interventions. In the end, it is almost always a human being that decides. Automation certainly has the potential to extend significantly beyond preparatory tasks. Dynamic risk-rated scenarios will most probably prepare the ground for semi-automated and fully automated processes. What now might look and feel wrong, will soon see rather wide acceptance in a connected reality of IoT.

Digitalisation and automation in NRAs' processes will most probably face a rather varied public discourse in different parts or Europe e. g. some regions have heavily challenged the concept of smart highways. Heterogeneous contexts in terms of fear-based public campaigning, varied industry policy, population density and traffic density, as well as safety hotspots on existing road networks strongly suggest that impacts from automation might turn out to be of highly heterogeneous nature.

From a road operator's perspective L4 freight automation has significant potential to making better use of scarce road capacity in a scenario of significantly increasing freight transport in Europe. However, under current operational practices and current legal frameworks it is not entirely clear, how this new operational mode could be effectively transferred beyond confined areas in harbours, industrial areas or forests – at least in Europe.

Automation on open roads is not only automation – it involves agendas like digitalisation, acceptability, operational mode of passenger cars and their respective assistive systems, availability of communication for safe cooperative manoeuvring including automated trucks and semi-automated passenger cars. Within automation futures all organisations will need entirely new forms of data strategy and cooperation strategies on data fusion.

Automation on vehicle level is far from being clearly defined or market ready. Several OEMs have down toned their deployment planning several times. On the other hand, several mobility transport service providers have continued to push ambitious deployment plans – in light of their financing rounds and the anticipation, the early gains in market share will contribute to economies of scale and the winner takes it all frames of reference. Cars will certainly not integrate all automated vehicle functions: "we cannot do everything we wanted because if we did the car would be $40.000 or in some cases $400.000 and more".

Recommendation: Need for selling the transition towards automation beyond false dichotomies

Improved and new narratives are needed for NRA's core business and in negotiation with their governmental partners to help overcome false dichotomies like either automation or new green deal, or either automation or safe and inclusive motorized road transport for all. Some of the rather challenging narratives on future organisational capabilities (both for NRAs and for vehicle manufacturers) so far have been:

- Big tech giants are naturally better at analysis of customer behaviour – really?
- Several vehicle manufacturers have recently established AI-related partnerships (e.g. Amazon web services and Netflix integrated AI tools into an upcoming Porsche AI Developer Platform). Implicitly, this can suggest leveraging effects or the fact that digitalisation and automation will make car manufacturers rather similar to Big Techs Giants?
- What are core processes in an age of automation? one lesson learnt for NRAs can be seen as three entirely different role models in the automated vehicle ecosystem: Some car manufacturers anticipate, that the car will remain the key technology and they can always buy data processing capacity from cloud services as almost a commodity; Some Big Tech companies maintain that they own the digital processes and can always build or buy a generic vehicle. And some (Asian) car manufacturer maintains he will focus on becoming an efficient mobility service provider and kind of pick components from both worlds. NRAs might well be facing similar road mapping challenges.
- A strong and high-tech friendly home market boosts an organisation's global competitive advantage (China, US as compared to rather fragmented European Single Market)
- Governments and road authorities cannot work like a start-up. Road authorities might find it rather challenging to cooperate with start-ups. Compare e. g. Transport for London's cooperation with a varied ecosystem of new mobility service providers via Bosch mobility services). Start-ups dream in years, plan in months and evaluate in weeks and ship in days. The government can't act like a start-up in their normal activities or processes.
- Automation holds not only opportunities, but many fears. Fear blocks teams from trying new things. Similar cultural challenges have been witnessed in traditional banking system vs entirely new Fintech players (including obvious lessons from banking legacy IT vs fintech newest platform IT systems)

- Next generation communication infrastructure in Europe has some overlap with a future ecosystem for automated driving and for automated processes in NRAs (IoT). However, it is not entirely clear whether this overlap is in the order of one per cent of any Europe-wide communication infrastructure or rather in the order of 30%. This involves even more risk with rather short break-even time windows for new communication technologies (until the next communication infrastructure needs to be rolled out).

Some public discourse on future European mobility tends to kind of ban innovative technological agendas or solutions and rather push rapid behaviour change. For NRAs, there is little to gain in an increasingly digitally enhanced automation and AI ecosystem, in avoiding the megatrends or even fighting the megatrend. On top of this big picture, some stakeholders request focus on inclusion and participation. However. diffusion of innovation has had validated evidence, that certain population segments adopt an innovation early or earlier and some rather late. Focussing on the wrong end, has the potential to waste financial resources.

Automation for NRAs has significant potential to face legal bottlenecks without documented statistic data (what is the basis for automation with new historic evidence)? On top of this challenge comes the challenge for addressing legal processes without clear project owner (yet). Automated driving can be seen – and has been framed by several global platform cooperations within this guiding metaphor "we on a board level have no idea, how we can achieve this, but we know we cannot do it alone. So we cooperate in a global ecosystem…"

9 Conclusions

In the following paragraphs we present the overall conclusions of this deliverable. Specific conclusions for each of the case studies examined were detailed in the previous chapters.

We used several different simulation tools to model the impact of various types of automated vehicles. Although simulation is a good tool to assess the impacts on travel behaviour and traffic efficiency, it should be noted that automated vehicles do not drive on the roads currently, and little is known on the actual impact of automated vehicles as well as on the interaction between manual car drivers and automated vehicles. This also means that calibration of simulation models is not possible. We can use the simulation results as a way to make an educated guess on the future situation, but we should not limit ourselves to the precise output values, as these may vary largely.

The modelling of Level 4 automation for cars (Chapter 3) and trucks (Chapter 4) examined future scenarios without infrastructure-to-vehicle communication but with vehicle-to-vehicle communication in the form of CACC, i.e. scenarios without major digital infrastructure requirements or costs for road operators. The findings generally point to benefits for *all* traffic with increased automation, whether of cars or of large trucks. The macro model of Rotterdam and the Hague indicated that automation could lead to a substantial decrease in delays. The microsimulation for both cars and trucks showed in general that increased automation shortened overall journey time, most likely because CACC-controlled vehicles drive with shorter headways. Negative side effects in the form of increased delays around entry and exit ramps were not observed. However, the car modelling scenario showed that automation may not be able to overcome deficiencies in the physical infrastructure: this is shown by the case of the 0 metre taper on the entry ramp, resulting in large delays and automated vehicles as well as cars not being able to enter the motorway.

We also assessed the safety of CACC vehicles using SSAM software (Surrogate Safety Assessment Model). This showed that the number of conflicts generally stayed equal with and without automation. However, it is questionable whether SSAM provides correct results, since the tool has been developed and calibrated based on human drivers and has not been calibrated for AVs. Simulation software does not simulate any crashes, so the only way of incorporating safety is to predict whether a potential crash could happen, given a certain reaction time. In terms of communicating AVs it is questionable whether reaction time is the main safety concern, as software or communication failures may cause much higher crash risks. More research to assess the safety impacts of CACC vehicles including fall-back modes if the vehicle exits its ODD is advised.

The modelling results of robotaxis adoption in Delft found that the effects are only in terms of modal shifts from existing car usage to the new mode, with little impact on public transport and cycling. On the other hand, there was an increase of the mileage of all light vehicles as a result of travel by the robotaxis while empty. These extra trips caused additional delay to all traffic in the network. Although the modelling examined a comparatively dense and quite compact urban area, it is expected that the same effects would occur on motorways as a result of the introduction of robotaxis.

The modelling of the automated maintenance use cases found that providing advanced knowledge exclusively to automated vehicles created substantial negative impacts on conventional vehicles: conventional vehicles could get blocked behind the maintenance vehicle. The situation becomes even more unbalanced as highly automated vehicle penetration rate increases. This imbalance did not occur when the road was modelled without communication. This indicates that communication should not be available just to highly automated but rather to all traffic. Alternatively, it should not be available at all.

The optimization of operational tasks is only as valuable as their actual contribution to the improvement of NRAs policy targets. The review of potential benefits from automated maintenance indicated that these could be substantial across all the criteria — safety, efficiency environment and customer service. Winter maintenance and work zone protection are the operational processes identified to have the biggest potential for improvement by connected and automated driving. In addition to those use cases also standardized linear road maintenance works like road marking are considered to be possible and interesting to be carried out by automated vehicles as well as maintenance and repair works or road assets and furniture.

10 References

AASHTO. (2018). *A Policy on Geometric Design of Highways and Streets*. Retrieved from

Abe, K. (2019). *The role of government for deploying connected and automated vehicle in Japan: Session AP04 - Automated driving of snowplows.* Paper presented at the 26th ITS World Conference 23.10.2019, Singapore.

Aigner, W., Kulmala, R., & Ulrich, S. (2019). MANTRA D2.1 Vehicle fleet penetrations and ODD coverage of NRA-relevant automation functions up to 2040. In. MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business.

Arabzadeh, A., Notani, M. A., Zadeh, A. K., Nahvi, A., Sassani, A., & Ceylan, H. (2019). Electrically conductive asphalt concrete: An alternative for automating the winter maintenance operations of transportation infrastructure. *Composites Part B: Engineering*, 106985.

Aria, E., Olstam, J., & Schwietering, C. (2016). Investigation of automated vehicle effects on driver's behavior and traffic performance. *Transportation research procedia, 15*, 761-770.

Bevly, D., Murray, C., Lim, A., Turochy, R., Sesek, R., Smith, S., Humphreys, L., Apperson, G., Woodruff, J., Gao, S., Gordon, M., Smith, N., Watts, A., Batterson, J., Bishop, R., Murray, D., Torrey, F., Korn, A., Switkes, J., & Boyd, S. (2016). Heavy truck cooperative adaptive cruise control: evaluation, testing, and stakeholder engagement for near term deployment: phase one final report. Auburn University, Alabama, USA.

Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L., & Walters, J. (2014). Effects of next-generation vehicles on travel demand and highway capacity. *FP Think Working Group*, 10-11.

Bladescanner. (2019). RISKMON Anlageninspektion und Risk-Monitoring mit Hochleistungsdrohnen und Sensorik. *Mobilität der Zukunft 2016*.

CoEXist. (2018). D2.3 Default behavioural parameter sets for Automated Vehicles

ERTRAC. (2017). *Automated Driving Roadmap*. Retrieved from http://www.ertrac.org/uploads/images/ERTRAC_Automated_Driving_2017.pdf

Commission Delegated Regulation (EU) No 886/2013 supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to data and procedures for the provision, where possible, of road safety-related minimum universal traffic information free of charge to users: No 886/2013, (2013).

Fellendorf, M., & Vortisch, P. (2001). *Validation of the microscopic traffic flow model VISSIM in different real-world situations.* Paper presented at the transportation research board 80th annual meeting.

Gehring, O., & Fritz, H. (1997). Practical results of a longitudinal control concept for truck platooning with vehicle to vehicle communication. *Proceedings of Conference on Intelligent Transportation Systems, Boston, Massachusetts, USA*, 117-122.

Gettman, D., Pu, L., Sayed, T., Shelby, S., & Siemens, I. (2008). Surrogate safety assessment model and validation. In: United States. Federal Highway Administration. Office of Safety Research and ….

Gipps, P. (1981). A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological, 15*, 105-111.

Jorge, D., Correia, G. H. A., & Barnhart, C. (2014). Comparing optimal relocation operations with simulated relocation policies in one-way carsharing systems. *IEEE Transactions on Intelligent Transportation Systems, 15*(4), 1667-1675. doi:10.1109/TITS.2014.2304358

Liao, C.-F., Donath, M., & et al. (2018). Development of Driver Assistance Systems to Support Snowplow Operations. Test and Demonstration of Connected Vehicles Applications to Maintenance Operations. CTS18-14. With assistance of University of Minnesota.

Martinec, D., Herman, I., & Sebek, M. (2014). Two-sided wave-absorbing control of a heterogenous vehicular platoon. *Proceedings of the 19th World Congress, The International Federation of Automatic Control, Cape Town, South Africa. August 24-29*, 8091-8096.

Mueller, S. (2012). The impact of electronic coupled heavy trucks on traffic flow. *Proceedings of the 40th European Transport Conference, Glasgow, Scotland*.

Next Mobility News. (2019). C2X-Kommunikation für einen effizienteren Winterdienst. Retrieved from https://www.next-mobility.news/c2x-kommunikation-fuer-einen-effizienteren-winterdienst-a-872528/?cmp=nl-392&uuid=2A64A51F-61C9-46CA-A09B-4EAF0263493C

Nowakowski, C., Shladover, S. E., & Lu, X.-Y. (2016). Operational concepts for truck maneuvers with cooperative adaptive cruise control. *Transportation Research Record, 2559*, 57-64.

Penttinen, M., van der Tuin, M. S., Farah, H., Correira, G. H. A., Wadud, Z., Carsten, O., & Kulmala, R. (2019). MANTRA D3.1 Impacts of connected and automated vehicles – State of the art.

Rijkswaterstaat. (2017). *Richtlijn Ontwerp Autosnelwegen 2017*. Retrieved from

Rios-Torres, J., & Malikopoulos, A. A. (2016). Automated and cooperative vehicle merging at highway on-ramps. *IEEE Transactions on Intelligent Transportation Systems, 18*(4), 780-789.

Schulz, S., Reusswig, A., Lülfing, R.-C., Thiel, J. v., Wulf, O., Rief, C., & et al. (2019). aFAS Automatisch fahrerlos fahrendes Absicherungsfahrzeug für Arbeitsstellen auf Bundesautobahnen. Gemeinsamer Schlussbericht. Version 01-00-00, checked on 3/14/2019.

Shladover, S. E., Su, D., & Lu, X.-Y. (2012). Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transportation Research Record, 2324*(1), 63-70.

Stolte, T., Reschka, A., Bagschik, G., & Maurer, M. (2015). *Towards Automated Driving: Unmanned Protective Vehicle for Highway Hard Shoulder Road Works.* Paper presented at the 2015 IEEE 18th International Conference on Intelligent Transportation Systems.

Tsugawa, S., Jeschke, S., & Shladover, S. E. (2016). A Review of truck platooning projects for energy savings. *IEEE Transactions on Intelligent Vehicles, 1*(1), 68-77.

Ulrich, S., Kulmala, R., Appel, K., Aigner, W., & Penttinen, M. (2020). MANTRA D4.2 Consequences of automation functions to infrastructure. In. MANTRA: Making full use of Automation for National Transport and Road Authorities – NRA Core Business.

van Beinum, A., Farah, H., Wegman, F., & Hoogendoorn, S. (2018). Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data. *Transportation Research Part C: Emerging Technologies, 92*, 426-441.

van Maarseveen, S. (2017). Impacts of truck platooning at motorway on-ramps: analysis of traffic performance and safety effects of different platooning strategies and platoon configurations using microscopic simulation. *Master of Science thesis, Delft University of Technology*.

Viti, F., Hoogendoorn, S. P., Alkim, T. P., & Bootsma, G. (2008). *Driving behavior interaction with ACC: results from a Field Operational Test in the Netherlands.* Paper presented at the 2008 IEEE Intelligent Vehicles Symposium.

Wadud, Z. (2017). Fully automated vehicles: a cost of ownership analysis to inform early adoption. *Transportation Research Part A: Policy and Practice, 101*, 163-176.

Wiedemann, R. (1991). Modelling of RTI-elements on multi-lane roads. *Advanced Telematics in Road Transport.* Washington DC: Transportation Research Board.

World Economic Forum. (2018). Reshaping Urban Mobility with Autonomous Vehicles - Lessons from the City of Boston.

Yarnold, M. T., & Weidner, J. S. (2019). Truck platoon impacts on steel girder bridges. *Journal of Bridge Engineering, 24(7): 06019003*.

Workshops and international discussions

Workshop PEB and CEDR CAD WG, Vienna, 31.08.2018

ITS world conference 2018, interactive panel discussion within the special interest session on “Systemic impacts from infrastructure-based management of connected and automated driving (SIS69)”, Copenhagen, 20.09.2018

Workshop CEDR CAD WG, Oslo, 06./07.11.2018

Expert Interview with Heimo Maier-Farkas, Head of Operational Services at ASFINAG Service GmbH, 23.01.2019

Workshop CEDR CAD WG, Tallinn, 06./07.03.2019

ITS Europe conference 2019 interactive panel discussion within the special interest session on “Touching the real infrastructure and embracing the unknown (SIS13)”, Eindhoven, 04.06.2019

Workshop with Asfinags team for ITS, automated and connected driving, Vienna, 06.05.2019

Kolloquium Future Mobility, Esslingen, 02.07.2019

Expert Workshop, Vienna, 10.09.2019