Assessing the impact of shared and autonomous vehicles on urban traffic

A simulation approach

Master thesis

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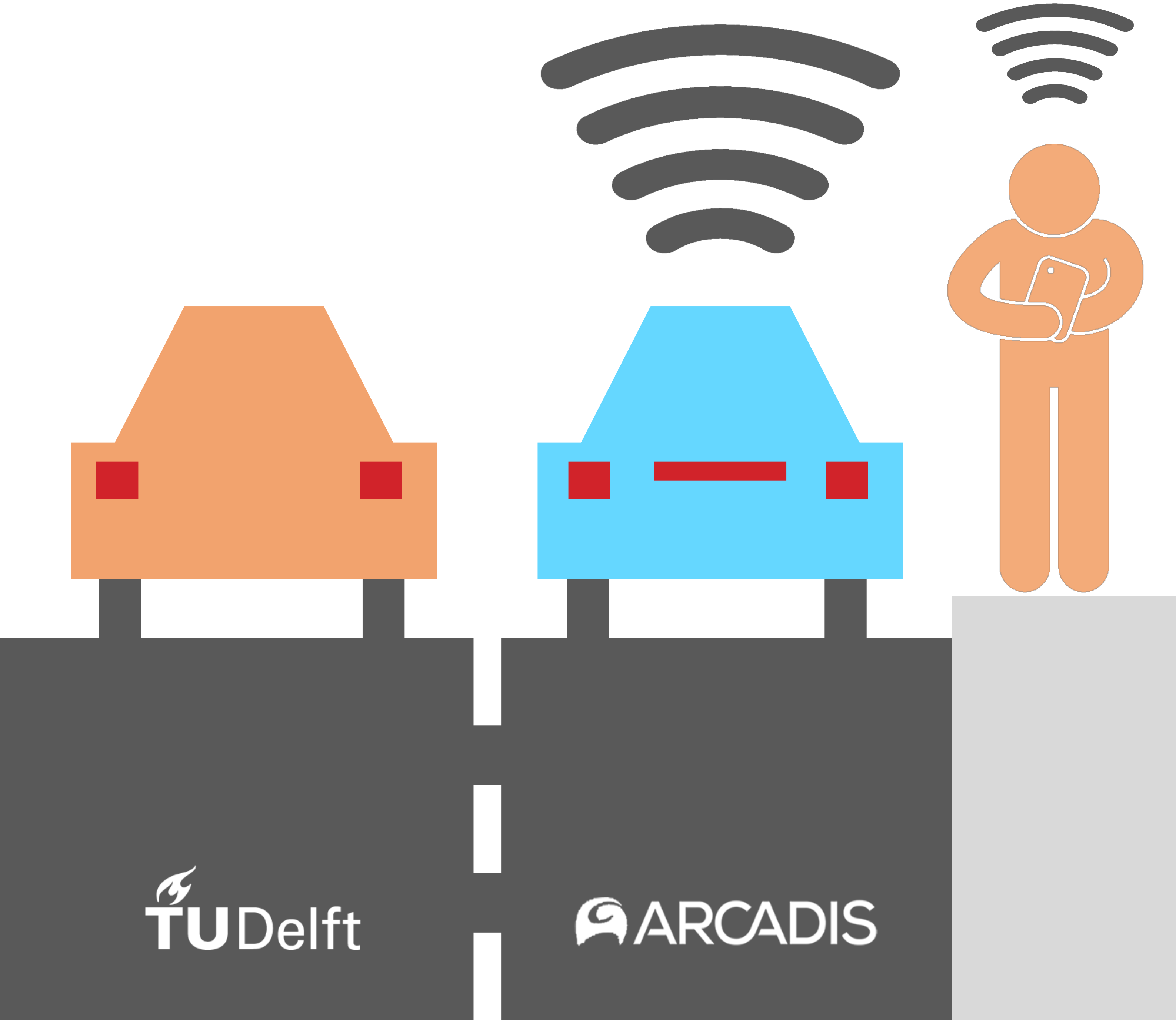

Assessing the impact of shared and autonomous vehicles on urban traffic: a simulation approach

by

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Preface

Before you lies the report of the final leg of the journey that has been my university studies. Since I started my first year at the Erasmus University Rotterdam in 2011, my studies have brought me to Delft, Canada, Monaco, Myanmar, and now finally to Amersfoort. Here I wrote my master thesis to obtain a degree in Transport, Infrastructure and Logistics at the Delft University of Technology. 8 years ago, I never would have expected to be graduating from TU Delft, with a thesis on autonomous vehicles, but I am very happy that this winding journey has brought me here.

During my time in Delft, I have become passionate about smart and sustainable mobility, and using simulation to solve complex problems. I am very happy that with this thesis topic, I found a way of combining both. I had a great time working on this project, which I was free to shape as I found fit. I really enjoyed my time at Arcadis, working in a stimulating environment with great co-workers. And I spoke to a lot of interesting people in the mobility sector who are all encaptured with the topic of shared and autonomous vehicles. I think AVs and SAVs will have a huge impact on mobility as we know it and I hope to be able to play an active role in this transition during my professional career.

Even though this has been an individual project, I received help from different quarters. I would like to thank a number of people in particular. First of all, the members of my committee, Alexander Verbraeck, Yilin Huang, Gonçalo Correia and Gerco Huisman, who helped shape this project, and who provided me with guidance and feedback along the way. Without this guidance, I would likely still be "swimming in the mayonnaise". It was great having such a diverse team, not only representing different disciplines, but also different cultures. One thing I definitely learned in Delft is that having diverse viewpoints really helps to improve your work.

I would also like to thank my co-workers at the strategy & policy in infrastructure department at Arcadis for showing interest in my work, providing me with help and input, and providing me with great facilities and a powerful computer. Without all this, I wouldn't have been able to finish the project within a reasonable amount of time, and I definitely wouldn't have enjoyed it this much.

I also want to express my gratitude to everyone else who contributed to my thesis. Hans Lodder from the municipality of The Hague for allowing me to use the simulation model for my study. PTV and TNO for providing me with a student license for EnViVer Pro, and for providing technical support for both EnViVer and Vissim. Jan Jaap Koops and Marc van den Burg from the municipality of The Hague, and Bettinka Rakic from Arcadis who made time for me to talk about their expectations for autonomous and shared mobility in The Hague. Andreas Frank from Arcadis who proofread my report. And the researchers and professionals who helped me during the model building phase and whom I interviewed for the model validation: Simeon Calvert, Niels van Oort, Maria Salomons, Erik Verschoor, Maarten Amelink, Anton van Meulen, Jaap Tigelaar and Ronald van Veen.

Finally, I would like to thank my friends and family who supported me throughout the entire process and who provided me with the necessary stress relief. A special thanks to my father Paul Overtoom and to Isabelle Vlasman who even read through the entire report to see if they could make sense of it.

All that remains for me to say is enjoy reading this report and do not hesitate to contact me if you have any questions or remarks.

I.A.E. (Irene) Overtoom
Amersfoort, 14 November 2018

“We have some exciting times ahead. The key question we need to answer in the years to come is this: how can we use all these smart mobility innovations to our advantage? In order to improve accessibility, safety and liveability.”

- Cora van Nieuwenhuizen, Dutch Minister of Infrastructure and Water Management, 20 March 2018

Executive summary

Autonomous vehicles (AVs) and shared autonomous vehicles (SAVs) are a very popular topic of discussion and research. Many researchers acknowledge that not only autonomous, but also connected and shared transport concepts may reshape urban mobility drastically. However, there is not a lot of consensus on how this will happen exactly. So what municipalities are left with, is the knowledge that their city is about to undergo drastic changes that they need to prepare for in terms of policy and infrastructure, but they do not know exactly which changes that will be. Understandably, they are adopting a wait-and-see attitude. However, car manufacturers and mobility services are rapidly moving forward, bringing new technologies and services to the market daily. It will not be long before autonomous cars will start appearing in urban traffic. Then the concern is not only related to how mobility as a whole will evolve, but also how the traffic is impacted on a tactical and operational level.

This research focuses on the effects of AVs and SAVs on the urban main road network in a transition period. The focus is on the microscopic level and on providing tangible results, so municipalities can already evaluate whether infrastructure and policy changes to facilitate the new traffic mixes are needed.

The main research question for this study is:
How can cities enable travellers to use autonomous and shared autonomous vehicles while reducing congestion effects for all road users, using easy-to-implement solutions?

This was answered by addressing the following sub-questions:

1. *What are the congestion effects of the on-road behaviour of AVs for different penetration rates on urban main roads, using the current infrastructure?*
2. *What are the congestion effects of the on-road behaviour of SAVs for different penetration rates on urban main roads, using the current infrastructure?*
3. *What are easy-to-implement solutions that aim at reducing congestion effects caused by AVs and SAVs, while keeping changes in the infrastructure low?*
4. *What are the congestion effects of using these easy-to-implement solutions under different penetration rates of AVs and SAVs?*

Method

For this study, a traffic model was made using the micro simulation software package Vissim and a case study network in The Hague during the morning peak period. The effects that could be expected to be displayed by the model were first researched by performing a literature study on urban traffic and developments in the automotive industry. Then inputs for the simulation model were defined. These inputs were based on scenarios that were formulated using mobility data from the Municipality of The Hague, research on the demand for and behaviour of AVs and SAVs, and interviews with experts. After the scenarios were conceptualized and specified in the model, results on the key performance indicators (KPIs) could be obtained. After this, it was evaluated how the results could be improved by applying alternative designs. These designs were conceptualized and specified in the modeling language, after which final results could be obtained and statistically tested.

Background: automotive developments in urban traffic

The urban road network serves two main functions: providing adequate flow for through traffic and providing access to surrounding real estate. On higher level roads, the emphasis lies more on the former, while on lower level roads, the emphasis lies more on the latter. Municipalities design their roads in such a way that adequate capacity is provided for the function of the road.

This capacity is largely determined by the road's users. The headways and speeds that they employ determine how many vehicles can pass a road section within a certain time period. When all users employ the same headway and speed, the flow is smooth and capacity high. However, in reality, drivers display highly

stochastic behaviour, both internally and compared to one another. This causes turbulence in the flow. Traffic control is the most important determinant of urban road capacity. In order to establish right-of-way, intersection control mechanisms significantly reduce average vehicle speed by forcing a portion of traffic to slow or stop.

The characteristics of urban traffic described here, can be influenced by new developments in the automotive industry. The specific developments that were focused on here, are vehicle automation, -connectedness and -sharing. Vehicles that are developed using these technologies, AVs and SAVs, can change urban mobility both on a macroscopic level and on a microscopic level.

The fortitude of these macroscopic and microscopic impacts, however, is dependent on how fast these technologies penetrate the mobility market. The market penetration of AVs and SAVs is widely debated in literature, and seems to be highly uncertain. Therefore, it was needed to formulate market penetration scenarios for this study. To formulate these scenarios, it was chosen to focus on the year 2040 as a study year. It was found that the market penetration of AVs could realistically be somewhere between 25% and 80% of all personal vehicles in 2040. For SAVs a market penetration of somewhere between 3% and 50% of all car travellers was found.

Macroscopically, travel demand and even land use could change significantly as a result of reduced generalized trip cost. A higher tolerance for longer travel times could cause both induced demand and urban sprawl. Further, autonomous, connected and shared applications are expected to co-develop and amplify each other's usefulness. Therefore, it is likely that as the penetration of AVs increases, so will the penetration of SAVs.

The literature is quite positive about the microscopic effects of AVs on the traffic flow. Literature was found reporting on smoother traffic flow and increase of road capacity. This is thanks to less deviation in behaviour, both over time in the same car and between cars, smoother acceleration and deceleration, and better anticipation. The positive effects were, however, on the condition that shorter headways are employed. Following research on emergency stop technologies, connected technologies and policies on data transmission, this was in fact assumed to be the case. Little research was available on the microscopic effects of SAVs. What was found in the research on macroscopic effects, though, was that SAVs can be expected to circulate empty on the network. Further, concerns were uttered about the future of curb use in the city when SAVs drop-off their passengers in front of their door instead of finding a parking spot.

From looking at the available research, it was found that the scientific gap could be found in looking at the combined effects of AVs and SAVs in a realistic urban environment in transition. This is therefore what was focused on in the modeling part of the study.

Conceptual model

Following the literature review, a conceptual model was formulated with various market penetration scenarios for AVs and SAVs (presented in table 1), system elements and KPIs. The names of the scenarios are uniformly structured to signify the penetration of AVs out of all personal vehicles and the penetration of travellers that are travelling to the case study area in a SAV. The formatting is as follows: <penetration AVs>/<penetration SAVs>.

Table 1: Scenarios

Scenario	AV (% of vehicles)	Shared (% of travellers)	Pax SAVs (# pax)	Buses
1. 20/3	20%	3%	1,1	AV
2. 50/25	50%	25%	1,5	AV
3. 80/50	80%	50%	2	AV
4. 0/0	0%	0%	N/A	Normal
5. 50/0	50%	0%	N/A	AV
6. 100/0	100%	0%	N/A	AV
7. 100/100	100%	100%	2	AV

It was expected that a higher penetration of AVs would increase the road capacity and reduce variations in traffic flow. This would in turn reduce vehicle delays and energy consumption. On the other hand, it was expected that a higher penetration of SAVs would reduce road capacity due to curbside stopping, increase traffic intensity on low capacity links due to (empty) circulation on the network, and increase variations in traffic flow. All this was expected to lead to an increase in vehicle delays, an increase in distance travelled, and an increase in energy consumption. These effects were expected to be slightly reduced when SAV occupancy was increased, simply by a reduction in traffic intensity.

Simulation model: scenario studies

As urban traffic is a highly complex system, it is difficult to summarize the above described effects in a simple mathematical model. Therefore, a simulation model was made. As a basis, a model that was used for a study for the municipality of The Hague was used. The network in this model contains a good balance between the traffic throughput function and the accessibility function.

The above described behaviours of AVs and SAVs were translated into the modeling language and various scenario models were made with different penetration rates of the different vehicle classes. Model verification was performed by comparing inputs in terms of vehicle intensities and penetration rates with measurements from the model, and by using the animation function of Vissim and emissions results to verify vehicle behaviour. Model validation was done by means of expert interviews and sensitivity studies. After model verification, model validation and determining the experimental set-up, results could be retrieved.

Results scenario studies

It was clear that higher penetration rates of AVs had a beneficial effect on vehicle delays and energy consumption. This is likely due to the increase in road capacity as a result of the shorter headways, smoother acceleration and deceleration, shorter reaction times and more deterministic behaviour. These effects could already be detected at low penetration rates, suggesting that AVs perform a buffer function for turbulent behaviour of human drivers.

The introduction of SAVs in the network, however, has negative effects on both delays of other road users and energy consumption. The total distance driven in the system does not significantly increase with SAVs, like it was suggested in the conceptual model as a result of extra network circulation. Therefore, it can be concluded that the negative effects on vehicle delay are not a result of increased traffic intensities, but rather of the turbulence SAVs cause in the traffic flow by forming blockages when they stop to drop off their passengers, and the queues they cause by overusing links of limited capacity to circulate the network. The scenarios where up to 50% of travellers used SAVs and personal vehicles were increasingly autonomous still performed better in terms of delay than did the scenario without AVs and SAVs. This is overall a positive outlook for the future of urban mobility.

Simulation model: design studies

From the scenario studies, it became clear that to allow travellers to make use of AVs and SAVs while minimizing road congestion for all users, it is needed to manage the SAVs to minimize their negative impact. In this study, two designs with this aim were tested that are easy-to-implement for the municipality as they require only small infrastructure adjustments and limited investments: dedicated lanes for SAVs and kiss & ride (K&R)-facilities for SAVs. These designs were further defined and implemented in the simulation models of the four scenarios with different penetration rates of SAVs (1: 20/3, 2: 50/25, 3: 80/0, and 7: 100/100). After defining the experimental set-up using the same methods as for the scenario studies, the experiments could be performed and results retrieved.

Results design studies

After implementing the two designs in four scenarios with varying penetration rates of SAVs, it was found that the dedicated lanes design was unsuccessful in reducing the delays and emissions, even though the distance driven by SAVs was significantly reduced with this design. The dedicated lanes even had a negative effect, namely on the bus delay. The K&R design, on the other hand, turned out to be an effective measure to reduce delays caused by SAVs. However, this was only the case when the penetration rate of SAVs was higher than 25% of travellers. Effects that this design had on the distance travelled and energy consumption were only noticeable in the extreme scenario of 100% market penetration of SAVs.

The results for distance travelled and energy consumption in all cases confirmed the fact that any differences found in the vehicle delays were attributable to differences in driving behaviour of the AVs and SAVs from conventional cars. Therefore, it could be concluded that the results for vehicle delay purely reflect the congestion effects of the AVs and SAVs in terms of driving behaviour. The delay results for both the scenario studies and the design studies are presented in table 2. In this table, a distinction is made between non-SAV vehicles (cars, LGVs and HGVs, either human driven or AV) and SAVs. This is because the SAVs spend more time in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted image of the effects.

Table 2: Scenario and design results for vehicle delays of non-SAVs and SAVs

	Non-SAV mean delay (mm:ss)			**SAV mean delay (mm:ss)**		
Scenario/design	**None**	**Dedicated lanes**	**K&R-facilities**	**None**	**Dedicated lanes**	**K&R-facilities**
1: 20/3	02:20	02:36	02:32	03:43	04:27	04:05
2: 50/25	02:55	02:50	02:50	04:00	04:22	03:49
3: 80/50	02:28	02:11	01:59	03:35	03:41	03:06
4: 0/0	04:00	-	-	-	-	-
5: 50/0	01:31	-	-	-	-	-
6: 100/0	01:16	-	-	-	-	-
7: 100/100	06:15	05:50	03:36	09:15	09:52	04:36

Recommendations

Following the results from the scenario studies and the design studies, it could be concluded that cities with similar networks like the case study (ie. an urban main road where high traffic throughput is combined with accessibility functions, and interactions with other traffic is controlled by signalized intersections), can count on AVs to have a positive influence on the traffic flow here, reducing congestion and energy consumption. However, SAVs, which are likely to gain popularity together with AVs, can have a negative influence on delays of other road users and energy consumption by forming blockages, causing turbulence in traffic flow and causing queues on low capacity links. The research pointed out that these negative effects can be reduced by facilitating the SAVs with a fine-meshed network of kiss and ride-facilities on the sides of the underlying road network. However, the results suggest that this will only become effective at higher penetration rates of SAVs. As the research already detects negative effects at lower penetration rates, it is advisable to perform more research on solutions that will work when less than 25% of travellers or less are using SAVs. Likely these solutions can be found in alternatives that divert SAVs away from the main roads, as this preserves the balance between traffic throughput and access to surrounding real estate.

Besides the above mentioned recommendations that specifically target the problems found in this research, it is advisable for municipalities to be cautious and closely monitor the situation when it comes to AVs and SAVs in their city. As these are new technologies and concepts, many other unexpected problems could occur like the ones found in this research. Furthermore, technological developments and market adoption are moving at a fast pace. Adopting a wait-and-see attitude in this could prevent the city from being able to benefit from these new mobility concepts or could even be potentially harmful. Therefore, it is advisable to pay attention to the impacts of (S)AVs in all future infrastructure plans.

Limitations

However, before interpreting the results of this research as a universal truth, its limitations should be taken into account. These can be found mainly in the forecasting, and the conceptualization and specification of the model.

There are many uncertainties when it comes to the technological and market developments of (S)AVs. Therefore, assumptions had to be made with regards to the demand effects and the driving behaviour of these vehicles. From the sensitivity tests, the model was found to be especially sensitive to the base demand and the AV headways. If these factors turn out to have a higher value in reality, this could have negative effects on congestion. The industry and mobility market should be closely monitored to see how these assumptions will relate to reality.

A model is always a simplified version of reality. Therefore, reductions have to be made. With each reduction, a piece of information is lost. Important reductions made in this research relate to the translation of demand forecasts and market penetration into OD matrices, the behaviour of AVs, and the network usage of SAVs.

Finally, the use of the case limits generalization of the results to parts of cities with similar networks. The effects of AVs on congestion and emissions could, for instance, be very different for a network with single lane roads, direct interaction with cyclists and unsignalized intersections.

Contents

List of Abbreviations

ACC	Adaptive cruise control
ADAS	Avanced driver assistance system
ADS	Automated driving system
ANOVA	Analysis of variance
AV	Autonomous vehicle
CACC	Communicative adaptive cruise control
CAV	Connected autonomous vehicle
D/C	Demand/capacity
HGV	Heavy goods vehicle
I/C	Intensity/capacity
IoT	Internet of things
KPI	Key performance indicator
K&R	Kiss and ride
LDW	Lane departure warning
LGV	Large goods vehicle
LKA	Lane keeping assistance
OD	Origin/destination
PCU	Passenger car units
PKT	Passenger-kilometres
PT	Public transport
SAV	Shared autonomous vehicle
SW	Shapiro Wilk normality test
TRB	Transportation Research Board
V2C	Vehicle-to-cloud
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VKT	Vehicle-kilometres
VOTT	Value of travel time savings

List of Figures

List of Tables

1

Introduction

When the first automobile appeared on the Dutch roads in 1896, there was a lot of disagreement about the potential of this technology. People were not convinced about the added value of this new mode and only saw safety issues. A few advocates saw the automobile as the pre-eminent means of enabling convenient long-distance travel. However, this was not possible with the then available infrastructure. The discussion faded to the background, until in the early twenties Henry Ford's affordable model T reached the Dutch mass market, causing an exponential increase in car ownership. It was not long until the government realized that the presence of these automobiles and their distinct use of the then available infrastructure required action. By 1927 a plan was presented outlining a completely new road infrastructure: separating motorized from non-motorized, and providing high speed corridors for automobiles. Looking back, this plan was the basis for the success of the automobile and how it reshaped Dutch society [1].

Now, almost a century later, we are at the dawn of a new era in mobility. Technologies are being developed and brought to the market that many researchers believe have the potential to reshape societies once more. Developments like vehicle automation, connected technologies and sharing are inspiring thinkers to dream about new kinds of cities. Cleaner cities, where public space is used more efficiently. Cities where the people who work there can live further away and go to work using on-demand autonomous services which bring them from their doorstep to their office. However, there are also people who foresee negative consequences: higher tolerance for longer travel times leading to road congestion, and issues around safety versus efficiency. Some examples of studies exploring these possible futures are Fagnant and Kockelman [15] and Tillema et al. [58]. They are unsure about how the transition will happen, but they are sure that it will happen and that it will change cities.

So municipalities know that change is underway. But they do not know exactly what to expect. A future where all cars are autonomous is still far away, likely far outside the term of politicians and civil servants who are now running the municipality. Therefore, understandably, many cities adopt a "wait-and-see" attitude. However, car manufacturers and mobility services are rapidly moving forward, bringing new technologies and services to the market daily. It will not be long before autonomous vehicles (AVs) and shared autonomous vehicles (SAVs) will start appearing in urban traffic. Then the concern is not only related to how mobility as a whole will evolve, but also how the traffic is impacted on a tactical and operational level. Just like in 1927, now we still have the power to shape how the transition will affect us. So it is not too early to start thinking about how to approach this transition.

Finding out how cities can prepare for the transition, requires knowing how vehicle automation, connected technologies and sharing may impact urban traffic. This is not as straightforward as it may seem, because the urban traffic system is highly complex. There are researchers who have investigated the traffic flow effects of AVs in mixed traffic, like Ioannou and Stefanovic [29], Bose and Ioannou [6] and Calvert et al. [8]. However, this was mostly done for traffic systems such as highways or fictional, isolated roads. Furthermore, they study the effects of single technological developments in isolation, even though researchers widely agree that developments like automation, connected technologies and sharing reinforce each other. To see the real effects of the transition towards autonomous and shared autonomous driving on urban networks, it is necessary to look at the whole system. In the urban network, there are many factors at play that can influence or be influenced by the interaction with new types of vehicles. There is interaction with different network levels and modes, there are signalized intersections, parking, and public transport.

In an attempt to fill this gap, this research focuses on the effects of autonomous and shared autonomous vehicles on the urban traffic system in a transition period. The focus will be on the microscopic level and on providing tangible results, so municipalities can already evaluate whether infrastructure and policy changes to facilitate the new traffic mixes are needed.

1.1. Scope

Autonomous driving is a source of many questions and uncertainties. Not all uncertainties can be addressed in this research. Some will need to be transformed into assumptions and scenarios, and some will fall entirely outside of the scope of this thesis.

Transportation research is often divided into two categories: demand modeling and supply modeling [10]. The former focuses on trip generation, trip distribution and mode choice, while the latter focuses on how traffic is assigned to the network and what that means for network loads. Neither of these categories is explicitly addressed in this research, but they do provide important input. The focus of this research is on a more tactical and operational level where traffic dynamics can be studied microscopically. Specifically, the effects of differences in driving behaviour on traffic dynamics, and consequently on congestion, will be studied.

The area of study will be urban main roads and large intersections. This is because these roads provide a combination of high traffic throughput and enough access points, causing traffic interaction. This combination allows making the effects of AVs and SAVs on urban traffic most visible and the opportunities to apply infrastructure changes are numerous. As a basis, the current state of these roads, intersections, and the intersection control is used. Highways and the low level urban network fall outside of the scope. Further, as road traffic is being considered, any modes which do not make use of roads fall outside of the scope. Modes that are not cars, but do make use of the roads, such as bicycles and buses, will be included on an assumption basis.

As the focus is the transition period with different types of vehicles on the road, it is important to see how these vehicles differ from each other microscopically. Therefore, vehicle capabilities are researched that cause differences in driving behaviour from normal vehicles. Only the driving behaviour that results directly from the advanced driver assistance systems (ADAS) or automated driving systems (ADS) will be taken into account. Any differences in driving behaviour as a result of psychological factors fall outside of the scope. The driving behaviour that is mostly focused on, in this respect, is how a vehicle reacts to its direct environment. More indirect decisions, for instance route choice, are left outside the scope.

A municipality can design its city's road configuration and traffic control in multiple ways in order to facilitate new road users such as AVs and SAVs. As this study aims to quantitatively assess the measures' effectiveness, only a small set of designs could be tested. It was chosen to focus on dedicated infrastructure and accompanying measures that are easy to build and implement on the short term.

1.2. Research objectives and research questions

Based on the gaps found in the literature, which will be further discussed in section 2.5, this research will focus on applying a model-based approach to evaluate effects of different mixes of AVs, SAVs and traditional cars on a city's primary road network. Further, this model will also be used to evaluate various changes made to this network. As a case study, a small network in the city of The Hague was chosen, and as a study period, 2040 was chosen.

The research goals were formulated as follows:

1. Provide insights in the congestion effects of AVs and SAVs on urban traffic in the transition period, focusing on the differences in microscopic behaviour as compared to normal cars.
2. Investigate which easy-to-implement solutions the municipality could apply to facilitate the new mix of urban traffic that can be expected in the future.

The main research question for this study is:
How can cities enable travellers to use autonomous and shared autonomous vehicles while reducing congestion effects for all road users, using easy-to-implement solutions?

This will be answered by addressing the following sub-questions:

1. *What are the congestion effects of the on-road behaviour of AVs for different penetration rates on urban main roads, using the current infrastructure?*
2. *What are the congestion effects of the on-road behaviour of SAVs for different penetration rates on urban main roads, using the current infrastructure?*
3. *What are easy-to-implement solutions that aim at reducing congestion effects caused by AVs and SAVs, while keeping changes in the infrastructure low?*
4. *What are the congestion effects of using these easy-to-implement solutions under different penetration rates of AVs and SAVs?*

1.3. Method

For this study, a traffic simulation model was made using the micro simulation software package Vissim, with as a case study, a road network in The Hague during the morning peak period. Micro simulation allows for the modeling of vehicle-level driving behaviour, which is the main independent variable in this research. Furthermore, Vissim is not only able to show effects in traffic dynamics by means of animation, but also congestion-, network usage and energy consumption effects on various aggregation levels.

Performance requirements and KPIs that were used for evaluation, were formulated up front based on literature and interviews with the municipality of The Hague. Inputs for this model were based on future scenarios for 2040 that were formulated using research on the demand effects and behaviour of AVs and SAVs, mobility data from the Municipality of The Hague, and interviews with experts. Expected relationships between the model input, model elements and model output were conceptualized in a conceptual model. After this conceptualization, the simulation model could be specified and calibrated. From experimentation with this model, results for the KPIs could be obtained.

Then, it was evaluated whether these results could be improved on by applying easy-to-implement solutions. This was done based on previous research and expert interviews. The resulting designs were conceptualized and specified in the modeling language, after which final results could be obtained and statistically tested.

The steps that are described here, are part of an iterative process. They are not merely performed sequentially in a constant feedback loop. In this way, insights that are obtained later on can be used to improve all stages of the study and designs continuously.

1.4. Reading guide

The report of this thesis project is structured into six chapters and six appendices. The background information and literature review is presented in chapter 2, which targets the basics of urban traffic, and addresses relevant developments in the automotive industry and their expected implications for urban traffic. The model that was used to answer the research questions and close the scientific gaps, is discussed in chapters 3, 4 and 5. The case, the system elements and their expected interrelations are introduced in the conceptual model in 3. The quantification of the conceptual model, building on an existent simulation model, is presented in chapters 4 and 5, where chapter 4 targets the scenario studies, and chapter 5 addresses the designs. The results of each of these studies are presented in their respective chapters. Finally, answers to the research questions, recommendations, limitations of this research and leads for further research are presented in the conclusion in chapter 6.

Additional information to support statements made in the main report, is provided in the appendices. Appendix A contains the summary of two interview sessions with representatives of the municipality of The Hague and Arcadis that were performed in the exploratory phase of the research. Appendices B and C contain detailed information on the inputs of the simulation model. Specifically, in appendix B these inputs are the origin-destination (OD) matrices for each vehicle type, and in appendix C these inputs are the parameter settings for the driving behaviour of each vehicle type. In appendix D, summaries are provided of the interviews that were conducted with experts in order to validate the simulation model. Finally, appendices E and F contain the results of statistical tests performed on the model output, where appendix E addresses the scenario studies and appendix F addresses the design studies.

2

Automotive developments in urban traffic

Recent developments in the automotive industry are a popular topic of scientific research and discussion. In this chapter a review is presented of the literature that addresses this topic. First, in section 2.1, an introduction will be provided to relevant aspects of urban traffic. Then, in sections 2.2, 2.3 and 2.4, developments in vehicle automation, connected technologies and sharing will be presented, as well as researchers' opinions of how fast they will penetrate the mobility market, what their macroscopic effects may be and what their microscopic effects may be.

2.1. An introduction to urban traffic

As the aim of this study is to research the effects of on-road behaviour AVs and SAVs on urban traffic, in terms of congestion, it is first important to determine the most important factors that determine congestion in the city. As congestion occurs when the intensity of vehicles on a road exceed the road's capacity, it is important to look further into these concepts in an urban setting. Additionally, congestion not only increases as the intensity of vehicles rises, but can also be made worse by an unstable traffic flow. In this section, these aspects of urban networks are discussed.

2.1.1. Road functions

A road can have several functions, which determines its design requirements and performance criteria. Categorizations of road functions can be found in multiple forms, but all resemble a scale from high-level to low-level. The Dutch knowledge institute CROW distinguishes only three road categories: through-roads or expressways, distributor- or arterial roads, and property access roads [32]. The American Transportation Research Board (TRB) distinguishes two functional categories: principal arterial and minor arterial. Each of these consists of two design categories: for principal arterial there are the high-speed roads and the suburban roads and for minor arterial there are intermediate roads and urban roads [59]. Finally, the municipality of The Hague, which will return later in this research as a case study, distinguishes five road categories: (inter)national main roads, regional main roads, urban main roads, district access roads, and property access roads [20]. The most important characteristic of all these scales is that when moving from higher level to lower level road types, a high traffic flow becomes less important and access to the surrounding area becomes more important. Therefore, lower level roads will contain more intersections, more parking facilities and more interaction with other road users such as cyclists, pedestrians and bus. In figure 2.1, the three categorizations are summarized.

In this research, the focus will be on roads that fall in the upper half of the urban road spectrum. These roads typically display a mix between providing high traffic throughput and providing access to local real estate and lower level roads. Accordingly, high traffic flow is encouraged, for instance by having enough lanes and separating the bicycle lanes from the road. Nonetheless, the flow is regularly interrupted by signalized intersections at which the turning movements are often greater than 20 percent of the total flow, because downtown flow typically involves a significant amount of circulatory traffic. Turbulence in the flow caused by stopping taxicabs, buses, trucks, and parking vehicles is typical to urban roads, although more common on the lowest level [59]. Later on in this research, it will be discussed what the introduction of AVs and SAVs means for this balance between traffic throughput and access that is typical to urban roads.

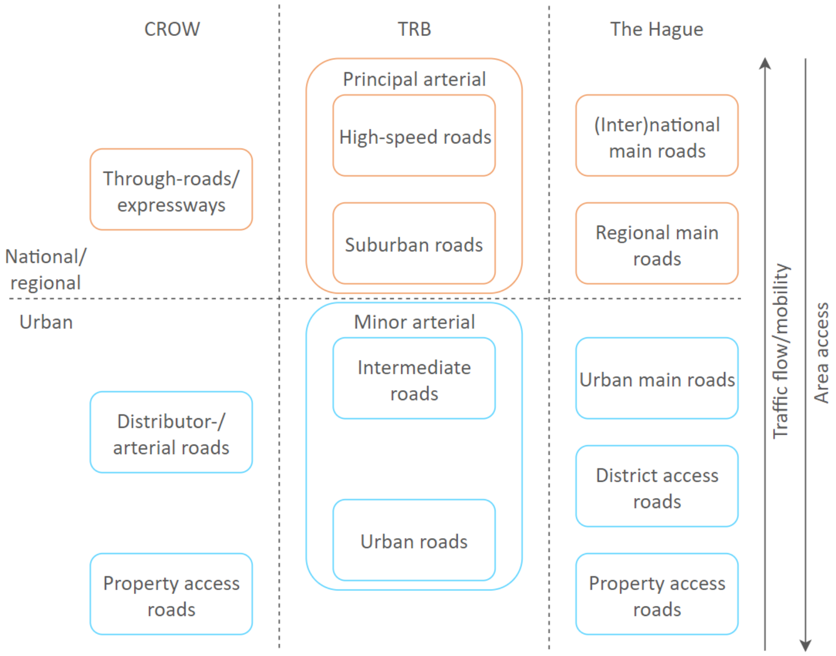


Figure 2.1: Road categorizations summarized. Source: KpVV CROW [32], TRB [59], Gemeente Den Haag [20]

2.1.2. Traffic flow and capacity

The traffic flow requirements that accompany a certain road function are attained by ensuring that the road has sufficient capacity. Capacity is defined by Wardrop [63] as being the maximum amount of passenger car units (PCU) that can traverse a road section at a minimum acceptable speed in a certain time period. Once this amount is exceeded, the consequential reduction in average speed will imply that the total amount of PCU traversing this road section within the same time period drops below the capacity value.

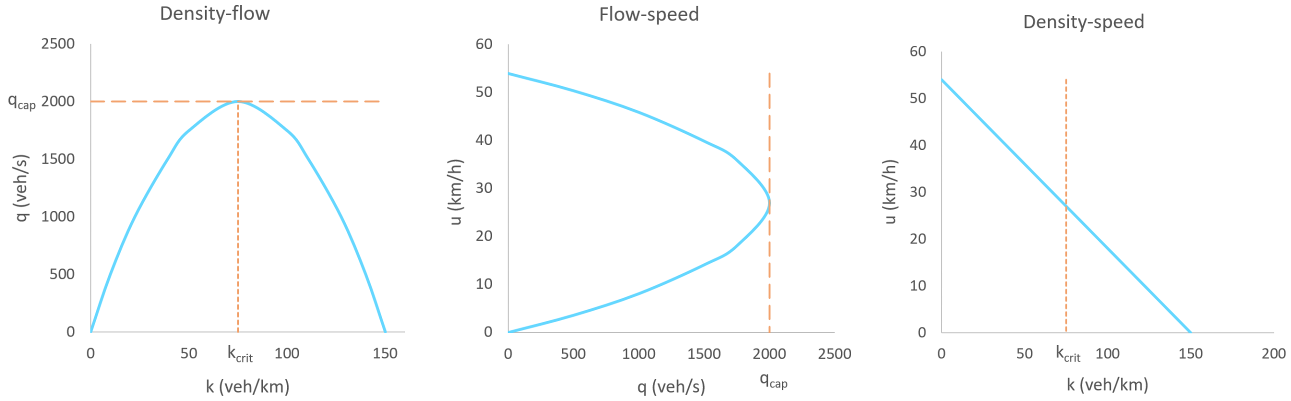
Especially in urban settings, there are a lot of factors that determine a road's capacity and its consequential flow. That the capacity of a road is largely dependent on its users can best be illustrated using a basic traffic flow theory principle: the fundamental diagram.

According to traffic flow theory, a traffic state can be described using three variables that are measured on microscopic level: speed (v), distance headways (s), and time headways (h). On road level, these variables can be used to calculate the states average speed (u), density (k) and flow (q) using $u = < v >$, $k = \frac{1}{<s>}$, and $q = \frac{1}{<h>}$. The primary relationship between these variables is described in equation 2.1 [23].

$$q = k * u \tag{2.1}$$

A clarification of possible traffic states is found when the bilateral relationships between each of the three variables is investigated. These relationships form the fundamental diagram, which is used as a basis for almost all traffic flow research. A simple version of the fundamental diagram, which was developed in 1934 by Greenshields [23], is depicted in the three different planes in figure 2.2. Figure 2.2a clearly shows that an increase in density will mean an increase in flow until the moment when the road reaches its capacity, which, as was found earlier, can be defined as the road's maximum flow. When this happens, flow will drop and can become zero (stopped traffic). Figure 2.2b shows that when there is little to no traffic (very low flow), drivers can drive their desired speed, and as traffic increases, this speed decreases until a point where the decrease in average speed causes a decrease in the traffic flow, and both flow and speed become zero in completely jammed conditions. The reason why drivers reduce their speed in higher traffic densities is because every driver has a desired time gap between him and the vehicle in front. As the density increases, the distance headways decrease, and the only way for a drive to keep his desired time headway is by reducing his speed. This is well portrayed in figure 2.2c where a negative linear relationship can be seen between density and average speed.

So each driver has an individual preferred time headway and they will adjust their speed and distance headway accordingly. Since the aggregate of this individual time headway is the flow, this means that the drivers' time headways influence the road's capacity: the longer the average time headway, the smaller the capacity is. This proves how important individual time headway is in determining a road's capacity. Later on in this study, it will be discussed to what extent AVs and SAVs can have an influence on the average time headway.



(a) Density-flow plane

(b) Flow-speed plane

(c) Density-speed plane

Figure 2.2: The fundamental diagram in three different planes by Greenshields [23]

The above described relationships are valid for a simple road section with an uninterrupted flow. However, this is rarely the case, especially in an urban setting. TRB [59] distinguishes three main factors that influence flow characteristics in urban settings: street environment, interaction among vehicles, and traffic control.

The street environment is comprised of its geometric characteristics (eg. number and width of lanes, speed limit), roadside activity (eg. parking, cyclists), and adjacent land uses. The interaction among vehicles is determined by traffic density (as discussed above), proportions of trucks and buses, and turning movements. These interactions are mostly present at intersections, but also between intersections. More roadside activity and more interaction among vehicles usually means that the road has an important access function to the lower level network and surrounding real estate. These are, however, elements that significantly reduce the road's capacity.

Traffic control is the most important determinant of urban road capacity [59]. In order to establish right-of-way, intersection control mechanisms significantly reduce average vehicle speed by forcing a portion of traffic to slow or stop. As the focus in this research is on urban main roads, which are typically often interrupted by signalized intersections, it is important to regard the influence that signalized intersections have on the network performance. Signalized intersections play an important role in providing access to the lower level road network and preserving traffic safety. On the other hand, their presence influences vehicle delays and emissions.

Traffic control algorithms are designed on a case-by-case basis, and are dependent on many factors, such as the average vehicle counts per direction [31]. The algorithm determines the capacity of the signalized intersection for each direction. However, in urban traffic it often happens that the queue on the destination link spills back, reducing the amount of vehicles that can enter the destination link during green time. Therefore, the average vehicle delay caused by a signalized intersection is difficult to determine in urban traffic.

In their review study on the effects of signalized intersections on local emissions, Pandian et al. [39] have found that traffic conditions found around signalized intersections heavily influence emission levels. These conditions are deceleration, dwelling and acceleration of vehicles. Therefore, signalized intersections are, along with other elements that may interrupt the traffic flow, not beneficial for air quality in the city.

The studies show that it is clear that in addition to individual time headway, the road's access characteristics and traffic control are important in determining a road's capacity. Later on in this study, it will be discussed how AVs and SAVs can influence this.

2.2. Automation

In addition to electrification, car manufacturers are now also investing in the development of technologies for the automation of their vehicles. Cars are being equipped with more and more sensors and actuators to assist and eventually replace the driver. According to Bengler et al. [3] who conducted a review of accomplishments and current research fields, both industry and research institutions are investing heavily in research and development of advanced driver assistance systems (ADAS). These systems are aimed at increasing safety and driver comfort.

However, a car that contains ADASs is not necessarily an autonomous car. In fact, the Society of Automobile Engineers (SAE) distinguishes six levels of automation [47]. SAE [47], Tillema et al. [58] and Shladover [50] provide a quite accurate description of these levels which is used as a basis here. The levels are schematically presented in figure 2.3.

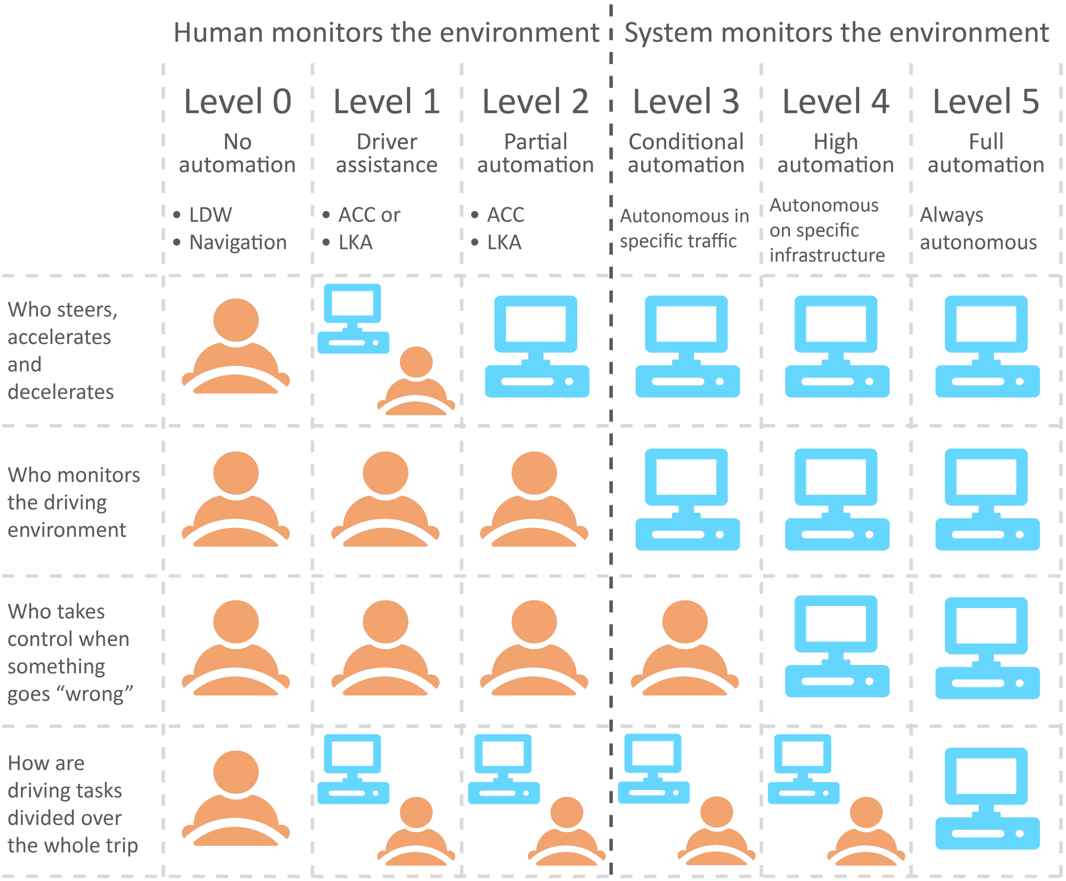


Figure 2.3: SAE levels of automation, source: Shladover [50]

In levels 0 to 2 the human driver is primarily responsible for monitoring the environment. In level 0, *no automation*, the driver is not assisted in any of the driving functions. Note that in level 0 informing and advising systems, such as navigation, blind spot warning, and intelligent speed advise, can be present in the car.

From level 1 upwards, the cars are increasingly equipped with ADASs. Examples of ADASs are adaptive cruise control (ACC), frontal collision avoidance (FCA) and lane keeping assistance (LKA). The SAE makes a distinction between systems that provide longitudinal monitoring and control (such as ACC and FCA) and systems that provide lateral monitoring and control (such as LKA). The distinction between level 1 and level 2 is then made in that vehicles of level 1 only contain longitudinal or lateral control and vehicles of level 2 contain both. These can be switched on and off by the driver and may only be able to operate under certain conditions.

In levels 3 to 5 the responsibility for monitoring the environment can gradually be given to the car. These levels are often called high to full automation and are an extension of the partially automated ADASs. This is because in principle, the vehicle is able to perform dynamic driving tasks by itself. In these levels, one starts speaking of automated driving systems (ADS).

In level 3 the driver can let the car drive and monitor the environment while doing something else, but needs to be ready to intervene when the system requests this. This can happen, for instance, in unexpected traffic conditions or when a system in the car behaves irregularly. In level 4 there are situations, for example on highways, when the system can do everything by itself, even handling unexpected situations, and the driver does not need to be ready to intervene. Note that level 3 and level 4 are often mentioned together in the same breath, because they both allow the car to drive itself fully, but human interference is possible. In level 5, the car can be called fully autonomous. There is no driver needed (there may not even be a steering wheel) for any of the car's functions. All the highly futuristic sketches where autonomous Ubers drive through the city the whole day to pick up and drop off people talk about vehicles of this level of automation.

Many different terms are coined when talking about cars that are equiped with ADASs and ADSs. Automated, autonomous, self-driving and driverless are the most common ones. In this thesis, only two terms will be used: automated when referring to cars with any level of automation higher than 0, and autonomous when referring to cars of level 3, 4 and 5.

The availability of vehicle automation can have an impact on urban traffic both macroscopically by influencing the travel demand, and microscopically in terms of the on-road behaviour of the vehicles. However, this is likely dependent on the extent to which AVs have penetrated the AV market. Therefore, literature forecasting market penetration rates of AVs was reviewed. This literature will be discussed in section 2.2.1. Afterwards, a discussion of literature dealing with the expected macroscopic effects of AVs will be presented in section 2.2.2. A discussion of the literature dealing with the on-road behaviour of AVs and consequential microscopic effects will be presented in section 2.2.3.

2.2.1. Market penetration

As market penetration rates of automated cars have a high impact on urban mobility, but also a high uncertainty, many researchers speculate about these rates. Some researchers, such as Fagnant and Kockelman [15], and Tillema et al. [58], use rough estimates for the development of their future scenarios. Others assume a future with 100% fully autonomous vehicles, like Correia and Van Arem [9] and Fagnant and Kockelman [14]. Fortunately, there are numerous studies that attempt to quantify market penetration rates over the next 40 years. These studies will be summarized here and based on these studies an estimate will be made for market penetration rates that will be used in this study.

Firstly, there is Milakis et al. [36], who constructed four market development scenarios for The Netherlands in 2030 and 2050. For each scenario, they estimated the moment of market introduction, the share of AVs in the fleet and the share of total vehicle-kilometres travelled (VKT) with AVs. Their estimations were based on expert opinions that were gathered in various workshops. Their conclusions were that market introduction of conditionally automated vehicles will take place somewhere between 2018 and 2028, while market introduction of fully autonomous vehicles will have to wait until somewhere between 2025 and 2045. Resulting market shares of conditionally and fully autonomous vehicles together for 2030 are between 1% and 11% of the total fleet and between 1% and 23% of total VKT. For 2050 this is between 7% and 61%, and between 10% and 71% respectively.

Secondly, Litman [34], who has a relatively pessimistic view on AV developments, made a projection for six stages of market penetration of fully autonomous vehicles based on experience with the market penetration of previous developments in the automotive industry. The six stages he defines are: (1) *Available with large price premium*, (2) *Available with moderate price premium*, (3) *Available with minimal price premium*, (4) *Standard feature included on most new vehicles*, (5) *Saturation (everybody who wants it has it)*, and (6) *Required for all new and operating vehicles*. According to Litman [34]'s projections, stage 1 should take place in the 2020s and will imply a vehicle fleet with 1-2% AVs and 1-4% of total VKT. Stage 2 would then follow in the 2030s with a fleet share of 10-20% and VKT share of 10-30%. Stage 3 is expected in the 2040s with a fleet share of 20-40% and a VKT share of 30-50%. Finally the last stage for which Litman [34] has quantitative estimations is stage 4 in the 2050s with a fleet share of 40-60% and a VKT share of 50-80%.

Thirdly, BCG [2] have conducted an impact analysis for the municipality of Amsterdam in which they made estimations about future VKT and AV shares in the city based on survey data. The estimations were made only for the year 2050 and only fully automated vehicles were discerned. Cars with lower levels of automation are assumed to be categorized with all other cars. They developed 4 future scenarios for this survey: (1) *AVs only on highways*, (2) *AVs also on main traffic arteries*, (3) *AVs everywhere in the city*, and (4) *AVs everywhere in the city with car- and ridesharing*. Their conclusions were that in scenario 1 the AV would be used for 28% of total VKT, in scenario 2 59%, and in scenarios 3 and 4 68%.

Aforementioned researchers have only focused on the share of fully autonomous vehicles or have not discerned between levels of automation. Fortunately, there are also researchers who have made forecasts for multiple levels of automation. Underwood et al. [60] held an extensive survey among a panel of experts on robotics, automotive and transportation engineering to obtain an estimate for the introduction year of vehicles of the highest three automation levels. They found that the introduction of level 3 on freeways could be between 2017 and 2019, the introduction of level 4 on highways and surface roads could be between 2024 and 2030 with a median value at 2025, and the introduction of level 5 could be anywhere between 2025 and 2035 with a median value at 2030.

Nieuwenhuijsen et al. [38] provide the most detailed insights in market penetration of AVs of all levels of automation. They constructed a system dynamics model with which they computed market penetration levels in The Netherlands for 2 scenarios: a base scenario and an optimistic scenario, where the optimistic scenario is based on the upper bound scenario in Milakis et al. [36]. The system dynamics model tries to capture the complex market dynamics around automated vehicles and distinguishes three main feedback loops: *Diffusion of innovation*, *Learning by doing* and *Word of mouth*. Results from this study show more complex behaviour over time and are therefore best presented by the graphs in figures 2.4 and 2.5.

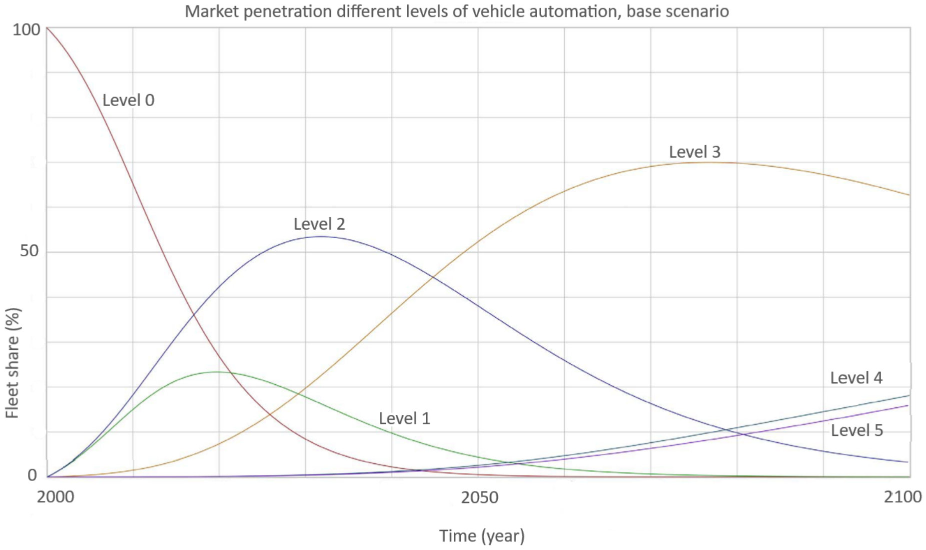


Figure 2.4: Results system dynamics model for AV fleet share, base scenario. Source: Nieuwenhuijsen et al. [38]

As can be seen in figure 2.4, in this base scenario, level 2 is initially the most popular type of AV and already reaches a 50% fleet share by 2025. After reaching its peak at 54% market penetration in 2032, level 3 starts to take over, which it eventually does in 2045 when both levels have reached a fleet share of 45%. Level 3 reaches its maximum fleet share of 70% in 2077 when vehicles of level 4 and 5 slowly start to take flight. Fleet shares for 2040 are as follows: level 0 2%, level 1 10%, level 2 49%, level 3 36%, levels 4 and 5 both 1,5%.

Figure 2.5 shows very different behaviour for the optimistic scenario. In this scenario, level 3 almost immediately overtakes level 1 and 2 in terms of fleet share to reach a maximum of 50% in 2026. Then fleet shares of level 3 start to decline as level 5 takes flight and level 4 wins some popularity. The fleet share of level 5 equals that of level 3 in 2037 at 32%, after which it keeps increasing to reach almost 100% in 2100. Fleet shares for 2040 are as follows: level 0 0%, level 1 1%, level 2 7%, level 3 26%, level 4 29% and level 5 37%.

Calvert et al. [8] also present an expectation of the market penetration. Their study mainly focuses on the short term (now until 2035) and on lower levels of automation. They discern only 5 levels of automation (0 to 4) where level 4 is full automation and level 3 is a combination of what is presented here as level 3 and 4. Their estimation of market penetration is instrumental to a traffic flow study and therefore not the main focus of their research. This is why their estimations are mainly based on literature findings.

Calvert et al. [8] estimate that to the extend that there will be automated vehicles in 2030, these will mainly be limited to level 1 which will comprise 15% of the total fleet. Level 2 will then have 10% of the fleet and level 3/4 only 3%. There will not be any fully autonomous vehicles yet. By 2035 level 2 will have taken a small sprint and will then comprise 20% of the total fleet just like level 1. Level 3/4 will have grown to 6% and there will still not be any fully autonomous vehicles.

Finally, the European Commission [12] wrote a roadmap to autonomous and connected driving in 2030. In this they describe a path for both autonomous and connected driving in Europe on the basis of developments and policies in member states. According to this report, they expect that autonomous driving in cities

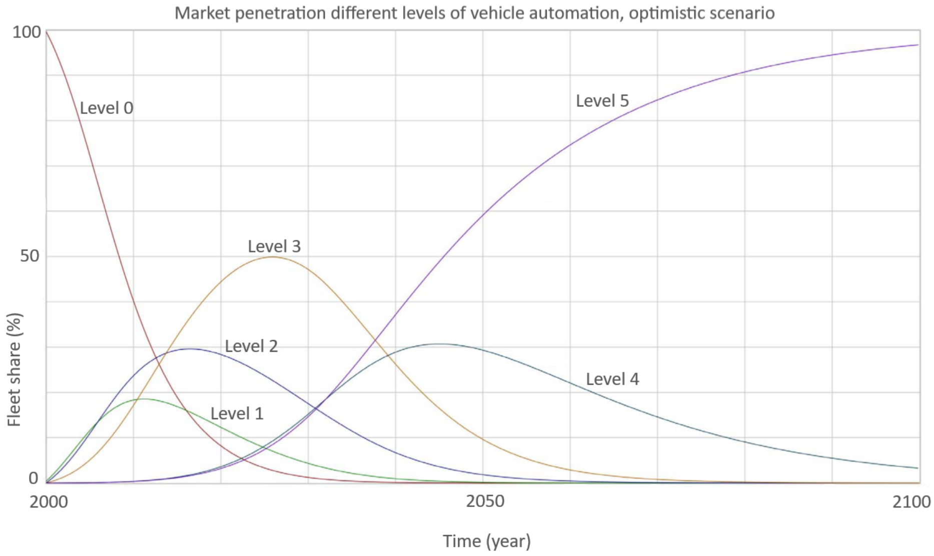


Figure 2.5: Results system dynamics model for AV fleet share, optimistic scenario. Source: Nieuwenhuijsen et al. [38]

will be already possible in The Netherlands between 2024 and 2030. When developments in connected technologies are added to this, fully connected and autonomous driving in cities will be possible in The Netherlands between 2028 and 2032. This might sound quite optimistic, but as it seems, both the European Commission and the Dutch Ministry of Infrastructure is prepared to make a lot of funds available and shape policy in order to make this possible [12, 58].

The above presented studies are only a few of the many studies that have attempted to quantify market penetration of automated vehicles. As these studies employ different methods and use different indicators for market penetration, they are rich in information when combined. To make educated and realistic estimations of the traffic mix to be expected in 2040, the researchers' predictions for year of market introduction, fleet share and VKT share of each level of automation are relevant. In table 2.1 an overview is presented of the studies' results regarding these indicators as far as there was information available.

As can be seen, there is a lot of inconsistency between the expectations of various researchers. It is safe to conclude that based on these findings, it is impossible to form one reliable traffic mix for this study. Therefore, the research will need to be done based on several scenarios. These scenarios are based on the literature and will be presented in chapter 3, section 3.2.

2.2.2. Macroscopic effects

Predictions of the macroscopic effects of autonomous driving can be found in all corners of society. For instance, Tillema et al. [58] predicts beneficial effects on the environment, social inclusion, traffic safety and economy (as a result of more efficient time usage). In this section, however, the focus will be in the macroscopic travel demand effects of autonomous driving. In section 2.2.1 it was discussed how the market share of AVs may develop over the next decades. However, it should be noted that the introduction of AVs may not only cause a shift in demand, but also an increase or relocation of demand. These higher level effects of AVs are not the focus of this study, but they are important to take note of.

To understand how demand and distance travelled is influenced by the availability of new mobility options, it is important to understand the working principles of the 4-step transportation model as explained in de Dios Ortuzar and Willumsen [10] and interactions between land use and mobility as explained by Wegener [64]. Wegener [64] states that there is a feedback circle between land use and transportation: if the generalized transport costs to location x are relatively low, this makes the location attractive, so more homes or offices will be built there. As there are more homes or offices on location x, more movements will take place towards x, but as more movements take place, the generalized costs per movement may increase due to congestion. High generalized transport costs make a location unattractive to live or work, so property development will stagnate unless investments are made to reduce the generalized transport costs. Generalized transport costs are usually defined as the price per kilometre multiplied with the access distance plus the traveller's value of travel time savings (VOTT) multiplied with the travel time to the location.

Table 2.1: Vehicle automation predictions for year of market introduction and penetration rates according to BCG [2], Calvert et al. [8], Litman [34], Milakis et al. [36], Nieuwenhuijsen et al. [38], Underwood et al. [60]

Autom. level			**Milakis et al.**	**Litman**	**BCG**	**Underwood et al.**	**Nieuwenhuijsen et al.**		**Calvert et al.**
							Base	**Optimistic**	
Level 1	**Year**		-	-	-	-	-	-	2015
	Fleet share	**2030**	-	-	-	-	18%	5%	15%
		2035	-	-	-	-	14%	2%	20%
		2040	-	-	-	-	10%	1%	-
		2050	-	-	-	-	4,5%	0%	-
Level 2	**Year**		-	-	-	-	-	-	2020
	Fleet share	**2030**	-	-	-	-	53%	17%	10%
		2035	-	-	-	-	53%	11%	20%
		2040	-	-	-	-	49%	7%	-
		2050	-	-	-	-	38%	2%	-
Level 3	**Year**		2018 - 2028	-	-	2017-2019	-	-	2025
	Fleet share	**2030**	-	-	-	-	20%	47%	3%
		2035	-	-	-	-	28%	37%	6%
		2040	-	-	-	-	36%	26%	-
		2050	-	-	-	-	52,50%	10%	-
Level 4	**Year**		2018 - 2028	-	-	2024-2030	-	-	2025
	Fleet share	**2030**	-	-	-	-	0,5%	15%	3%
		2035	-	-	-	-	1%	24%	6%
		2040	-	-	-	-	1,50%	29%	-
		2050	-	-	-	-	3%	29,50%	-
Level 5	**Year**		2025 - 2045	2020 - 2030	-	2025 - 2035	-	-	>2035
	Fleet share	**2030**	-	10-20%	-	-	0,5%	14%	0%
		2035	-	-	-	-	1%	26%	0%
		2040	-	20-40%	-	-	1,50%	37%	-
		2050	-	40-60%	-	-	2,50%	59%	-
	VKT share	**2030**	-	10-30%	-	-	-	-	-
		2035	-	-	-	-	-	-	-
		2040	-	30-50%	-	-	-	-	-
		2050	-	50-80%	28-68%	-	-	-	-
Total AVs	**Fleet share**	**2030**	1-11%	-	-	-	-	-	-
		2035	-	-	-	-	-	-	-
		2040	-	-	-	-	-	-	-
		2050	7-61%	-	-	-	-	-	-
	VKT share	**2030**	1-23%	-	-	-	-	-	-
		2035	-	-	-	-	-	-	-
		2040	-	-	-	-	-	-	-
		2050	10-71%	-	-	-	-	-	-

de Looff et al. [11] conducted a discrete choice experiment to pinpoint the VOTT in AVs and found that this value is 25% lower than it is for conventional vehicles. This, however, only holds true for full AVs in which it is possible to put the travel time to productive use. This would mean that a longer travel time is easily accepted and would yield the same generalized transport costs as a shorter travel time in a conventional car. Milakis et al. [36] conducted several interview sessions with transport experts to develop scenarios for 2030 and 2050, and estimated that the reduction of VOTT for AV users would be between 2 and 31% by 2050. Additionally, there are other aspects to AVs that may reduce generalized transport costs. In their literature review on the opportunities and barriers of AVs, Fagnant and Kockelman [15] found that better fuel efficiency, parking benefits and crash savings may yield the AV a much cheaper option than the conventional car.

As shown by studies from de Dios Ortuzar and Willumsen [10] and Wegener [64], this reduction in generalized transport costs may have the effect that a longer travel time or distance is much easier accepted. This may have several effects: people may switch from a different mode to the AV (as discussed in section 2.2.1), it may generate travel demand from different locations, and it may have an effect on land use: where people choose to live and work. All these effects ultimately mean that there will be more total distance travelled and more cars on the road. This is what is called latent demand.

This was applied to AVs by Correia and Van Arem [9], who found that the generalized cost reductions associated with AVs could significantly increase the distance travelled by car and the amount of cars on the road. They came to this conclusion by means of an optimization problem defined for mode choice, departure time and route choice with as the only available modes privately owned AVs and PT. Trip generation and the possible effects of a reduction in the VOTT is not even included in this optimization problem yet. Interviewees of Milakis et al. [36] agreed with this vision of the future, estimating a total VKT increase of 0 up to 27% by 2050.

As this research focuses on the microscopic effects of AVs and SAVs, the above described macroscopic effects will be left largely underexposed in the modeling study. If the demand effects were fully taken into account, this would make it difficult to isolate and study the microscopic effects in detail. However, it is important to realize that in reality, these effects would definitely play a role. Therefore, the demand is included as a factor in the conceptual model, and an optimistic estimate of the base demand is used in the modeling study. This will be discussed more elaborately in chapter 3.

2.2.3. Vehicle behaviour and microscopic effects

The goal of this research is to study the microscopic effects of AVs on congestion in urban traffic. Microscopic effects is coined here as a term to describe the effects that result from on-road driving behaviour and differences herein compared to conventional vehicles. In this, this study builds on various other research on the traffic effects of AVs. There is still a lot of debate about whether the driving behaviour of AVs will influence road capacity and traffic flow positively or negatively. In this section various views are presented. The focus will be on the effects of automation on itself, not combined with connected technologies. However, some studies may implicitly also take into account the effect of connected technologies on traffic flow. In this section, the research that was found on AV driving behaviour and its effects on traffic congestion will be presented.

The vehicle driving behaviours that result from ADASs and ADSs are widely discussed in literature. Here a distinction is made between differences in vehicle driving behaviour that result directly from the operating systems and differences in driving behaviour that result from humans reacting to the automatic systems in their own car or in other cars on the road. The latter are researched extensively by Sullivan et al. [53], but as mentioned in section 1.1, these effects will not be taken into account any further in this study. In terms of differences in longitudinal and lateral driving behaviour resulting directly from the ADASs and ADSs, Bose and Ioannou [6], González et al. [21], Ioannou and Stefanovic [29], Peng et al. [41], Saleh et al. [48] provide some insights based on the control algorithms developed for longitudinal and lateral control. The first research and development of these algorithms and technologies dates from 1986 when the Program on Advanced Technology for the Highway (PATH) was founded at the University of California Berkeley [41, 51].

As this study particularly focuses on urban traffic, the urban driving behaviour is taken into account. It can be argued that drivers of level 1 and 2 vehicles could choose to switch off their ADASs, because urban traffic is more dense and the flow is regularly interrupted by intersections. Indeed, Varotto et al. [61], Pauwelussen and Feenstra [40] and Klunder et al. [30] who all did research into changes in driving behaviour when ACC is deactivated and (re)activated argue that these are often reasons for drivers to switch the systems off. In this case, the level 1 and level 2 vehicles act as level 0 vehicles. Therefore, from here onward, only the vehicles which have additional systems to deal with urban traffic and intersections are considered as AVs. Their longitudinal and lateral behaviour is, however, still distilled from studies on lower level longitudinal and lateral control.

González et al. [21] performed a scientific review of automated vehicles' motion planning techniques. In this study they thoroughly investigated the calculative nature of the decision making process in automated vehicles. For more tactical decisions, the vehicles make use of algorithms such as *Dijkstra's shortest path algorithm*. For more operational decisions, their behaviour is defined by threshold values. In longitudinal control this threshold value is a predefined headway. When the sensors detect a longer or shorter headway, the actuators will directly respond. This takes away a lot of the stochasticity in longitudinal control.

There is some debate as to whether the longitudinal control implemented in AVs is beneficial for the traffic flow or not. Bose and Ioannou [6] argued in 2003 that vehicles with ACC could serve as a filter for rapidly accelerating and decelerating vehicles, because the use of sensors and control allows them to detect these changes earlier and react in a more smooth fashion. In 2005, however, Ioannou and Stefanovic [29] published an article revisiting the statements and results from this previous research. They argue the smooth acceleration of ACC vehicles leaves gaps that would in normal traffic not be there. These gaps cause cut-ins by other road users, which causes additional disturbances. So despite the fact that ACC stabilizes the traffic flow somewhat, it should be corrected by this effect. Calvert et al. [8] performed extensive simulation studies into the effects of various AV properties on the traffic flow. They confirm that vehicles with low level automation might only disturb the traffic flow at a penetration rate below 70%. An important reason that they mention is that vehicles of low automation levels usually employ longer headways than normal cars for safety reasons. This causes them to take up much more space, decreasing the road capacity and encouraging other vehicles to cut in. Further, if a penetration rate of 70% is ever to be reached, the vehicles are unlikely to be of such a low level of automation.

It seems that the traffic flow effects of the longitudinal control of AVs hinge on the minimum headway that they employ. However, the minimum headway that will be employed in AVs in the future is exactly a topic that researchers do not agree on. Above, Ioannou and Stefanovic [29] and Calvert et al. [8] assume conservative, low level ACCs which employ a large time headway with enough safety margin. This safety margin is needed, because AVs with a classical, sensor driven, ACC system can only see as far ahead as the car directly in front of them, while human drivers can see further ahead. Sullivan et al. [53] performed an extensive review of studies from 1995 to 2014 which looked at speeds and time headways employed by vehicles using ACC. They found that a lot of researchers found no difference between cars using this system and manually driven cars, but the researchers that did report a difference were also not in agreement with each other.

So the headway effects of classical ACC systems are quite debatable. But there are developments on the way that make it very likely that newer ACC systems all enable short time headways. Bose and Ioannou [6] report that the integration of ACC systems with frontal collision avoidance systems can allow much shorter headways, because the car will always be able to stop in case of unexpected events.

When looking at lateral control, the only behavioural difference that was measured in research was path deviation. In 1992, Peng et al. [41] already developed some of the first lateral control lane keeping algorithms which depended on discrete magnetic path markers. After field tests, none of the algorithms showed a path deviation of more than 30 cm. 21 years later, the technology and algorithms have developed to a much more mature stage. In 2013 Saleh et al. [48] developed and tested a lane keeping algorithm designed to share control with the driver. They performed a driving simulator experiment with one participant doing an unaided and an aided run. The experiment showed a reduction in path deviation by 28,9% and a reduction of the standard deviation of path deviation by 25,8%. This shows that lateral control algorithms cause a reduction in stochasticity around the intended path. Many researchers, such as Tillema et al. [58] suggest that due to this reduction in deviation, vehicles can drive much closer together, opening up possibilities to reduce the width of driving lanes.

In general, two studies were found explicitly reporting positive effects of AVs on traffic congestion. As early as 2003 Bose and Ioannou [6] conducted a simulation experiment testing the effects of introducing 10% semi-automated vehicles in a simple traffic setting. They found that semi-automated vehicles in mixed traffic cause a smoother traffic flow by filtering out rapidly accelerating vehicles. They did, however not conclude whether this could also increase the traffic flow. The experts interviewed by Milakis et al. [36] did present an idea about the effects of AVs on urban traffic flow. However, this was either positive or negative depending on the market penetration scenario. Especially with low penetration rates, they estimated that AVs may have a small negative influence on the road capacity, but for higher penetration rates, the road capacity could increase up to 6% by 2050. Their estimations for urban roads was slightly more pessimistic than those for motorways, because of the amount of signalized intersections and interaction in urban traffic.

Vaudrin et al. [62], who conducted a simulation study of mixed traffic in an urban setting, were indecisive on the effects of AVs on traffic congestion. Differences that they measured in traffic flow-related indicators were reported to be mainly attributable to the traffic light systems, not to the presence of AVs.

Lastly, there are also researchers who explicitly report negative effects of AVs on traffic flow. In 2005, Ioannou and Stefanovic [29] published an article that raised a critical note to their previous article from 2003. What they found was that while semi-automated vehicles may filter out rapid acceleration, by doing so, they may also invite cut-ins. This has an adverse effect on smoothness of the traffic flow. Calvert et al. [8] drew similar conclusions from their simulation model testing the traffic flow effects of several penetration rates of automated vehicles. They found that the long safety distance these vehicles may maintain may only cause negative effects on the traffic flow at low penetration rates (<70%). Additionally, they were unable to prove their hypothesis that the automated vehicles may have a positive effect on traffic flow by a reduction in lane changes.

In short, the microscopic effects of automation in itself are widely debated. The main advantage, which will return in the conceptual model of this study in chapter 3, being that they show a lot less deviation in behaviour due to control algorithms. However, combining these technologies with connectedness between vehicles may prove to have significantly further improved effects, especially with regards to reaction times and length of the headway. In the modeling study, the vehicle behaviours resulting from automation and connected technologies will be combined. In the next section, connected technologies will be discussed.

2.3. Connected technologies

As Wilmink et al. [67] describe, the development of autonomous cars is the result of two game changers. The first one is the movement from manual control to automated control, as described above, and the second one is the movement from autonomous towards cooperative systems. Vehicles equipped with these systems do not only receive data about the environment from their sensors, but also from vehicles around them (vehicle-to-vehicle or V2V), from transmitters at the roadside (vehicle-to-infrastructure or V2I), or from the cloud (vehicle-to-cloud or V2C). For the last two functions it is necessary for the government to invest in these facilities [58]. The communication with other systems allows vehicles to anticipate situations like potential collisions, green light waves and the location of free parking spots much earlier than the vehicle's sensors can. Figure 2.6 gives a schematic overview of the modes of cooperation being developed by car manufacturers.

(a) V2V cooperation (b) V2I cooperation (c) V2C cooperation

Figure 2.6: Most common connected systems being developed by car manufacturers

It is expected that connected technologies, in addition to automation, can impact urban traffic on a microscopic level. This is, however, dependent on the amount of vehicles on the road that actually have this technology built in. Therefore, it is important to investigate how researchers expect that connected technologies will penetrate the automotive market in the coming decades. In section 2.3.1 this will be discussed. After, in section 2.3 the expected microscopic effects will be discussed.

2.3.1. Market penetration

Significantly less studies have been done on the market penetration of V2V and V2I technologies. It seems that it is much more difficult to make estimations about this, because it is highly dependent on the development and market penetration of automation technologies, as Bengler et al. [3] states. In addition to dependence on the automation technology developments, cooperative systems also strongly depend on network effects: it is only useful to install them when other vehicles and infrastructure also employ them. These factors make it difficult to predict the market development. Nonetheless, some estimations can be found in literature. These estimations mainly address V2V and V2I technologies in general, and do not contain any statements specifically for The Netherlands or The Hague.

Bengler et al. [3], who performed a very extensive review on three decades of driver assistance systems (DAS) and ADAS, estimate that V2V technologies will be deployed in mid 2020s. They also state that this deployment is very co-dependent on the development of automation technologies. That is, their estimation is that developments will likely advance simultaneously.

The CAMP Vehicle Safety Communications Consortium [57] consisting of BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and Volkswagen, performed an extensive study for the US department of National Highway Traffic Safety into the safety effects of V2V technologies. Following a market penetration model that they developed, they concluded that the fleet share containing these technologies will be 27% 10 years after the deployment. So combining this statement with the estimation of Bengler et al. [3], that means that by 2035 27% of all vehicles will have V2V technologies on board. It is not stated how this penetration will be within the AV fleet.

Sivaraman and Trivedi [52] performed a literature review on cooperative, predictive driver assistance systems. They acknowledge that market adoption of V2V technologies is likely to happen quite fast after it becomes available. However, they believe that the penetration of V2I will be much slower as it depends on governments installing the right equipment in their infrastructure. This is therefore highly dependent on decisions made by municipalities, provinces and national governments.

In the roadmap to connected automated mobility by the European Commission [12] that was mentioned in section 2.2.1, relevant developments in cooperative vehicle technologies in The Netherlands are presented in a timeline. Some current projects involving data collection through cameras and sensors, and predictive information provision and advise via road signs and apps are presented as forerunners of the "real" V2V, V2I and V2C technologies. These are expected to be rolled out between 2020 and 2025 when automated and connected technologies will merge and complement each other.

Further, the European Commission [13] states in their *Europe on the Move* strategy for automated and connected vehicles that by 2022 all new vehicles should transmit data to the internet. This means that vehicles with systems that make use of data transmitted by other vehicles will even receive data from vehicles which do not have these systems. To enable this, they are working hard on measures for privacy protection and protection against hackers.

Following the research on market penetration of connected technologies, it can be concluded that it is likely that by 2040 a large part of AVs are also connected. Furthermore, governments are eager to facilitate the usage of connected technologies by equipping infrastructure with connected devices and mandating all vehicles to transmit data. In this research, these findings are further included by assuming a high level of connectedness of AVs, as described in the conceptual model, in chapter 3.

2.3.2. Vehicle behaviour and microscopic effects

Connected vehicle technologies can play a large role in reducing minimum headways. If vehicles are continuously kept up-to-date about the actions and intentions of not only their direct predecessor, but also the vehicles in front of their predecessor, they are much better able to anticipate others' actions and can drive at shorter distances. Systems that make use of this data are called Communicative Adaptive Cruise Control (CACC).

Vaudrin et al. [62] who performed a simulation study to look at the effects of communicative autonomous vehicles on mixed traffic reports that this technology is promising, but only when a CACC vehicle follows another CACC vehicle. Friedrich [18], who wrote the technical chapter of the book *Autonomous Driving: Technical, Legal and Social Aspects* confirms that because of this limitation even one manually driven car interrupting a platoon of CACC vehicles can annul all positive traffic flow effects of the CACCs. However, Tettamanti et al. [56] rightly states that this is not necessarily the case. It is enough if a vehicle has V2I, V2V or V2C capabilities to allow CACC vehicles to use their data and reduce its headway. TU Delft traffic flow researcher Dr Simeon Calvert agrees [1]: as long as vehicles transmit data about their actions, not all vehicles on the road need to have CACC to allow for shorter headways. In fact, his expectation is that by 2040 all vehicles, also manually driven ones, will be obliged to transmit data so as to enable connected systems to improve traffic flow. As mentioned in section 2.3.1, European policy indeed seems to be developing in that direction.

Talebpour and Mahmassani [55] performed a study applying various models with different penetration rates of connected and autonomous vehicles to test the effects on traffic flow. What they found was that connected technologies could significantly improve the performance of autonomous vehicles by providing a much wider view than just the sensors can. This improves response time and vehicle efficiency, yielding a higher and more stable traffic flow.

These findings on the microscopic effects of connected technologies along with the notion that in the future most AVs will likely be equipped with these technologies, led to a set of driving behaviour characteristics that in this research will be applied to all AVs. The essence of this driving behaviour is less deviation, fast responses and shorter headways. More about this in the conceptual model in chapter 3.

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[1] Personal communication with Dr Simeon Calvert, 30/5/2018 and 14/8/2018

2.4. Car- and ridesharing

Another important trend in the automotive market is car- and ridesharing. The difference being that carsharing is a system where one car can be used by multiple people as a personal vehicle which they drive themselves and ride-sharing is a system where one car can be used by multiple people consecutively (as a sort of taxi) or at the same time to get to their destination [34]. These systems are already becoming more widely employed as companies like Car2go, Snappcar, BlaBlaCar and Uber are flourishing.

It is conceivable, however, that the concepts or car- and ridesharing will grow much closer to each other when AVs are being used. AVs are particularly suitable for sharing, as they can provide door-to-door service, they do not need a driver and do not need to be parked at the destination of the last user. Burns et al. [7] researched how the combination of the Internet-of-Things (IoT), AVs, sharing, specific purpose vehicles and electric vehicles can radically transform personal mobility in the coming decades. They believe that the correlation between these developments is very strong and that shared vehicles will soon be largely autonomous. This reshapes the idea of car- and ridesharing completely. Burns et al. [7] developed a model based on an idealistic image of how sharing with AVs could work. The idea is that one system dispatches all shared autonomous vehicles (SAVs), sends them to people's doorsteps to pick them up, calculates a route through the network to drop them off directly at their destination and then reassigns them to the next customer. On location there is no need for parking, because the vehicle immediately leaves to pick up the next customer.

Many researchers, such as Litman [34], and Fagnant and Kockelman [15] fear negative effects of automated vehicles. They expect that the positive effects on traffic flow and parking problems [26, 55] as well as a reduction of the value of travel time savings due to the ability to work in your car [9, 11] will cause induced demand. Congested streets could be the result. They recognize that SAVs could be the primary solution to this problem. Therefore many researchers are advocating policy that promotes SAV systems. However, it is quite unclear whether a system with SAVs will have the same positive effects on congestion as regular car- and ridesharing.

Just like AVs, SAVs are likely to have both macroscopic and microscopic effects on urban traffic. However, this is also largely dependent on how the SAV market will develop. Therefore, a review was performed of literature addressing the market penetration of sharing in general and SAVs specifically. This review is presented in section 2.4.1. After, statements found in literature about potential macroscopic effects of SAVs are presented in section 2.4.2, and statements about driving behaviour and consequential microscopic effects can be found in section 2.4.3.

2.4.1. Market penetration

In order to assert the effects of car- and ridesharing on urban traffic, it is necessary to study the size of the market and its potential for growth. From literature, one can easily conclude that there are two sides to the market development of sharing: there is the question of how these platforms will develop with current technologies and there is the question of how automation may accelerate this process.

Already without AVs, the car- and ridesharing market has shown significant growth over the past years. In figure 2.7 the growth of the amount of shared cars per 100.000 inhabitants in The Netherlands over the last 10 years is projected. What can be seen is that in the entire country, but especially in heavily urbanized areas, carsharing has taken flight quickly.

Tachet et al. [54] developed a simple model to calculate a city's market potential for ride sharing based on the city's size (in terms of surface), trips density and traffic characteristics. They found that shareability is specifically high in cities which are densely and homogeneously populated. Shaheen and Cohen [49] conducted an extensive review of carsharing trends worldwide. They found that key forces in the success of carsharing in a region are energy costs, economic uncertainty, mainstreaming of carsharing, the expansion of multinational carsharing operators, growth in one-way carsharing and personal vehicle sharing, and new technologies that support carsharing. These new technologies include automation, which better enables one-way carsharing, and electrification. Neither Tachet et al. [54] nor Shaheen and Cohen [49] comment on the potential of sharing services in terms of PKT or VKT share.

Many researchers, such as Litman [34], Tillema et al. [58] and Hoekstra [25] acknowledge that vehicle automation could have a significant impact on ride sharing. However, not all of them attach a quantitative value to this effect. Tillema et al. [58] develops 4 market scenarios based on a grid with an automation axis and a sharing axis. So even though they acknowledge the influence, they still treat automation and sharing as two mutually independent variables in scenario development.

Litman [34], however, is not afraid to make a quantitative estimation of the size of the ride-sharing market in urban areas as a result of automation. According to his rough estimation, shared autonomous ve-

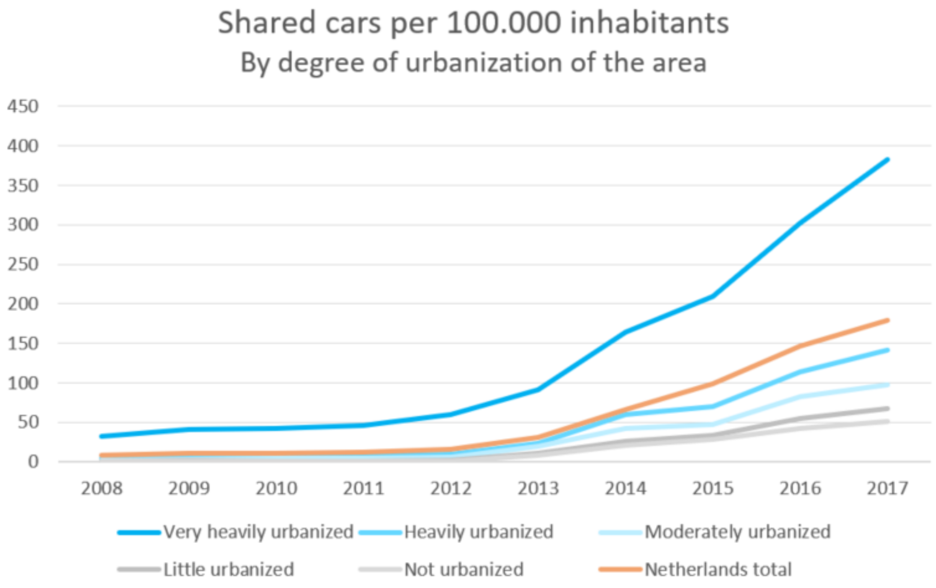

Figure 2.7: Amount of shared cars per 100.000 inhabitants in The Netherlands, source: KpVV CROW [33]

hicles (SAVs) will cause a shift in market share from owning to sharing of 1% per year. However, there are two problems with this vision: Firstly, Litman does not specify whether this market share is expressed in passenger-kilometres (PKT) or in vehicle-kilometres (VKT). This could make a large difference when talking about sharing, because the high car occupancy can cause the total VKT in a city to decrease while the PKT stays roughly the same. Secondly, Litman only accounts for modal share shifting away from owned vehicles to shared vehicles. But ride sharing can also cause modal share to shift away from other modes.

Moreno et al. [37] gave a more detailed quantitative estimation of the demand for SAVs. They performed a two-phase study of the potential and effects of SAVs in the area of Munich. The first phase was a stated choice experiment of which they used the results to calculate the area-wide modal split in a future where AVs and SAVs are available. They found that the car (regular, AV and SAV) would account for 51,1% of all trips and that the SAV would account for 26,3% of all car trips. However, the design of this experiment was not open to the possibility of people switching from other modes like bicycle or public transport (PT) to SAV.

In fact, some researchers, like Hoekstra [25] and International Transport Forum [27] even foresee a scenario (which should be avoided) where ridesharing only causes a shift from PT and bicycle to the (shared) car. This could increase the amount of cars on the roads greatly. For both car owners and PT users sharing services offer an attractive alternative. Car users can continue enjoying the benefits and comfort of using a car at a much lower cost and without parking problems. PT users can enjoy door-to-door service with less fellow passengers at a comparable price to public transport. As was found at a workshop organized at the municipality of The Hague on 4 July 2018, the success of sharing services in the city hinges largely on the price.

The European Commission [13] is very optimistic about the potential of ride sharing in combination with vehicle automation. In May 2018 they presented their third iteration on the *Europe on the Move* program. This program includes some drastic policy measures, guidelines and the provision of billions of euros of funds for research and development to make mobility in Europe more safe, connected, autonomous, clean and accessible. It is among their ambitions to have 25% of all trips in cities covered by SAVs by 2030. On the one hand, this sounds very optimistic. But on the other hand, just like with the encouragement of automated and connected technologies, the European Commission and national ministries have the policy tools and funds to accelerate the transition towards ride sharing. Companies such as Uber and Volkswagen-Audi are lining up to employ vehicle automation technologies in taxi- and ridesharing services and are merely waiting for policy makers to allow this [24].

All in all, from the literature it can be concluded that SAVs are likely to gain popularity quickly when they become available. Especially with high levels of vehicle automation, sharing vehicles will become attractive. Further, governments are eager to promote the usage of SAV services in urban areas. Therefore, this research includes optimistic levels of SAV usage in the conceptual model in chapter 3, especially in scenarios with high

AV penetration.

2.4.2. Macroscopic effects

Popular opinion is that SAVs will have positive consequences for the economy, social inclusiveness, the environment and traffic flow through the city [4, 34, 35, 58]. This is because in principle, sharing allows efficient use of resources: less cars are needed for the same amount of movements. Furthermore, people have access to affordable transport options, non-drivers such as elderly and handicapped people have access to transport and people can be productive while traveling. Finally, the automated and cooperative nature of the cars improves the traffic flow as long as there is no congestion. However, whether SAVs will have a positive effect on traffic congestion, remains the question. There are both macroscopic and microscopic factors at play here. The latter will be discussed in section 2.4.3. The former will be discussed here. These are all factors that basically determine the amount of cars that are simultaneously on the road: demand, fleet size, vehicle occupancy and VKT.

The demand for SAVs is basically the amount of people who would choose an SAV for their trip instead of any other mode. This is directly related with the amount of PKT that this mode accounts for. In many cases, both researchers who specifically look at demand, such as Litman [34] and Moreno et al. [37] as well as researchers who make assumptions about demand for their modeling studies, such as Fagnant and Kockelman [14], Boesch et al. [5] and Zhu and Kornhauser [68], only account for the direct replacement of the personal car mode with SAVs.

However, as acknowledged by International Transport Forum [27] and Martinez and Viegas [35], the availability of SAVs may cause travellers to switch from other modes (like bicycle or PT) to this mode. Furthermore, it may even cause induced travel demand, as it provides an easy and affordable means of transportation. This will likely cause extra transportation demand among people for whom accessibility or price have previously been a barrier. The factors which are at play here, are similar to the advantages that autonomous mobility offers, and are described in section 2.2.2. This last notion has not been explicitly taken into account in the SAV demand research that was found. However, it is often named in the discussion, for instance by Moreno et al. [37]. In short, it is likely that the introduction of the SAV will draw more people to the car mode.

Whether this means that there will be more cars on the roads, partly depends on the fleet size of SAVs that would be needed to serve this demand. Several researchers have looked into this question. Martinez and Viegas [35] performed an agent based simulation based on a discrete choice experiment to compute the potential fleet size and vehicle occupancy of shared autonomous taxis in a scenario where the options available were walking, subway or rail, and SAVs (so no regular cars). For the case study in Lisbon, they found that (taking in to account the fact that also more people would choose PT or walking) a fleet reduction of 95% could be accomplished. A limitation of this study is that the conventional car is not seen as an alternative, so these results are only valid for a network of SAVs and PT.

Boesch et al. [5] performed a similar research with Zurich as a case study. He used a MatSim model to estimate the needed fleet size of automated taxis relative to the fleet of conventional cars that would be needed to serve a given level of demand and with a given accepted waiting time. They found that if 5-10% of the driving agents would be served by SAVs and the accepted waiting time would be 5 min, the fleet for these agents could be reduced by 75%. For an accepted waiting time of 10 min, this reduction could even be 90%. For a smaller percentage of driving agents served by SAVs, the fleet reduction decreases. Unlike Martinez and Viegas [35], Boesch et al. [5] does account for a large percentage of agents choosing the conventional car as their mode. However, they do not account for agents replacing public transport modes by SAVs.

Additionally, Fagnant and Kockelman [14] also performed an agent based model study to investigate several effects of SAVs on the mobility in a city. They used a fictional, grid-based city for this with SAVs as the only mode. They found that with a certain accepted waiting time, 1 SAV could replace 11 conventional vehicles.

As opposed to the previous two studies, International Transport Forum [27] accounts for the possible added demand coming in from public transport. In a multi-layer agent based model of the city of Lisbon, they looked at several effects of the introduction of SAVs in this city. The first was the fleet replacement potential. They found that even with poor public transport facilities, SAVs could remove 8 out of 10 cars from a mid-sized European city.

It seems logical that the needed fleet size for a city depends largely on how many passengers the SAVs transport simultaneously: the average vehicle occupancy. This is a tricky subject, because a high average vehicle occupancy can greatly reduce the the amount of cars on the road, but it requires a high density of demand, good planning and some sacrifices. Some SAV impact studies did not take into account the possibility of increasing vehicle occupancy with SAVs. Moreno et al. [37] made an assumption of single occupancy for simplification reasons and Boesch et al. [5] made no comments about the vehicle occupancy whatsoever. Fagnant and Kockelman [14] assumed the same occupancy as with private transportation for their model of a fictitious city where they aimed to assert the impacts of SAVs in terms of demand, travel times, VKT and emissions.

Two years later, Fagnant and Kockelman [16] conducted the Austin study specifically because they found that combining SAV rides could change the impact that SAVs have. With their dynamic ridesharing strategies, they accomplished a vehicle occupancy of 2 with a SAV penetration rate of only 1,3%. This meant a reduction of VKT, but did come at the cost of extra individual travel time.

Martinez and Viegas [35] and International Transport Forum [27] both studied the effects of deploying a SAV system with normal-sized SAVs in addition to a high capacity PT system. In this system, these would be the only two modes. Tests with an agent-based model resulted in an average vehicle occupancy of 2,5 to 3 passengers. What's more, International Transport Forum [27] found that the elasticity for party size is 1,07, meaning that with every 1% growth in demand for SAVs, the vehicle occupancy grows with 1,07%.

A higher vehicle occupancy may reduce the amount of SAVs on the road, but this does not necessarily mean that the total amount of VKT covered by this limited amount of SAVs is less than it would be when there are more SAVs on the road. The amount of VKT covered per SAV is also an important factor in this. And there are some aspects to shared mobility that may heavily increase this amount compared to regular vehicles. There are two components to the amount of VKT of an SAV: the distance covered while occupied and the distance covered while empty.

In their agent-based model of a fictional city with just SAVs, Fagnant and Kockelman [14] found that the use of SAVs results in 10% more distance covered per trip than non-shared trips due to empty kilometres. Additionally, Fagnant and Kockelman [14] are predicting an overall increase in VKT due to induced demand. Besides Fagnant and Kockelman [14], more researchers are concerned with the empty kilometres issue and have therefore set out to develop and test strategies which could limit these empty kilometres. Zhu and Kornhauser [68] tested several repositioning strategies for a fleet of high capacity SAVs in New Jersey using linear programming algorithms. For a fleet size of 10% to 50% of total vehicles, they found that their repositioning strategies could accomplish an empty VKT share of 5,2% to 8,3% of the loaded VKT. The abovementioned Fagnant and Kockelman [16] study of 2016 where dynamic ridesharing strategies were tested using an agent based model found a reduction in empty VKT of 8,7% to 4,5% compared to situations when no dynamic ridesharing system is used. However, this did come at the cost of extra distance covered with passengers on board, meaning that the total VKT per SAV was still more than it would be for the same trips with regular vehicles.

As was found in this section, the effects that SAVs could have on road congestion on a macroscopic level, is dependent on many factors. Many researchers are positive, because SAVs allow a significant fleet reduction. However, as SAVs are used much more intensively and could accumulate a high number of empty kilometres, this fleet reduction might not imply a reduction in total VKT in a city. This strongly depends on the occupancy of the vehicles and the relocation strategy. Moreover, the convenience of this mode could cause travellers to switch from PT or bicycle to SAVs as well as cause induced travel demand. The total effects are therefore still quite unclear. This research includes effects of SAV usage on traffic intensities by looking at the extra distance that they drive and by incorporating various vehicle occupancy rates.

2.4.3. Vehicle behaviour and microscopic effects

Little research is devoted to what the operation of shared AVs does to the traffic dynamics. First and foremost, SAVs are obviously also AVs. This means that the behaviours and microscopic effects identified in section 2.2.3 also count for SAVs. But there are also properties of SAVs that distinguish them from personal AVs, which are discussed in this section.

As mentioned in section 2.4.2, researchers like Fagnant and Kockelman [14] expect SAVs to drive longer distances for the same trips than conventional vehicles would, due to repositioning and empty kilometres. In other words, the vehicles will likely circulate on the network. When vehicles circulate through a network to pick up new customers after dropping off the previous customer, they are likely not to use the typical routes that the network was designed for, thereby using links and traffic signals that have insufficient capacity. As mentioned in section 2.1, traffic signal control algorithms are designed on a case-by-case basis, depending on the traffic intensities that were measured at the moment of designing. This might cause long queues and high delays. However, none of the researchers addressing the repositioning and empty kilometres issue acknowledge that the extra distance driven may involve low capacity links, and little to no research has been done into these possible effects of this network circulation. This research aims to fill this gap, and therefore this expected effect is included in the conceptual model.

Another expected microscopic effect of SAVs that little research pays attention to, is the negative effects of curbside stopping. If people are being picked up and dropped off alongside the road without using a parking space, this will form temporary bottlenecks. The International Transport Forum [28] did, however, dedicate a study to how curbside use is changing. They found that ridesharing services are contesting cities' classical concepts of curb use. As people are choosing shared modes more and more over personal vehicles, the curbside will be under increasing pressure, which could have negative consequences for other curb users as well as on-road traffic. Their advice is firstly, to get rid of long-term curbside parking. And secondly, to design curbs as flexible-use spaces, allowing different road users, like cyclists, goods delivery trucks and ridesharing vehicles, to make use of them. Specifically for the ridesharing services, they recommend designing passenger pick-up and drop-off zones. In this study, curbside stopping is included as an effect of SAVs in the conceptual model.

2.5. Scientific gaps

In this chapter, it was found that new developments in the automotive industry may have a large impact on mobility in general. However, not all aspects of the direct impacts of these development on urban traffic have been addressed. In this section, some scientific gaps will be identified that will be focused on in this study.

Firstly, many studies that look at the microscopic effects of new technologies, do so in a simplified traffic environment. However, especially in an urban setting, traffic is rarely simple. On-road situations are a result of many traffic streams and modes coming together along with traffic management facilities, parking, and other infrastructural attributes. Therefore, to get a real grip on the effects of new technologies on urban traffic, one must look at the urban traffic as a holistic system. In this research a case study of a real-life urban traffic network is used, allowing to see the effects of AVs and SAVs on the entire system.

Similarly, most studies focus on the effects of connected vehicles, autonomous vehicles, connected autonomous vehicles (CAVs) or shared vehicles in isolation. However, as many researchers state, automation, connected technologies and sharing will very likely develop in an integrated manner. Therefore, if the ambition is to study the holistic future urban traffic system, it is needed to study the effects of these three developments together. Therefore, in this research, scenarios are defined proposing realistic combinations of market penetration for AVs and SAVs.

In addition, the transition period is still relatively underexposed in current literature. Although this period is already quite close in the future and it raises the most questions for municipalities. This is because if intervention is needed, it will need to be planned for soon. Hence, it is necessary to study the effects of AVs and SAVs for different penetration rates.

Lastly, many studies look at the possible effects that AVs and SAVs may have on traffic, but do not propose how infrastructure may be adjusted to facilitate this. Studies that do suggest infrastructural changes, do not test their effects. It may be useful for a municipality to see if and how they can prepare themselves for the transition period that is soon to come, and to quantify the effects of possible interventions. In this study, some easy-to-implement solutions will be tested to see whether they are able to facilitate the new traffic mixes and reduce congestion.

Upon close inspection, AVs and SAVs also represent the in section 2.1 described trade-off between high traffic throughput and high accessibility. Where AVs may improve traffic throughput, increasing a road's capacity, SAVs may provide a higher level of access to surrounding real estate, thereby decreasing the road's capacity. This research aims to inspect these effects more closely. By looking at these effects in unison, on a holistic urban traffic system, for different penetration rates, and under the application of different infrastructural measures, it is attempted to close the scientific gaps. The model that was constructed to study these effects, will be discussed in the next chapters.

3

Conceptual model

As the system under study is a highly complex one, it cannot be described with a singular mathematical model. This makes simulation necessary. However, some relationships can be identified that could explain changes in the state of the urban traffic system when elements such as AVs and SAVs are introduced. In this chapter, the system elements and underlying relations that partly explain the system's state, are presented. This conceptual model is largely generalizable, but was slightly further specified with the help of the case study: in determining the scenarios and requirements, some input from the municipality of The Hague and a large traffic demand study of The Hague was used. As will become clear, a simulation model is indeed needed to investigate further complex emergent behaviour. The simulation model is described in subsequent chapters.

This chapter commences with a short description of the case study in section 3.1. After, the scenarios that were defined for this study is introduced and explained in section 3.2. In section 3.3 the expected effects of the scenario elements on the system is described. In section 3.4 the key performance indicators (KPIs) are introduced. And finally, in section 3.5 a synthesis of the expected effects is summarized in a causal diagram.

3.1. Case introduction: The Hague

As a case study for this research, a road network in the city of The Hague during the morning peak period was chosen. With more than 500.000 inhabitants, The Hague is the third largest city in The Netherlands. It is the home of the national government, an important centre of business and commerce, and it is situated at the coast in the middle of the Dutch metropolitan area. All these factors make The Hague an interesting case study. Furthermore, the municipality of The Hague is in close contact with commissioner Arcadis and education institute TU Delft. Therefore, models and data can be easily obtained.

In this section, the case study in The Hague is introduced. First, mobility in The Hague in general and mobility plans are discussed. Then the network under study is presented. And finally, a reflection on the generalisability of this case study is given.

3.1.1. Mobility in The Hague

As a city, The Hague has many functions: governmental, economic, commercial and coastal. Consequentially, the city receives a high amount of traffic daily. The expectation is that the amount of movements will only keep growing in the coming decades. Managing all movements through the city in a smart way in order to maintain a good flow and traffic safety, is one of the municipality's highest priorities. Therefore, they wrote the *Haagse Nota Mobiliteit* [19] in 2011. In this report, their expectations for urban growth and mobility patterns are presented as well as eight policies aimed at facilitating and guiding these developments.

For the period 2011-2020, the municipality expected an increase in the average daily distance travelled per inhabitant (which in 2011 was 23 km/day), an increase of the amount of movements by 20-30%, and an increase in car ownership by 15-20%. This is partially a result of continuous population growth of 6% annually, an increase in the amount of jobs by 14% and more (14%) visitors of the city centre. Further, the distance travelled keeps increasing, because people choose to live further away from their work and also travel further for leisure activities. The car remains the most popular mode of transportation in The Hague. In 2008 it already accounted for 37% of all movements, and since the distance per movement was expected to increase, this percentage was also expected to grow as long as there are no attractive public transport alternatives. It should be noted that the effects of AVs and SAVs on the distance travelled, the amount of movements and car ownership is not yet taken into account in these predictions. To facilitate and guide these developments, the municipality designed several policy directions. The main focus of these policies is on spreading the demand over multiple modes and limiting nuisance caused by motorized traffic.

The main urban structure in terms of motorized traffic is presented in figure 3.1. The road categories depicted here correspond to the categories that were introduced in section 2.1. The municipality attempts to concentrate all through traffic on a few (inter)national (purple), regional (red) and urban (orange) main roads. An adequate traffic flow on these roads will therefore need to be ensured, so drivers naturally choose these routing options.

Figure 3.1: Map showing the main road structure in The Hague. Source: Gemeente Den Haag [19]

On 30 May 2018, an interview was conducted with Jan Jaap Koops, who works as a traffic engineer at the department of transport policy at the Municipality of The Hague. The goal of this interview was on the one hand to investigate general developments and implemented policies with regards to the Haagse Nota Mobiliteit, which was written 7 years ago. On the other hand, this interview was held to test the municipality's expectations and plans regarding autonomous and shared autonomous mobility. A summary of this interview can be found in appendix A section A.1.

According to Jan Jaap, the predictions made in 2011 as described above were more or less accurate. Traffic has been increasing as well as total car ownership in the city. This is, however, a result of an increase in the total amount of households in the city. Interestingly enough, the car ownership per household has decreased in the past 7 years. Despite efforts of the municipality to shift their focus towards other modes than the car, the modal split in The Hague still leans more strongly towards the car than in other cities. This is because the composition of their population is relatively unique to The Netherlands.

The municipality does not expect AVs to have a large impact on car ownership. They are actively encouraging car- and ridesharing initiatives, but they do not expect this to be of a large impact on traffic during the peak hours, because everyone still wants to travel then. In terms of infrastructure, Jan Jaap expects that the current denseness of the roads, signs, markings and bicycle paths will form an obstacle for AVs to operate freely. However, this is not a reason for the municipality to adjust this. Rather, the vehicles should be adapted to deal with the infrastructure and traffic conditions present in The Hague. What the municipality does do, is install the newest sensing and control technologies whenever they replace traffic signals at an intersection.

3.1.2. Modeled network

As mentioned in section 1.1, the focus of this research is on the urban main roads. As a case study, a network was chosen containing a prominent urban main road that serves as a connection between the regional main road and the lower level road network as well as the surrounding real estate: the Prins Clauslaan. The throughput versus access disparity is clearly present in this network, as the main road has multiple lanes and separation of directions and modes on the one hand, but also multiple signalized intersections, roadside parking and bus stops on the other hand. Figure 3.2 shows a map of the network that was used in the simulation.

Figure 3.2: Map showing the network that was modeled in the simulation

Of this network, a base simulation model was already available, as it was built by Arcadis for the purpose of a traffic study to test alternative road configurations around a large real estate project that is planned for 2030. Arcadis developed several different models for each possible road configuration around the new buildings, but the model used in this study is the base alternative, which does not take into account the real estate project yet. This network does contain some minor changes to the current state network that the municipality is going to make in the next couple of years. These include a bicycle crossing on the Bezuidenhoutseweg and a parking garage entrance on the Prins Clauslaan. It also includes five signalized intersections. The network and intersection control closely resembles reality. In terms of traffic, an origin-destination (OD) matrix was derived for the morning peak based on a static demand model for the year 2030. For the buses that make use of this network, the current schedule was assumed.

3.1.3. Generalisability

While the use of a case study allows creating a realistic situation and deriving quantitative effects, it also decreases the generalisability of the results. In this section, a reflection will be presented on both the unique and the generic properties of the case study, and to which extent this makes the research generalisable.

For Dutch standards, The Hague is relatively car-friendly. Cars are offered a lot of space and priority throughout the city. This makes the city preeminently suitable for AVs and SAVs. As was said, there are not a lot of cities in The Netherlands that offer this much space to cars. Amsterdam is a prime example of a city that does not. In these cities, AVs could still deal with a lot of traffic safety issues because they interact much more with cyclists and pedestrians. Further, SAVs could cause even larger problems, because the roads are of much lower capacity and do not have much space at the curb. Examples of other cities in The Netherlands that offer the same amount of space and priority to cars are Rotterdam and Eindhoven.

Besides the amount of space and priority offered to cars, there are also other properties of this case study that should be looked for in other cases to apply the findings of this research. The main road in this network offers a combination of high traffic throughput and access to the surrounding real estate. This real estate houses places of interest on the activity end of a journey. In this case ministries, companies, schools, shops and access to the trains. So not only is there a lot of traffic flowing through the area, there is also a lot of traffic going to this area during the morning peak. These are properties that should also be searched for when looking for similar cases.

The fact that the case study focuses on the morning peak period, is also a point of interest. The effects of AVs on traffic congestion will likely not differ when looking at the evening peak or off-peak. However, the effects of SAVs on urban traffic might very well be different during a different period of the day. Travellers are mainly flowing into the city, instead of outward. Passengers of SAVs are mainly being dropped off, instead of being picked up. When this is the other way around, SAVs may move differently through the city and may have longer dwell times. Therefore, a separate study is needed to look at these effects for the evening peak.

The case study might seem quite specific, but in fact the division of urban streets into the categories described in section 2.1 is relatively universal. Most cities will have streets that follow roughly the same configuration and that are located between the national/regional network and the city's real estate. Infrastructurally speaking, this makes it an easily generalisable case. The difference however, can be made by how the network is loaded: the intensities and composition of the traffic. For any network with similar utilization of the surrounding real estate, during the morning peak, and with a location as input link to the city, this will not differ much from the case study.

3.2. Scenario definition

For this study, seven future scenarios will be tested regarding vehicle automation and ridesharing. Some scenarios are more realistic (1-3), and others are more extreme "what-if" scenarios (4-7). Based on literature studies as presented in chapter 2, and a workshop organized at the municipality of The Hague, of which the summary can be found in appendix A section A.2, it was chosen to differentiate on four variables. These variables are: share of vehicles that is autonomous, share of travellers using SAVs, average vehicle occupancy of SAVs, and bus automation.

In the scenario building, five parameters were assumed to differ from the current situation, but not differ among the scenarios. Firstly, the base travel demand on the network was kept equal across scenarios and determined for 2040. More about how this was determined in the next section. Medium freight vehicles and heavy freight vehicles are assumed to have equal automation shares as passenger cars. Further, based on what was found in section 2.4.2, empty VKT of SAVs is assumed to be a considerable share of the loaded VKT. Additionally, it was assumed that all shared vehicles are all autonomous. Finally, all autonomous vehicles were assumed to be connected to the extent that they employ reduced headways, short reaction times and further lookahead distances. This is because a strong correlation between automation and connected technologies was found in the literature in section 2.3. To limit the amount of scenarios and increase the realism of the scenarios, only logical combinations of the four variables were used for scenario building. This means that when a certain correlation could be found between the scenario variables, only logical combination of variable values with regards to this correlation were used.

3.2.1. Base demand

The base OD-matrix in the case study simulation model was constructed based on research by Goudappel Coffeng [22]. As this matrix was constructed for the year 2030, the intensities needed to be extrapolated towards 2040. Because little is known about mobility developments towards that year, and the basic demand effects of autonomous and shared vehicles are very difficult to predict, a standard growth rate was used.

In their own studies, the Municipality of The Hague always uses a growth rate of car intensities of 1%

per year and of bicycle intensities of 2,5%, which they admit is relatively high. In the research of Goudappel Coffeng [22], they estimate an average growth rate for motorized traffic of 0,5% and for bicycles 1%, assuming that population growth remains that same as well as socio-demographic and economic factors.

However, the Prins Clauslaan network seems to be already reaching its capacity in the highest point of the morning peak with the 2030 matrix. Any increase will cause congestion to a point where drivers are more likely to choose other alternatives such as a different mode, route or departure time. Dr Niels van Oort, a researcher who supervised the Goudappel Coffeng project, confirmed that if the capacity of the Prins Clauslaan remains the same, it would be more likely that the growth in demand will spread to other times, modes and routes [1]. Any growth in the vehicle intensities on the network would then only be distinguishable at the edges of the peak period when the network is not yet at capacity.

To test this hypothesis, historical growth data was compared to detect a pattern. Count data collected by Nationale Databank Wegverkeersgegevens (NDW) of the Utrechtsebaan was used to find this pattern. For every Thursday in the years 2011 and 2017 the average intensities for each 15 minutes of the morning peak were calculated and compared to find whether there was a statistically significant difference. As expected, any statistically significant increases in the counts could be found in the beginning and end of the morning peak, not at the highest point. A graph presenting mean intensities over the morning peak period for both 2011 and 2017 is presented in figure 3.3. Note that not all differences visible in this graph are statistically significant.

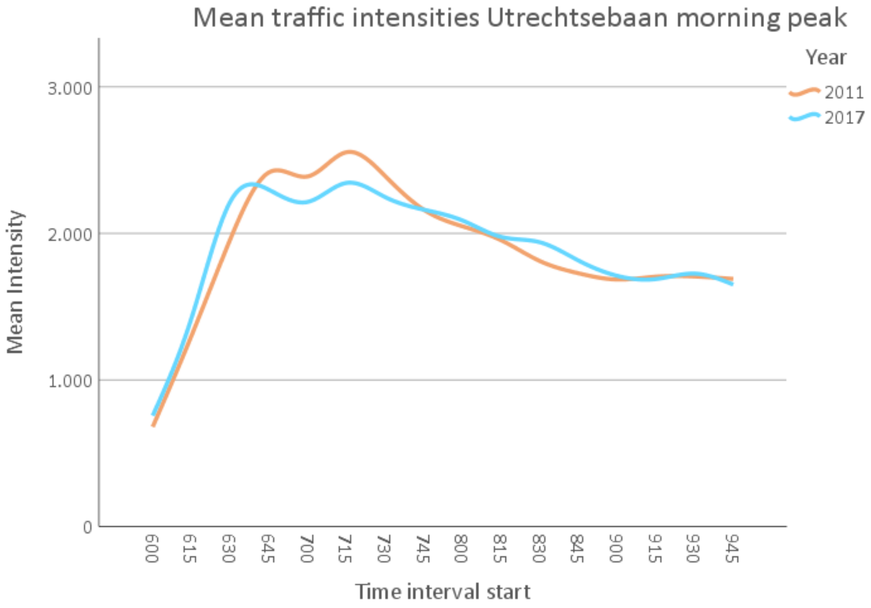

Figure 3.3: Mean intensities Utrechtsebaan 2011 and 2017

As this statistical test confirmed the hypothesis that in this network, the growth in demand that is predicted by Goudappel Coffeng [22] is more likely to occur at the edges of the peak period instead of a the highest point, the OD-matrix in the model was extrapolated accordingly. The growth rates that were defined, can be found in table 3.1. The resulting OD-matrix will be called *base demand 2040*.

Table 3.1: Growth rates applied to 2030 matrix to obtain 2040 matrix

Interval start	7:00	7:15	7:30	7:45	8:00	8:15	8:30	8:45
Annual growth rate	0,5%	0,25%	0,25%	0%	0%	0,25%	0,25%	0,5%

3.2.2. Penetration AVs

Following the extensive market penetration study in sections 2.2.1 and 2.4.1, an assessment was made of what penetration rates would be realistic for 2040. The focus here was on level 4 and 5 vehicles. Level 3 and under

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[1] Personal communication with Dr Niels van Oort, 12/7/2018

is seen as non-autonomous in this study, because their ADASs are likely to be switched off in the city as found in section 2.2.3.

In section 2.2.1, it was found that realistically, the share of level 4 and 5 cars on the road in 2040 will likely be somewhere between 20% and 80%. Therefore, scenarios were formed with 20%, 50% and 80% AV penetration. However, special interest was expressed to see the difference between results with these penetration rates and scenarios where there are either no AVs or all cars are AVs. Therefore, there were also scenarios formed with 0% and 100% AV penetration.

3.2.3. Penetration SAVs

Based on what was found in the literature about the rising popularity of car- and ridesharing as presented in section 2.4.1, the positive correlation between automation and sharing, and the policy intentions of both the European Commission and the Municipality of The Hague, scenarios were constructed on the penetration of sharing. Realistically speaking, it was found, as mentioned in section 2.4.1, that the penetration of SAVs in 2040 will be between 3% and 50% of travellers who currently travel by personal car. It is important to note that for this research it was chosen to only look at the percentage of travellers switching from personal car to shared vehicles and not the travellers that switch from public transport to shared vehicles. This is because there is little data available about the latter and the focus in this research is on traffic effects, not on demand.

3.2.4. Occupancy of SAVs

As found in seciton 2.4.2, the distance driven per trip by SAVs as compared to conventional cars, is something that many researchers consider in their demand studies. Therefore, it is an important factor to include in this study as well. As mentioned in section 2.4.2, the total distance driven by all SAVs in a network is dependent on many factors. Therefore, it is difficult to say to what extent the intensity of cars on the road will be increased or reduced due to a higher market penetration of SAVs. The studies mentioned in section 2.4.2 show both reduction and increase in total distance. Therefore, it was chosen to leave the intensity of SAVs roughly the same as with regular cars, with one exception: the occupancy of the SAVs that are dropping off passengers alongside the road in the network under study. This is because these cars do not only have an influence on the network in terms of traffic intensity, but also in terms of the microscopic effects that were discussed in section 2.4.3: curbside stopping and network circulation.

The occupancy of these vehicles was defined based on the studies presented in section 2.4.2 and the basic morning vehicle occupancy in The Hague. As was found in the static demand study of The Hague by Goudappel Coffeng [22], vehicle occupancy for home-work commutes in The Hague is 1,1. Therefore, the occupancy for the low market penetration scenario (scenario 1, 3% market penetration), was also set at 1,1. For higher market penetration rates of SAVs, it becomes easier to combine rides. However, studies discussed in section 2.4.2 presented quite diverse numbers for their achieved average occupancy with high market penetration rates. Especially the studies targeted at designing an efficient ride combining strategy, accomplished high occupancies. However, in this study no assumptions will be made about the efficiency of the ride combining strategy, and therefore it was chosen to use occupancies at the low end of the spectrum. Also, the shape of the relationship between the penetration rate and the occupancy is unknown, but a linear relationship seems unlikely. Therefore only small steps of increase were chosen. For a penetration rate of 25% an average occupancy of 1,5 passengers was chosen, for 50% and for 100% an average occupancy of 2 passengers was chosen.

3.2.5. Automation of buses

In the workshop with the municipality on 4 July 2018 (see appendix A), the policy makers expressed the intention to invest in automated public transport. Therefore, it was chosen to model all buses as autonomous buses in all scenarios that include AVs. In the scenario that does not include AVs, there is clearly some large barrier for vehicle automation, so the buses are also left non-autonomous.

3.2.6. Conclusion

In table 3.2 the values of each of the above described variables for each of the seven scenarios are presented. The names of the scenarios are uniformly structured to signify the penetration of AVs out of all personal vehicles and the penetration of travellers that are travelling to the case study area in a SAV. The formatting is as follows: <penetration AVs>/<penetration SAVs>. The variables which are used to alternate, are (in order from left to right) the percentage of personal vehicles that is autonomous, the percentage of travellers using a SAV, the average occupancy of SAVs and whether or not the buses are autonomous.

Table 3.2: Scenarios

Scenario	AV (% of vehicles)	Shared (% of travellers)	Pax SAVs (# pax)	Buses
1. 20/3	20%	3%	1,1	AV
2. 50/25	50%	25%	1,5	AV
3. 80/50	80%	50%	2	AV
4. 0/0	0%	0%	N/A	Normal
5. 50/0	50%	0%	N/A	AV
6. 100/0	100%	0%	N/A	AV
7. 100/100	100%	100%	2	AV

3.3. System elements and variables

Now that the very basics of the traffic flow principles governing the network at hand have been discussed, a conceptual model can be constructed which can be used to describe the expected impact of new external factors on the network. In this case, those factors are AVs and SAVs. Below, the expected individual effects of AVs and SAVs are discussed. Figure 3.5 portrays how these effects may influence the factors in the fundamental diagram and the KPIs.

3.3.1. Autonomous vehicles

As found in the literature described in section 2.2.3, the introduction of AVs will lead to the presence of vehicles on the road which behave differently from other vehicles. Not a lot of information is available on the exact differences in behaviour, so some educated assumptions have to be made. For these assumptions, two sources were used: firstly, statements found in literature, as presented in section 2.2.3, and secondly, an example simulation model of PTV Group in which they simulate the behaviour of AVs [42]. For this example simulation model, PTV Group used empirical data from studies with the University of Aachen, the University of Karlsruhe and the research project RoTraNoMo [2] [46]. The obtained parameter values and distributions were validated using literature and surveys. As statements found by PTV Group were mostly in line with what was found in the literature, some unambiguous assumptions could be made.

In table 3.3 the differences in driving behaviour of an automated vehicle as compared to a conventional car that will be assumed for this study are summarized. What was found, was that vehicle automation in itself causes a decrease in stochasticity in the behaviour, meaning that there will be less deviation of a vehicle's own behaviour in similar situations and there will be less deviation between vehicles. As mentioned in section 3.2, all AVs were assumed to also be connected, leading to shorter headways, shorter reaction times and further lookahead distances.

Table 3.3: Differences in driving behaviour AV

Factor	Difference from conventional car
Time headway	Shorter, less deviation
Distance headway	Shorter, less deviation
Speed	Less deviation
Reaction time	Shorter, less deviation
Lookahead distance	Further
Acceleration/deceleration	Smoother, less deviation
Path deviation	Smaller

3.3.2. Shared autonomous vehicles

In the literature as described in chapter 2 section 2.4, it was mentioned that little information could be found on the effects of an increase in SAVs on the traffic dynamics of an urban network. Based on a sketch made by Burns et al. [7] about how an autonomous ride sharing system could work and a report by International

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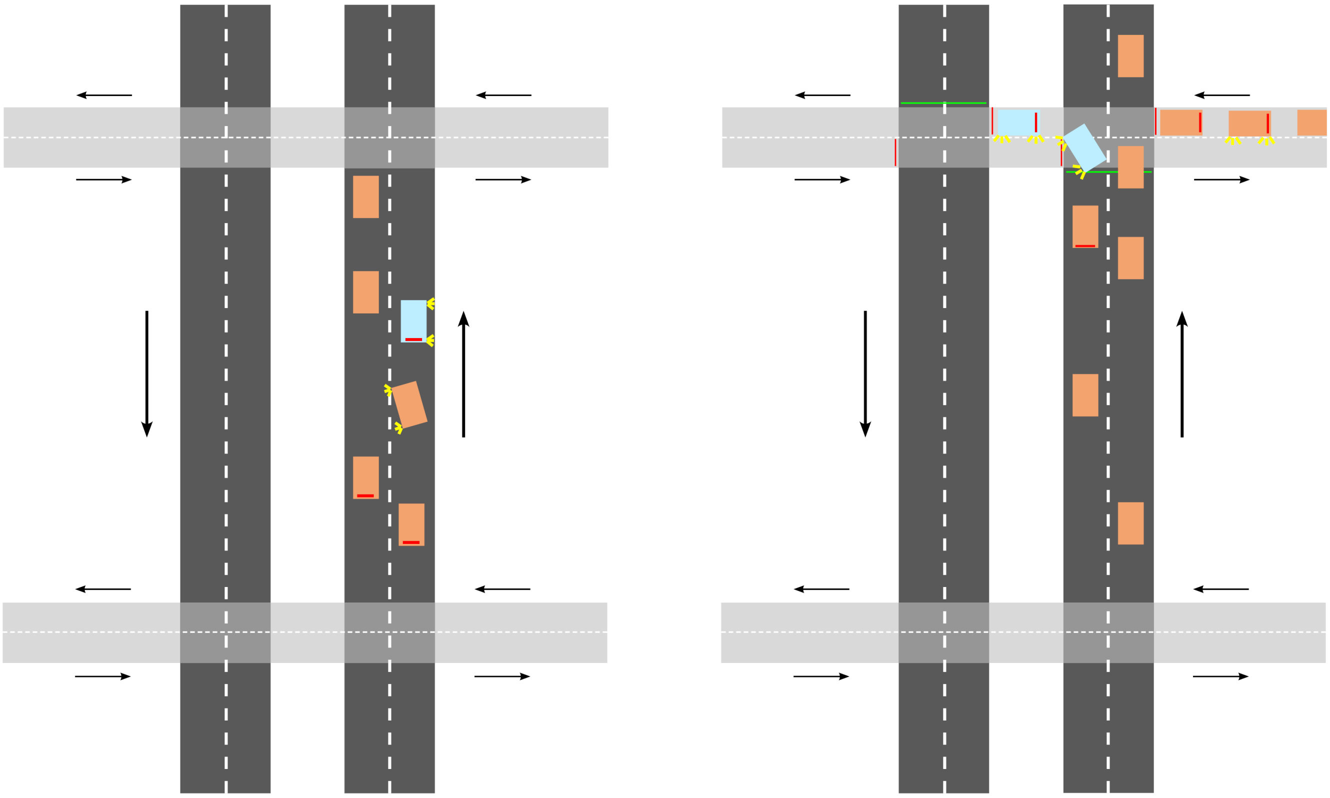
[2] Personal communications with PTV Group employee Jared Best, 14 June 2018

Transport Forum [28] on curb use, some concerns were raised. A possible effect could be the forming of bottlenecks as a result of vehicles stopping on the road at the curbside to drop people off directly at their destination without finding a parking spot. Another effect could be an increase in traffic density on low capacity links as a result of vehicles circulating the network to reach their next customer. This increased traffic density then causes an excess in demand for the traffic lights that were designed for a smaller amount of traffic, causing long cycle times and longer queues. The above mentioned effects are schematically displayed in figure 3.4 for an urban network with an urban main road which is intersected by feeder roads.



(a) Bottleneck caused by SAV stopping on the road at the curbside (b) SAVs using low capacity links, overloading the traffic light

Figure 3.4: Expected effects of SAVs on traffic dynamics. Orange: personal car; blue: SAV

3.4. Key performance indicators

In order to be able to assess the effects, compare the scenarios and evaluate designs, some definition of performance should be given. For this reason, a set of key performance indicators (KPIs) are formulated. These are quantitatively measurable indicators that together form a complete image of the performance of the system. It is vital to define these KPIs in such a way that all aspects of the system's performance that are deemed to be of importance to answer the research questions, are covered. Therefore, the research questions were used to inform the definition process of the KPIs. Additionally, multiple interview sessions with policy makers from the municipality of The Hague were held to inquire about their performance requirements for road networks and infrastructural changes. A summary of these interview sessions can be found in appendix A. Their outcomes were used to formulate the KPIs.

In this section, each KPI is introduced with a short description of the function that the KPI serves for answering the research questions. Also, where applicable, a description of the municipality's attitude towards this KPI is given. Finally, a summary of all KPI's and their measurement units is given in table 3.4.

3.4.1. Vehicle delay

Avoidance of large scale road congestion is a main priority for the municipality. It depends on the type of road to which extent congestion is accepted. However, as the Prins Clauslaan is a main road that may spill back to the national road Utrechtsebaan when congested, keeping congestion to a minimal level is vital. Additionally, the municipality is of the opinion that no single mode should suffer disproportionally under congestion. Therefore, this should be measured for all modes. To evaluate congestion for all modes, the delay should be measured and reported for different road users. To ensure the meaningfulness of this KPI, a few normative origin-destination (OD) pairs can be selected in terms of the number of travellers and the usage of the network. This delay will be reported as the average delay per vehicle in minutes.

3.4.2. Distance travelled

Evaluating the network usage serves two goals. On the one hand, it gives an idea of how much extra distance SAVs cover within the network as compared to non-SAVs due to network circulation. On the other hand, it helps assess whether differences in delay are merely due to differences in total and individual usage of the network, or due to the differences in vehicle behaviour and resulting traffic dynamics. Especially the individual extra distance driven by SAVs could potentially increase the total distance driven by all cars on the network, thereby increasing traffic intensity. Or the increased occupancy of SAVs could reduce the total vehicle intensity to a level where the total distance driven on the network is reduced. If, for instance, it is found that an increase in delay comes paired with an increase in the total distance driven on the network, it cannot be concluded for certain that the extra delay is due to the vehicle behaviour as described in section 3.3. Fortunately, the results for energy consumption per kilometre could then provide extra information.

In an attempt to measure network usage, the distance covered by these vehicles should be measured and reported. This indicator will be measured as the distance travelled between each OD pair, and will be reported as a total value for all vehicles in the network, and as an average value per vehicle for non-SAVs and SAVs separately.

3.4.3. Emissions

As mentioned above, energy consumption should be measured and reported. It is chosen to do this by means of measuring emission values. This is not to provide insights in the air quality effects, even though high levels of air quality are one of the municipality's main priorities. As average vehicle exhausts are likely to be completely different by 2040, emissions figures in this research are rather treated as a measure of energy consumption than as a measure for air quality effects. When an equal number of vehicles is injected into the network, emissions figures give information about the traffic dynamics in terms of deceleration, waiting and acceleration. To filter out differences in emissions that are caused merely by a slightly different amount of vehicles or different amounts of vehicle-kilometres, emissions are measured in grams per kilometre driven by each individual car and then aggregated to network level. The gases that are reported on, are CO_2, NO_x and PM_{10}.

Table 3.4: Key performance indicators

Category	Specification	Unit
Vehicle Delay	Non-SAV SAV Bus Bicycle	Min
Distance travelled	Total	Km
	Non-SAV SAV	Km/veh
Emissions	CO_2 NO_x PM_{10}	g/km

3.5. Causal diagram

How the scenario factors, designs, system elements and KPIs relate to each other, can be summarized in a causal diagram. In the causal diagram depicted in figure 3.5, a distinction is made between elements that fall within the system under study and elements which fall at the edge. Scenario factors are located at the edge of the urban traffic system, because they are influenced by an external power, but they exert an influence on the urban traffic system. The system elements are influenced either by the scenario factors or by each other, and their combined interrelations finally determine the output in terms of KPIs. Relations between two elements are expressed by arrows and the (expected or proven) direction of this relation is indicated with a plus (positively correlated) or minus (negatively correlated) sign.

As can be seen, the scenario factors were formulated as *penetration AVs*, *automation bus*, *penetration SAVs*, *Occupancy SAVs* and *Total demand*. The main effects on the system that are identified, are threefold: effects of AV driving behaviour, effects of SAV driving behaviour, and intensity effects. The AV driving behaviour effects are caused by higher penetrations of AVs, automation of buses, and higher penetration rates of SAVs (as these are in essence also AVs). As described in section 3.3, an increase in these factors leads to reduced average reaction times, headways and mutual speed deviations. These all directly or indirectly lead to an increase in road capacity for motorized vehicles, which in turn leads to a reduced intensity/capacity (I/C) ratio, reducing the indicator *vehicle delay* for motorized vehicles like buses and cars. Additionally, a reduction in mutual speed deviation leads to a reduction in traffic flow variations, meaning that abrupt deceleration and acceleration is reduced. This leads to a reduction in energy consumption and thereby a reduction in the indicator *emissions*.

In addition to these AV driving behaviour effects, SAVs also cause their own SAV driving behaviour effects. As described in section 3.3, possible unfavorable effects of SAVs are their circulation on the network and stopping on the curbside to let passengers out. The network circulation leads to an increase of the distance driven on the network and thereby an increased traffic intensity. This directly affects the indicator *distance travelled SAVs* and thereby *total distance travelled*.

The SAV driving behaviour effects affect the indicators *vehicle delay* in three ways: Firstly, by increasing the traffic intensity through increased network circulation, thereby increasing the I/C ratio. Secondly, by using links for U-turns with low capacity traffic signals, increasing its demand/capacity ratio and thereby its cycle time. This in turn causes longer queues and spillback. And lastly, by stopping on the curbside, they cause bottlenecks, reducing both directly and indirectly the road's capacity. Directly, because they temporarily cause unavailability of a lane, and indirectly through the more heavy deceleration and acceleration of vehicles passing the bottleneck, causing variations in traffic flow. This reduction in the road's capacity leads to a higher I/C ratio, causing higher vehicle delays. Among the vehicle delay indicators, *bicycle delay* is only affected by the traffic signal cycle times, while *bus and car delay* are affected by both the cycle times and the I/C ratio.

The SAV driving behaviour also has an effect on the indicator *emissions*. By causing bottlenecks, the SAVs cause more heavy deceleration and acceleration in cars that are passing this bottleneck. These variations in traffic flow cause a higher average energy consumption, and therefore higher value for *emissions per driven kilometre*.

Finally, there are the demand effects. These are caused by the external factors *base demand* and *occupancy SAVs*. The most straightforward effect is that an increase in demand causes higher traffic intensities, and thereby more kilometres driven on the network and higher vehicle delays by increasing the I/C ratio and the traffic signal cycle times. In the scenarios in this research, the demand is kept constant, but as was found in sections 2.2.2 and 2.4.2, this may be higher in reality due to new mobility concepts. On the other hand, an increase in the occupancy of SAVs both reduces the negative effects that SAVs have through network circulation and curbside stopping, simply by reducing the amount of SAVs, and it slightly reduces the total traffic intensity. This has an influence on *distances travelled*, *vehicle delays* and *emissions*. The influence of the base demand in the simulation model, however, was reduced to a minimum in order to provide a clear view of the effects due to differences in driving behaviour.

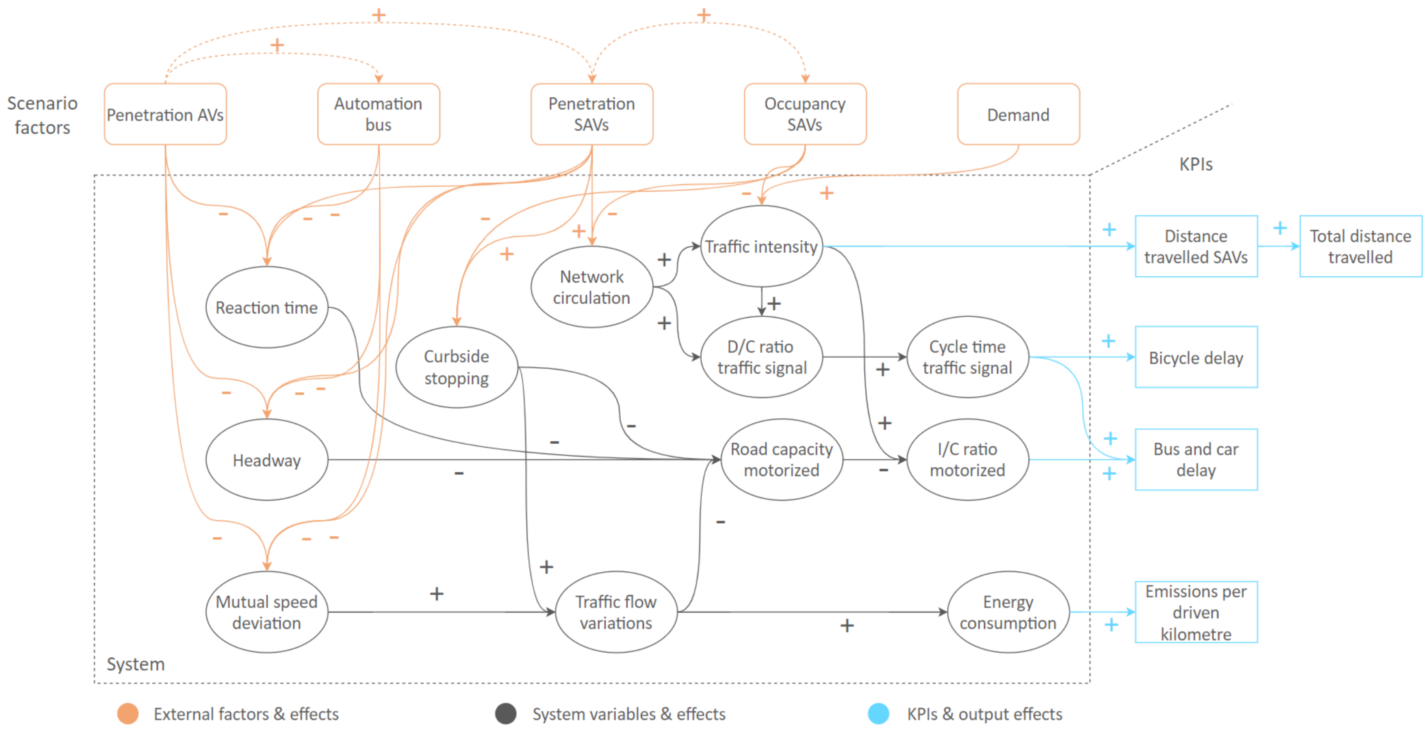


Figure 3.5: Causal diagram

4

Model application: scenario studies

As described in chapter 3, the relationships studied in this research are not easily summarized in one mathematical model. Therefore, a simulation study is performed using a case study network in The Hague. In this model, lower level inputs like traffic intensities, penetration rates and vehicle behaviour is defined by the user. By translating this into thousands of decision rules and draws from probability distributions, the model then displays emergent behaviour which can be measured using numerous indicators. The selected model input and indicators that were selected for this study, are introduced in chapter 3. These were implemented on an existing model of the case study network. This existing model is first described in section 4.1. How the scenarios were implemented on this model, how the scenario models were verified and how they were validated, is explained in sections 4.2, 4.3 and 4.4. Finally, the experimental set-up and results are presented in sections 4.5 and 4.6, showing the effect of the scenarios on the urban network without any intervention.

4.1. Current state model

To investigate the behaviour of the system, a traffic simulation model was used that was made by Arcadis for the Municipality of The Hague to test the impacts of a real estate project in the area in 2030. In this section, the specifications of this model are discussed as well as some core results.

A traffic simulation model has four main elements: the physical road network, the traffic assignment, the internal driver behaviour, the traffic management and control, and performance measurement. These elements can be specified in such a way that is assumed to best represent reality. In this section, the specification of each of these elements is further discussed.

4.1.1. Physical road network

The physical road network in this model consists of origin/destination (OD) zones and the road links connecting them. In the model at hand, cars, buses and freight vehicles use the same network and a separate network is modeled for bicycles. There is no pedestrian network modeled. The motorized network and the bicycle network only meet at the intersections.

The model contains 20 OD zones for motorized traffic and 11 OD zones for bicycles. These OD zones as well as each of the intersections are modeled as nodes. Based on the links between these nodes, the model determines a number of edges connecting each neighbouring pair of nodes. Based on these edges, the model determines a set of possible paths between each pair of nodes. This is then used for traffic assignment, as will be discussed in section 4.1.2.

In figure 4.1, the physical network that is used in the model, is displayed. Grey links are roads for motorized traffic, pink links are bicycle paths and blue areas are nodes. One additional OD zone is added as compared to the current network (see figure 3.2). This zone (4) is the parking garage of a building that is planned to be built on that location between now and 2030. Further, the deepened part of the Utrechtsebaan is included in the model, but is made invisible. This is because it has an influence on the modeled area, but the traffic on this road is not studied. The influence of the Utrechtsebaan traffic on the rest of the network and the other way around can be studied by including a few hundred metres of the Utrechtsebaan in the South Eastern part of the network, as can be seen in figure 4.1. Some zone numbers have been added to this figure for easy communication. These are not the original zone numbers in the OD matrix. Zones that are not numbered are either coupled to a different numbered zone, or they are bicycle or bus zones.

Zones 4, 8, 9 and 10 are parking garages. This notion will be used later on when determining which travellers have a destination inside this network. These are the travellers that originally had one of the parking garages as their destination. In the modeling study, a part of these travellers will now be dropped off in the network by a SAV instead of driving to the parking garage.

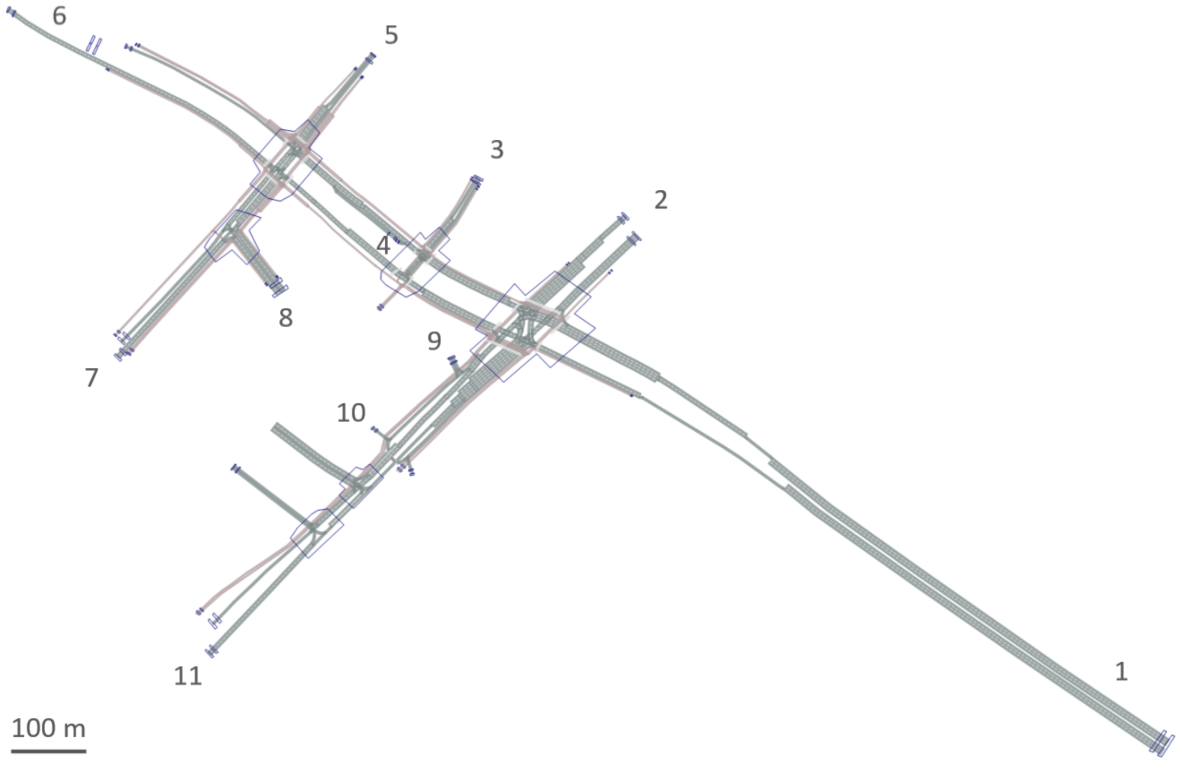


Figure 4.1: Graphical representation of the physical network in the model

4.1.2. Traffic assignment

In this original model, traffic is assigned to the network dynamically. An exception to this are the buses: they are instantiated according to a predefined timetable and follow predefined routes. The cars, freight vehicles and bicycles are assigned to the network according to an origin-destination (OD) matrix. Note that as the original study was for the year 2030, this matrix was constructed for the year 2030. Based on the amounts of traffic that this matrix defines between each OD pair, inter-arrival times are determined according to a probability distribution and generated traffic assigned dynamically to the network. This means that the vehicles decide their route to their destination based on the previously computed "costs" (travel times) of all possible paths between the sets of nodes. However, since this is an open network (i.e. there are no loops), only one route is feasible between each OD pair.

For this model, the modes bicycle, car, large goods vehicles (LGV) and heavy good vehicles (HGV) each have a separate OD matrix. The frequencies in this matrix are given for the entire 2-hour morning peak, after which they are distributed proportionally over 15 minute intervals. Based on the resulting intensities, Vissim determines inter-arrival times for each mode per 15 minute interval. The factors that were used to make this distribution, can be found in table 4.1.

Table 4.1: Factors used to divide OD matrices over 2 hour time interval morning peak

Interval start	7:00	7:15	7:30	7:45	8:00	8:15	8:30	8:45
Factor	0,1125	0,125	0,125	0,1375	0,1375	0,125	0,125	0,1125

It is important to comment on how the OD matrices were made, because they form a basis for this research. The matrices that were used in this traffic model are the result of an extensive static traffic assignment study that was performed for the Municipality of The Hague and the Haaglanden area by the mobility research company Goudappel Coffeng [22]. They applied the full four stage model approach to obtain trip generation, trip distribution and modal split, and trip assignment using national mobility data, socio-economic data and scenarios for the Haaglanden area, and the modeling software package Omnitrans.

Goudappel delivered estimations for the years 2011, 2015, 2020 and 2030. However, they did not take into account some planned real estate project in the area around the network that was modeled by Arcadis. Therefore, Arcadis reiterated on the traffic assignment delivered by the Goudappel model using expected production and attraction rates of the locations that are planned to be built. Then Arcadis made a cut-out from the static traffic assignment model and extracted the traffic that was assigned to this specific network. Based on this, they made the OD matrices.

4.1.3. Driver behaviour

How road users act and react is determined by the driver behaviour model that is used. This driver behaviour model is a set of rules that are built in in each agent. Some of these rules are deterministic, but most are stochastic to best represent the diversity in types of drivers in real-world traffic. Vissim has default driver behaviour models which usually differ between motorized traffic, non-motorized traffic, urban traffic and highway traffic. The drivers follow a set of rules for car following, lane change, lateral behavior and reaction to signals. Besides this, drivers are assigned an initial desired speed, acceleration curve and deceleration curve from a predefined distribution. At points in the network where the maximum speed changes or where a reduced speed is desired (eg. in a turn), drivers are assigned a new desired speed from a distribution.

The standard driver behaviour models employed by Vissim are based on Wiedemann's research from 1974 and 1991 [65, 66]. In PTV's user manual for Vissim, they provide an accurate description of how Wiedemann's traffic flow model is applied [44]. This model discerns four driving states: free driving, approaching, following and braking. In each of these states, acceleration is computed for each subsequent time step as a function of speed, speed difference and distance to preceding vehicle in the current time step. Individual driver and vehicle characteristics are also taken into account here. Another driving state is reached when a threshold is passed which is a function of speed difference and distance. The perception of speed differences, the desired speed and the safety distance kept vary between drivers.

The driving behaviour models used as default in Vissim were validated with real-world traffic data by Fellendorf and Vortisch [17]. They found that the behaviour resulting from these models quite accurately resembles behaviour observed in the real world for similar situations. This is, however, subject to where it is tested. The Vissim default is particularly applicable to driving behaviour on German roads. If the model is applied to other countries with different behaviour, the parameters need to be recalibrated.

In the Vissim model of The Hague, the basic Vissim cycle-track model is used for cyclists and the basic Vissim urban (motorized) model is used for cars, freight vehicles and buses. Furthermore, default distributions for the desired speeds are binned per 10km/h with each a uniform distribution between a minimum and a maximum speed. Lastly, default acceleration and deceleration curve distributions are defined for the desired and maximum acceleration and deceleration of a car. In appendix C the used set of parameters can be found for the base model as well as for the scenario models.

4.1.4. Traffic management and control

Traffic management and control elements are external factors governing the driving behaviour. These elements are the total set of traffic rules, traffic signs, speed limits and intersection controls governing the network. In the current state model, there are control elements that regulate speed, priority and lane selection.

Speed in the network is regulated with decision points that appoint a new desired speed to vehicles once they pass them. Each vehicle that is generated in the model receives an initial desired speed between 48 and 58 km/h, which is drawn from a probability distribution. Once a car passes a decision point, a new desired speed is appointed based on another draw from a probability distribution. The network contains points that assign a speed of ca. 70 km/h on the Utrechtsebaan, points that assign a speed of ca. 50 km/h when vehicles exit the Utrechtsebaan, and points that assign a speed of ca. 30 km/h in turns.

Priority is regulated in a couple of different ways in the network. Firstly, there are five signalized intersections where priority is primarily regulated by the traffic lights. These lights are controlled by signal controllers which take into account several detection loops when determining cycle time and green times. The signal controllers of the three main intersections in the network run on an external module that is coupled to the CCOL algorithm, which is used in reality on these roads.

In addition to the traffic signals, there are also priority rules in place. On every location where two traffic streams meet, these priority rules dictate who receives priority. Additionally, they can dictate that vehicles may not block the conflict area if there is not enough space available downstream.

Finally, there are traffic management instruments in place in the model that help the vehicles to select the correct lane to pursue their desired direction at an upcoming intersection. At a predefined "lane change distance" before the intersection, vehicles are notified that they should attempt to reach the desired lane. If they have not reached that lane at the predefined "emergency stop distance", they halt and wait until there is a gap available in the desired lane. In reality drivers tend not to wait very long for an available gap and rather just push their car in between, but this behaviour could not successfully be simulated in Vissim yet. Therefore, vehicles that wait for longer than a predefined "diffusion time" are removed from the network so as not to block the other vehicles for too long. The diffusion time used in this model is 60 seconds.

4.1.5. Performance evaluation

To determine the values of the key performance indicators, performance should be measured and recorded per run. Evaluation of performance is done by three different means in the model: delay measurements, network performance measurements and vehicle records. The explanation of how these measurements work was derived both from calibrating the model and from the PTV Vissim user manual [45].

The delay measurements are coupled to travel time measurement points. Each route contains a set of two measurement points of which one is located at the beginning of the route and the other at the end of each route. For each vehicle that passes both of the measurement points, the travel time is recorded. The delay measurements then calculate for each vehicle the difference between this actual travel time and the travel time which they would have had if they could drive their desired speed over the entire route. This "ideal travel time" only takes into account the distance travelled and the desired speed that the vehicle has had during each leg of the route. This desired speed may change when the vehicle passes a desired speed decision, for instance when the maximum speed is reduced or the vehicle makes a turn. These (temporary) changes in desired speed are taken into account when calculating the vehicle delay. What is *not* taken into account, are the traffic lights. Each second spent waiting for a red light, is therefore added to the delay. This is recorded as their vehicle delay. The results of the delay measurements are collected each time a vehicle exits the model, and reported as an amount of vehicles-weighed average per 15 minutes for each route. This is done for cars and freight, as well as for buses and bicycles. Aggregate values over the entire simulation period are also reported.

The distance travelled is a property that each individual vehicle in the model reports to the network performance measurements at each time step. For vehicles that already exited the model, the value is also saved. The results are collected each time step and reported per 15 minute interval as a total distance of all vehicles or as an amount of vehicles-weighed average. This is done separately for all vehicles that were still in the model at the end of the time interval and all the vehicles that exited the model during that interval. Aggregate values over the entire simulation period are also reported. A distinction can be made between vehicle classes when reporting the results.

To calculate performance in terms of emissions, an external module called EnViVer Pro is used which takes vehicle records produced by the simulation model as input. Vehicle records track a number of predefined attributes for each vehicle on the model for each time step. This is recorded in a file that contains a row for each vehicle for each time step with the values of the desired attributes. The attributes that are tracked in order to make the emissions calculations are the type of the vehicle, its identification number, its speed, its location, the simulation second, and the gradient of the link which it is on. The vehicle record file, containing several million rows of data, can then be imported into EnViVer Pro. In this module, the Vissim vehicle types can be coupled to predefined or user defined vehicle classes with each their own emissions specifications [43]. When this is done, EnViVer Pro calculates total emissions, emissions per vehicle class, emissions per vehicle class per kilometre, and shows several plots of the dispersion of emissions in the network.

4.2. Scenario specification

To model the in chapter 3 defined scenarios, values and assumptions rooted in these scenarios needed to be translated into the modeling language used. In this section, a description is provided of how this translation was done. The description is divided into the aspects that are different in the scenario models compared to the current state model: base demand, penetration rates and vehicle occupancy (defining traffic intensities and composition) and vehicle behaviour of human drivers, AVs and SAVs.

4.2.1. Base demand, penetration rates and occupancy

In section 4.1.2 it was explained how in the original model the traffic demand is implemented by means of a 2-hour matrix for each mode which is then divided into 15-minute intervals by predefined multiplication factors. Further, in section 3.2 results from historic traffic counts were presented, confirming that any growth occurring in the traffic demand, only occurs at the edges of the peak period. This is because the roads are already at capacity in the middle of the peak period. This notion, combined with an expected average growth rate for motorized traffic estimated by Goudappel Coffeng et al. [22] of 0,5%, led to the conclusion to add the annual growth rates to the original matrices that are presented in table 3.1 in section 3.2 with more growth at the edges of the peak period and no growth in the middle. These growth rates were applied by simply increasing the 15-minute multiplication factors by this annual percentage over a 10-year period. For cyclists, a uniform growth rate of 1% per year was determined for the entire 2-hour period.

Additionally, the matrices for the car mode were split up into two sets (depending on the scenario): one set of matrices for personal cars and on set for SAVs. For the purpose of this model, the only SAVs that were considered as being of interest, are the SAVs that have passengers to drop off directly in the area under study. This is because SAVs that only drive through the area, but whose passenger's destination is elsewhere, will behave as normal AVs in the area and will therefore not need to be distinguished. Further, only passenger drop-offs are considered, because this is the morning peak period and most of the surrounding real estate are activity-end buildings, not residences. Therefore, it was analysed which vehicles in the original model had a destination within the modeled area and found that those were the ones who traveled to one of the four zones that were identified in section 4.1.1 as representing a parking garage: zones 4, 8, 9 and 10. Of these travellers, a certain percentage (depending on the scenario) was transferred to the SAV-matrix.

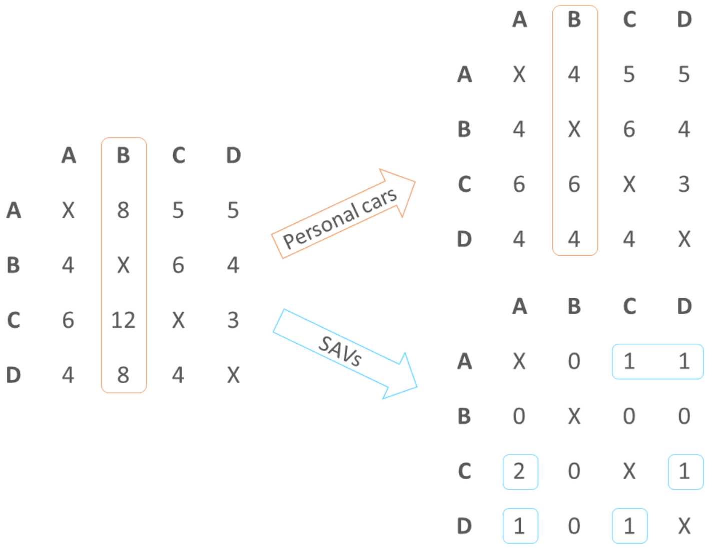
The SAV occupancy was then implemented by dividing this number by a reduction factor. This reduction factor was obtained by observing that the average vehicle occupancy of personal vehicles for home-work commute in The Hague, as found by Goudappel Coffeng et al. [22], is 1,1. It is possible to do this, because the study period is the morning rush-hour and the surrounding buildings are almost all employers. This means that it would be necessary to multiply the original matrix of personal cars by 1,1 to obtain a matrix of travellers.

The cars that end up in this SAV matrix will be assigned a destination outside the network where they will go to pick up their next passenger. However, they will first make a stop in the network to drop off their current passenger before moving on to the next one. The destination zone to pick up their next passenger is assigned by ratio of the destinations of the other traffic.

A simple example of what the resulting personal car and SAV matrices would look like, can be found in figure 4.2. In this case, zone B is a parking garage, the percentage of travellers taking SAVs is 50% and the SAV occupancy is twice the occupancy of personal cars. This results in the two matrices as presented in the figure. As can be seen, the amount of personal cars driving to zones A, C and D remains the same. The amount of personal cars driving to zone B is reduced by half, because the remaining travellers now take a SAV. These remaining travellers are divided over half the amount of SAVs, since the occupancy is twice the amount of conventional cars. This amount of SAVs is divided proportionally to the original matrix over zones A, C and D where they will leave the network to pick up their next passenger after the current passengers have been dropped off. The personal car matrix will later be divided into AVs and non-AVs.

This leads to 50 matrices being loaded into Vissim: 10 for each mode (8x15 minutes plus 2x15 minutes warm-up and cool-down). The modes being distinguished here are car, SAV, LGV, HGV and bicycle. Besides these modes, buses are also implemented in the model by means of static assignment according to a schedule. The actual bus schedule needed to be translated into several frequency tables for the model. Many buses temporarily leave the modeled area to make a stop at the station and then return into the network. These buses are modeled as two separate buses, while in reality they are one and the same. This is why the used frequency table does not resemble the actual bus schedule, but it has the same effect. The 2-hour matrices as well as the bus frequency table that were used as input for the model are presented in appendix B.

Where the SAV and bicycle matrices only instantiate a single vehicle class, the car and LGV matrices instantiate multiple vehicle classes. Depending on the penetration rates of AVs, a certain percentage of vehicles instantiated by these matrices are AVs. Furthermore, for the car and LGV mode, the remaining "human" drivers are divided into three types of drivers: defensive, average and assertive. The reason for this is to create some more differentiation between human drivers in the model in an attempt to increase the validity of the model. The proportion defensive:average:assertive is determined to be 0,25:0,5:0,25. This is implemented in Vissim by specifying the rates of certain vehicle classes for each matrix. For example, for scenario 2 (with 50% AVs), a car matrix would be divided into defensive:average:assertive:AVs by the ratios 0,125:0,25:0,125:0,5.



	A	B	C	D
A	X	8	5	5
B	4	X	6	4
C	6	12	X	3
D	4	8	4	X

	A	B	C	D
A	X	4	5	5
B	4	X	6	4
C	6	6	X	3
D	4	4	4	X

	A	B	C	D
A	X	0	1	1
B	0	X	0	0
C	2	0	X	1
D	1	0	1	X

Figure 4.2: Example of division matrices personal cars/SAVs

These matrices and further specification in Vissim lead to a unique traffic composition for each scenario. The vehicle classes being instantiated per matrix (depending on the scenario) are presented in table 4.2.

To allow for the SAVs to be routed to drop-off spots in the network and continue their journey to the next passenger afterwards, it is necessary to implement static routing in the model. As the network under study is an open network, meaning that between each two points in the network, there is only one route possible, it is no problem to apply static routing in the model. However, since matrices are a tool for dynamic assignment, they can only be used in combination with dynamic routing. The use of matrices allows easy definition of base demand, demand growth, and division into vehicle classes. Therefore, the assignment and routing is first defined using the above defined matrices, after which Vissim is asked to convert this traffic assignment into static assignment and -routing.

Upon doing so, Vissim creates vehicle inputs at each origin zone and defines arrival rates per 10 minutes. Vissim also creates vehicle compositions which are then linked to these arrival rates. This way, Vissim combines all the matrices attached to this origin zone. When the option is selected to make the arrival rates stochastic, the registered rates are treated as parameters for a poisson distribution for inter-arrival times. Destinations are then assigned to the vehicles by a routing decision which the vehicles pass directly after being instantiated. This routing decision assigns a destination and route to a vehicle by ratio of the destinations as previously defined in the matrix. Additionally, the SAVs are also influenced by a parking routing decision, which assigns them a place in the network where they will stop to drop off a passenger. This will be further elaborated on in section 4.2.4.

4.2.2. Behaviour human drivers

As discussed in section 4.1.3 the driving behaviour of a vehicle is defined by a set of driving behaviour parameters, desired speed distributions, and acceleration and deceleration curves. For urban motorized traffic, Vissim has default settings which are validated using real-world data. However, for the purpose of this study, it was chosen to differentiate between three classes of human drivers: defensive, average and assertive. The difference being that assertive drivers have a higher desired speed, and accelerate/decelerate faster, while defensive drivers have a lower desired speed, and accelerate/decelerate slower. The parameters of the Wiedemann car-following model, the lane change model and the reaction time are kept equal. This is because no evidence has been found suggesting that these parameters should differ per type of human driver. Furthermore, an increase/decrease in desired speed already leads to the expected differences in behaviour (eg. a lot of lane changes in an attempt to overtake one's preceding vehicle) under equal Wiedemann and lane change parameters. The distributions used for desired speed, acceleration and deceleration can be found in appendix C. Which distributions are assigned to which vehicle class, is presented in table 4.2.

4.2.3. Behaviour AVs

In contrast to the different types of human drivers, AVs are subject to a different set of Wiedemann, lane change and reaction time parameters. These parameters are adjusted to reflect the differences in driving behaviour from normal cars as defined in section 3.3, table 3.3: no stochasticity, shorter headways and reaction times, smoother acceleration/deceleration, and longer lookahead distances. This is translated into changes in the parameters of the Wiedemann car following function, a twofold increase in the amount of observed vehicles, a fixed standstill distance, and the application of "smooth close-up behaviour". A full overview of the driving behaviour parameters can be found in appendix C.

Furthermore, the desired speed distributions as well as the acceleration/deceleration curve distributions are modified to be deterministic. This means that, for instance, in a 50 km/h area, the AVs desired speed when not obstructed is always exactly 50 km/h. Furthermore, depending on the current speed, AVs always apply the same acceleration/deceleration rate. These changes are not recorded in appendix C, because they are simply the original distributions, but then deterministic. The parameter sets and distributions assigned to each vehicle class, can be found in table 4.2

4.2.4. Behaviour SAVs

In the basis, SAVs are obviously also AVs. This means that their driving behaviour parameters and distributions are equal to those of normal AVs in Vissim. However, the difference is that the SAVs that are defined for this model, as was stated above, are dropping off a passenger in the network and then continue on to their next passenger. To enable this, some changes needed to be made to the Vissim network and the vehicles needed to be assigned a drop-off location, dwell time, and final destination.

To allow Vissim to assign drop-off locations to the vehicles, these locations first need to be defined. Therefore, a careful analysis of the network was conducted to identify locations where people would *want* to go during the morning peak and where vehicles are *able* to drop passengers off. If in the real-world network, there are parking spots available on the location, the Vissim link needed to be expanded by one lane on which parking spots were placed. If, however, there were *no* parking spots available at the location and the vehicles need to stop on the driving lane, this was modeled as "parking spots" located on the driving lane. The locations that were selected, can be found in figure 4.3. In this figure, all blue areas located on the links are "parking spots" where the SAVs may stop. The stopping locations that are actual parking spots, and are therefore not located on the driving lane, are marked with a blue "P". The stopping locations where vehicles may stop on the lane itself (exclusively on the curbside), are marked with an orange "S". Further, the main places of interest in the network and the zone numbers of the O/D zones are indicated. In the parts of the network not displayed in this image, there were no viable stopping places.

Once the SAVs are instantiated and have been assigned a final destination (where they will go afterwards to pick up their next passenger), they are assigned one of the on the map indicated places where they will briefly stop to drop off their current passenger. The stopping places are assigned at random. However, it was ensured that SAVs *only* drive to drop-off locations that they would logically take a route through this network for to reach. For example, a car coming from zone 2 (on the right in figure 4.3) who needs to drop off a passenger at the school in the top of the image, is more likely to use a different road than the ones in this network. Therefore, cars coming from zone 2 are not given this option.

After having been assigned a drop-off location, the vehicles take the shortest route to this location. Once they reach the drop-off location, they park and dwell there for a short amount of time. The dwell time is drawn from a normal distribution with a mean value of 20 seconds and a standard deviation of 5 seconds. After this, they leave the parking spot and take the shortest route to their final destination.

To ensure that all SAVs are able to reach all parking spots and to reach their final destination from the parking spots, some small adjustments needed to be made to the network. On some links and intersections, the possibility to make a U-turn needed to be built in. This was only done on locations where in the real-life network it is also possible to make a U-turn.

4.3. Model verification

When using a computerized model to test theories from a conceptual model, it is always important to verify that the computerized model adequately represents the conceptual model. This needs to be done before the model is used for experimentation to ensure that the results obtained from the experiments accurately represent the conceptual model.

In this case, the computerized model was made using specialized traffic simulation software. The software

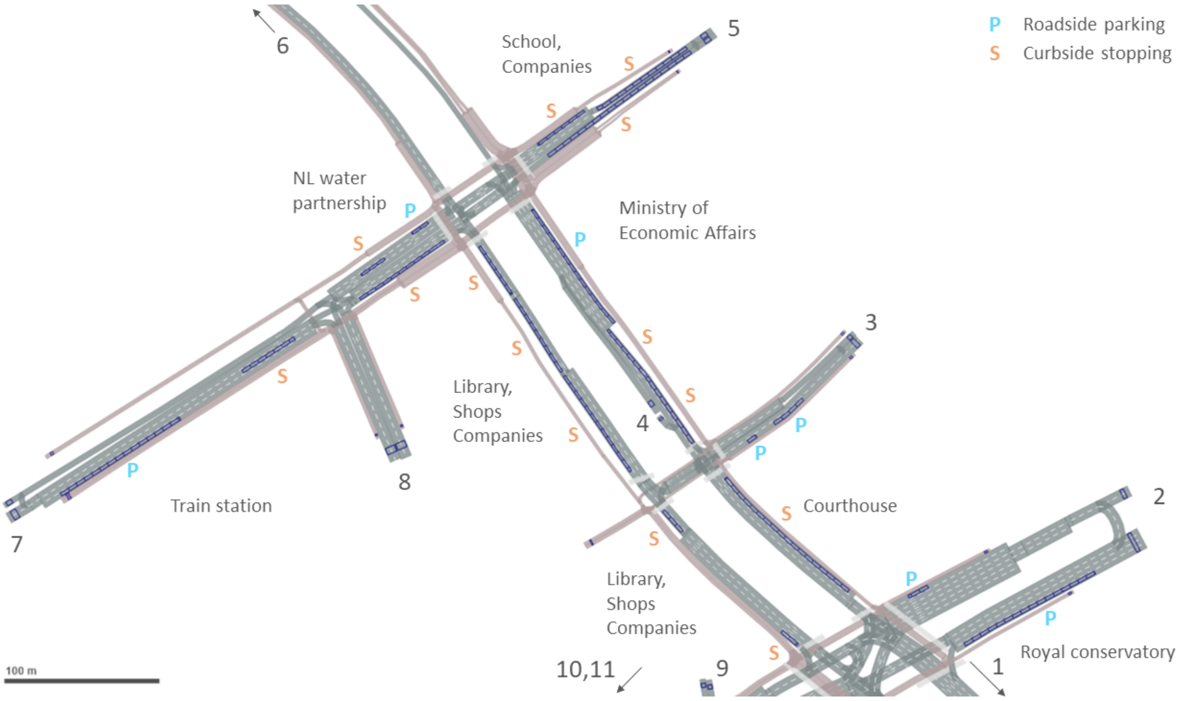


Figure 4.3: Stopping locations SAVs, places of interest, and O/D zones

Table 4.2: Vehicle classes and corresponding driving behaviours, speeds, and acceleration/deceleration

Mode	**Vehicle class**	**Driving behaviour parameters**	**Desired speed distributions**	**Desired acceleration/ deceleration curves**
Car	Car-average	Urban motorized	Average	Average
	Car-defensive		Defensive	Defensive
	Car-assertive		Assertive	Assertive
	Car-AV	Urban AV	AV	AV
SAV	Car-SAV	Urban AV	AV	AV
LGV	LGV-average	Urban motorized	Average	Average
	LGV-defensive		Defensive	Defensive
	LGV-assertive		Assertive	Assertive
	LGV-AV	Urban AV	AV	AV
HGV	HGV	Urban motorized	Average	HGV
	HGV-AV	Urban AV	AV	
Bicycle	Bicycle	Cycle track	Bike	Bike
Bus	Bus	Urban motorized	Average	Bus
	Bus-AV	Urban AV	AV	

developer, PTV, has already taken steps to verify the default driving behaviour in the model as well as the driving behaviour of the autonomous vehicles. Further, the properties of the physical network, the initial traffic assignment, and the traffic management and control measures have been verified by Arcadis as the original model is being used for a project for the Municipality of The Hague. So what is left to verify are the changes made to the default settings and original model in order to answer the research question. This is the new traffic assignment numbers, the penetration rates, and the driving behaviour of the various new vehicle classes.

4.3.1. Demand

First it was checked whether the road users registered by Vissim matched the base demands as defined in section 3.2. For this, results from the Vissim model were collected for the amount of vehicles per vehicle class that had exited the network or was still in the network at the end of the measurement period. This was then compared to the matrices that were defined on the basis of the scenarios. This step was necessary, because the matrices were converted to static assignment and then re-stochasticized. Therefore, the matrices were not direct input to the model anymore at the moment of the experiments.

In table 4.3 a comparison of the matrix values (as found in appendix B) and the measured values is presented. The difference is given in percents deviation of the matrix value. As can be seen, all differences are below 10%. However, a few differences stand out and will need some explanation.

It should first be noted, as mentioned above, that the static assignment was created on the basis of one run of the model using dynamic assignment. After this, the static assignment is converted into a poisson distribution for inter-arrival time with the registered value for number of arrivals that was recorded using the dynamic assignment as parameter. It may be the case that the recorded value is just on the low or high end of the spectrum of arrivals generated by the matrix. In that case, the mean number of arrivals will always convert to this higher or lower amount. This is a limitation of the model that needs to be considered when interpreting the results.

Secondly, it should be taken into account that the model works with a warm-up period for which a separate warm-up matrix is used. This warm-up period is used to ensure that by the time the measurements start, there are enough vehicles already in the network to create realistic traffic situations. Therefore, it may be the case that by the time the first measurement is taken (15 minutes after the start of the actual simulation period), there are still some vehicles in the model that entered during the warm-up period. This may lead to a higher recorded amount of vehicles in the model than is in the matrix.

Thirdly, for some scenarios it was the case that congestion occurred during the simulation period which spilled back towards the point where one of the vehicle inputs was located. As a result, not all vehicles that were planned to enter during the simulation period were able to enter the model. This then caused a lower recorded amount of vehicles of the classes entering through that vehicle input than was defined in the matrix. This is especially the case for scenarios 4 (0/0) and 7 (100/100).

Table 4.3: Verification of base demand: input (matrix) values and measured (model) values

Scenario		**Cars**	**SAVs**	**LGVs**	**HGVs**	**Bicycles**	**Buses**
1: 20/3	Matrix	16.532	57	590	214	6.606	246
	Model	16.575	54	610	220	6.534	247
	Difference	0%	-5%	3%	3%	-1%	0%
2: 50/25	Matrix	16.112	350	590	214	6.606	246
	Model	16.125	372	600	208	6.534	247
	Difference	0%	6%	2%	-3%	-1%	0%
3: 80/50	Matrix	15.635	525	590	214	6.606	246
	Model	15.702	544	592	214	6.545	247
	Difference	0%	4%	0%	0%	-1%	0%
4: 0/0	Matrix	16.589	0	590	214	6.606	246
	Model	16.153	0	586	223	6.545	246
	Difference	-3%	0%	-1%	4%	-1%	0%
5: 50/0	Matrix	16.589	0	590	214	6.606	246
	Model	16.648	0	606	199	6.531	246
	Difference	0%	0%	3%	-7%	-1%	0%
6: 100/0	Matrix	16.589	0	590	214	6.606	246
	Model	16.623	0	599	222	6.544	247
	Difference	0%	0%	1%	4%	-1%	0%
7: 100/100	Matrix	14.680	1.050	590	214	6.606	246
	Model	13.517	1.031	562	210	6.530	246
	Difference	-8%	-2%	-5%	-2%	-1%	0%

4.3.2. Penetration rates

Next, the proportions of vehicle classes for each scenario were analysed to verify whether the penetration rates defined in section 3.2 matched those in the computer model. For the penetration rate of AV cars, LGVs and HGVs this was very straightforward. For each scenario the amount of AV cars, LGVs and HGVs, and the amount of non-AV cars, LGVs and HGVs was recorded. These amounts are presented in table 4.4 as well as the resulting percentage of AVs in the model. As can be seen, all recorded proportions accurately represent the market penetration rates from the scenarios. Only there is one percent difference in scenario 1 (20/3). The reason for this may again be as simple as the conversion from dynamic to static assignment in Vissim.

Table 4.4: Verification proportion AVs: calculation of measured proportions

Scenario	AVs	Non-AVs	Total	Proportion AVs
1: 20/3	3.591	13.814	17.405	21%
2: 50/25	8.454	8.480	16.933	50%
3: 80/50	13.210	3.298	16.508	80%
4: 0/0	0	16.963	16.963	0%
5: 50/0	8.740	8.713	17.453	50%
6: 100/0	17.444	0	17.444	100%
7: 100/100	14.290	0	14.290	100%

For the penetration rate of SAVs, this was slightly more tricky. This is because this rate was defined as a percentage of travellers and implemented focusing on travellers with one of the parking garages in the network, and considering a certain vehicle occupancy. Therefore, it was needed to first calculate the personal car equivalent of the amount of SAVs that were recorded in the model by dividing the amount of SAVs by the reduction factor that was previously used to implement the vehicle occupancy. This personal car equivalent value was then added to the amount of regular cars recorded in the model to obtain the total amount of cars equivalent value. From the matrices, it was found that originally 11,5% of all cars went to one of the parking garages, so using the total amount of cars equivalent value, the "parking equivalent" could be calculated. Then it was verified whether the proportion of recorded personal car equivalent of SAVs compared to this parking equivalent matched the penetration rate as defined in the scenarios. Table 4.5 presents the total amount of cars equivalent value, the parking equivalent and the personal car equivalent of SAVs that were recorded for each scenario, as well as the proportion of travellers using SAVs following these values.

As can be seen in the table, there is a slight deviation from the scenarios, especially when it comes to scenario 7 (100/100). It is interesting to see that the proportion of SAVs to personal cars is higher than anticipated, while the absolute amount of SAVs (as can be seen in table 4.3) is lower. This can again be explained by the conversion of dynamic assignment to static assignment. It needs to be taken into account when studying the results. However, it is not entirely unrealistic that there are more travellers being dropped off in the area by SAVs than there previously were parking in one of the parking garages. But this is a point for model validation, not verification.

Table 4.5: Verification proportion SAV travellers: calculation of measured proportions

Scenario	Total cars equivalent	Parking equivalent	Personal car equivalent of SAVs	Proportion SAV travellers
1: 20/3	16.629	1.921	54	3%
2: 50/25	16.632	1.921	508	26%
3: 80/50	16.692	1.928	990	51%
4: 0/0	16.153	1.858	0	0%
5: 50/0	16.648	1.915	0	0%
6: 100/0	16.623	1.912	0	0%
7: 100/100	15.391	1.778	1.874	105%

4.3.3. Driving behaviour

Verifying the driving behaviour is slightly more difficult. For AVs in general, a number of differences were named in the conceptual model between their behaviour and the behaviour of normal cars: a reduction in headway, less deviation in headway, less deviation in speed, a shorter reaction time, a further lookahead distance, smoother acceleration and deceleration, less deviation in acceleration and deceleration, and a smaller path deviation.

The animation function of Vissim allows the user to study the behaviour of the vehicles during simulation. Not only can their actions and interactions be studied, but it is possible to request details from specific vehicles such as their current speed, desired speed and acceleration. From a simple face validation test using these animation functionalities of Vissim, it seems like the AVs are behaving as expected compared to normal cars. They employ shorter headways, they always keep the same headway, they have a shorter reaction time at the traffic light and they always attempt to drive exactly the maximum speed.

The desired speeds and acceleration of the various types of vehicles (average drivers, defensive drivers, assertive drivers and AVs) is illustrated in figure 4.4a where each of these vehicles is shown in free flow conditions. As can be seen, the defensive car has a lower desired and current speed than the average car, while the assertive car has a higher desired and current speed. The AV has a desired speed of exactly the speed limit.

The headways and standstill distances that each type of vehicle employs is illustrated in figure 4.5 where the different types of vehicles are shown waiting in front of a red light and pulling away at a green light. Figure 4.5a shows that just like it was defined in the driving behaviour parameters which are presented in appendix C, the AVs keep a standstill distance of approximately 1 meter from the car in front. The human-driven vehicles, on the other hand, keep a standstill distance of approximately 2 meters from the vehicle in front. The AV at the front of the queue keeps a distance from the stop line of exactly 0,5 meter, just like it was defined in the driving behaviour parameters. The human-driven car at the front of the queue keeps a distance from the stop line of approximately 0,5 meter. In the driving behaviour parameters, this is defined as distributed normally around 0,5 meter.

In figure 4.5b, the headways are difficult to see, because they depend on the vehicle's current speed. At the speeds that were measured for these vehicles and based on the Wiedemann parameters as presented in appendix C, it was calculated that both the AVs and the cars with an assertive driver should have a headway of less than 1 second and the other cars should have a headway of more than 1 second. The former was indicated with a red arrow and the latter was indicated with a green arrow.

The SAV behaviour as described in the conceptual model could also be verified using the simulation animation function. The animation showed SAVs stopping on the roadside, forming a bottleneck for other road users, as well as SAVs often making U-turns and making more use of low capacity links than other road users do. Both types of behaviour are shown in figure 4.6 where in both images the selected (pink) cars are SAVs.

Figure 4.6a shows a SAV which is stopping to let out his passenger. The car behind the SAV needs to swerve to the left to be able to continue. As will the car behind that car. This causes some turbulence with extra lateral movements causing extra braking and accelerating. If another car had been diagonally behind the first blue car (in the left lane), this car would have needed to brake to allow for this car to enter his lane.

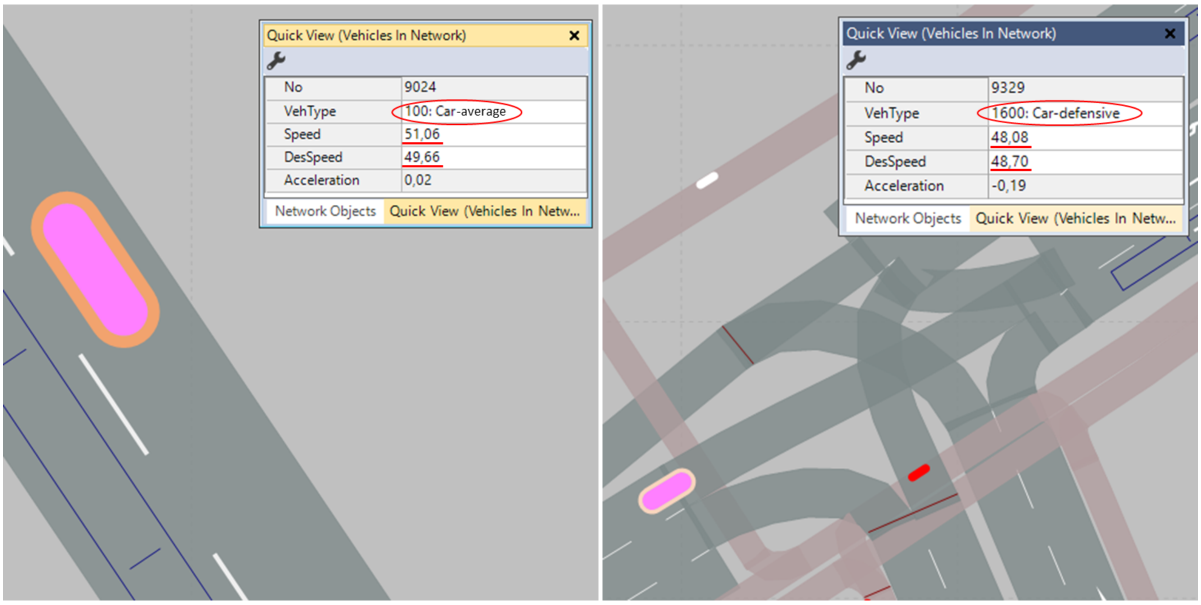
Figure 4.6b shows the link between the two parts of the main road. This link is actually meant for cars turning left, but now it is being used by two SAVs (pink) which are making a U-turn either before or after dropping off a passenger. The two (blue) cars behind these SAVs are waiting to turn left, but the queue is of such a size that they need to wait in front of the conflict area with the link coming from the other direction. This causes the queue to spill back over the bicycle path and almost to the previous traffic light.

The AV behaviour was verified in one more way, namely using the EnViVer Pro module for emissions calculations. This module uses direct output from Vissim and emissions data from standard vehicle fleets to calculate the emissions that would have occurred in the specific model run. The direct output that Enviver uses is for each simulation step, the vehicle class, exact location, speed and acceleration of each vehicle in the model at that moment as well as the slope of the link which they are on. When this data is loaded into the model, each vehicle class can be linked to one of the emission classes in the Enviver database to calculate emissions. These emissions are reported in grams per driven kilometre.

As stated in section 2.2.3, the reduction in headway, less deviation in speed and path, and smooth acceleration of AVs should reduce energy consumption and thereby the emissions calculated here. So it was tested whether the vehicles actually displayed this behaviour, using the Enviver Pro module. For scenario 2 (50/25), where 50% of personal vehicles, LGVs and HGVs are manually driven and 50% are AVs, the emissions per driven kilometre were calculated both these classes using the same predefined classes from the Enviver database. This was done for 10 runs. The results are presented in table 4.6. As can be seen, the emissions values for CO_2/km as well as NO_x/km and PM_{10}/km are lower for the AVs than they are for the manually driven vehicles. Although the differences are small, after performing a paired samples t-test, all differences were found to be statistically significant. The t-statistics as well as the p-values are reported in the table.

4.4. Model validation

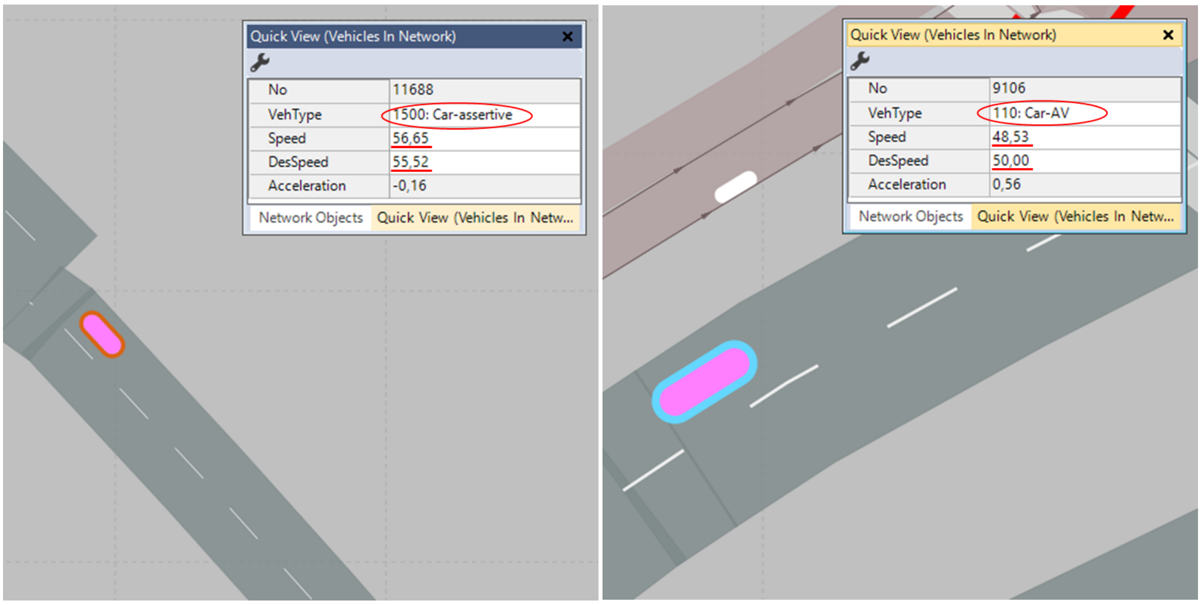
The last step before the model can be used for experimentation and the results can be assumed to be adequate for answering the research questions, is model validation. In this step, it is checked whether the model



No	9024
VehType	100: Car-average
Speed	51,06
DesSpeed	49,66
Acceleration	0,02

No	9329
VehType	1600: Car-defensive
Speed	48,08
DesSpeed	48,70
Acceleration	-0,19

(a) Average car (b) Defensive car



No	11688
VehType	1500: Car-assertive
Speed	56,65
DesSpeed	55,52
Acceleration	-0,16

No	9106
VehType	110: Car-AV
Speed	48,53
DesSpeed	50,00
Acceleration	0,56

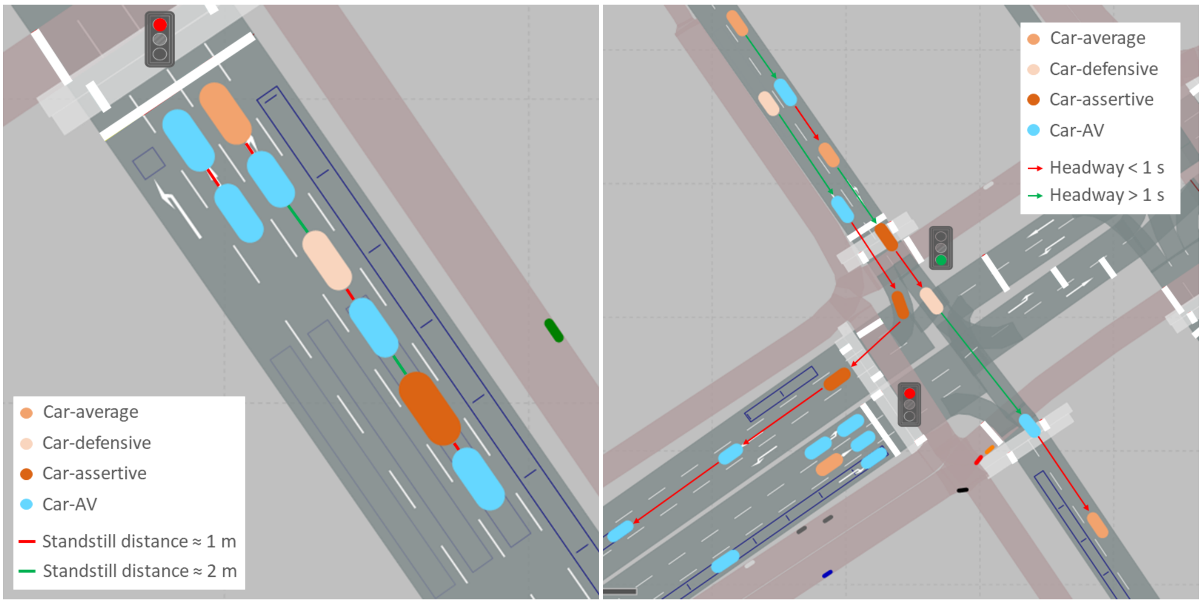
(c) Assertive car (d) AV

Figure 4.4: Different types of vehicles in free flow with current speed, desired speed and acceleration

Table 4.6: Verification of emissions as a result of driving behaviour non-AVs/AVs. N=10

	CO_2/km	**NO_x/km**	**PM_{10}/km**
Non-AV	295	0,444	0,041
AV	290	0,433	0,040
Difference	2%	2%	2%
t/p	5,48/0,00	3,24/0,01	7,85/0,00

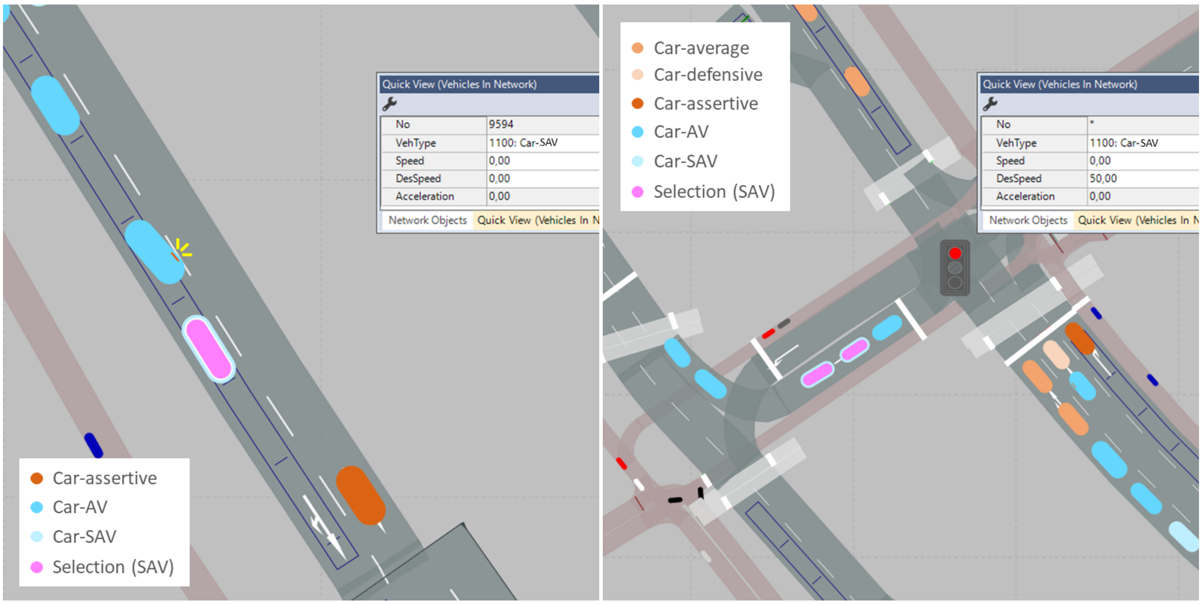
sufficiently represents the (hypothetical) real-life situation to answer the research questions. For models that use a current state as a starting point, validation can be done by comparing initial results with measurement data from the field. However, since this model uses a hypothetical future situation as a starting point, this is impossible to do. Therefore, validation was carried out in two ways: face validation through interviews with various experts and sensitivity testing.



(a) Standstill distances at red traffic light

(b) Headways when pulling away at traffic light

Figure 4.5: Standstill distances and headways of different vehicle types



Quick View (Vehicles In Network)

No	9594
VehType	1100: Car-SAV
Speed	0,00
DesSpeed	0,00
Acceleration	0,00

Quick View (Vehicles In Network)

No	*
VehType	1100: Car-SAV
Speed	0,00
DesSpeed	50,00
Acceleration	0,00

(a) Bottleneck created by SAV

(b) SAVs using a low capacity link

Figure 4.6: Behaviour of SAVs in the Vissim model

4.4.1. Expert validation

For the face validation of the model, six experts were interviewed during four different sessions. An extensive report of the information provided during these sessions, the questions asked and the feedback can be found in appendix D. In selecting and inviting the experts, it was deemed of high importance that various organizations were represented as well as different areas of expertise. As such, the following people were interviewed:

Name	Expertise	Organization
Jan Jaap Koops	Transport policy	Municipality of The Hague
Dr. Simeon Calvert	Traffic engineering & AVs	TU Delft
Maarten Amelink	Intelligent transport systems	Arcadis
Anton van Meulen	Traffic dynamics & simulation	Arcadis
Ronald van Veen	Urban mobility & traffic management	Arcadis
Erik Verschoor	Intelligent transport systems	Arcadis

During the sessions, the experts were provided with information about the goals of the research, the scenarios used, and the case study. They were briefly informed about what types of vehicles they could expect to see in the model, but information about their behaviour was not given in order to avoid bias. Then they were shown a few videos of the model in action for several scenarios and the first delay results. Afterwards, the experts were asked a number of questions about how realistic they thought the model was, how realistic the results were and to what extent the model would be useful to answer the research questions.

Judging from the videos and first results, the experts were relatively positive about the applicability for the model to answer the research questions. One major point of critique was that there are a lot of assumptions on the basis of the model, so the results will have to be seen in light of these assumptions. Also, the practical application of the model was questioned as the situations in most of the scenarios is quite theoretical (it is, for instance, unlikely that urban traffic in 2040 will consist for 100% of AVs). But on the other hand, the experts did agree that it was useful to show these situations for the purpose of the research. Further, most of the experts thought that it was unrealistic to assume such a high amount of SAVs stopping at the roadside without the municipality intervening. But when it was explained that the next step was to apply different designs for intervention, this was accepted.

4.4.2. Sensitivity tests

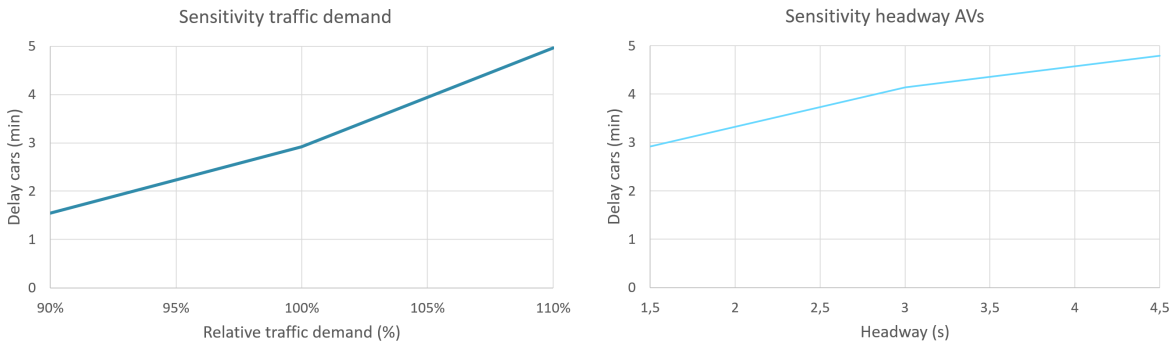
As was remarked in the expert validation, there are a lot of assumptions on the basis of the model. However, in reality it is uncertain whether factors influenced by these assumptions will actually conform to this. Therefore, the sensitivity of the model to these uncertain factors can be tested to establish how the results should be interpreted. If, for example, the model is very sensitive to a certain factor, it is important to have an accurate prediction of the actual value of this factor, otherwise the results are invalid. When interpreting the results, the accuracy of this factor should be named as the first condition. Factors that should be tested for sensitivity either have a high uncertainty or a high expected impact on the model, or both. Going back to the conceptual model, the input factors that were identified to be of the highest importance to be tested for model sensitivity are:

- Traffic demand
- Headway of AVs
- Deviation behaviour of human drivers
- Drop-off time SAVs

For these four factors, a lower bound, middle value and upper bound were established with equal distances from each other. This was implemented in the model of scenario 2 (50/25), after which 10 model runs were performed. As indicator the average delay for non-SAV motorized vehicles over four of the most significant routes was chosen. These routes all have a combination of a minimum 2-hour car demand of 200 and a significant usage of the network under study. How this indicator reacted to the deviations in the four sensitivity factors, is presented in figure 4.7.

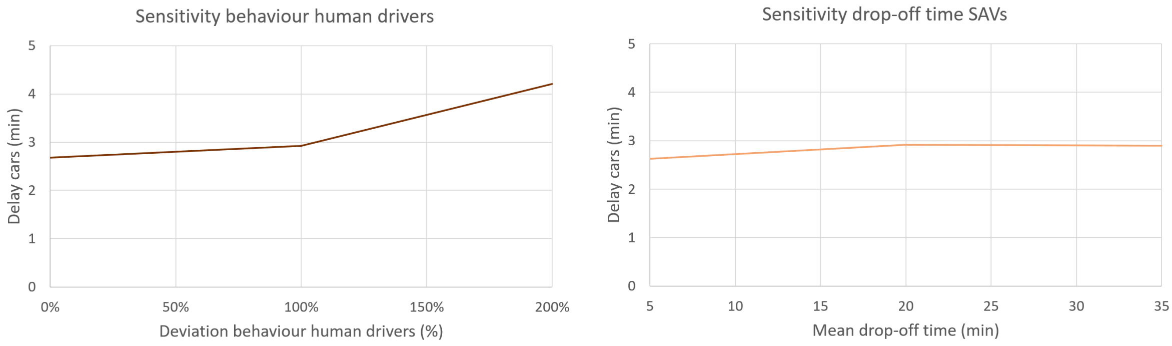
As can be seen, the model displays some sensitivity to these factors to a different extent. However, no overly excessive vehicle delays were detected. The traffic demand turns out to be a factor with relatively high sensitivity. This is logical considering the fact that the network is close to reaching its capacity in the scenario runs. Increasing the demand can therefore easily cause congestion, and thereby almost exponentially increasing delays. On the one hand, it is important to keep the accuracy of the demand in mind when interpreting the results. On the other hand, it can also be assumed that (infrastructural) interventions will have been taken by 2040 if the increase in demand turns out to cause significant congestion.

The headways of AVs is still a very uncertain factor. In this research, a very low headway (max 1,5 s) was assumed. However, in current ADASs, the headway employed is longer than the average for human drivers. As the headway holds a direct relationship with the capacity of the road, it is to be expected that the model will show some sensitivity to this factor, considering the results found in figure 4.7b. It is likely that the model



(a) Traffic demand

(b) AV headway



(c) Behaviour human drivers

(d) Drop-off time SAVs

Figure 4.7: Sensitivity of the vehicle delay of (non-SAV) cars to differences in input factors

would show even more sensitivity if the percentage of AVs was higher (in this case it is 50%). The accuracy of the headway value is an important condition to keep in mind when interpreting the results.

The deviation of behaviour between human drivers is intentionally adjusted in the model as compared to the default settings. This is because it was found that human drivers in Vissim do not show enough deviation from each other. However, this does mean that it is important to test the model's sensitivity to this factor. Therefore, the research model (100%) was compared to a version with the default settings (0%) and a version with twice as much deviation between human drivers than the research model (200%). The sensitivity between the default version and the research model is not very high, but it increases when more deviation in behaviour is implemented. Therefore, it seems like the deviation that was implemented in the research model, is safe.

For the drop-off time, two other probability distributions were tested with both 15 seconds difference in the mean from the research model's value. Judging from the results, the sensitivity of the model for this factor seems to be very low. The mean value that was used in the research model, can therefore safely be used.

4.5. Experimental set-up

The system under study is a stochastic system. Many factors are approximated with a probability distribution and one or two factors that determine the exact shape of this distribution. In each model run and at each time step, values are drawn from these distributions using a random seed that is unique for a model run. As such, each model run represents a unique combination of factors. Factors that are dependent on probability distributions in this model are:

- Inter-arrival times
- Composition of arrivals
- Destination and route choice
- Drop-off destination choice for the SAVs
- Dwell time SAVs

- Driving behaviour factors such as desired speed, acceleration and headway

As a result, multiple model runs are needed to ensure that the results have converged to a value that can be expected in reality. In this section, it is discussed how the data was prepared, how the needed amount of runs was determined and how the resulting amount of data was processed. The words *(simulation) run*, *replication* and *case* are used alternately.

4.5.1. Data preparation

In order to have enough data to be able to perform the data analysis after data preparation, 35 runs were performed for each scenario. Before establishing the needed sample size, the data needed to be cleaned. Outlier runs were identified and removed from the data. Two reasons were identified that could qualify a run as an outlier: grid lock and near-grid lock situations.

When studying the animation of the simulation, it can be seen that in some cases a certain combination of parameter inputs cause a grid lock in the model where vehicles from conflicting streams wait unnecessarily for each other. It is a limitation of the Vissim software that these grid locks are not solved, where in reality they probably would be solved. Therefore, results from the replications where this occurs are deemed unrealistic and are removed from the dataset. Runs in which grid locks occurred, were detected by looking at the vehicle delay values and the amount of vehicles that passed the travel time measurements. If for a certain travel time measurement, no vehicles are detected from a certain moment onward, this means that they are being held up somewhere in the network by a grid lock.

In some cases, a situation occurred that can be described as near-grid lock. Vehicles from conflicting streams wait unnecessarily long for each other, causing a queue that spills back, but this situation is partly solved by an event like a traffic light turning green. Nonetheless, unrealistic behaviour (unnecessary waiting) was detected in these situations. This is a reason to remove these cases from the results. They are detected by performing a case anomaly test and an outliers test in the data analysis software SPSS. These tests both report the 5 most unusual cases. The anomaly test does this by identifying peer groups and computing an anomaly index for each case within this peer group. The outlier test merely orders all cases by value and reports the five highest and lowest. These tests are performed for the variables *vehicle delay* and *amount of vehicles* per travel time measurement. An anomaly index for *vehicle delay* of higher than 5 for a high delay value and the presence of this case in the high end of the outlier list is a reason to flag a certain run. Then, the corresponding *amount of vehicles* is checked. If this value is low to the extent that it also appears in the anomaly list or the low end of the outlier list, this means that a near-grid lock situation existed in the network during the corresponding time interval. Cases where this is detected, are removed from the dataset. Sometimes this is paired with unusually low delays for a partly conflicting route that is lacking traffic during that time interval due to the near-grid lock.

After removing the outliers, all scenarios had at least 30 replications left in the dataset. In order to have an equal amount of replications for all scenarios, all datasets were reduced to 30 replications by removing the last cases. So the result of the data preparation process was a set of 30 cases for each scenario.

4.5.2. Establishment of sample size

After the data was cleaned, the needed sample size could be determined. To ensure that the results for each KPI had converged, it was needed to compare the difference in results between sets of a different number of replications to each other until this difference was found to be statistically insignificant.

The normality of the results was checked using a Shapiro-Wilk test. Then, for each KPI a number of subsets of this dataset were compared using an independent samples t-test to find whether there was a statistically significant difference. When no statistically significant difference was found, the conclusion could be drawn that the results had converged. As such, the sample sizes for each KPI as presented in table 4.7 could be determined.

For vehicle delay and distance travelled, a subset of 20 replications and one of 30 replications were compared for each scenario using an independent samples t-test. As the difference turned out not to be significant ($p > 0,05$ in all cases), a set of 20 replications could be used. However, it was chosen to use 30 replications as these were already available. For the emissions results, it is a time consuming activity to obtain these. Therefore it was chosen to start with a subset of 3 replications and one of 5 replications. The difference between these subsets already turned out to be insignificant ($p > 0,05$ in all cases), meaning that 5 and even 3 replications was enough.

Table 4.7: Sample sizes for each KPI

KPI	Sample size	Scenario
Vehicle delay	30	All
Distance travelled	30	All
Emissions	5	All

4.5.3. Data processing

Following these tests, the mean values for each KPI and each scenario could be obtained and statistical tests could be performed to compare the results between scenarios. As mentioned before, results from each scenario were tested on normality using a Shapiro Wilk test. In very few cases, the data was found not to be normally distributed (p < 0,05). However, as comparison tool, the ANOVA test was used and this test is quite lenient in terms of normality: accurate results can be obtained as long as the data follows roughly the same shape between scenarios. Therefore, in most of these cases the results from the ANOVA test could be accepted as representative for the population. Only for cases that both turned out to be not normally distributed and produced borderline results for the ANOVA test, extra caution was needed in interpreting the results. Detailed results for the Shapiro Wilk tests can be found in appendix E.

As said, the ANOVA test was used to determine whether observed differences between scenarios could be found to be statistically significant. One more condition for the ANOVA test is that variances should be roughly equally distributed across scenarios. To test this, the Levene's statistic was used. However, in many cases, the variances were found not to be equally distributed (p < 0,05). This is likely due to the fact that 7 scenarios were compared at once in the ANOVA test, which is a high number. In order to bypass this equality of variances assumption, the robust Welch ANOVA test was used. When this test found statistically significant differences in the data (p < 0,05), a Tukey post-hoc test was used to find which scenarios were found to differ significantly from each other. Detailed results of the Levene's tests, ANOVA tests, Welch ANOVA tests and Tukey post hoc tests can be found in appendix E.

4.6. Results

After performing the experiments as described above, the data could be analysed to obtain results. In this section, the mean values for each KPI are presented as well as the conclusions from the statistical tests and an interpretation of the results. In appendix E, the detailed results of the statistical tests can be found.

4.6.1. Vehicle delay

To obtain results for the vehicle delay, four representative routes were selected for each mode under study. This is because there are many routes in the model that are less meaningful for answering the research question as they have very little users or make very little use of the network under study. Delay results for these routes would only cause "noise" in the data. The vehicle-weighed averages of the delays for each mode, aggregated over the entire 2-hour morning peak period, are presented in table 4.8. Furthermore, figure 4.8 shows how the vehicle delay for (non-SAV) motorized vehicles propagates over time for each scenario. In this table and figure, a distinction is made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because the SAVs spend more time in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted idea of the effects.

Table 4.8: Mean vehicle delays

Scenario	Cars, LGV, HGV (mm:ss)	SAVs (mm:ss)	Bicycles (mm:ss)	Buses (mm:ss)
1: 20/3	02:20	03:44	00:30	03:10
2: 50/25	02:55	04:00	00:30	03:10
3: 80/50	02:28	03:35	00:28	02:58
4: 0/0	04:00	N/A	00:35	03:13
5: 50/0	01:31	N/A	00:29	02:31
6: 100/0	01:16	N/A	00:26	02:18
7: 100/100	06:15	09:15	00:36	04:34

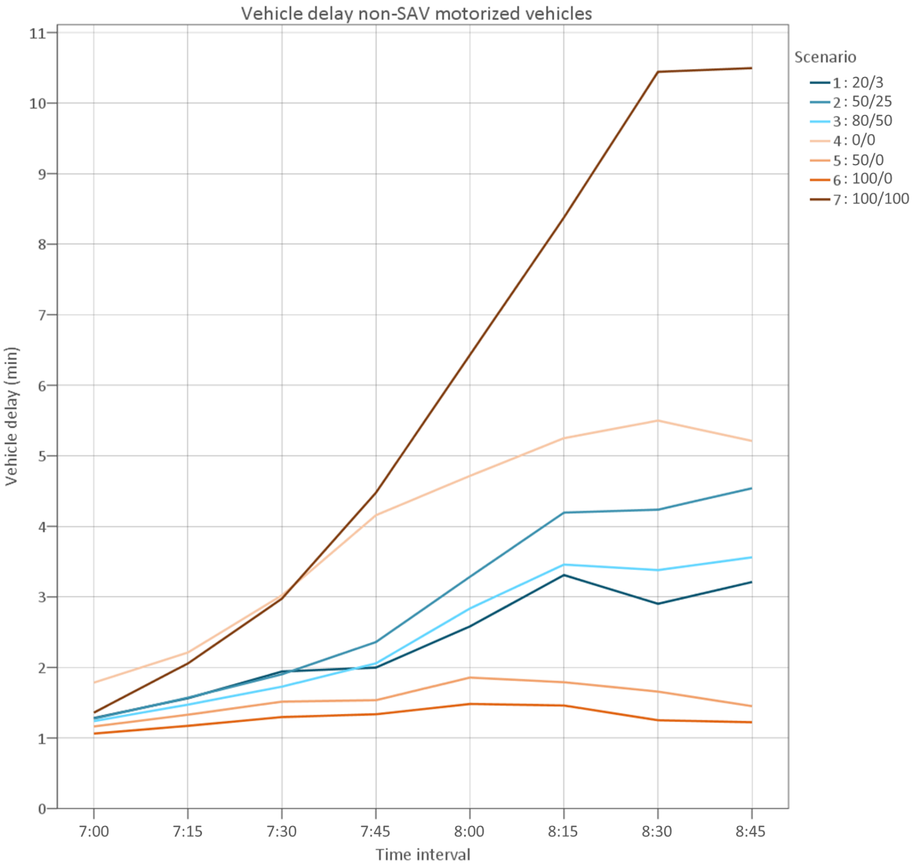


Figure 4.8: Vehicle delay cars (non-SAV) propagation over morning peak

The first thing that can be noticed from these results is that across scenarios all modes display roughly the same pattern of in terms of the delay length. It does not seem like there is one mode that is specifically advantaged or disadvantaged by the mix of traffic. Overall, the best performing scenarios are the ones with AVs, but without SAVs: scenarios 5 (50/0) and 6 (100/0). The worst performing scenarios are the scenario without AVs, scenario 4 (0/0), and the scenario where 100% of travellers use a SAV, scenario 7 (100/100).

When looking at the ANOVA and Tukey post hoc test results (fully presented in section E.1 appendix E), it can be seen that for the non-SAV motorized vehicles, most differences between scenarios are statistically significant. Only scenario 1 (20/3) and 3 (80/50) (p=0,974), and 5 (50/0) and 6 (100/0) (p=0,488) show no significant difference. For the SAVs, on the other hand, the the only scenario that differs significantly from the rest, is scenario 7 (100/100). All other differences were found to be insignificant. For the cyclists, only scenario 4 (0/0) and 7 (100/100) are significantly worse than the rest, while scenario 6 (100/0) is significantly better than the rest. All other scenarios are largely equal. However, since all bicycle delays are somewhere around 30 seconds, the differences should not be weighed very heavily. For the bus, scenario 7 (100/100) also performs significantly worse than the rest while scenarios 5 (50/0) and 6 (100/0) perform significantly better. All other scenarios are relatively equal.

To interpret the results of scenarios 1 (20/3), 2 (50/25) and 3 (80/50), it is useful to first have a look at the results from scenarios 4 (0/0), 5 (50/0), 6 (100/0) and 7 (0/0). When looking at the delay results from scenarios 5 (50/0) and 6 (100/0) as compared to scenario 4 (0/0), it can clearly be seen that a higher penetration of AVs can have a large positive influence on the average vehicle delay. Clearly, their stable, deterministic and smooth behaviour has a positive influence on the traffic flow. This is even so much so, that the positive effects are noticeable at low penetration rates. This confirms the expectation that AVs can serve as a buffer for turbulent behaviour of human drivers.

However, when in addition to a full penetration of AVs, all travellers start making use of SAVs, like in scenario 7 (100/100), the vehicle delays start increasing by a large amount. Note that in the way vehicle delay is measured here, the time it takes for an SAV to drop off their passenger and return to the route to their next passenger, is included in the delay time. For the cars and buses, however, the delay is mostly due to the bottlenecks created by SAVs that are stopping to drop off passengers and the increased queues caused by SAVs using low capacity links to make U-turns to circulate the network. The bicycles are mainly delayed by longer waiting times at the traffic lights. These are operating at full capacity when queues become longer, increasing the cycle time and thereby the waiting time of the bicycles.

Going back to scenarios 1 (20/3), 2 (50/25) and 3 (80/50), it can be seen that the positive effects of the increasing penetration of AVs is completely compensated by the increasing use of SAVs. For scenario 2 (50/25), the delay of non-SAV cars is even significantly worse than scenario 1 (20/3), even though the penetration of AVs has doubled. In scenario 3 (80/50), it is likely thanks to the combination of a further increase in penetration of AVs and an increase of the occupancy of the SAVs that the delays are reduced again compared to scenario 2 (50/25). However, all three scenarios still perform better than scenario 4 (0/0), in which neither AVs nor SAVs are present, meaning that a future with AVs (and SAVs) has a positive prospect in terms of travel times as long as the SAVs do not become too prevalent.

4.6.2. Distance travelled

Now it is the question whether this increase in delay is a result of the sheer increase in distance driven in the network, which could cause the intensity/capacity ratio to flip the wrong way, or whether it is a result of the unusual behaviour of SAVs as described in chapter 3. To test the first possibility, it was checked whether the total distance driven by all motorized vehicles in the model significantly differed between scenarios. The mean values for the total distance driven by motorized vehicles in each scenario are presented in table 4.9. Note that unlike for the delay results, for the distance results the mean values for all trips in the entire network are taken as a measure.

Table 4.9: Total distance covered by all motorized vehicles

Scenario	Total distance (km)
1: 20/3	23.679
2: 50/25	23.663
3: 80/50	23.663
4: 0/0	22.624
5: 50/0	23.671
6: 100/0	23.679
7: 100/100	21.001

The results of the statistical tests performed on to compare these mean values (as well as the results from the normality tests) are presented in section E.2 in appendix E. From ANOVA and Tukey post hoc test results, it could be concluded that the only significantly different scenarios are scenario 4 (0/0) and 7 (100/100). For scenarios 4 and 7, it can be partly attributed to the fact that queues in these models started to spill back, causing some of the vehicle inputs to be unable to release all the planned vehicles within the simulation period (this is not the case for the other scenarios). For another part, it can be attributed to the fact that delays became so high that not as many vehicles could reach their destination by the end of the simulation period as in the other scenarios, reducing the total distance. And lastly, for scenario 7 (100/100) it could also be attributed to the fact that the SAV occupancy was so high, reducing the total amount of vehicles in the model significantly.

These explanations aside, it can clearly be seen from these results that the increase in delays of non-SAV motorized vehicles in scenarios with more SAVs is not caused by an increase in the total distance driven. The higher delays are therefore likely caused by the unusual behaviour that SAVs display: parking, stopping on the road and using low capacity links to circulate the network.

To make the results for the distance travelled more meaningful, the distance travelled per vehicle was calculated. This way, the effects caused by a varying amount of vehicles that have entered and exited the model are removed from the equation. This allows comparing the scenarios to each other and comparing the distance travelled by different modes per scenario. The modes that are distinguished here are non-SAV motorized vehicles and SAVs. In table 4.10 the results are presented. Note that unlike for the delay results, for the distance results the mean values for all trips in the entire network are taken as a measure. In this table and, a distinction is made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because the SAVs drive a longer distance in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted idea of the effects.

Table 4.10: Mean distance travelled per vehicle

Scenario	Non-SAV (km/veh)	SAV (km/veh)
1: 20/3	1,36	1,57
2: 50/25	1,36	1,54
3: 80/50	1,38	1,55
4: 0/0	1,33	N/A
5: 50/0	1,36	N/A
6: 100/0	1,36	N/A
7: 100/100	1,37	1,39

These results were analysed using both an ANOVA test and Tukey post hoc to compare different scenarios, and a paired samples t-test to compare the two modes within each scenario. The results from these tests (as well as from the normality tests) are presented in section E.2 in appendix E. What is remarkable from the non-SAV results, is that the distance covered scenarios containing no SAVs or a small amount of SAVs, is slightly, but significantly shorter. A possible explanation for this could be that less lane changes are needed, because there are no (or less) SAVs stopping on the road. From the SAV results, it is striking that the distance covered in scenario 7 (100/100) is significantly shorter than in the other scenarios. In reality this would be logical, because a higher penetration of SAV usage means that routes can be planned more efficiently. However, this element is not present in the model. This result in the model can only be attributed to the fact that due to the high delays in this scenario, many SAVs have not covered their entire route yet by the end of the simulation period. This effect does not influence the mean value for non-SAVs, because there are much more non-SAV vehicles in the model (vehicles who do not need to drop off a passenger in the network, are modeled as non-SAVs).

When comparing the results of non-SAVs to the results of SAVs, the SAVs cover a significantly longer distance in each scenario than non-SAVs. This is due to the detour that they need to make to drop off their passenger and return to the shortest route to their next passenger.

4.6.3. Emissions

To obtain insights in the driving behaviour, such as acceleration, deceleration and stopping, that cause an increase in emissions from exhausts as well as from mechanical components like brakes and tires, the emissions were calculated for each scenario. This was done by feeding the vehicle records into the external EnViVer module after which all motorized vehicles were linked to a vehicle class in the EnViVer database (light city/medium city/heavy city/bus city). In order to obtain results that are easily comparable in terms of driving behaviour, AVs and non-AVs were both linked to respectively the same vehicle classes, even though it is likely that in reality more AVs than non-AVs will be zero-emission vehicles.

The EnViVer module creates a report with the total emissions, the emissions per hour and the emissions per kilometre driven. To allow for easy comparison of the results and to isolate the effects of differences in driving behaviour, the emissions per kilometre driven are reported here. The emissions in terms of CO_2, NO_x and PM_{10} can be found in table 4.11.

Table 4.11: Mean emissions per kilometre travelled

Scenario	CO_2 (g/km)	NO_x (g/km)	PM_{10} (g/km)
1: 20/3	292	0,453	0,041
2: 50/25	301	0,467	0,042
3: 80/50	292	0,450	0,040
4: 0/0	316	0,499	0,044
5: 50/0	280	0,428	0,039
6: 100/0	280	0,425	0,039
7: 100/100	345	0,565	0,048

The emissions results were analysed statistically by means of ANOVA tests. The results of these tests (as well as the normality test results) can be found in section E.3 in appendix E. What is immediately striking, is that just like for the other KPIs, scenarios 5 (50/0) and 6 (100/0) perform exceptionally well, while scenarios 4 (0/0) and 7 (100/100) perform poorly. In the Tukey post hoc test, these are also the only scenarios that differ significantly from the rest.

When comparing scenarios 5 (50/0) and 6 (100/0) to scenario 4 (0/0), it is clear that AVs are very effective in providing a smoother traffic flow, reducing emissions. However, when looking at the results for scenario 7 (100/100), it can be seen that the presence of SAVs imposes such turbulence in the traffic flow, that emissions values suffer significantly from it.

Scenarios 1 (20/3), 2 (50/25) and 3 (80/50) perform significantly better than scenario 4 (0/0), which gives a positive outlook for a future with AVs. However, most of the emissions results do not differ significantly between these scenarios. From the fact that emission values do not improve between these scenarios, it can be concluded that the negative effects of an increase in SAVs compensate the positive effects of an increase in AVs. The only difference that is significant, is the increase in PM_{10} emissions for scenario 2 (50/25) as compared to scenarios 1 (20/3) and 3 (80/50). As communicated by TNO [1], this substance is not only emitted by the exhaust pipes, but also by mechanical wear and tear of brakes and tires. Whether the difference in PM_{10} emissions in scenario 2 (50/25) is a result of this wear and tear, is to be debated, but it is certainly a possibility.

4.7. Design definition

It seems as though the introduction of AVs and SAVs causes the need to find a new balance between traffic throughput and access to surrounding real estate on the urban network. As mentioned in section 2.1, urban roads are designed for conventional cars to provide a certain combination of throughput and access, depending on the road level. As AVs provide a higher level of throughput and SAVs provide a higher level of access, but neither in the way that conventional cars do, solutions are needed to help restore the balance.

Therefore, it is needed to find a way to reduce the negative impacts that they have on other traffic, while maintaining the advantages of SAVs in general (fast door-to-door service). Also, as this research is about the transition period, it is desirable to keep the current network largely in tact and to limit the needed investment in new infrastructure. Therefore, easy-to-implement solutions are preferred. With this in mind, two designs were defined: dedicated lanes, and kiss and ride (K&R)-facilities. These designs were already suggested as being effective by Jan Jaap Koops and Marc van den Burg from the municipality of The Hague during the workshop on 4 July 2018, a summary of which can be found in appendix A. Further, the study on curb use by International Transport Forum [28] as presented in section 2.4.3 also proposed a system with special pick-up and drop-off zones for SAV passengers. Finally, during the validation interviews, a summary of which can be found in appendix D, Erik Verschoor mentioned that dedicated infrastructure like dedicated lanes and K&R-facilities would be advisable to look into. These designs will be further explained below.

4.7.1. Dedicated lanes

The idea behind this design is to create an extra lane on the main road where only the SAVs and buses are allowed to drive. On this lane, they can stop anywhere they like and on the rest of the network, they are not allowed to stop. This would put more emphasis on the access function of the main road network, while maintaining the traffic flow function. The increased access is created by increasing the capacity of the road and while reducing the amount of parking movements. For SAV passengers, a more fine-meshed network than the PT network is ensured, where they do not need to cross large intersections or multi-lane roads to reach their destination. For other road users, the smaller roads do not get blocked by SAVs anymore.

Possible negative side-effects that this design may have are an increase in weaving movements on the main roads. Besides that, there might be more SAVs making U-turns on the main road than before, putting even more pressure on those low-capacity links. Finally, as the bus stops are also located on these lanes, the SAVs may cause some extra hinder to the buses.

4.7.2. Kiss and ride facilities

The other design is aimed to do exactly the opposite of what the first design does. Instead of increasing the capacity of the road network and leading the SAVs to the main road, SAVs are ushered away from the main road to special K&R-facilities located mainly on the underlying road network, directly at the roadside. The K&R-facilities are located near entries of popular destinations and where it is possible to place them at the

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[1] Personal communications with ir. Arjan Eijk from TNO, 21 August 2018

maximum cost of removing some roadside parking. For the SAV passengers, this should offer a more fine-meshed network than the PT network, where they do not have to cross any large intersections or multi-lane roads to reach their final destination. In contrast to the dedicated lanes design, the SAVs will likely not cause extra hinder to buses and will likely not make any U-turns on the main road anymore.

Possible negative side-effects of this design is that in contrast to the dedicated lanes design, parking movements are needed in order to enter the drop-off facility. Additionally, the SAVs may need to cover some extra kilometres to get to the K&R facility from the main road, only to return to the main road afterwards. Finally, some roadside parking may need to be removed to create the needed space.

4.8. Conclusion

The goal of the scenario studies was to provide insights in the traffic effects of different possible futures in terms of AVs and SAVs. The scenarios as formulated in chapter 3 were translated into model inputs that were implemented in an existing model of a network in The Hague, as described in section 4.1. After verification and validation of the model, an experimental set-up was determined and executed. This yielded interesting results for the KPIs that were defined in chapter 3.

What was clear from the delay results, was that while AVs have a positive influence on travel times, the presence of SAVs works in an exactly opposite way. The question remained, however, whether this increase in delay was a result of a possible increase in the amount of kilometres driven in the network, causing the intensity/capacity fraction to flip the wrong way, or whether it was a result of the driving behaviour of SAVs causing turbulence in the traffic flow, as suggested in the causal diagram in section 3.5. This question was answered by the results for the distance travelled and the emissions results.

The former showed that vehicles in the scenarios with a higher penetration of SAVs did not cover more distance than in the other scenarios. This relationship between the penetration of SAVs and the total distance driven, suggested in the causal diagram in section 3.5, turned out not to be significant. The emissions results showed that the energy consumption was significantly higher in the SAV scenarios, indicating more turbulence in the traffic flow. This confirms the relationship suggested in the causal diagram in section 3.5 between the penetration of SAVs and emissions per kilometre.

Nonetheless, the overall results are quite positive. The first three scenarios, which are all realistic estimations of what the vehicle mix will look like in urban traffic in 2040, perform better than scenario 4 (0/0), with neither AVs nor SAVs. Nonetheless, it could be useful to look at possible interventions to restore the balance between traffic throughput and access, limiting the negative effects of SAVs on traffic flow. Therefore, two designs were defined and tested on the four scenarios with different penetration rates of SAVs: scenarios 1 (20/3), 2 (50/25), 3 (80/50) and 7 (100/100). A description of these designs can be found in section 4.7. A description of the implementation and results can be found in chapter 5.

5

Model application: design

In an attempt to limit the negative effects of SAVs in urban traffic, two designs were defined in chapter 3 that the municipality could implement relatively easy. These designs are *dedicated lanes* and *kiss and ride (K&R)-facilities*. In this chapter, it is discussed how these designs were implemented in the computer model as presented in chapter 4, how the experiments with this model were set up and what the results were in terms of the KPIs.

5.1. Design specification

To obtain results, the designs as defined in chapter 3 needed to be translated firstly into concrete measures for the network at hand, and secondly into the modeling language used in Vissim. In this section, a description is provided of how both these steps were taken for each design.

5.1.1. Dedicated lanes

The idea behind the dedicated lanes design is to create extra capacity of SAVs on the main road and to divert them from the lower level network. In the case study network, the main road is the Prins Clauslaan. Therefore, the dedicated lanes should be placed on this road (in each direction). This road contains three intersections, which are quite complex as it is. It was chosen not to increase the complexity of these intersections by placing the extra lane between the intersections and not increasing the amount of lanes and possibly the amount of conflicts on the intersections. An exception is the middle intersection (with the Theresiastraat), direction South. An extra lane could be added to this intersection without increasing the complexity as there is no right turn possibility. The Prins Clauslaan also contains two bus stops. These bus stops were placed on the extra lane, making it a dedicated lane for both SAVs and buses. Further, the network contains an off-road parking facility on the Juliana van Stolberglaan, which was kept as a drop-off possibility for SAVs.

In the Vissim model, this was implemented by extending all links on the Prins Clauslaan with one lane on the curbside and placing "parking spots" over the entire length of those lanes except for on and around the intersections. The intersection with the Theresiastraat direction South was extended with extra detectors and a signalhead for through traffic connected to the signal controller. The extra lanes were specified as being for specific use of vehicles of the type SAV and bus. Routing of SAVs was redefined. This also required re-evaluation of the logic of where an SAV would want to stop depending on the street from where they enter the network.

Figure 5.1 shows the Vissim network of this design. The location of the dedicated lanes and the places of interest are indicated as well as the parking on the Juliana van Stolberglaan.

5.1.2. Kiss and ride facilities

To identify suitable K&R-locations, the network was analysed to find places with enough space to construct these facilities near the places of interest that were identified earlier. Emphasis was put on placing these K&R-facilities off the main road, but in some cases the Prins Clauslaan itself also offered very suitable space in front of places of interest. Therefore, a few K&R-facilities are placed directly off the Prins Clauslaan itself. Attention was also paid to the fact that the facilities were placed on each side of a large intersection or multi-lane road, so passengers do not have to cross these to reach their final destination.

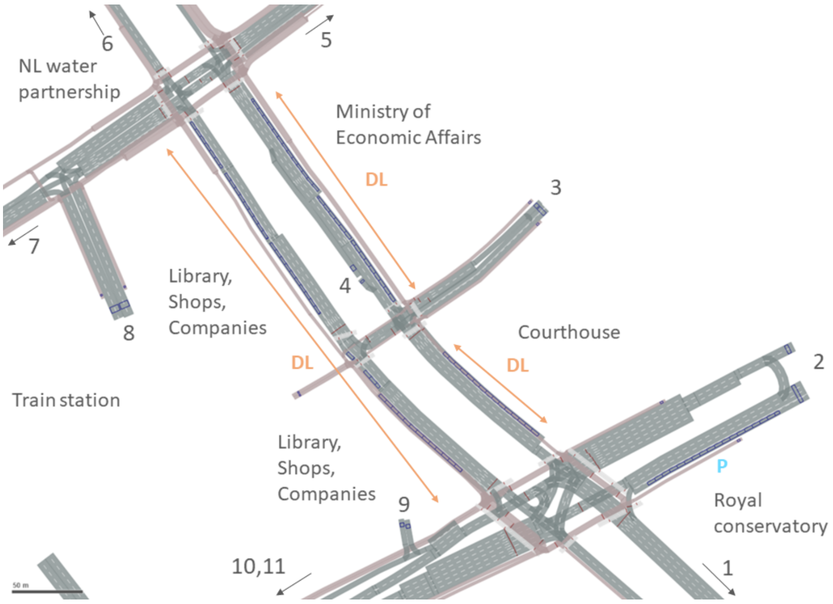

Figure 5.1: Location dedicated lanes in the network

As mentioned earlier, stopping places for SAVs need to be modeled as "parking spots" in Vissim and to be able to model parking spots, a lane of road should be available. Therefore, at the locations that were identified as suitable for K&R-facilities, a lane was added to the link at the curbside and parking spots were placed on this link. The remaining length of the link where the K&R was not intended, was made inaccessible. Just like with the dedicated lanes, the routing of SAVs was redefined looking at logical combinations of entry streets and drop-off destinations. When performing the first model runs, a reoccurring problem was detected at the Bezuidenhoutseweg direction North-East. SAVs making a turn here after dropping off their passengers, often had to wait very long to find an opening in the opposite direction, which caused a jam that spilled back to the intersection and caused a grid lock. It is very unrealistic that this would happen in reality. Therefore, a small bypass was constructed offering both the SAVs and the cars behind them more space.

Figure 5.2 shows the Vissim network for this design. The locations of the K&Rs are indicated as well as the locations of the places of interest. In the upper right hand corner, the bypass on the Theresiastraat is visible.

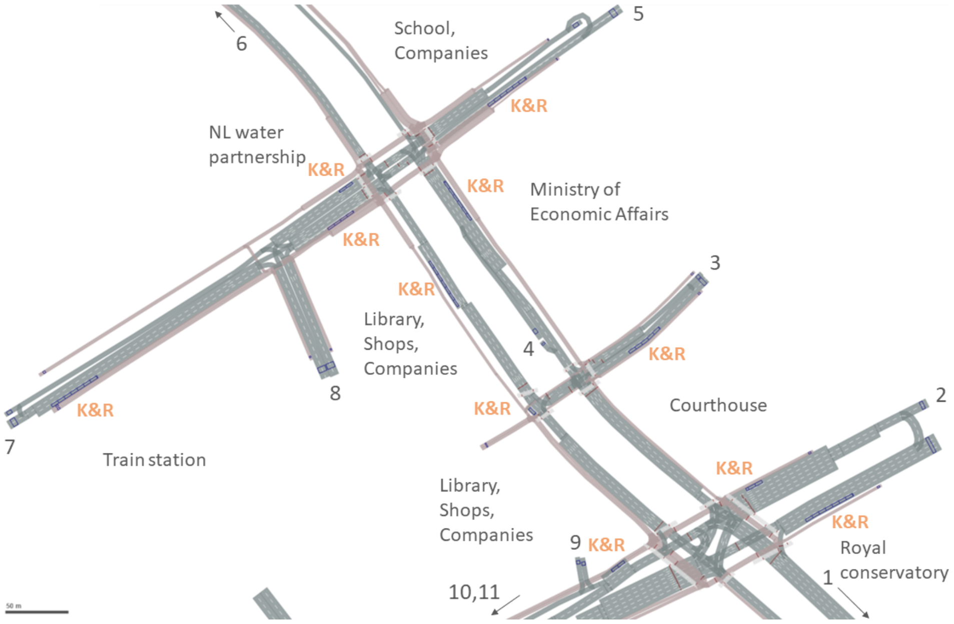

Figure 5.2: Location K&R-facilities in the network

5.2. Experimental set-up

As the models of the designs are largely the same as the scenario models, no further verification and validation was needed before moving on to defining the experimental set-up. In both designs, the same stochastic input factors are of influence to the results as for the scenarios. Therefore, the same tactic was employed as for the scenarios to determine the sample size needed to have converged results. However, when establishing the needed sample size for the scenario studies, it was noticed that convergence was reached quite easily. Therefore, it was chosen to perform less runs for the design studies, to save time. After performing 25 runs for each file (2 designs x 4 scenarios), outliers were identified and removed from the dataset following the same methodology as was used for the scenario studies. Afterwards, different subsets of replications were compared to each other for each KPI using an independent samples t-test to see whether the results had converged ($p > 0,05$). Following this methodology, the sample sizes were determined as presented in table 5.1.

Table 5.1: Sample sizes for each KPI

KPI	Sample size	Scenario x Design
Vehicle delay	20	All
Kilometres travelled	20	All
Emissions	5	All

Once all the data was gathered, Shapiro Wilk tests were performed to see whether the distribution of the data adequately resembled a normal distribution. This is a condition for most other statistical tests. After this, for each scenario and each KPI, the results of the "do nothing"-alternative were compared to the results of the designs and the results of the designs were compared to each other using an ANOVA test. It was chosen to perform the ANOVA test instead of two separate independent samples t-tests, because the ANOVA also allows comparison of the two designs to each other. In the case that both designs offered an improvement, this allows to see which of the two is significantly better than the other, or if both are equally good. When the differences between categories were found to be significant by the ANOVA test, a Tukey post hoc test was performed to see which categories exactly differed significantly from each other. Further, the distance driven by non-SAVs was compared to the distance driven by SAVs for each scenario and design by means of a paired samples t-test.

The conditions for the ANOVA test are that the data is normally distributed and that the variances are roughly equally distributed across the categories. The former was checked using a Shapiro Wilk test, the latter was checked using a Levene's test. In some cases, the data was not entirely normally distributed ($p < 0,05$) or the variances were found not to be equally distributed ($p < 0,05$). This is not necessarily a problem, as the ANOVA test is quite lenient in terms of normality, and a robust Welch ANOVA test can be performed when significant differences are found in variance distributions. In these cases, it is important to be cautious for test bias.

The only KPI that was not compared in this part of the research, was the bicycle delay. This is because in the scenario comparison, it was found that this KPI does not give any extra information about the performance of the system in addition to the non-SAV motorized vehicles, SAV and bus delays.

5.3. Results

After performing the experiments as described above, the data could be analysed and compared. In this section, the results will be presented per KPI as well as the conclusions that can be drawn from the statistical tests mentioned in section 5.2 and an interpretation of the results. A detailed report of the statistical test results can be found in appendix F. As a reminder, the scenarios studied here are presented again in table 5.2

5.3.1. Vehicle delay

In reporting on the vehicle delays, the only distinction that is made, is between non-SAV motorized vehicles (cars, LGVs and HGVs), SAVs and buses. The bicycle delay is left outside the scope when studying the effectiveness of the designs, as it was found when studying the scenarios, this measure offered little to no extra information about the network performance. Just like for the scenario results, the results presented here are weighed average delay times per vehicle over four selected routes that are most representative for the network (in an attempt to cancel out "noise" in the data), aggregated over the entire 2-hour morning

Table 5.2: Scenarios used for the designs

Scenario	AV (% of vehicles)	Shared (% of travellers)	Pax SAVs (# pax)	Buses
1. 20/3	20%	3%	1,1	AV
2. 50/25	50%	25%	1,5	AV
3. 80/50	80%	50%	2	AV
7. 100/100	100%	100%	2	AV

peak period. These results are presented in table 5.3. In this table, the distinction is again made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because the SAVs spend more time in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted idea of the effects.

Table 5.3: Mean vehicle delays designs

Design/ scenario	**Non-SAV (mm:ss)**				**SAV (mm:ss)**				**Bus (mm:ss)**			
	1 20/3	**2 50/25**	**3 80/50**	**7 100/100**	**1 20/3**	**2 50/25**	**3 80/50**	**7 100/100**	**1 20/3**	**2 50/25**	**3 80/50**	**7 100/100**
None	02:20	02:55	02:28	06:15	03:44	04:00	03:35	09:15	03:10	03:10	02:58	04:34
Dedicated lanes	02:36	02:50	02:11	05:50	04:27	04:22	03:41	09:52	03:31	03:21	03:01	04:25
K&R-facilities	02:32	02:50	01:59	03:36	04:05	03:49	03:06	04:36	03:28	03:18	02:49	03:14

It can be concluded from the ANOVA and Tukey post hoc tests as presented in section F.1 in appendix F that any differences found in the mean delay values for non-SAV motorized vehicles and SAVs are statistically insignificant up until scenario 3 (80/50) and that the dedicated lanes design do not provide solace in terms of delay in any of the scenarios. For scenarios 1 (20/3) and 2 (50/25), which have relatively low SAV penetration, this design even causes a longer delay for the buses. This is likely because the SAVs share the dedicated lane with the buses, causing an extra inconvenience for them when they make stops. The vehicle delay for both non-SAV and SAV was only improved by the K&R design, and only in scenarios 3 (80/50) and 7 (100/100), with the highest penetration of SAVs. Any other differences found in the results (also increases in delay) are insignificant. The improvement found for scenario 7 with the K&R alternative is remarkable. However, the performance is still not as good as it is for scenarios with less SAVs.

Dedicated lanes do not seem to be effective at all. Even though they provide extra capacity, it is likely that in such a dense urban network, the extra weaving has a stronger negative effect than the extra capacity has a positive effect. Furthermore, the use of these dedicated lanes still promotes taking U-turns on the main road (for instance when a passenger needs to be dropped on the opposite side of the road). The buses also experience extra hinder with the dedicated lanes design, as they share this lane with the SAVs, meaning that they will likely be held up a lot behind stopping SAVs.

Judging from the results, the implementation of K&Rs starts to help reduce traffic delays when between 25% and 50% of travellers use SAVs. However, it is likely that the K&R solution increases the distance driven in the network, while the dedicated lanes solution reduces this. These effects will be discussed in the next section. The positive effects associated with the K&R design can be attributed to the fact that the SAVs are led away from the main road, where less traffic is hindered and where they stop on the side of the road. Additionally, the amount of U-turns made on the main road, using low capacity links, are kept to a minimum. This way, the traffic lights can easily process the queues that form.

5.3.2. Distance travelled

The distance travelled under the different designs could shed a different light on the delay results. The expectation is that the SAVs cover less distance with the dedicated lanes design, because they primarily stay on the main road, which is central in the network. With the K&R design, however, it is the expectation that SAVs will cover more distance, as they need to drive to a decentral drop-off place. Whether and how the distance driven by non-SAVs will be affected, is uncertain. First, the total distance driven by all motorized vehicles is presented in table 5.4. Then, the average distance driven per vehicle is given for non-SAVs and SAVs separately in table 5.5. Note that unlike for the delay results, for the distance results the mean values for all trips in the entire network are taken as a measure.

Table 5.4: Total distance travelled by all motorized vehicles designs

	Total distance (km)			
Design/scenario	**1: 20/3**	**2: 50/25**	**3: 80/50**	**7: 100/100**
None	23.679	23.663	23.663	21.001
Dedicated lanes	23.567	23.554	23.266	21.354
K&R-facilities	23.589	23.682	23.678	23.322

The total distance covered by all vehicles in the network does not contain much information about the performance of each scenario. As can be concluded from the ANOVA and Tukey post hoc tests in section F.2 in appendix F, only three significant differences could be found: between the scenario 1 (20/3) null alternative and k&R-facilities (p=0,044) and between the scenario 7 (100/100) null alternative and both designs (both p=0,000). The difference found for scenario 1 seems illogical, since this difference should surely have been detected in scenarios 2 (50/25) and 3 (80/50) as well, since they have more SAVs. Seeing as the p-value of the Tukey test is also close to 0,05, this difference is regarded as being a coincidence. For scenario 7, however, the difference seems indeed very logical as both designs decrease the vehicle delay (at least for non-SAVs) significantly. In the null-alternative, not all vehicles that were planned are able to enter the network and not as many vehicles are able to complete their route within the simulation time as a result of the high delays. A reduction of the delays could simply mean that the vehicles are able to drive the distance that they planned to in the first place. Whether this is indeed the case, can be brought to light by the results for distance driven per vehicle, as reported below.

To study whether the designs really do not have an influence on the distance travelled, it is useful to split up this indicator into distance travelled by non-SAVs and distance travelled by SAVs. To filter out the differences in amounts of non-SAVs and SAVs, this indicator is presented as the average distance travelled *per vehicle*, in table 5.5.

Table 5.5: Mean distance travelled per vehicle designs

	Non-SAV (km/veh)				SAV (km/veh)			
Design/scenario	**1: 20/3**	**2: 50/25**	**3: 80/50**	**7: 100/100**	**1: 20/3**	**2: 50/25**	**3: 80/50**	**7: 100/100**
None	1,36	1,36	1,38	1,37	1,57	1,54	1,55	1,39
Dedicated lanes	1,35	1,36	1,38	1,38	1,49	1,46	1,46	1,31
K&R-facilities	1,36	1,37	1,39	1,41	1,58	1,54	1,56	1,46

In contrast to the total distance travelled, this indicator does reveal some interesting differences between the null alternatives and the designs. From the ANOVA and Tukey post hoc tests, the details of which can be found in section F.2 in appendix F, it was found that scenarios 1 (20/3), 2 (50/25) and 3 (80/50) only display significant differences for the distance travelled by SAVs between the null alternative and the dedicated lanes design. As expected, this distance is shorter in the dedicated lanes design, because SAVs primarily stay on the main road. For scenario 7 (100/100), not only the reduction in distance per SAV for the dedicated lanes design was found, but also a significant *increase* in distance for *both* non-SAVs and SAVs for the K&R design. This is a very interesting finding, because the *delays* where found to significantly decrease for this design in this scenario. Clearly, this decrease in delay should then be caused by less blockages and weaving, and shorter queues at the traffic lights. Another interesting insight, is that as confirmed by the paired samples t-test, scenario 7 (100/100) with dedicated lanes was the only case where the distance driven by non-SAVs (i.e. vehicles that do not need to drop off a passenger in this network) was higher than the distance driven by SAVs that did need to drop off a passenger in this network. This is not because the non-SAV distance increased compared to the null alternative (which it did not), but because the SAV distance decreased by a large amount. Perhaps when the distances driven by non-SAVs and SAVs are this close together, the differences in their OD matrix start playing a role. In this scenario, the only difference in their OD matrix is that the vehicles taking the Utrechtsebaan are exclusively non-SAVs (i.e. vehicles that do not need to drop off a passenger in this network).

5.3.3. Emissions

In the previous sections it was found that the higher the penetration rate of SAVs, the more effect the designs had on vehicle delays and distances driven. Where the dedicated lanes design was unsuccessful in reducing the vehicle delays, it did manage to significantly reduce the distance driven by SAVs. The K&R alternative, on the other hand, did manage to reduce vehicle delays significantly, but with high SAV penetration rates, it also increased the distance driven both by SAVs and non-SAVs. It seems as though the vehicle behaviour is more determinant in reducing vehicle delays than the distance driven is. But how does this reflect on the energy consumption and thereby the measured emissions? Surely, an increase in distance is unfavorable for emissions, but turbulent behaviour and long stationary queues are as well. To gain insight in these effects, the emissions results were obtained using the Enviver module. These are reported in table 5.6.

Table 5.6: Mean emissions per kilometre travelled designs

	CO_2 (g/km)				**NO_x (g/km)**				**PM_{10} (g/km)**			
Design/ scenario	**1 20/3**	**2 50/25**	**3 80/50**	**7 100/100**	**1 20/3**	**2 50/25**	**3 80/50**	**7 100/100**	**1 20/3**	**2 50/25**	**3 80/50**	**7 100/100**
None	292	301	292	345	0,453	0,467	0,450	0,565	0,041	0,042	0,040	0,048
Dedicated lanes	299	306	301	341	0,465	0,476	0,470	0,556	0,042	0,042	0,042	0,048
K&R-facilities	295	301	291	311	0,459	0,467	0,447	0,489	0,041	0,042	0,040	0,043

As can be seen from these results, few large differences can be detected. And indeed, when studying the results of the ANOVA and Tukey post hoc tests, which can be found in section F.3 in appendix F, only few differences turn out to be statistically significant. Again, this is only the case for the scenario with the highest penetration of SAVs, scenario 7 (100/100), and only for the K&R design. For this design, both the CO_2 and the NO_x emissions were significantly lower than for the null alternative. This seems to suggest that the decrease in turbulence of the traffic flow and reduction in stationary delay because of the different driving behaviour is more powerful in reducing emissions than the increase in distance travelled is in increasing emissions.

5.4. Conclusion

To test how the negative effects caused by the driving behaviour of SAVs, as found in chapter 4, can be reduced, the effectiveness of two different designs was tested: dedicated lanes and K&R-facilities. This was done by implementing these designs in the Vissim computer model and running similar experiments as was done for the scenario studies. The scenarios that were used for this part of the research were those with a variety of SAV penetration rates: scenarios 1 (20/3), 2 (50/25), 3 (80/50) and 7 (100/100). This allows not only studying the effectiveness of the measures, but also seeing whether this effectiveness increases with the penetration of SAVs.

After having implemented the measures in the models, having determined the experimental set-up and running the experiments, the results could be retrieved and analysed. In terms of reducing the vehicle delays, only the K&R-facilities were successful. The effectiveness of this measure was noticeable somewhere between 25% and 50% penetration of SAV usage. This measure was even successful in nearly halving the average vehicle delay in the extreme scenario 7 with 100% of the travellers using SAVs. However, the delay in this scenario was still not nearly as short as in the scenarios with fewer SAVs.

The average distance driven per vehicle offered some extra insights in the performance of the scenarios. As could be expected, the distance driven by SAVs was for each scenario reduced when the dedicated lanes scenario was implemented. For scenario 7 (100/100), a significant increase in the distance driven by SAVs was detected for the K&R design. This was remarkable, since their delay was significantly decreased by the design. This in combination with the fact that none of the delays were reduced by the dedicated lanes design, led to the conclusion that the reduction of blockage, queues, U-turns and use of low capacity links by SAVs was more effective in reducing vehicle delays than was the reduction on distance covered and increase in road capacity. Even the emission results showed an improvement when the K&R-facilities were implemented, proving that the reduction in flow turbulence and stationary queues for this design made a larger positive difference than the increase in distance made a negative difference.

All in all, it can be concluded that building fine-meshed K&R-facilities off the main road is an effective tool for reducing vehicle delays and extra emissions caused by SAVs. However, this tool starts being effective only when there is a high penetration rate (>25%) of SAV usage.

6

Conclusion

The goal of this research was to provide insights in the congestion effects of AVs and SAVs on urban traffic in the transition period. A special focus was put on the differences in microscopic behaviour as compared to normal cars. Another goal was to see which easy-to-implement solutions the municipality could apply to facilitate the new mix of urban traffic that can be expected in the future. In section 6.1 of this chapter, the steps taken to attain these research goals will be summarized, the outcomes of the research will be discussed as well as the answers to the research questions. In section 6.2, the recommendations following from these outcomes will be presented. After, the caveats attached to the outcomes and recommendations will be discussed in section 6.3. Finally, some suggestions for further research will be presented in section 6.4.

6.1. Summary of research and outcomes

To answer the research questions, first a thorough review of the literature on urban roads and -traffic, and in which ways this can be influenced by recent developments in the automotive market, was needed. The specific developments that were focused on here, are vehicle automation, -connectedness and -sharing. Vehicles that are developed using these technologies, AVs and SAVs, can change urban mobility both on a macroscopic level and on a microscopic level. The fortitude of these effects is largely dependent on how fast these technologies will penetrate the market. This is dependent on many factors that researchers do not seem to agree on yet. Therefore, this study was based on scenarios with regard to market penetration. Macroscopically, travel demand and even land use could change significantly as a result of reduced generalized trip cost. Further, autonomous, connected and shared applications are expected to co-develop and amplify each other's usefulness. Therefore, it is likely that as the penetration of AVs increases, so will the penetration of SAVs.

However, the focus of this research, are the microscopic effects of AVs and SAVs on the traffic flow. The literature was quite positive about the effects of AVs on the traffic flow. Research was found reporting on smoother traffic flow and increase of road capacity. This is thanks to less deviation in behaviour, both over time in the same car and between cars, smoother acceleration and deceleration, and better anticipation. The positive effects were, however, on the condition that shorter headways are employed. Following research on emergency stop technologies, connected technologies and policies on data transmission, this was in fact assumed to be the case. Little research was available on the microscopic effects of SAVs. What was found in the research on macroscopic effects, though, was that SAVs can be expected to circulate empty on the network. However, concerns were only uttered purely about the extra distance driven, not about the manner in which the vehicles circulate the network. Further, concerns were uttered about the future of curb use in the city when SAVs drop-off their passengers in front of their door instead of finding a parking spot. From looking at the available research, it was found that the scientific gap could be found in looking at the combined effects of AVs and SAVs in a realistic urban environment in transition.

As mentioned above, this study was based on several market penetration scenarios. To formulate these scenarios, it was chosen to focus on the year 2040 as a study year. From literature research, many different predictions were found for the market penetration of AV and SAV technologies in 2040. It was found that the market penetration of AVs could realistically be somewhere between 25% and 80% of all personal vehicles in 2040. For SAVs a market penetration of somewhere between 3% and 50% of all car travellers with a destination in the city was found. Effects on travel demand and on modal split between car and PT or bike were largely left outside the scope.

To allow for easy quantitative analysis, a case study network was selected with the properties that could bring forward the effects of the differences in driving behaviour: a high traffic throughput, access to surrounding real estate, and to some extent controlled interaction with other traffic. The case study selected is a network around the central station of The Hague, during the morning peak period. For this type of network, a conceptual model was made, describing the elements in the system and their relationships. The following KPIs were derived: vehicle delay, distance driven and emissions. It was expected that while higher penetration rates of AVs would have a positive effect on these KPIs, higher penetration rates of SAVs would have a negative effect.

It was acknowledged that the effects described in the conceptual model could not easily be translated into a straightforward mathematical model because of the complexity of the system. Therefore, a simulation model was built using the traffic micro simulation software Vissim. An existing model of the network under study was used as a basis on which the scenarios and designs were built by translating the inputs defined in the conceptual model into the modeling language. After verification and validation of the model, experiments were performed to obtain statistically adequate results for the KPIs. From the experiments, interesting results were obtained that helped to answer the research questions.

Effects of AVs
It was clear that higher penetration rates of AVs had a beneficial effect on vehicle delays and emissions. This is likely due to the increase in road capacity as a result of the shorter headways, smoother acceleration and deceleration, shorter reaction times and more deterministic behaviour. This confirms the relationships that were suggested in the causal diagram in section 3.5. These effects could already be detected at low penetration rates, suggesting that AVs perform a buffer function for turbulent behaviour of human drivers.

Effects of SAVs
The introduction of SAVs in the network, however, has negative effects on both delays of other road users and emissions. As the total distance driven in the system does not significantly increase with SAVs, it can be concluded that these negative effects are a result of the turbulence they cause in the traffic flow by forming bottlenecks when stopping to drop off passengers and using low capacity links to make U-turns, increasing the queues at the traffic lights which are not designed for this.

The scenarios where up to 50% of travellers used SAVs and personal vehicles were increasingly autonomous still performed better in terms of delay than did the scenario without AVs and SAVs. Overall, this is a positive outlook for the future of urban mobility. It seems as though the introduction of AVs and SAVs causes the need to find a new balance between traffic throughput and access to surrounding real estate on the urban network. As mentioned in section 2.1, urban roads are designed for conventional cars to provide a certain combination of throughput and access, depending on the road level. As AVs provide a higher level of throughput and SAVs provide a higher level of access, but neither in the way that conventional cars do, solutions are needed to help restore the balance.

Easy-to-implement solutions
Two easy-to-implement designs were defined that could possibly reduce these negative effects: dedicated lanes and kiss and ride (K&R)-facilities. Both designs were defined as such that they preserve the fine-meshedness of the SAV network while guiding SAVs to locations where they would reduce hinder for other traffic. In the dedicated lanes case, this was on an extra lane on the main road, while in the K&R case this was at special parking places on the side of the roads in the underlying network. Accordingly, the dedicated lanes design will likely concentrate SAV presence on the main road, which has an increased capacity, while the K&R design decentralizes SAV presence.

Effects of designs
After implementing the two designs in four scenarios with varying penetration rates of SAVs, it was found that the dedicated lanes design was unsuccessful in reducing the delays and emissions, even though the distance driven by SAVs was significantly reduced with this design. Even though this design implied an increase in the road's capacity, the increase in weaving movements and the increase in U-turns taken on the main road had a negative effect on the vehicle delays and emissions to the extent that the values for these KPIs remained statistically equal for the non-SAV motorized vehicles. The delays for the bus even increased with this design. This is due to the fact that the SAVs share the dedicated lane with the bus, which can therefore be held up by

stopping SAVs.

The K&R design, on the other hand, turned out to be an effective measure to reduce delays caused by SAVs. However, this was only the case when the penetration rate of SAVs was higher than 25% of travellers. Effects that this design had on the distance travelled and emissions were only noticeable in the extreme scenario of 100% market penetration of SAVs. The positive effects associated with this design can be attributed to the fact that the SAVs are led away from the main road, where less traffic is hindered and where they stop on the side of the road. Additionally, the amount of U-turns made on the main road, using low capacity links, are kept to a minimum. This way, the traffic lights can easily process the queues that form.

Synthesis

The goal of this research was to investigate the congestion effects of AVs and SAVs, both on the current infrastructure and under the implementation of easy-to-implement designs, focusing on the microscopic differences in behaviour of AVs and SAVs compared to normal cars. As described above, the vehicle delay, which is the main indicator for congestion effects, decreases with higher penetration rates of AVs and increases with higher penetration rates of SAVs. This emphasizes the trade-off that is always present on urban roads between high throughput (promoted by AVs) and access to surrounding real estate (promoted by SAVs).

Distance driven and emissions (an indicator for energy consumption) were added as indicators to verify whether differences in vehicle delay were indeed due to differences in microscopic behaviour, or due to differences in network usage. Results for these two indicators confirmed the fact that differences in vehicle delays could be attributed to differences in driving behaviour. Therefore the results for the indicator vehicle delay truly display the effects of different penetrations of AVs and SAVs, and the implementation of the designs on congestion of the urban network. These vehicle delay results for all scenarios and designs are presented in table 6.1. In this table, a distinction is made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because the SAVs spend more time in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted idea of the effects.

Table 6.1: Scenario and design results for vehicle delays of non-SAVs and SAVs

	Non-SAV mean delay (mm:ss)			**SAV mean delay (mm:ss)**		
Scenario/design	**None**	**Dedicated lanes**	**K&R-facilities**	**None**	**Dedicated lanes**	**K&R-facilities**
1: 20/3	02:20	02:36	02:32	03:43	04:27	04:05
2: 50/25	02:55	02:50	02:50	04:00	04:22	03:49
3: 80/50	02:28	02:11	01:59	03:35	03:41	03:06
4: 0/0	04:00	-	-	-	-	-
5: 50/0	01:31	-	-	-	-	-
6: 100/0	01:16	-	-	-	-	-
7: 100/100	06:15	05:50	03:36	09:15	09:52	04:36

6.2. Recommendations

Following the results from the scenario studies and the design studies, it can be concluded that cities with similar networks like the case study (ie. an urban main road where high traffic flow is combined with accessibility functions and interactions with other traffic is controlled by signalized intersections), can count on AVs to have a positive influence on the traffic flow here, reducing congestion and emissions. However, SAVs, which are likely to gain popularity together with AVs, can have a negative influence on delays of other road users and emissions by forming blockages, causing turbulence in traffic flow and causing queues on low capacity links.

It is advisable for a city to look for ways in which the balance between traffic throughput and access that was intended on the urban main roads, can be restored. As it is desirable to leave the current infrastructure largely in tact during the transition period, and to limit costs of infrastructure investments, easy-to-implement solutions will likely take precedence.

The research pointed out that these negative effects can be reduced by facilitating the SAVs with a fine-meshed network of kiss and ride-facilities on the sides of the underlying road network. However, the results suggest that this will only become effective at higher penetration rates of SAVs. As the research already detects negative effects at lower penetration rates, it is advisable to perform more research on solutions that will work when less than 25% of travellers or less are using SAVs.

It is likely that effective solutions will involve diverting SAVs away from the main roads to drop off their passengers. This is because the main roads have an important traffic throughput function. Allowing SAVs to stop on the main roads, would put more emphasis on the access function, which is undesirable, as was found in this research.

Besides the above mentioned recommendations that specifically target the problems found in this research, it is advisable for municipalities to be cautious and closely monitor the situation when it comes to AVs an SAVs in their city. As these are new technologies and concepts, many other unexpected problems could occur besides the ones found in this research. Furthermore, technological developments and market adoption are moving at a fast pace. Adopting a wait-and-see attitude in this could prevent the city from being able to benefit from these new mobility concepts or could even be potentially harmful. Therefore, it is advisable to pay attention to include AVs and SAVs in all future infrastructure plans.

6.3. Limitations

The results of this research can unfortunately not be accepted as a universal truth. In this section, the caveats will be discussed that need to be taken into account when interpreting the findings. These limitations are mainly related to uncertainties with regard to the future, and the simplification of reality into a model by means of conceptualization and specification.

Firstly, the developments in vehicle automation and connected technologies are still very uncertain. The assumptions of what the behaviour of the AVs will look like, are based on what was found in literature about how these technologies are currently working and are expected to work in the future. However, researchers are not in agreement on this topic. More accurate information could probably be retrieved from car manufacturers, but they are very reserved when it comes to sharing technical information, since they do not want it to end up in the hands of their competition. If the technological developments are not as was expected in this research, the on-road behaviour of the vehicles could be different from what was defined in the model, which could change the outcomes of the research. The effects of on-road behaviour of AVs on congestion was found to be very positive, but this could, for instance, be compromised if it turns out that the headways will not be as expected.

Secondly, the implementation of the effects of AV technologies on behaviour of the vehicles was confined by the capabilities of the modeling language. Vissim is a specialized traffic simulation software in which many assumptions are based on the behaviour of human drivers. PTV is working on building capabilities for the modeling of AVs, but these are still relatively limited.

A third limitation is how the market penetration is defined in this research. For simplicity reasons, the market penetration is taken as a share of the travellers that according to the Goudappel Coffeng demand model would travel by car on this network and at this time. However, as was found in the literature study, the availability of new mobility concepts like AVs and SAVs could transform the urban mobility and land use as a whole, changing travel demand at its roots. This could have significant consequences for the intensities of traffic on the network under study. And as was found in the model validation, the results are quite sensitive to the traffic intensities. If they become much higher, the extra capacity created by the presence of AVs, can quickly be filled again, leading to congestion.

SAVs were implemented in a relatively simple way in this research: they were modeled as normal AVs who enter the network and are then assigned a drop-off location and a destination to exit the network. Also their effects on traffic intensities were simplified by confining these to the cars that have their destination in the network, and largely based on assumptions about occupancy, detours and empty kilometres. However, in reality SAVs might move through the city differently. A lot more insight in these movements and their effects on traffic intensities could be created with a case study of a larger network, or of the city as a whole. This would also allow studying the effects of various relocation and ride combining strategies that were found in the literature. However, increasing the size of the network would make it more difficult to study the traffic dynamics in detail.

Because of the confinement of the case study research to the morning peak period, generalization to other times of the day is not directly possible. In general, the morning peak period differs from the evening peak in terms of duration, intensity and types of travellers. Moreover, the OD-matrices of the morning- and evening peak are largely reversed. This has an effect of the traffic intensities and may have an effect on the assumptions made in terms of vehicle occupancy. But more relevant for this research, is that in the morning peak, SAVs are more likely to drop passengers off in the case study area, while in the evening peak, they are more likely to pick passengers up. This has large consequences for the dwell time distribution of SAVs and perhaps even on the way in which they circulate this specific network.

When interpreting the results, especially with regard to the total distance driven, it was found that the duration of the simulation formed a limitation in some cases. For scenario 4 (0/0) and 7 (100/100), the simulation time was often too short to be able to discharge all the planned vehicles and for the vehicles in the model to be able to all reach their destination. This made comparison of the total distance results to other scenarios and to the designs difficult.

Finally, the usage of this case study limits generalization of the results to parts of cities with similar networks. The effects of the on-road behaviour of AVs on congestion could, for instance, be very different for a network with single lane roads, direct interaction with cyclists and unsignalized intersections. However, the division of urban streets into the categories mentioned in section 2.1 is considered sufficiently universal for cities. It is likely that comparative networks, even if they are small, can be found in most cities.

6.4. Further research

There are still a lot of aspects of the effects of AVs and SAVs on urban mobility left to research. Following the limitations of this research that were described above, three research directions can be recommended specifically. These research directions are discussed in this section.

Firstly, more research is needed to translate the capabilities of AVs, and the demand and strategies for SAVs into concrete on-road behaviour. On an operational scale, it is still very difficult for policy makers and urban planners to envision the effects that these concepts will have on their urban traffic. By providing insights in these effects, policy makers and urban planners will be able to adopt a more pro-active stance and take concrete steps to reshape the city for new mobility.

Secondly, more large scale, holistic research is needed looking at the possible travel demand effects that the availability of AVs and SAVs can have. These concepts can change land use and mobility at its roots, having large consequences for the city of tomorrow.

Thirdly, to gain more insights into the effects of SAVs on urban traffic, it is needed to perform research combining the strategical and tactical decisions that SAVs make in terms of routing, relocation and ride combining, with their operational behaviour. This can be done with and without the implementation of K&R-facilities. To be able to do this a network should be studied that is larger than the network under study here, but small enough to study the traffic dynamics.

Finally, this study can be repeated by the time that there is more certainty about the driving behaviour of AVs and SAVs, and about the strategic policies of municipalities with regard to AVs and SAVs. To increase generalisability, a different case study can be chosen and the study can also be performed for the afternoon/evening peak period.

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A

Interviews

In the exploratory phase of this research, a number of interviews were conducted to get a view of how municipalities (specifically the municipality of The Hague) view the future of urban mobility. Specific attention was paid to the role that AVs and SAVs can play in this future. In section A.1 a summary is given of an interview with a mobility policy advisor at the municipality of The Hague. In section A.2 a summary is presented of a workshop that was organized with mobility advisors from Arcadis as well as policy advisors from the municipality of The Hague.

A.1. Jan Jaap Koops, Municipality of The Hague - 30/05/2018

On 30 May 2018 a meeting was held with Jan Jaap Koops, a mobility policy advisor at the Municipality of The Hague. Jan Jaap is mostly occupied with assessing effects on traffic of large scale (real estate) projects in The Hague. The goal of this meeting was to investigate general developments and policies in terms of mobility of The Hague, to find out their main design criteria when adapting their network/infrastructure, and to test the municipality's expectations and plans regarding automated driving. Below a brief summary of the meeting is presented.

- In the Nota Mobiliteit [19], which was written 7 years ago, the municipality expects a growth in car ownership and kilometers driven. Did you observe these developments in reality?
    - The amount of cars has indeed increased, but that is mainly because the amount of households has increased. There was a slight decrease in car ownership per household, but in total the amount of cars has increased.
    - The amount of kilometers driven per car has increased regionally, but not within the city.
    - The modal split in The Hague still leans more strongly towards the car than in other cities, because we have a different composition of the population. For instance, The Hague has a lot of people with a different ethnic background, who do not take the bike as quickly as Dutch people do.
- How have the policies mentioned in the Nota Mobiliteit, especially the policy regarding concentrating traffic towards the urban main roads, worked out?
    - We have actively been implementing measures to pursue this and it is working quite well.
- What are your expectations for automatic driving in The Hague regarding car ownership, distances driven, and the use of the urban network?
    - I don't see any reasons why car ownership of automated cars would be any different from the rest of The Netherlands.
    - The urban infrastructure in The Hague will, however, form a lot of obstacles for the use of automated cars on the urban network. An example is the emergency stop system built into those cars. If this system is too sensitive, the car will stop much too often, because everything is built so close together.

- Do you have or are you developing a policy regarding automated vehicles?
  - We do not have a policy yet. The municipality is now adopting a more passive stance where we monitor the developments and where needed we will intervene.
  - Right now we are not working on constructing roads in such a way that automated cars are explicitly accounted for. We are more expecting those cars to adjust themselves to the traffic and infrastructure we have. We do, however, install traffic lights with communicative capabilities whenever we renew an intersection.
  - If the municipality decides to become more active regarding automated vehicles, I think we will first start with self-driving public transport pilots and then move further from there.
- When you (re)design a road or intersection, what are your main criteria?
  - Our basic design criteria are all written down in the Handbook Public Space. The most important criteria are:
    - ◇ The traffic flow should not deteriorate. In (rare) cases where deterioration of the traffic flow is accepted, the classification of this road should be devaluated.
    - ◇ The traffic safety should always stay the same or improve. This is non-negotiable: if an adjustment means deterioration of traffic safety, we will not do it.
  - We test traffic flow and traffic safety integrally for all modes. In line with our policies in the Nota Mobiliteit, the focus is gradually moving more towards other modes than the car. So we see more often that car lanes are being omitted to offer cyclists and pedestrians more space. This is all dependent on the function of the road. For instance, the Vrijheidsplein is part of an important cyclist corridor from the train station, so we want to offer cyclists more space there.
  - For the policy department, individual travel time is becoming less important, because we try to focus on providing a good traffic flow for all modes.
  - Currently, The Hague is the most car friendly city of The Netherlands (a parking license only costs €3 per month), but we are trying to change that.
- Do you think car- and ridesharing will make the car a more favourable mode for the municipality?
  - We definitely see the advantages of car- and ridesharing and we have an encouragement program. However, this way of transportation is only beneficial if people use it at different moments and not all during peak hours.
- What are your plans regarding public transport and automation?
  - We just closed a new concession with HTM, which is valid until the mid 2020s. The contract does not include anything about automation. It does, however, set targets for electrification of the fleet.

A.2. Workshop Municipality of The Hague - 04/07/2018

On 4 July 2018, a workshop was organized at the Municipality of The Hague to gather input on how they think autonomous and shared vehicles will influence traffic in 2040 and what the municipality can do to anticipate this. After a brief presentation about the research and a round of definitions, participants were asked to respond to a few propositions using an online polling tool, after which an open discussion was held per proposition. For this workshop, several policy advisors, mobility advisors and innovation experts were invited. As all attendants were Dutch, the workshop was held in Dutch. In the summary below, questions and statements are translated and sometimes paraphrased. Because of time shortage, some questions could not be addressed as extensively as others. This specifically applies to questions 3b and 4a about infrastructure design.

The following people attended the workshop:

- Bettinka Rakic - Mobility advisor at Arcadis
- Gerco Huisman - Mobility advisor/traffic engineer at Arcadis
- Jan Jaap Koops - Mobility advisor at the Municipality of The Hague
- Marc van der Burg - Policy advisor/innovation expert at the Municipality of The Hague

- Irene Overtoom - Student Transport, Infrastructure and Logistics at TU Delft

As mobility advisors for Arcadis, Bettinka Rakic and Gerco Huisman work on all sorts of mobility issues for municipalities, provinces and the state. They are interested in the impact of autonomous vehicles as this becomes more and more a topic of interest when looking at future-proof designs.

Jan Jaap Koops, who works at the traffic policy department of the municipality, is mostly occupied with assessing the traffic effects of large-scale (real-estate) projects in the city. His direct involvement with autonomous vehicles is limited to some pilot shuttle projects, but he is interested to see what private autonomous transportation can bring.

Marc van der Burg is a policy advisor at the municipality whose main topics are innovation and strategy. In terms of mobility, he is looking into MaaS and carsharing applications, such as the MaaS pilot that was started to make Rotterdam The Hague airport more accessible. He is interested in learning more about how policy can shape the way people use autonomous transport.

The propositions will be given as numbered item. For each proposition a few discussion questions were asked, which are indicated by letters.

1. In 2040 all newly sold cars will be able to drive autonomously, also in the city. - agree: 2, disagree: 2.
    (a) Will manually driven cars even be sold?
        - Bettinka: It is likely that every newly sold car is a "hybrid": it can operate autonomously, but it can also be operated by a human driver.
        - Gerco: There will always be people who need to use the manual functions of a car. For instance a forest ranger will want to drive manually in the forest, but autonomously on the road. That’s why I think most cars will be hybrid.
        - Jan Jaap: 2040 is quite soon already. We already have some pretty concrete ideas of what place autonomous vehicles will have in society and the city in 2030 and I don’t think this will change very radically in just ten years. However, I do think that by that time all newly sold cars will have the ability to drive autonomously. How much this function will be used remains the question.
        - Marc: I am sure that by that time there will still be people who will want to keep using manually driven cars.

    (b) What is this dependent on?
        - Jan Jaap: Whether or not we will see the self-driving car on the roads in 2040 is for a large part dependent on laws and regulations, safety margins, and results from safety tests. If it’s not proven to be safe, the city will not allow it.
        - Marc: I think the success of autonomous mobility is for 90% dependent on human behaviour and acceptance. It might now seem frightening to people, but as it becomes more and more normal to drive autonomously, it will seem frightening to people that we used to all drive manually.
        - Gerco: It’s all about policy and right now there are two camps among the policy makers: those who think autonomous transportation will reduce the space needed in the city for traffic, making the city a more attractive place, and those who think that autonomous vehicles will only need more asphalt in order to enjoy the benefits. Which of the two is right, will be essential for the success of autonomous vehicles.
        - Jan Jaap: But the question remains whether you want to adjust your city to the cars or whether the cars should adjust to your city. And more important: do you even want the autonomous car in your city or do you want to create hubs at the edges, making the autonomous car a more long-distance mode.

    (c) For what kind of use would you want to buy an autonomous car?
        - Jan Jaap: To be able to reach places which cannot be reached with public transport.
        - Marc: To be able to spend your travel time in a useful way. You can also do this in public transport, but an autonomous car is more comfortable and private. You will also be able to plan meetings on the road.
        - Bettinka: Public transport organizations are not all that happy with these promised functionalities, because they feel superseded.

(d) Will it even still be the norm to buy a car or will everyone just subscribe to an on-demand service?

   - Bettinka: This will be very much dependent on the price of those services.
   - Gerco: Personally, I would like to keep my own car, but it will help that these services will enable groups like elderly and teenagers to use a car independently.
   - Jan Jaap: If you compare it to the shift toward the personal car, it took decades after it was introduced before it was commonly accepted and normal to have one. But especially when the price is attractive and especially in dense cities, you can see that people's mindsets can really shift.
   - Marc: The shift toward on-demand services as opposed to car ownership is, just like the shift towards autonomous transportation very much dependent on human behaviour and acceptance. People need time to get used to the idea, but price is a very good trigger to accelerate this and change fundamental behaviour. I think that even though people might think so now, it is not necessarily so that everyone will want to own a car.

2. Which effect is the strongest:

   In 2040 car ownership and -usage in The Hague will have increased, because the value of time is lower in autonomous cars.

   In 2040 car ownership and -usage in The Hague will have decreased, because ride sharing will become more attractive with autonomous cars.

   - increase: 2, decrease: 0, none: 2.

   - Bettinka: I doubt that sharing services will lead to less cars on the road, because it is difficult to organize sharing in such a way that there is high car occupancy.
   - Gerco: I think ownership will decrease, especially in the city, because of high availability of sharing services. But I also think that usage will increase, because when something is cheap and easy, people will definitely use it.
   - Jan Jaap: If sharing is easy, the use of cars as a mode will definitely increase. Then it is the trick to increase ride sharing to limit the amount of cars on the road. For some people, ride sharing can be a very attractive alternative. But it would be nice if you are able to choose who you share a ride with.

   (a) Would the convenience of using a self-driving cars for people traveling from or to The Hague mean that they are more likely to choose the car, even if this means that their travel time increases?

      - Bettinka: This can be likely, because car is already an attractive mode in itself, regardless of travel time. A very relevant statement I once heard is: "Car is a prolongation of home and train is a prolongation of work."
      - Marc: I am actually not so sure that an efficient use of travel time always weighs up to the status of having your own vehicle and having a moment for yourself to drive. Some people don't even mind being in a traffic jam, because it gives them a moment to themselves.

   (b) If on-demand sharing services become popular in The Hague thanks to the convenience and attractive price, could this mean a decrease in traffic during the peak hours?

      - Bettinka: Only if the rides are shared, increasing car occupancy.

3. The (societal) advantages of self-driving cars cannot be utilized optimally if they drive in a city with mixed traffic. - agree: 3, disagree: 1.

   (a) What are the societal advantages of self-driving cars?

      - Gerco: Many of the advantages of self-driving cars are actually quite individualistic, such as efficient use of travel time, easy use and cheap use. It is difficult to pinpoint advantages for the city collectively.
      - Bettinka: There are definitely some positive effects, such as a reduction of emissions and better traffic flow, that you will want to stimulate, but also some negative effects, such as an increase in demand and safety issues, that you want to mitigate.

    - Jan Jaap: There are definitely positive effects individually, but if you can make a societal cost-benefit analysis as a policy-maker, I think you might be disappointed by the overall results. The question will arise whether you even want these cars in your city. But decision-making on these topics will take place in very small steps. Most policy-makers now will not want to occupy themselves with these topics if they will only become relevant in 2040.
    - Marc: In mixed traffic I don't think you will see many benefits, but if you have a confined system which is fully autonomous, you will definitely see the large scale benefits. That is why it is important to look at phased implementation, for instance pilots with autonomous shuttle buses on dedicated infrastructure. This will also help us to learn, because when the municipality constructs or renews a road now, and decides to make it future-proof for self-driving cars, they have no idea where to start or what to install.

   (b) Will it be useful to make dedicated infrastructure in order to attain these advantages?

    - Jan Jaap: Dedicated lanes could be an option, but mostly for safety.
    - Marc: As stated above, benefits will only be attained when you have a total system, not mixed. Dedicated lanes could help in this.

4. What will be the effects on traffic if everyone will suddenly use self-driving taxis that keep on circulating through the network and stop in random places?

   - Gerco: In Shanghai, parking is more expensive than hiring a driver, so people just let their driver circulate through the city the whole day. This results in so much extra traffic that it causes congestion. Also, cars that stop in the road the entire time will cause bottlenecks.

   (a) Could these problems be solved with infrastructural adjustments, for instance multi-purpose lanes?

    - Jan Jaap: In the US they have also done tests with multi-purpose lanes for turning traffic, and it was no success. It creates chaos and confusion.

B

Origin-destination matrices

In this appendix, the OD-matrices are presented that were used to build the scenario simulation models. Figure B.1 gives a recap of the network and the locations of the zones. Tables B.1 to B.5 display the matrices for cars for all scenarios. For the scenarios that include SAVs, these matrices are divided into a non-SAV car matrix and a SAV car matrix. Table B.6 presents the matrices used for LGVs, table B.7 those of HGVs, and table B.8 those of bicycles. The car, LGV and HGV matrices are later divided over AVs and non-AVs. Table B.9 show the frequencies of the buses that are present in the model.

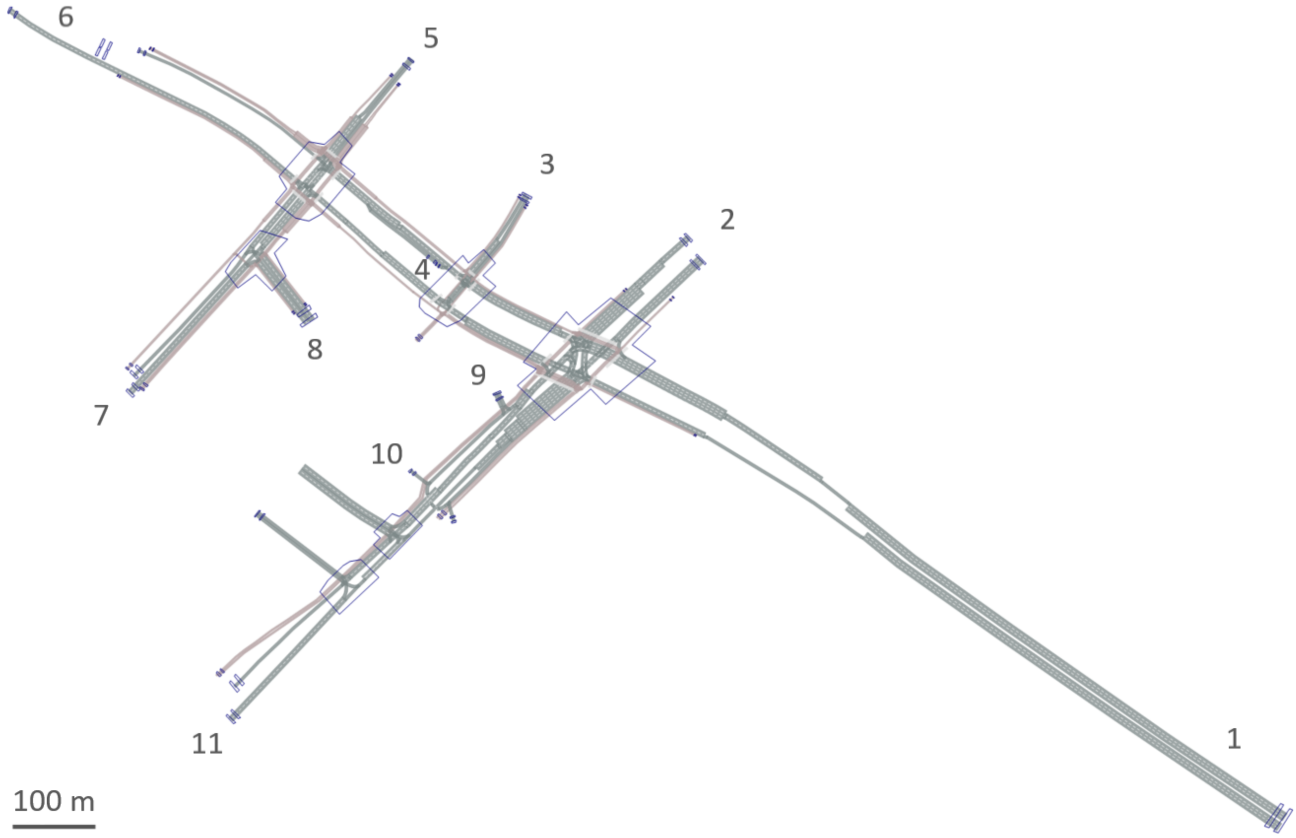

Figure B.1: Graphical representation of the modelled network with zone locations

Table B.1: Matrix cars scenario 1 (20/3)

Non-SAV

O/D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sum**
1	0	267	457	26	128	4485	694	172	70	415	583	7297
2	358	0	21	2	5	31	166	12	13	134	143	884
3	305	0	0	0	103	108	68	5	18	77	162	844
4	11	5	6	0	0	0	2	0	0	0	4	29
5	7	0	0	10	0	31	432	106	0	50	0	636
6	3532	254	59	14	65	0	164	77	33	65	38	4300
7	92	91	55	21	224	126	0	331	23	148	0	1112
8	70	28	8	0	65	0	90	0	0	2	9	272
9	28	16	10	0	0	1	17	0	0	0	0	73
10	221	84	36	0	4	7	75	2	0	0	42	472
11	175	173	155	0	5	0	0	0	28	0	78	614
Sum	4799	919	808	73	598	4789	1708	705	184	890	1059	16532

SAV

O/D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sum**
1	0	1	1	0	0	14	2	0	0	0	2	21
2	2	0	0	0	0	0	1	0	0	0	1	5
3	1	0	0	0	0	0	0	0	0	0	1	3
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	5	0	0	0	0	5
6	0	3	1	0	1	0	2	0	0	0	0	6
7	3	3	2	0	6	3	0	0	0	0	0	16
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	1
Sum	6	6	4	0	8	19	10	0	0	0	4	57

Table B.2: Matrix cars scenario 2 (50/25)

Non-SAV

O/D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sum**
1	0	267	457	20	128	4485	694	133	54	321	583	7143
2	358	0	21	2	5	31	166	9	10	104	143	848
3	305	0	0	0	103	108	68	4	14	59	162	821
4	11	5	6	0	0	0	2	0	0	0	4	29
5	7	0	0	8	0	31	432	82	0	38	0	598
6	3532	254	59	11	65	0	164	59	25	50	38	4257
7	92	91	55	16	224	126	0	256	18	115	0	993
8	70	28	8	0	65	0	90	0	0	2	9	271
9	28	16	10	0	0	1	17	0	0	0	0	73
10	221	84	36	0	4	7	75	2	0	0	42	471
11	175	173	155	0	5	0	0	0	22	0	78	608
Sum	4799	919	808	56	598	4789	1708	545	142	688	1059	16112

SAV

O/D	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Sum**
1	0	5	9	0	2	87	14	0	0	0	11	129
2	15	0	1	0	0	1	7	0	0	0	6	30
3	8	0	0	0	3	3	2	0	0	0	4	19
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	2	29	0	0	0	0	31
6	0	15	4	0	4	0	10	0	0	0	2	36
7	16	15	9	0	38	21	0	0	0	0	0	99
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	2	2	1	0	0	0	0	0	0	0	1	5
Sum	41	38	24	0	47	115	61	0	0	0	24	350

Table B.3: Matrix cars scenario 3 (80/50)

Non-SAV

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	267	457	13	128	4485	694	89	36	214	583	6967
2	358	0	21	1	5	31	166	6	7	69	143	806
3	305	0	0	0	103	108	68	3	9	39	162	796
4	11	5	6	0	0	0	2	0	0	0	4	29
5	7	0	0	5	0	31	432	55	0	26	0	555
6	3532	254	59	7	65	0	164	39	17	33	38	4209
7	92	91	55	11	224	126	0	171	12	76	0	858
8	70	28	8	0	65	0	90	0	0	1	9	271
9	28	16	10	0	0	1	17	0	0	0	0	73
10	221	84	36	0	4	7	75	1	0	0	42	471
11	175	173	155	0	5	0	0	0	14	0	78	601
Sum	4799	919	808	37	598	4789	1708	364	95	459	1059	15635

SAV

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	8	13	0	4	131	20	0	0	0	17	193
2	23	0	1	0	0	2	10	0	0	0	9	46
3	12	0	0	0	4	4	3	0	0	0	6	28
4	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	3	43	0	0	0	0	47
6	0	23	5	0	6	0	15	0	0	0	3	53
7	23	23	14	0	56	32	0	0	0	0	0	148
8	0	0	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	1
11	2	2	2	0	0	0	0	0	0	0	1	8
Sum	61	57	36	0	70	172	92	0	0	0	37	525

Table B.4: Matrix cars scenarios 4 (0/0), 5 (50/0), 6 (100/0)

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	267	457	27	128	4485	694	177	72	428	583	7318
2	358	0	21	2	5	31	166	12	13	138	143	889
3	305	0	0	0	103	108	68	5	18	79	162	847
4	11	5	6	0	0	0	2	0	0	0	4	29
5	7	0	0	10	0	31	432	110	0	51	0	641
6	3532	254	59	14	65	0	164	79	34	67	38	4306
7	92	91	55	22	224	126	0	341	24	153	0	1128
8	70	28	8	0	65	0	90	0	0	2	9	272
9	28	16	10	0	0	1	17	0	0	0	0	73
10	221	84	36	0	4	7	75	2	0	0	42	472
11	175	173	155	0	5	0	0	0	29	0	78	615
Sum	4799	919	808	75	598	4789	1708	727	190	918	1059	16589

Table B.5: Matrix cars scenario 7 (100/100)

Non-SAV

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	267	457	0	128	4485	694	0	0	0	583	6615
2	358	0	21	0	5	31	166	0	0	0	143	723
3	305	0	0	0	103	108	68	0	0	0	162	744
4	11	5	6	0	0	0	2	0	0	0	4	29
5	7	0	0	0	0	31	432	0	0	0	0	470
6	3532	254	59	0	65	0	164	0	0	0	38	4112
7	92	91	55	0	224	126	0	0	0	0	0	589
8	70	28	8	0	65	0	90	0	0	0	9	270
9	28	16	10	0	0	1	17	0	0	0	0	73
10	221	84	36	0	4	7	75	0	0	0	42	470
11	175	173	155	0	5	0	0	0	0	0	78	587
Sum	4799	919	808	0	598	4789	1708	0	0	0	1059	14680

SAV

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	16	27	0	7	262	41	0	0	0	34	387
2	45	0	3	0	1	4	21	0	0	0	18	91
3	23	0	0	0	8	8	5	0	0	0	12	56
4	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	0	0	6	87	0	0	0	0	94
6	1	46	11	0	12	0	30	0	0	0	7	107
7	47	46	28	0	113	64	0	0	0	0	0	297
8	0	0	0	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0	1
11	5	5	4	0	0	0	0	0	0	0	2	16
Sum	123	113	73	0	141	344	184	0	0	0	73	1050

Table B.6: Matrix LGV all scenarios

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	0	12	0	2	104	3	1	1	12	16	152
2	0	0	7	0	0	9	3	1	0	8	18	47
3	17	0	0	0	0	1	0	0	0	1	13	33
4	0	0	0	0	0	0	0	0	0	0	0	0
5	2	0	0	0	0	2	2	1	0	0	2	9
6	128	10	1	0	3	0	0	7	1	2	3	156
7	2	1	0	0	4	0	0	11	1	6	0	26
8	2	3	2	0	9	0	15	0	0	0	0	32
9	0	1	0	0	2	0	0	0	0	0	0	3
10	18	14	1	0	4	2	12	0	0	0	0	52
11	31	12	29	0	6	0	0	0	0	0	2	80
Sum	201	42	52	0	31	118	36	22	3	30	55	590

Table B.7: Matrix HGV all scenarios

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	0	2	0	0	63	0	0	0	8	4	77
2	0	0	0	0	0	5	0	0	0	2	2	9
3	2	0	0	0	0	0	0	0	0	0	0	2
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	67	4	0	0	0	0	0	10	0	0	0	81
7	2	0	0	0	0	0	0	2	0	0	0	4
8	0	0	0	0	8	0	1	0	0	0	0	9
9	0	0	0	0	0	0	0	0	0	0	0	0
10	10	5	0	0	0	0	2	0	0	0	0	17
11	8	1	2	0	3	0	0	0	0	0	0	14
Sum	89	10	4	0	11	68	3	12	0	10	6	214

Table B.8: Matrix bicycles all scenarios

O/D	1	2	3	4	5	6	7	8	9	10	11	Sum
1	0	0	0	0	0	0	0	0	0	0	0	0
2	110	0	0	243	0	66	353	88	0	110	331	1303
3	44	0	0	44	0	0	110	0	0	0	44	243
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	110	641	55	0	0	55	862
6	66	22	110	0	66	0	199	0	0	0	0	464
7	88	110	110	110	376	110	0	442	0	0	0	1348
8	0	0	0	0	177	0	1215	0	0	0	0	1392
9	0	0	0	0	0	0	0	0	0	0	0	0
10	133	88	0	0	0	0	110	0	0	0	0	331
11	177	177	133	110	66	0	0	0	0	0	0	663
Sum	619	398	353	508	685	287	2629	585	0	110	431	6606

Table B.9: Vissim bus frequency table

Bus	2-hour frequency
Bus 18 (Rijswijk)	16
Bus 18 (Clingendael)	10
Bus 22 (duindorp)	23
Bus 22 (Duinzigt)	31
Bus 24 (Kijkduin)	33
Bus 24 (Mariahoeve)	28
Bus 28	7
Bus 29 (Brinckhorst)	7
Bus 43	9
Bus 44	10
Bus 45	16
Bus 46	9
Bus 90	4
Bus 380	4
Bus 381	6
Bus 382	5
Bus 383	9
Bus 385	11
Bus 386	8
Sum	246

C

Driving behaviour parameters

In this appendix, the details are given for how the driving behaviour of different vehicle classes are specified in the simulation model. Table C.1 provides an overview of the modes, their vehicle classes, and corresponding driving behaviour parameter sets. Table C.2 lists the specific settings of the driving behaviour parameter sets used. Table C.3 presents the lower and upper bounds of the desired speed distributions used. Tables C.4 and C.5 show the distributions of the desired acceleration- and deceleration curves used.

Table C.1: Vehicle classes and corresponding driving behaviours, speeds and acceleration/deceleration

Mode	**Vehicle class**	**Driving behaviour parameters**	**Desired speed distributions**	**Desired acceleration/ deceleration curves**
Car	Car-average	Urban motorized	Average	Average
	Car-defensive		Defensive	Defensive
	Car-assertive		Assertive	Assertive
	Car-AV	Urban AV	AV	AV
SAV	Car-SAV	Urban AV	AV	AV
LGV	LGV-average	Urban motorized	Average	Average
	LGV-defensive		Defensive	Defensive
	LGV-assertive		Assertive	Assertive
	LGV-AV	Urban AV	AV	AV
HGV	HGV	Urban motorized	Average	HGV
	HGV-AV	Urban AV	AV	
Bicycle	Bicycle	Cycle track	N/A	N/A
Bus	Bus	Urban motorized	Average	Bus
	Bus-AV	Urban AV	AV	

Table C.2: Driving behaviour parameters

Driving behaviour	**Urban motorized**	**Urban AV**	**Cycle track**
Car following			
Look ahead distance			
Min	0,00 m	0,00 m	10,00 m
Max	250,00 m	250,00 m	250,00 m
Observed vehicles	2	4	2
Look back distance			
Min	0,00 m	0,00 m	0,00 m
Max	150,00 m	150,00 m	150,00 m
Smooth close-up	No	Yes	No
Standstill dist	Variable	0,50 m	Variable
Car following model	Wiedemann 74	Wiedemann 74	Wiedemann 99
Avg standstill dist.	2,00 m	1,00 m	0,50 m
Additive part safety dist.	2,00	1,50	N/A
Multiplic. Part safety dist.	3,00	0,00	N/A
Lane change			
General	Free lane selection	Free lane selection	Free lane selection
Own			
Max deceleration	4,00 m/s^2	4,00 m/s^2	4,00 m/s^2
Accepted deceleration	1,00 m/s^2	1,00 m/s^2	1,00 m/s^2
Trailing			
Max deceleration	3,00 m/s^2	3,00 m/s^2	3,00 m/s^2
Accepted deceleration	1,00 m/s^2	1,00 m/s^2	1,00 m/s^2
Min headway	0,50 m	0,50 m	0,50 m
Safety dist reduction factor	0,60	0,60	0,60
Waiting time before diffusion	60,00 s	60,00 s	60,00 s
Advanced merging	Yes	Yes	No
Vehicle routing look ahead	Yes	Yes	No
Signal control			
Behaviour at amber	Continuous check	Continuous check	Continuous check
Reaction time	~N(0.75,0.10) s	0,00 s	0,00 s

Table C.3: Desired speed distributions, ~U(lower bound, upper bound)

Speed distribution	**Lower bound (km/h)**	**Upper bound (km/h)**
Average		
30	30	35
50	48	58
70	68	78
Defensive		
30 defensive	25	30
50 defensive	43	53
70 defensive	63	73
Assertive		
30 assertive	35	40
50 assertive	53	63
70 assertive	73	83
AV		
30 AV	30	30
50 AV	50	50
70 AV	70	70

Table C.4: Desired acceleration curves

Velocity (km/h)	**Mean accel. (m/s^2)**	**Min accel. (m/s^2)**	**Max accel. (m/s^2)**	**Velocity (km/h)**	**Mean accel. (m/s^2)**	**Min accel. (m/s^2)**	**Max accel. (m/s^2)**
Average				**AV**			
0	3,50	1,96	3,50	0	3,50	3,50	3,50
10	3,20	1,49	3,50	10	3,20	3,20	3,20
20	2,79	1,30	3,50	20	2,79	2,79	2,79
30	2,47	1,15	3,50	30	2,47	2,47	2,47
40	2,20	1,03	3,50	40	2,20	2,20	2,20
50	1,96	0,92	3,27	50	1,96	1,96	1,96
60	1,75	0,82	2,92	60	1,75	1,75	1,75
70	1,55	0,73	2,59	70	1,55	1,55	1,55
80	1,37	0,64	2,29	80	1,37	1,37	1,37
Defensive				**HGV**			
0	2,82	1,28	2,82	0	2,50	2,50	2,50
10	2,52	0,99	2,82	10	2,50	2,40	2,50
20	2,11	0,78	2,82	20	2,50	1,12	2,50
30	1,79	0,64	2,82	30	2,00	0,73	2,50
40	1,51	0,50	2,81	40	1,52	0,53	2,35
50	1,27	0,42	2,58	50	0,95	0,32	1,55
60	1,23	0,42	2,40	60	0,79	0,25	1,31
70	1,19	0,36	2,23	70	0,64	0,19	1,10
80	1,11	0,38	2,03	80	0,52	0,15	0,90
Assertive				**Bus**			
0	3,50	1,96	3,50	0	1,24	1,04	1,49
10	3,40	1,89	3,54	10	1,24	1,04	1,49
20	3,24	1,75	3,58	20	1,24	1,04	1,49
30	3,06	1,75	3,56	30	1,24	1,04	1,49
40	2,82	1,65	3,52	40	1,10	0,92	1,32
50	2,58	1,54	3,48	50	1,00	0,84	1,20
60	2,33	1,39	3,20	60	0,90	0,76	1,08
70	2,07	1,24	3,02	70	0,80	0,67	0,96
80	1,85	1,13	2,76	80	0,60	0,50	0,72

Table C.5: Desired deceleration distributions

Deceleration distribution	**Mean decel. (m/s^2)**	**Min decel. (m/s^2)**	**Max decel. (m/s^2)**
Average	-2,75	-3,00	-2,55
Defensive	-2,25	-2,50	-2,05
Assertive	-3,25	-3,50	-3,05
AV	-2,75	-2,75	-2,75
HGV	-1,25	-1,50	-1,05
Bus	-0,85	-1,00	-0,73

D

Expert validation sessions

As part of the model validation, several sessions were held with experts on traffic engineering, transport policy, autonomous vehicles and simulation. All experts were given the same information and were asked questions about the validity of the model. The the name, expertise and organisation of the participating experts are given below. In this appendix, the information given to the experts is summarized as well as the experts' answers to the validation questions.

Name	**Expertise**	**Organization**
Jan Jaap Koops	Transport policy	Municipality of The Hague
Dr. Simeon Calvert	Traffic engineering & AVs	TU Delft
Maarten Amelink	Intelligent transport systems	Arcadis
Anton van Meulen	Traffic dynamics & simulation	Arcadis
Ronald van Veen	Urban mobility & traffic management	Arcadis
Erik Verschoor	Intelligent transport systems	Arcadis

D.1. Information

The goal of this validation session is to determine with the help of experts whether the model that is used for this study shows enough resemblance to the (hypothetical) reality to be able to answer the research questions.

The goal of this research is to study the effects of AVs and shared AVs on urban traffic in a transition period. To attain this goal, a hypothetical future situation needs to be mapped in detail. Simulation is an appropriate method for this as it allows studying a situation that is not present in reality now, and which entails a large number of interrelations. A case study was chosen of a small network in The Hague, which can be seen in figure D.1.

The types of road users in this model are:

- Normal cars and vans with an average driver (orange)
- Normal cars and vans with an assertive driver (dark orange)
- Normal cars and vans with a defensive driver (light orange)
- Normal trucks
- Autonomous cars and vans (blue)
- Autonomous trucks (blue)
- Shared autonomous cars (light blue)
- Buses (normal or autonomous)
- Cyclists

All road users follow in principle the only route from their origin to their destination (which has been determined on beforehand). The shared AVs who transport a passenger who has his destination in the network, will make a stop on the way at one of the buildings to drop off the passenger. After this they will continue their journey empty.

Figure D.1: Case study network

In the information package, an overview of the scenarios is also given as well as the first results (based on 3 runs) in terms of vehicle delay and emissions. For three of the eight scenarios, a video was shown of the model in operation. This was done for scenario 4 (no AVs), scenario 2 (50% AVs, 25% shared), and scenario 7 (100% AVs, 100% shared).

D.1.1. Questions

After watching the videos and studying the results, the experts were asked 9 questions:

1. What is your first response after seeing the model? You can think of:
    - (a) Amount of vehicles
    - (b) Origins and destinations
    - (c) Speeds
    - (d) Interaction between vehicles
    - (e) Reaction to traffic lights
    - (f) Route finding behaviour
2. Do the AVs show significantly distinct behaviour? Is this behaviour realistic?
3. Do the shared AVs show significantly distinct behaviour? Is this realistic?
4. How do the normal (orange) cars respond to the AVs and shared AVs? Is this realistic?
5. What do you remark from the vehicle delay results? Is this logical?
6. What do you remark from the emission results? Is this logical?

7. Is there anything that can be changed to make the model better resemble the reality that is being sketched by the scenarios?
8. Is there anything that can be changed to make the model better suitable to attain the research objectives?
9. When enough runs are being performed, can the results be assumed to be representative for the hypothetical reality?

D.2. Responses

D.2.1. Jan Jaap Koops, 22/8/2018

1. What is your first response after seeing the model?
    - The model still seems quite theoretical and unsuitable for direct application. Firstly, some of the scenarios are quite extreme and unlikely to happen, like 100% autonomous and shared traffic. It needs to be noted that these scenarios are only designed to show the extremes and not to depict an actual situation. Further, it is unlikely that in reality the shared AVs will actually stop on the road during rush hour. Human drivers would reasonably see that it is too dangerous to stop, whether there is a prohibition sign or not. If AVs actually tend to stop on the road, because they are computers that have not seen a prohibition sign, then it is likely that prohibition signs will soon be placed. It should be noted that this behaviour will only take place if the computers actually reason like that and the municipality does not place prohibition signs as a result of this.
    - It is important to note that between now and 2040 a lot can happen in terms of mobility. We are working on policies to reduce car ownership and car use and also in case the road traffic intensities keep growing at the same rate, the infrastructure will likely be adapted. Actual road traffic demand numbers for 2040 are still very unclear. Of course you have to start somewhere, so it's logical to use the current state infrastructure and it is reasonable to use a conservative growth rate towards 2040 along with it. The current infrastructure cannot handle larger numbers. These are reasonable choices, but the question remains whether they are realistic. Results will have to be seen in light of this.
    - In terms of general driving behaviour nothing special can be remarked. It seemed quite realistic.
2. Do the AVs show significantly distinct behaviour? Is this behaviour realistic?
    - I think the behaviour shown by the AVs is realistic. They seem to have a positive influence on the traffic flow because of the short headways, more homogeneous behaviour and short reaction times. The short headways seem realistic for that time. If AVs kept longer headways than normal cars, it remains the question whether the municipality would allow them on the road, because that impacts the traffic flow negatively.
3. Do the shared AVs show significantly distinct behaviour? Is this realistic?
    - As mentioned before, a human driver would not reasonably stop on a 50 km/h road during rush hour. They would seek out a different place to stop. It can definitely be reasoned that the shared AVs are computers and that once they have reached their destination and have not seen a prohibition sign on the road, they could just stop. However, the municipality would then intervene. The AVs should adapt to the traffic in the city. So it should definitely be noted that the current infrastructure without prohibition signs is being assumed and that it is being assumed that the shared AVs reason primitively that they can just stop anywhere if there is no sign saying that they may not.
    - Further, it is realistic that you see the shared AVs making more kilometres because they are circulating the network empty after dropping off their passengers. This might actually form a problem.
4. How do the normal (orange) cars respond to the AVs and shared AVs? Is this realistic?
    - They now react to them as they would react to a normal car. But in reality they might drive more carefully. This should definitely be noted.
5. What do you remark from the vehicle delay results? Is this logical?

- The vehicle delay results seem realistic with the demand that is being used. But, as already noted, it is difficult to say if that demand is realistic.

6. What do you remark from the emission results? Is this logical?

    - Do the emission results contain enough information to answer the research questions?
    - You are now assuming all AVs to be electric. But how about the other cars? It seems logical that a large part of them may be electric by 2040. But this would if you incorporate this, it adds another uncertain factor to your research.
    - Relatively speaking, they look logical with regards to the scenarios.

7. Is there anything that can be changed to make the model better resemble the reality that is being sketched by the scenarios?

    - The model could be made more practical instead of theoretical.
    - The shared AVs can be given a prohibition to stop on the Prins Clauslaan, but as I understand that is the plan for the next step.

8. Is there anything that can be changed to make the model better suitable to attain the research objectives?

    - I think it serves very well to attain your research goals.

9. When enough runs are being performed, can the results be assumed to be representative for the hypothetical reality?

    - Enough runs is always a very theoretical term for civil servants. In my opinion one run is enough to see what is going on. But I think they can.

D.2.2. Simeon Calvert, 22/8/2018

1. What is your first response after seeing the model?

    - It does not actually seem very busy seeing as it is supposed to be 2040 with the current infrastructure. But I understand that you shouldn't add much more vehicles to the network, as it blurs the effects of the AVs and shared AVs.
    - Scenario 7 looks much more busy than scenario 4, which can be explained by the shared AVs circulating the network and stopping.
    - There is nothing particularly remarkable about the general vehicle behaviour. It looks valid.

2. Do the AVs show significantly distinct behaviour? Is this behaviour realistic?

    - In light of the fact that these are fully automated and connected AVs, the behaviour looks valid. There is always the question of how long the headways should be, but in light of the assumptions, the headways look good.

3. Do the shared AVs show significantly distinct behaviour? Is this realistic?

    - It is an interesting point that shared AVs might just stop on the roadside if no one tells them not to. It is still unknown whether and how this behaviour will be regulated by municipalities, manufacturers or dispatchers, so it is okay for now to assume that they will if no one interferes.
    - Empty vehicles circulating on the network seems logical.

4. How do the normal (orange) cars respond to the AVs and shared AVs? Is this realistic?

    - I understand that in this model the normal cars do not respond differently to AVs than they do to other normal cars. It is very unclear how this will be in reality. This is still on my wish list to incorporate in my own research, but it cannot be done yet.

5. What do you remark from the vehicle delay results? Is this logical?

- Based on 3 runs, the results for the first (20% AV, 3% shared) and third scenario (80% AV, 50% shared) are very similar. It is as if the advantages of AVs are completely annulled by the disadvantages of the shared AVs. However, if that is the case, then the results for the second scenario (50% AV, 25% shared) should be equally similar. This is not the case. But this might be a result of one run where there is a large blockage. You should check this.
- It is remarkable that the delay in scenario 5 (50% AV, 0% shared) compared to scenario 4 (0% AV, 0% shared) is so large, but it can definitely be explained by the homogeneity that AVs introduce and the increase in capacity due to the short headways and the fast reaction times. The difference between scenario 5 (50% AV, 0% shared) and scenario 6 (100% AV, 0% shared) is much smaller, but this is probably due to the fact that the road capacity has already been almost sufficiently increased by introducing 50% AVs and another 50% only increases the capacity above the demand, which will not reduce the delays much further. But the relationship between demand/capacity ratio and the delay is nonlinear and can impossibly be approximated mathematically. So it can also be due to a factor that we cannot explain analytically. This is why we need simulation.
- You should indicate that these results are trajectory delay results and not network delay.
- You should indicate that the delay is calculated with regard to the ideal travel time and that in this ideal travel time, delays due to traffic lights are not taken into account. In that light, the small delays that are reported in scenario 6 might only be due to waiting for the light to turn green and nothing else.

6. What do you remark from the emission results? Is this logical?

   - The emission results do not look surprising in light of the scenarios.

7. Is there anything that can be changed to make the model better resemble the reality that is being sketched by the scenarios?

   (a) Only the possible interventions the municipality or dispatcher might take. But this follows in the next phase.

8. Is there anything that can be changed to make the model better suitable to attain the research objectives?

   - I think this model is suitable and valid to attain the research objective.

D.2.3. Maarten Amelink, Anton van Meulen & Ronald van Veen, 24/8/2018

1. What is your first response after seeing the model?

   - On the one hand, the model is based on a lot of assumptions about what the future with AVs and shared AVs will look like. On the other hand a lot of aspects are kept unchanged to the current situation, such as the presence of buses and the traffic control algorithm, which are likely to have changed in a future with AVs. Of course it is needed to make assumptions about certain things and to keep other things as they are, but it is necessary to see the results in light of this. In fact, the future with AVs is very uncertain and changing too many parameters in the model will lead to unusable results.
   - In the scenarios with empty circulating shared AVs, the traffic control algorithms are really given a challenge because they were already performing at capacity and now they are getting extra demand at places where they were already facing a bottleneck. Logically, they would have to be re-optimized.
   - It would be interesting to look at the total amount of kilometres covered for different scenarios.

2. Do the AVs show significantly distinct behaviour? Is this behaviour realistic?

   - It is clear that the AVs have shorter headways, that the headways are in principle always equal and that they have a short reaction time to the signal.

- At the traffic light, they still depart one-by-one instead of in a fashion like they are "catapulted" away. But this seems logical as they need to observe a minimum headway which is not achieved if they keep the same distance to each other as they have when waiting in front of the traffic light. Otherwise it might be researched whether it would be more efficient to let the AVs wait in front of the light at the same distance from each other as they would want as a headway on that road, so that they can depart instantaneously when the light switches. But this is for another study.
- All AVs in this model behave exactly the same: same desired speed, same acceleration/deceleration curves, same reaction time and same headway. In reality this will probably differ slightly per manufacturer. Or it could even be desirable that passengers can define how they want their vehicle to behave. For example, when you are drinking coffee, you do not want your vehicle to accelerate as fast as usual. But this too is for a different research.

3. Do the shared AVs show significantly distinct behaviour? Is this realistic?
    - It is clear that the fashion in which they circulate on the network is causing significant bottlenecks. In reality, it is realistic that this will be a problem, but there are factors in play in this model which might magnify that effect:
        - As said, the signal control is not optimized for this amount of turning movements. If there actually are as many turning movements, the signal control would realistically be re-optimized.
        - If a turning lane becomes too congested, a shared AV would realistically seek a different route, but this is not possible in this case, because the network is too small.
        - If a turning lane becomes too congested, a shared AV could also realistically choose to drop off their passenger at the opposite side of the street. But this is impossible to model in this case.
    - The abovementioned points would reduce these effects, but cannot be modeled now. So they should be taken into account when interpreting the results.
    - Further, this research does not incorporate how the shared vehicles do order picking and route optimization. This is another interesting point which can be optimized on an individual level or a network level and which could significantly impact your delay results. But this is also something for a different research.
4. What do you remark from the vehicle delay results? Is this logical?
    - The delay results interestingly show the positive effects of AVs and negative effects of shared vehicles. They do not show, however, whether these negative effects are as a result of the sheer amount of extra kilometres driven or as a result of their unusual behaviour of stopping on the road and making u-turns. It would be interesting to correct these results for the total amount of kilometres driven by the shared AVs.
5. What do you remark from the emission results? Is this logical?
    - It would be better to assume a single fleet distribution in terms of electric/non-electric across all vehicle types in the model. This better allows comparison of the results.
6. Is there anything that can be changed to make the model better resemble the reality that is being sketched by the scenarios?
    - Not if you want to keep the same infrastructure as in the current situation.
    - For next steps, it can be interesting to look at shared AV "stops", just like bus stops, but at shorter distances.
    - It could also be interesting to look at removing the traffic lights in the scenarios where all cars are autonomous.
7. Is there anything that can be changed to make the model better suitable to attain the research objectives?
    - In the context of all the assumptions and reductions made, this model can be deemed suitable to answer the research questions for the scenarios painted.

D.2.4. Erik Verschoor, 27/8/2018

1. What is your first response after seeing the model?
    - I think it looks realistic considering the scenarios.
    - With regards to speed, it could be interesting in the future to see whether AVs should actually drive more slowly in the turns, because they are more uncomfortable for a passenger than for the driver.
    - For the scenarios where you have 100% AVs it is likely that the intersection control will be re-optimized, because there is no need to take into account the safety factors that account for human behaviour.
2. Do the AVs show significantly distinct behaviour? Is this behaviour realistic?
    - The behaviour looks very homogeneous, so that is realistic.
    - In some cases in Vissim, cars at a busy intersection are allowed to drive "through" each other, because you get unrealistic gridlocks if the priority rules in Vissim are set too tight. Human drivers would in these cases push through, avoiding a gridlock situation. But wouldn't AVs also have these tight priority rules programmed, meaning that at such a busy intersection, they could end up in a gridlock? This is a very interesting point for further research.
3. Do the shared AVs show significantly distinct behaviour? Is this realistic?
    - For this relatively exploratory research they act realistically enough.
    - For further research, it would be interesting to look at drop-off behaviour (eg. situations when SAVs drop-off their user right in front of the door versus across the street or around the corner).
    - It is actually quite weird that everyone assumes that SAVs will be the same vehicle type as we have now. It is much more likely that the vehicle type will differentiate based on the purpose. For home-work travel they can just be eggs on wheels as they only have to transport one or a few passengers with little luggage. This could have an impact on the road capacity.
4. What do you remark from the vehicle delay results? Is this logical?
    - They look logical in light of the scenarios. But as the research is quite exploratory, I wouldn't look at them on a low level of significance. You really need to implement some nuances when interpreting these results.
    - Regarding the SAVs, the results are in line with other research performed by PTV in Karlsruhe, where they found that a lot of traffic moves to the underlying urban road network.
5. Is there anything that can be changed to make the model better resemble the reality that is being sketched by the scenarios?
    - If you take into account that this is an exploratory study and that this is the phase of the research where the infrastructure is kept as is, no changes need to be made.
    - In next steps it could be advisable to look at dedicated infrastructure for AVs and SAVs (dedicated lanes and kiss & rides)
    - If the time is available, it could be interesting to experiment with the vehicle length of the SAVs to simulate those "eggs".
6. Is there anything that can be changed to make the model better suitable to attain the research objectives?
    - For your research objective, the model is fine.
    - What it does really well is create awareness that the municipality should not sit back and do nothing when it comes to SAVs.
7. When enough runs are being performed, can the results be assumed to be representative for the hypothetical reality?
    - For this objective and in light of the scenarios, it is good enough.

- You shouldn’t report the results on decimal level.
- You should mention that the modal shift from PT to SAVs is not taken into account, which is understandable.

E

Statistical tests scenario results

In this appendix, the results of the statistical tests are presented that were performed to analyse the data from the scenario studies. Tables E.1 to E.6 show the results for the vehicle delays. Tables E.7 to E.12 present the results for the distance travelled. Finally, tables E.13 to E.17 contain the results for the emissions data.

E.1. Vehicle delay

The results of the statistical tests performed on the vehicle delay data are presented in tables E.1 to E.6. Table E.1 presents the mean values and results of the Shapiro Wilk normality tests for the vehicle delay results. Table E.2 contains the results for the ANOVA tests conducted to compare the means and variance of the vehicle delay results of the scenarios to each other. Finally, tables E.3 to E.6 contain the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference.

E.2. Distance travelled

The results of the statistical tests performed on the distance travelled data are presented in tables E.7 to E.12. Table E.7 presents the mean values and results of the Shapiro Wilk normality tests for the distance travelled results. Table E.8 contains the results for the ANOVA tests conducted to compare the means and variance of the distance travelled results between scenarios. Tables E.9 to E.11 contain the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference. Finally, table E.12 gives the results of the paired samples t-test that was performed to compare the distance travelled by non-SAVs with that of SAVs for each scenario.

E.3. Emissions

The results of the statistical tests performed on the emissions data are presented in tables E.13 to E.17. Table E.13 presents the mean values and results of the Shapiro Wilk normality tests for the emissions results. Table E.14 contains the results for the ANOVA tests conducted to compare the means and variance of the emissions results of the scenarios to each other. Finally, tables E.15 to E.17 contain the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference.

Table E.1: Vehicle delay mean values and Shapiro Wilk (SW) normality test results

	Non-SAV			**SAV**			**Bicycle**			**Bus**		
Scenario	**Mean (mm:ss)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
1: 20/3	02:20	0,955	0,228	03:43	0,941	0,231	00:30	0,968	0,486	03:10	0,964	0,391
2: 50/25	02:55	0,985	0,944	04:00	0,961	0,330	00:30	0,950	0,173	03:10	0,967	0,466
3: 80/50	02:28	0,961	0,334	03:35	0,955	0,224	00:28	0,969	0,501	02:58	0,961	0,336
4: 0/0	04:00	0,953	0,200	N/A	N/A	N/A	00:35	0,959	0,284	03:13	0,971	0,574
5: 50/0	01:31	0,943	0,109	N/A	N/A	N/A	00:29	0,940	0,093	02:31	0,984	0,923
6: 100/0	01:16	0,943	0,113	N/A	N/A	N/A	00:26	0,955	0,228	02:18	0,983	0,891
7: 100:100	06:16	0,964	0,391	09:15	0,971	0,564	00:36	0,828	0,000	04:34	0,960	0,306

Table E.2: Vehicle delay Levene test and ANOVA scenario comparison test results

	Non-SAV		**SAV**		**Bicycles**		**Buses**	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	12,976	0,000	8,535	0,000	2,066	0,048	9,727	0,000
ANOVA	323,143	0,000	208,958	0,000	121,197	0,000	153,035	0,000
Welch ANOVA	397,153	0,000	102,567	0,000	114,565	0,000	150,603	0,000

Table E.3: Vehicle delay non-SAV motorized Tukey post hoc test results

Scenario	**Mean (mm:ss)**	**Tukey post hoc (p)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	02:20	x	0,000	0,974	0,000	0,000	0,000	0,000
2: 50/25	02:55	0,000	x	0,009	0,000	0,000	0,000	0,000
3: 80/50	02:28	0,974	0,009	x	0,000	0,000	0,000	0,000
4: 0/0	04:00	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	01:31	0,000	0,000	0,000	0,000	x	0,488	0,000
6: 100/0	01:16	0,000	0,000	0,000	0,000	0,488	x	0,000
7: 100/100	06:16	0,000	0,000	0,000	0,000	0,000	0,000	x

Table E.4: Vehicle delay SAVs Tukey post hoc test results

Scenario	**Mean (mm:ss)**	**Tukey post hoc (p)**			
		1	**2**	**3**	**7**
1: 20/3	03:43	x	0,842	0,982	0,000
2: 50/25	04:00	0,842	x	0,415	0,000
3: 80/50	03:35	0,982	0,415	x	0,000
7: 100/100	09:15	0,000	0,000	0,000	x

Table E.5: Vehicle delay bicycles Tukey post hoc test results

Scenario	**Mean (mm:ss)**	**Tukey post hoc (p)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	00:33	x	0,545	0,000	0,000	0,068	0,000	0,000
2: 50/25	00:30	0,545	x	0,089	0,000	0,968	0,000	0,000
3: 80/30	00:28	0,000	0,089	x	0,000	0,616	0,000	0,000
4: 0/0	00:35	0,000	0,000	0,000	x	0,000	0,000	0,123
5: 50/0	00:29	0,068	0,968	0,616	0,000	x	0,000	0,000
6: 100/0	00:26	0,000	0,000	0,000	0,000	0,000	x	0,000
7: 100/100	00:36	0,000	0,000	0,000	0,123	0,000	0,000	x

Table E.6: Vehicle delay buses Tukey post hoc test results

Scenario	**Mean (mm:ss)**	**Tukey post hoc (p)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	03:10	x	1,000	0,142	1,000	0,000	0,000	0,000
2: 50/25	03:10	1,000	x	0,205	0,997	0,000	0,000	0,000
3: 80/50	02:58	0,142	0,205	x	0,035	0,000	0,000	0,000
4: 0/0	03:13	1,000	0,997	0,035	x	0,000	0,000	0,000
5: 50/0	02:31	0,000	0,000	0,000	0,000	x	0,103	0,000
6: 100/0	02:18	0,000	0,000	0,000	0,000	0,103	x	0,000
7: 100/100	04:34	0,000	0,000	0,000	0,000	0,000	0,000	x

Table E.7: Distance travelled mean values and Shapiro Wilk (SW) normality test results

Scenario	**Total Mean (km)**	**SW**	**p**	**Non-SAV Mean (km/veh)**	**SW**	**p**	**SAV Mean (km/veh)**	**SW**	**p**
1: 20/3	23.679	0,956	0,245	1,36	0,959	0,295	1,57	0,944	0,113
2: 50/25	23.663	0,938	0,082	1,36	0,976	0,717	1,54	0,980	0,824
3: 80/50	23.663	0,932	0,057	1,38	0,909	0,014	1,55	0,935	0,065
4: 0/0	22.624	0,957	0,257	1,33	0,950	0,171	N/A	N/A	N/A
5: 50/0	23.671	0,961	0,330	1,36	0,916	0,022	N/A	N/A	N/A
6: 100/0	23.679	0,955	0,234	1,36	0,916	0,021	N/A	N/A	N/A
7: 100/100	21.001	0,969	0,507	1,37	0,956	0,238	1,39	0,960	0,303

Table E.8: Distance travelled Levene test and ANOVA scenario comparison test results

Test	**Total Statistic**	**p**	**Non-SAV Statistic**	**p**	**SAV Statistic**	**p**
Levene	16,81	0,00	11,448	0,000	5,169	0,001
ANOVA	293,82	0,00	138,145	0,000	64,749	0,000
Welch ANOVA	113,44	0,00	144,181	0,000	69,620	0,000

Table E.9: Total distance of all motorized vehicles Tukey post hoc test results

Scenario	**Mean (km)**	**Tukey post hoc (p)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	23.679	x	1,000	1,000	0,000	1,000	1,000	0,000
2: 50/25	23.663	1,000	x	1,000	0,000	1,000	1,000	0,000
3: 80/50	23.663	1,000	1,000	x	0,000	1,000	1,000	0,000
4: 0/0	22.624	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	23.671	1,000	1,000	1,000	0,000	x	1,000	0,000
6: 100/0	23.679	1,000	1,000	1,000	0,000	1,000	x	0,000
7: 100/100	21.001	0,000	0,000	0,000	0,000	0,000	0,000	x

Table E.10: Distance travelled per non-SAV motorized vehicle Tukey post hoc test results

Scenario	**Mean (km/veh)**	**Tukey post hoc (p)**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	1,36	x	0,000	0,000	0,000	1,000	0,957	0,000
2: 50/25	1,36	0,000	x	0,000	0,000	0,001	0,011	0,034
3: 80/50	1,38	0,000	0,000	x	0,000	0,000	0,000	0,000
4: 0/0	1,33	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	1,36	1,000	0,001	0,000	0,000	x	0,996	0,000
6: 100/0	1,36	0,957	0,011	0,000	0,000	0,996	x	0,000
7: 100/100	1,37	0,000	0,034	0,000	0,000	0,000	0,000	x

Table E.11: Distance travelled per SAV Tukey post hoc test results

Scenario	**Mean (km/veh)**	**Tukey post hoc (p)** **1**	**2**	**3**	**7**
1: 20/3	1,57	x	0,317	0,900	0,000
2: 50/25	1,54	0,317	x	0,847	0,000
3: 80/50	1,55	0,900	0,847	x	0,000
7: 100/100	1,39	0,000	0,000	0,000	x

Table E.12: Distance travelled per non-SAV motorized vehicle and SAV paired samples t-test results

Scenario	**Non-SAV (km/veh)**	**SAV (km/veh)**	**t**	**p**
1: 20/3	1,36	1,57	-14,206	0,000
2: 50/25	1,36	1,54	-27,081	0,000
3: 80/50	1,38	1,55	-33,075	0,000
7: 100/100	1,37	1,39	-3,257	0,003

Table E.13: Emissions per kilometre mean values and Shapiro Wilk (SW) normality test results

	CO_2			**NO_x**			**PM_{10}**		
Scenario	**Mean (g/km)**	**SW**	**p**	**Mean (g/km)**	**SW**	**p**	**Mean (g/km)**	**SW**	**p**
1: 20/3	292,28	0,842	0,170	0,453	0,899	0,402	0,041	0,740	0,024
2: 50/25	301,25	0,924	0,558	0,467	0,915	0,497	0,042	0,885	0,335
3: 80/50	292,15	0,889	0,353	0,450	0,886	0,339	0,040	0,845	0,179
4: 0/0	316,29	0,787	0,063	0,499	0,906	0,442	0,044	0,816	0,108
5: 50/0	280,39	0,928	0,583	0,428	0,857	0,217	0,039	0,912	0,480
6: 100/0	280,24	0,898	0,401	0,425	0,847	0,186	0,039	0,872	0,275
7: 100/100	345,05	0,965	0,843	0,565	0,984	0,955	0,048	0,949	0,730

Table E.14: Emissions Levene test and ANOVA scenario comparison test

	CO_2		**NO_x**		**PM_{10}**	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	2,415	0,042	1,626	0,164	2,344	0,047
ANOVA	181,947	0,000	145,645	0,000	204,302	0,000
Welch ANOVA	166,871	0,000	118,953	0,000	192,612	0,000

Table E.15: CO_2 emissions Tukey post hoc test results

Scenario	**Mean (g/km)**	**Tukey post hoc (p)** **1**	**2**	**3**	**4**	**5**	**6**	**7**
1: 20/3	292,28	x	0,008	1,000	0,000	0,000	0,000	0,000
2: 50/25	301,25	0,008	x	0,007	0,000	0,000	0,000	0,000
3: 80/50	292,15	1,000	0,007	x	0,000	0,000	0,000	0,000
4: 0/0	316,29	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	280,39	0,000	0,000	0,000	0,000	x	1,000	0,000
6: 100/0	280,24	0,000	0,000	0,000	0,000	1,000	x	0,000
7: 100/100	345,05	0,000	0,000	0,000	0,000	0,000	0,000	x

Table E.16: NO_x emissions Tukey post hoc test results

Scenario	Mean (g/km)	Tukey post hoc (p)						
		1	2	3	4	5	6	7
1: 20/3	0,453	x	0,163	0,999	0,000	0,001	0,000	0,000
2: 50/25	0,467	0,163	x	0,051	0,000	0,000	0,000	0,000
3: 80/50	0,450	0,999	0,051	x	0,000	0,006	0,001	0,000
4: 0/0	0,499	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	0,428	0,001	0,000	0,006	0,000	x	0,999	0,000
6: 100/0	0,425	0,000	0,000	0,001	0,000	0,999	x	0,000
7: 100/100	0,565	0,000	0,000	0,000	0,000	0,000	0,000	x

Table E.17: PM_{10} emissions Tukey post hoc test results

Scenario	Mean (g/km)	Tukey post hoc (p)						
		1	2	3	4	5	6	7
1: 20/3	0,041	x	0,150	0,755	0,000	0,000	0,000	0,000
2: 50/25	0,042	0,150	x	0,003	0,000	0,000	0,000	0,000
3: 80/50	0,040	0,755	0,003	x	0,000	0,011	0,001	0,000
4: 0/0	0,044	0,000	0,000	0,000	x	0,000	0,000	0,000
5: 50/0	0,039	0,000	0,000	0,011	0,000	x	0,990	0,000
6: 100/0	0,039	0,000	0,000	0,001	0,000	0,990	x	0,000
7: 100/100	0,048	0,000	0,000	0,000	0,000	0,000	0,000	x

F

Statistical tests design results

In this appendix, the results from the statistical tests that were performed to analyze the design results are presented. Tables F.1 to F.14 contain the results for vehicle delays. Tables F.16 to F.32 contain results for the distance travelled. Finally, tables F.33 to F.42 contain the results for emissions.

F.1. Vehicle delays

The results of the statistical tests performed on the vehicle delay data are presented in tables F.1 to F.15. Tables F.1 and F.2 present the mean values and results of the Shapiro Wilk normality tests for the vehicle delay results. Tables F.4 to F.15 contain the results for the ANOVA tests conducted to compare the means and variance of the vehicle delay results of each scenario with the designs, and the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference.

F.2. Distance travelled

The results of the statistical tests performed on the distance travelled data are presented in tables F.16 to F.32. Tables F.16, F.17 and F.18 present the mean values and results of the Shapiro Wilk normality tests for the distance travelled results. Table F.19 gives the results of the paired samples t-test that was performed to compare the distance travelled by non-SAVs with that of SAVs for different scenarios and designs. Tables F.23 to F.32 contain the results for the ANOVA tests conducted to compare the means and variance of the distance travelled results of each scenario with the designs, and the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference.

F.3. Emissions

The results of the statistical tests performed on the emissions data are presented in tables F.33 to F.42. Tables F.33 to F.35 present the mean values and results of the Shapiro Wilk normality tests for the emissions results. Tables F.36 to F.42 contain the results for the ANOVA tests conducted to compare the means and variance of the emissions results of each scenario with the designs, and the results of the Tukey post hoc tests that were performed for cases where the ANOVA test pointed out a significant difference.

Table F.1: Vehicle delay non-SAV motorized mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (mm:ss)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	02:20	0,978	0,899	02:55	0,985	0,944	02:28	0,961	0,334	06:15	0,964	0,391
Dedicated lanes	02:36	0,883	0,097	02:50	0,971	0,701	02:11	0,856	0,005	05:50	0,961	0,458
K&R-facilities	02:32	0,925	0,233	02:50	0,978	0,835	01:59	0,945	0,209	03:36	0,949	0,304

Table F.2: Vehicle delay SAVs mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (mm:ss)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	03:44	0,941	0,231	04:00	0,961	0,330	03:35	0,955	0,224	09:15	0,971	0,564
Dedicated lanes	04:27	0,866	0,058	04:22	0,937	0,138	03:41	0,883	0,017	09:52	0,946	0,223
K&R-facilities	04:05	0,915	0,161	03:49	0,976	0,792	03:06	0,934	0,122	04:36	0,909	0,045

Table F.3: Vehicle delay buses mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (mm:ss)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	03:10	0,964	0,391	03:10	0,967	0,466	02:58	0,961	0,336	04:34	0,960	0,306
Dedicated lanes	03:31	0,977	0,809	03:21	0,968	0,623	03:01	0,962	0,562	04:25	0,982	0,926
K&R-facilities	03:28	0,941	0,185	03:18	0,979	0,873	02:49	0,943	0,192	03:14	0,962	0,540

Table F.4: Vehicle delays scenario 1 (20/3) and designs Levene- and ANOVA test results

	Non-SAV		**SAV**		**Bus**	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	2,269	0,110	3,477	0,039	0,739	0,481
ANOVA	2,290	0,108	1,517	0,230	7,701	0,001
Welch ANOVA	2,259	0,115	1,282	0,297	8,430	0,001

Table F.5: Vehicle delay buses scenario 1 (20/3) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (mm:ss)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	03:10	x	0,002	0,008
Dedicated lanes	03:31	0,002	x	0,919
K&R-facilities	03:28	0,008	0,919	x

Table F.6: Vehicle delays scenario 2 (50/25) and designs Levene- and ANOVA test results

	Non-SAV		**SAV**		**Bus**	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	0,878	0,420	3,638	0,031	2,318	0,105
ANOVA	0,138	0,871	3,018	0,055	3,282	0,043
Welch ANOVA	0,150	0,861	2,623	0,083	3,312	0,045

Table F.7: Vehicle delay buses scenario 2 (50/25) and designs Tukey post hoc test results

Design	Mean (mm:ss)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	03:10	x	0,048	0,157
Dedicated lanes	03:21	0,048	x	0,849
K&R-facilities	03:18	0,157	0,849	x

Table F.8: Vehicle delays scenario 3 (80/50) and designs Levene- and ANOVA test results

	Non-SAV		SAV		Bus	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	1,177	0,314	2,026	0,139	1,251	0,292
ANOVA	5,771	0,005	4,860	0,010	4,109	0,020
Welch ANOVA	6,736	0,003	6,471	0,003	3,998	0,026

Table F.9: Vehicle delay non-SAVs scenario 3 (80/50) and designs Tukey post hoc test results

Design	Mean (mm:ss)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	02:28	x	0,146	0,004
Dedicated lanes	02:11	0,146	x	0,418
K&R-facilities	01:59	0,004	0,418	x

Table F.10: Vehicle delay SAVs scenario 3 (80/50) and designs Tukey post hoc test results

Design	Mean (mm:ss)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	03:35	x	0,865	0,033
Dedicated lanes	03:41	0,865	x	0,016
K&R-facilities	03:06	0,033	0,016	x

Table F.11: Vehicle delay buses scenario 3 (80/50) and designs Tukey post hoc test results

Design	Mean (mm:ss)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	02:58	x	0,719	0,085
Dedicated lanes	03:01	0,719	x	0,022
K&R-facilities	02:49	0,085	0,022	x

Table F.12: Vehicle delays scenario 7 (100/100) and designs Levene- and ANOVA test results

	Non-SAV		SAV		Bus	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	1,121	0,331	9,053	0,000	4,332	0,017
ANOVA	67,663	0,000	91,133	0,000	50,926	0,000
Welch ANOVA	77,299	0,000	154,839	0,000	91,945	0,000

Table F.13: Vehicle delay non-SAVs scenario 7 (100/100) and designs Tukey post hoc test results

Design	Mean (mm:ss)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	06:15	x	0,173	0,000
Dedicated lanes	05:50	0,173	x	0,000
K&R-facilities	03:36	0,000	0,000	x

Table F.14: Vehicle delay SAVs scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (mm:ss)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	09:15	x	0,278	0,000
Dedicated lanes	09:52	0,278	x	0,000
K&R-facilities	04:36	0,000	0,000	x

Table F.15: Vehicle delay buses scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (mm:ss)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	04:34	x	0,455	0,000
Dedicated lanes	04:25	0,455	x	0,000
K&R-facilities	03:14	0,000	0,000	x

Table F.16: Total distance travelled by all motorized vehicles mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (km)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	23.679	0,956	0,245	23.663	0,938	0,082	23.663	0,932	0,057	21.001	0,969	0,507
Dedicated lanes	23.567	0,971	0,725	23.554	0,899	0,028	23.266	0,725	0,000	21.354	0,965	0,555
K&R-facilities	23.589	0,957	0,414	23.682	0,920	0,052	23.678	0,927	0,084	23.322	0,761	0,000

Table F.17: Distance travelled per non-SAV motorized vehicle mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (km/veh)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	1,36	0,959	0,295	1,36	0,976	0,717	1,38	0,909	0,014	1,37	0,956	0,238
Dedicated lanes	1,35	0,949	0,297	1,36	0,983	0,957	1,38	0,816	0,001	1,38	0,965	0,545
K&R-facilities	1,36	0,920	0,067	1,37	0,947	0,220	1,39	0,961	0,468	1,41	0,901	0,030

Table F.18: Distance travelled per SAV mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (km/veh)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	1,57	0,944	0,113	1,54	0,980	0,824	1,55	0,935	0,065	1,39	0,960	0,303
Dedicated lanes	1,49	0,955	0,392	1,46	0,970	0,705	1,46	0,674	0,000	1,31	0,913	0,040
K&R-facilities	1,58	0,972	0,738	1,54	0,967	0,563	1,56	0,964	0,522	1,46	0,968	0,672

Table F.19: Paired samples t-test comparing distance travelled by non-SAV and SAV for each design

Scenario	**Design**	**non-SAV (km/veh)**	**SAV (km/veh)**	**t**	**p**
1: 20/3	**Dedicated lanes**	1,35	1,49	-14,709	0,000
	K&R-facilities	1,36	1,58	-13,642	0,000
2: 50/25	**Dedicated lanes**	1,36	1,46	-17,201	0,000
	K&R-facilities	1,37	1,54	-22,577	0,000
3: 80/50	**Dedicated lanes**	1,38	1,46	-8,494	0,000
	K&R-facilities	1,39	1,56	-27,248	0,000
7: 100/100	**Dedicated lanes**	1,38	1,31	11,04	0,000
	K&R-facilities	1,41	1,46	-5,46	0,000

Table F.20: Total distance travelled all scenarios and designs Levene- and ANOVA test results

	1: 20/3		2: 50/25		3: 80/50		7: 100/100	
Test	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**	**Statistic**	**p**
Levene	1,107	0,336	1,350	0,265	13,760	0,000	3,851	0,026
ANOVA	3,525	0,035	2,113	0,128	6,455	0,003	96,949	0,000
Welch ANOVA	3,710	0,033	1,494	0,236	2,804	0,073	126,357	0,000

Table F.21: Total distance travelled scenario 1 (20/3) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	23.679	x	0,044	0,123
Dedicated lanes	23.567	0,044	x	0,892
K&R-facilities	23.589	0,123	0,892	x

Table F.22: Total distance travelled scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	21.001	x	0,103	0,000
Dedicated lanes	21.354	0,103	x	0,000
K&R-facilities	23.322	0,000	0,000	x

Table F.23: Distance travelled scenario 1 (20/3) and designs Levene- and ANOVA test results

	Non-SAV		SAV	
Test	**Statistic**	**p**	**Statistic**	**p**
Levene	1,997	0,143	2,326	0,105
ANOVA	0,674	0,513	9,684	0,000
Welch ANOVA	0,496	0,613	15,061	0,000

Table F.24: Distance travelled SAVs scenario 1 (20/3) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,57	x	0,001	0,771
Dedicated lanes	1,49	0,001	x	0,000
K&R-facilities	1,58	0,771	0,000	x

Table F.25: Distance travelled scenario 2 (50/25) and designs Levene- and ANOVA test results

	Non-SAV		SAV	
Test	**Statistic**	**p**	**Statistic**	**p**
Levene	0,451	0,638	1,389	0,256
ANOVA	1,096	0,340	44,158	0,000
Welch ANOVA	1,191	0,313	59,701	0,000

Table F.26: Distance travelled SAVs scenario 2 (50/25) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,54	x	0,000	0,990
Dedicated lanes	1,46	0,000	x	0,000
K&R-facilities	1,54	0,990	0,000	x

Table F.27: Distance travelled scenario 3 (80/50) and designs Levene- and ANOVA test results

	Non-SAV		SAV	
Test	**Statistic**	**p**	**Statistic**	**p**
Levene	14,528	0,000	0,678	0,511
ANOVA	3,939	0,024	50,017	0,000
Welch ANOVA	6,259	0,004	31,347	0,000

Table F.28: Distance travelled non-SAVs scenario 3 (80/50) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,38	x	0,400	0,215
Dedicated lanes	1,38	0,400	x	0,018
K&R-facilities	1,39	0,215	0,018	x

Table F.29: Distance travelled SAVs scenario 3 (80/50) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,55	x	0,000	0,831
Dedicated lanes	1,46	0,000	x	0,000
K&R-facilities	1,56	0,831	0,000	x

Table F.30: Distance travelled scenario 7 (100/100) and designs Levene- and ANOVA test results

	Non-SAV		SAV	
Test	**Statistic**	**p**	**Statistic**	**p**
Levene	0,562	0,573	1,387	0,256
ANOVA	72,658	0,000	57,217	0,000
Welch ANOVA	78,806	0,000	62,714	0,000

Table F.31: Distance travelled non-SAVs scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,37	x	0,136	0,000
Dedicated lanes	1,38	0,000	x	0,000
K&R-facilities	1,41	0,136	0,000	x

Table F.32: Distance travelled SAVs scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (km/veh)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	1,39	x	0,000	0,000
Dedicated lanes	1,31	0,000	x	0,000
K&R-facilities	1,46	0,000	0,000	x

Table F.33: CO_2 emissions mean values designs and Shapiro Wilk (SW) normality test results

Scenario	**1: 20/3**			**2: 50/25**			**3: 80/50**			**7: 100/100**		
Design	**Mean (g/km)**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**	**Mean**	**SW**	**p**
None	292,28	0,859	0,224	301,25	0,941	0,671	292,15	0,874	0,282	345,05	0,909	0,462
Dedicated lanes	298,65	0,898	0,399	305,62	0,959	0,801	301,15	0,871	0,270	340,78	0,789	0,065
K&R-facilities	295,24	0,915	0,496	301,08	0,991	0,984	290,72	0,960	0,807	311,13	0,910	0,467

Table F.34: NO_x emissions mean values designs and Shapiro Wilk (SW) normality test results

Scenario Design	1: 20/3 Mean (g/km)	SW	p	2: 50/25 Mean	SW	p	3: 80/50 Mean	SW	p	7: 100/100 Mean	SW	p
None	0,453	0,935	0,631	0,467	0,938	0,652	0,450	0,957	0,788	0,565	0,915	0,496
Dedicated lanes	0,465	0,898	0,401	0,476	0,942	0,677	0,470	0,879	0,303	0,556	0,850	0,193
K&R-facilities	0,459	0,957	0,783	0,467	0,977	0,919	0,447	0,955	0,774	0,489	0,925	0,560

Table F.35: PM_{10} emissions mean values designs and Shapiro Wilk (SW) normality test results

Scenario Design	1: 20/3 Mean (g/km)	SW	p	2: 50/25 Mean	SW	p	3: 80/50 Mean	SW	p	7: 100/100 Mean	SW	p
None	0,041	0,978	0,926	0,042	0,915	0,500	0,040	0,891	0,360	0,048	0,947	0,715
Dedicated lanes	0,042	0,901	0,417	0,042	0,981	0,941	0,042	0,859	0,225	0,048	0,895	0,381
K&R-facilities	0,041	0,945	0,703	0,042	0,983	0,951	0,040	0,971	0,879	0,043	0,909	0,463

Table F.36: Emissions scenario 1 (20/3) and designs Levene- and ANOVA test results

Test	CO_2 Statistic	p	NO_x Statistic	p	PM_{10} Statistic	p
Levene	5,224	0,023	4,485	0,035	4,429	0,036
ANOVA	0,852	0,451	0,717	0,508	0,791	0,476
Welch ANOVA	1,055	0,407	0,892	0,458	0,990	0,426

Table F.37: Emissions scenario 2 (50/25) and designs Levene- and ANOVA test results

Test	CO_2 Statistic	p	NO_x Statistic	p	PM_{10} Statistic	p
Levene	0,542	0,595	0,305	0,743	0,936	0,419
ANOVA	0,305	0,743	0,319	0,733	0,444	0,651
Welch ANOVA	0,235	0,797	0,246	0,788	0,351	0,716

Table F.38: Emissions scenario 3 (80/50) and designs Levene- and ANOVA test results

Test	CO_2 Statistic	p	NO_x Statistic	p	PM_{10} Statistic	p
Levene	16,135	0,000	12,013	0,001	17,962	0,000
ANOVA	1,599	0,242	1,565	0,249	1,945	0,186
Welch ANOVA	0,847	0,471	0,816	0,483	0,995	0,422

Table F.39: Emissions scenario 7 (100/100) and designs Levene- and ANOVA test results

Test	CO_2 Statistic	p	NO_x Statistic	p	PM_{10} Statistic	p
Levene	3,714	0,056	2,331	0,140	1,880	0,195
ANOVA	20,471	0,000	22,887	0,000	24,310	0,000
Welch ANOVA	11,808	0,005	13,613	0,004	14,746	0,003

Table F.40: CO_2 emissions scenario 7 (100/100) and designs Tukey post hoc test results

Design	Mean (g/km)	Tukey post hoc (p) None	Dedicated lanes	K&R-facilities
None	345,053	x	0,745	0,000
Dedicated lanes	340,781	0,745	x	0,001
K&R-facilities	311,134	0,000	0,001	x

Table F.41: NO_X emissions scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (g/km)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	0,565	x	0,733	0,000
Dedicated lanes	0,556	0,733	x	0,000
K&R-facilities	0,489	0,000	0,000	x

Table F.42: PM_{10} emissions scenario 7 (100/100) and designs Tukey post hoc test results

		Tukey post hoc (p)		
Design	**Mean (g/km)**	**None**	**Dedicated lanes**	**K&R-facilities**
None	0,048	x	0,707	0,000
Dedicated lanes	0,048	0,707	x	0,000
K&R-facilities	0,043	0,000	0,000	x

Assessing the impacts of shared and autonomous vehicles on congestion in urban traffic

An adaptation of a traffic micro-simulation model of a case in The Hague

Irene Overtoom

Abstract New developments in the automotive world have the power to change mobility, but because of high uncertainties, municipalities are adopting a wait-and-see attitude. Nonetheless, autonomous, connected and shared vehicle technologies are in a far stage of development and it is only a matter of time before AVs and SAVs enter urban traffic. This research aims to provide insights in the congestion effects of AVs and SAVs on urban traffic, focusing on the differences in microscopic behaviour from conventional cars, and to investigate which easy-to-implement solutions a municipality could apply to facilitate the new mix of traffic. This was researched by performing a simulation study, using the traffic simulation package Vissim and a case study of a network in The Hague during the morning peak in 2040. Several AV and SAV market penetration scenarios were tested. Additionally, two network designs were implemented: dedicated lanes for SAVs and kiss & ride (K&R)-facilities. From the results, it was clear that AVs were able to relieve congestion by increasing road capacity and providing a more smooth traffic flow. SAVs, however, caused higher levels of congestion by stopping at the curbside to drop off passengers, forming bottlenecks for other road users, and by circulating on the network using low capacity links. The dedicated lanes design was unsuccessful at reducing this congestion caused by SAVs. The K&R design, however, was successful at reducing delays, but only for SAV penetration rates of higher than 25%. The advice for municipalities is to closely monitor the situation and to account for AVs and SAVs in each new infrastructural project.

Keywords Autonomous vehicles · Shared autonomous vehicles · Urban traffic · Simulation

1 Introduction

Just like they have one century ago, developments in the automotive industry are now at the verge of reshaping our idea of mobility, and society as a whole. The Dutch research institute for mobility, KiM, expects autonomous, connected and shared vehicles to reshape cities in the 21^{st} century [18]. People may live further away from the city, transforming the city into a meeting place where people travel to daily in autonomous vehicles (AVs) that they may own or share on a subscription basis (SAV). This is just one of the many futures that is being foreseen, and it is one of the more positive ones. The KiM also provides the some less optimistic visions: where the tolerance for longer travel times causes high levels of road congestion and where the eternal struggle between safety and efficiency cripples the industry. However, few studies mention what the driving behaviour of AVs and SAVs on the roads may mean for congestion levels.

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How cities and their traffic will change exactly, is highly uncertain and dependent on many factors. Understandably, municipalities are adopting a wait-and-see attitude toward these new mobility concepts. However, just like they did one century ago with the introduction of the automobile, municipalities have an important role in determining how AVs and SAVs may affect urban traffic and mobility in general. One thing is for certain: autonomous, connected and shared vehicle technologies are in a far stage of development and it is only a matter of time before AVs and SAVs enter urban traffic. What this will mean for the traffic on a microscopic level, and whether municipalities should intervene, is still unclear.

1.1 Research goals

The goal of this research is twofold: firstly, to provide insights in the congestion effects of different penetration rates of AVs and SAVs in urban traffic, focusing on the differences in microscopic behaviour as compared to normal cars, and on the urban main road network. Secondly, to investigate how the municipality could intervene using easy-to-implement solutions to facilitate the new mix of urban traffic that can be expected in the future.

2 Methodology

A modeling study was performed consisting of two parts: a scenario study and a design study. For the model input in terms of demand, market penetration, vehicle behaviour, and designs, a literature review was performed. Then, a conceptual model was formulated, sketching the expected relationships between model input and model output. After, a simulation model was specified using the traffic simulation software Vissim, in an attempt to quantify these relationships. A case study network was chosen in The Hague that contains an urban main road linking the national road network to the lower level road network. Since a simulation model of this network was already available, only adaptation was required to implement AVs and SAVs. As a modeling year, 2040 was chosen, and as time of day the morning peak period. First, a set of scenario studies were performed to investigate the effects of different penetration rates of AVs and SAVs. Then, a set of network designs were defined, modeled and tested in the design studies. As findings in later stages of the study also informed inputs in earlier stages of the study, the entire process was an iterative cycle.

3 Literature review

Road congestion typically occurs when the traffic intensity exceeds the road's capacity [19]. Traffic intensities are the result of an array of human choices constituting travel demand. The road capacity for urban roads is quite tricky to determine. Urban roads are designed in such a way that they provide a good balance between access to the lower level road network and surrounding real estate, and adequate traffic throughput. KpVV CROW [10] introduced a ranking of Dutch urban roads where the emphasis in higher levels is more on throughput, while the emphasis in lower levels is more on access. This because road elements that improve accessibility, reduce a road's capacity: low speed limits, roadside activity, interaction with other vehicles, and traffic control.

AVs and SAVs can influence congestion in urban traffic both in terms of traffic intensities, and in terms of road capacity. The former is a result of macroscopic effects influencing travel demand, and the latter is a result of microscopic effects of differences in driving behaviour from normal cars. Both are dependent on how the market develops and consequential penetration rates of AVs and SAVs in urban traffic. Therefore, market penetration scenarios were formulated for this research, and macroscopic and microscopic effects were further investigated.

3.1 Market penetration AVs and SAVs

Many researchers have attempted to study market developments in vehicle automation and forecast future penetration rates. According to Milakis et al.[14], who formulated market scenarios with a panel of experts, full AVs will be introduced in the market somewhere between 2018 and 2045, with penetration rates between 10% and 71% by 2050. Litman[11], who bases himself on earlier automotive developments, believes this market introduction will likely be before 2030, with penetration rates of 30-50% by 2040 and 50-80% by 2050. Finally, Nieuwenhuijsen et al.[15], who conducted a quantitative system dynamics study, came to the conclusion that market penetration by 2040 should be somewhere between 3% and 66%, and between 5% and 90% by 2050. These penetration rates found here were used for the formulation of scenarios for this study.

Market research about SAVs is less straightforward, as it mostly targets the vehicle sharing market in general, while this research is focused on shared *autonomous* vehicles only. According to figures from KpVV CROW [9], regular vehicle sharing is gaining popularity quickly in The Netherlands, especially in urban areas where in 2017 there were almost 400 shared cars per 100.000 inhabitants. The European Commission is very enthusiastic about what the combination of vehicle automation and sharing could mean for urban mobility, and has set as a target that by 2030, 25% of all urban trips should be performed by a SAV [3]. In formulating the scenarios for this study, these notions were taken into account.

What all researchers agree on, is that new mobility concepts, like automation, sharing and connected technologies, reinforce each other. Indeed, applying connected technologies is only logical in an automated vehicle, and the functioning of an AV is highly improved by connected technologies. Further, vehicle sharing becomes much easier when the vehicles are autonomous, and can drive themselves to your doorstep and to the next customer. Therefore, a positive correlation is expected between the market development of these technologies. This correlation was taken into account when formulating the scenarios for this study.

3.2 Macroscopic effects AVs and SAVs

It is important to note macroscopic travel demand effects that AVs and SAVs may have and that may influence urban traffic. However, the focus in this research will largely be on the microscopic on-road effects. To understand how demand and distance travelled is influenced by the availability of new mobility options, it is important to understand the working principles of the 4-step transportation model as explained in de Dios Ortuzar and Willumsen[2] and interactions between land use and mobility as explained by Wegener [20]. The essence of these works is that low generalized transport cost with a specific mode to a certain location will induce travel demand to this location. Generalized transport costs are usually defined as the price per kilometre multiplied with the access distance plus the traveller's value of travel time savings (VOTT) multiplied with the travel time to the location. Using a discrete choice experiment, De Looff et al. [12] found that the VOTT for AVs lies around 25% lower than for conventional vehicles. Further, Fagnant and Kockelman [5] found that additional savings on the generalized transport cost of AVs are achieved as a result of better fuel efficiency, parking benefits, and crash savings. All these cost reductions could mean that AVs may induce significant numbers of travel demand. This is an important notion to take into account when interpreting the results of AV studies like this one.

How SAVs may influence travel demand and congestion, is less straightforward, and is determined by the SAV demand, fleet size, vehicle occupancy and VKT. If SAV demand is only coming from travellers who previously travelled with their own car, like Litman [11] is suggesting, this will mean little to nothing for total travel demand. However, other researchers, like Martinez and Viegas [13], acknowledge that the attractiveness of having a door-to-door transport option at a low trip price and having all the advantages of general AVs, may induce extra demand. How this demand is satisfied, is dependent on a city's fleet size and average vehicle occupancy. Fagnant and Kockelman [6] found that impacts of this induced demand on road congestion can be reduced by combining a good strategy of determining the needed fleet size with good strategies for sharing rides of multiple passenger, increasing the vehicle occupancy. However, negative effects on road congestion are also expected as SAVs cover a lot more distance than normal vehicles would for the same trips. This is due to repositioning and empty kilometres [4]. What is remarkable, is that the researchers only comment on the sheer extra distance driven, without taking into account the fact that the way in which SAVs may circulate the network may differ from what the network was designed for, and may therefore have negative effects. This is focused on in this study.

3.3 Microscopic effects AVs and SAVs

As mentioned earlier, this research focuses on the microscopic effects of AVs and SAVs on urban traffic. This is partly because there is little known about these effects. And research that *does* investigate this topic, does not seem to reach a consensus about whether the effects on traffic congestion are positive or negative. Therefore, it is useful to first look at how exactly the driving behaviour of AVs and SAVs differs from conventional cars before conclusions are drawn about the microscopic effects.

When looking at longitudinal and lateral driving behaviour, Saleh et al. [16] and Gonzalez et al. [7] report that the advanced sensor systems and control algorithms greatly reduce stochasticity in the driving behaviour of AVs. Additionally, Bose and Ioannou [1] argued that the acceleration and deceleration of AVs is conducted in a much more smooth fashion, also allowing them to filter out turbulent behaviour of other vehicles. If this is complemented with connected technologies, Talebpour and Mahmassani [17] argue, the AVs are additionally able to generate a much wider view of the traffic, allowing them to drive closer to each other, reacting faster and in a much smoother fashion. All in all, the driving behaviour of AVs could be summarized as presented in table 1. These behaviours are expected to improve traffic flow, thereby increasing the road's capacity.

Table 1 Differences in driving behaviour AV

Factor	**Difference from conventional car**
Time headway	Shorter, less deviation
Distance headway	Shorter, less deviation
Speed	Less deviation
Reaction time	Shorter, less deviation
Lookahead distance	Further
Acceleration/deceleration	Smoother, less deviation
Path deviation	Smaller

For SAVs it was much more difficult to find literature about their expected driving behaviour. Apart from being AVs and therefore also displaying all the AV driving behaviour characteristics as described above, some other behaviour is also expected. Firstly, Fagnant and Kockelman [4] earlier already predicted that SAVs would cover more distance than conventional vehicles because of empty kilometres and repositioning. However, they did not mention that this likely involves circulatory movements, using links and traffic signals that do not have sufficient capacity. This could cause disproportionally long queues and delays. Secondly, if people are being picked up and dropped off alongside the road without using a parking space, this will form temporary bottlenecks. The International Transport Forum [8] dedicated a study to how curbside use is changing, and confirmed that the use of shared modes will put the curbside under increased pressure, having negative consequences for other curb users as well as on-road traffic.

Upon close inspection, AVs and SAVs also represent the above described trade-off between high traffic throughput and high accessibility. Where AVs may improve traffic throughput, increasing a road's capacity, SAVs may provide a higher level of access to surrounding real-estate, thereby decreasing the road's capacity. These effects were inspected more closely in this research by means of a simulation study, which is described in the next section.

4 Application

The effects of AVs and SAVs that were found in the literature, were combined and translated into a conceptual model for this research. This model was then quantified using the traffic simulation software Vissim and a case study of a network in The Hague during the morning peak in 2040. The first part of the model studies focused on finding the effects of different market penetration scenarios, and the second part focused on finding the effects of two easy-to-implement designs.

4.1 Scenario studies

Based on what was found in the literature, a set of 7 scenarios were established with regard to the penetration of AVs, SAVs and occupancy of SAVs. Additionally, assumptions were made based on the literature and real life data with regard to the base demand, the behaviour of AVs and the behaviour of SAVs. An overview of the scenarios is presented in table 2. The names of the scenarios are uniformly structured to signify the penetration of AVs out of all personal vehicles and the penetration of travellers that are travelling to the case study area in a SAV. The formatting is as follows: <penetration AVs>/<penetration SAVs>.

Table 2 Scenarios

Scenario	**AV (% of vehicles)**	**Shared (% of travellers)**	**Pax SAVs (# pax)**	**Buses**
1. 20/3	20%	3%	1,1	AV
2. 50/25	50%	25%	1,5	AV
3. 80/50	80%	50%	2	AV
4. 0/0	0%	0%	N/A	Normal
5. 50/0	50%	0%	N/A	AV
6. 100/0	100%	0%	N/A	AV
7. 100/100	100%	100%	2	AV

It was expected that a higher penetration of AVs would increase the road capacity and reduce variations in traffic flow. This would in turn reduce vehicle delays and emissions. On the other hand, it was expected that a higher penetration of SAVs would reduce road capacity due to curbside stopping, increase traffic intensity and the demand/capacity ratio of traffic lights due to (empty) circulation on the network, and increase variations in traffic flow. All this was expected to lead to an increase in vehicle delays, an increase in distance travelled, and an increase in emissions. These effects were expected to be slightly reduced when SAV occupancy was increased, simply by a reduction in traffic intensity. The base demand was also included as an external factor that could influence the system by increasing traffic intensities and thereby the total distance driven, and the vehicle delays. The influence of the base demand in the simulation model, however, was reduced to a minimum in order to provide a clear view of the effects due to differences in driving behaviour. These expected relationships are summarized in the causal diagram in figure 1.

The above described behaviours of AVs and SAVs were translated into specific vehicle classes in Vissim that were loaded onto the network at different penetration rates based on the scenarios. The base demand was equal for all scenarios and was obtained by extrapolating a the base demand that was derived from a static demand model for 2030. The model was verified by comparing measurements of traffic intensities and animation of vehicle behaviour with the model input as defined in the conceptual model. Model validation was done by means of several expert interviews and a sensitivity analysis of a number of factors that were based on assumptions: the base demand, the headway of AVs, the amount of deviation between human drivers, and the dwell time of SAVs when they drop off a passenger. The model was found to be especially sensitive to the values for the base demand and the AV headway. Higher values for both factors, caused higher vehicle delays. Therefore, it should be taken into account that when interpreting the results, different values for these factors in reality could yield different

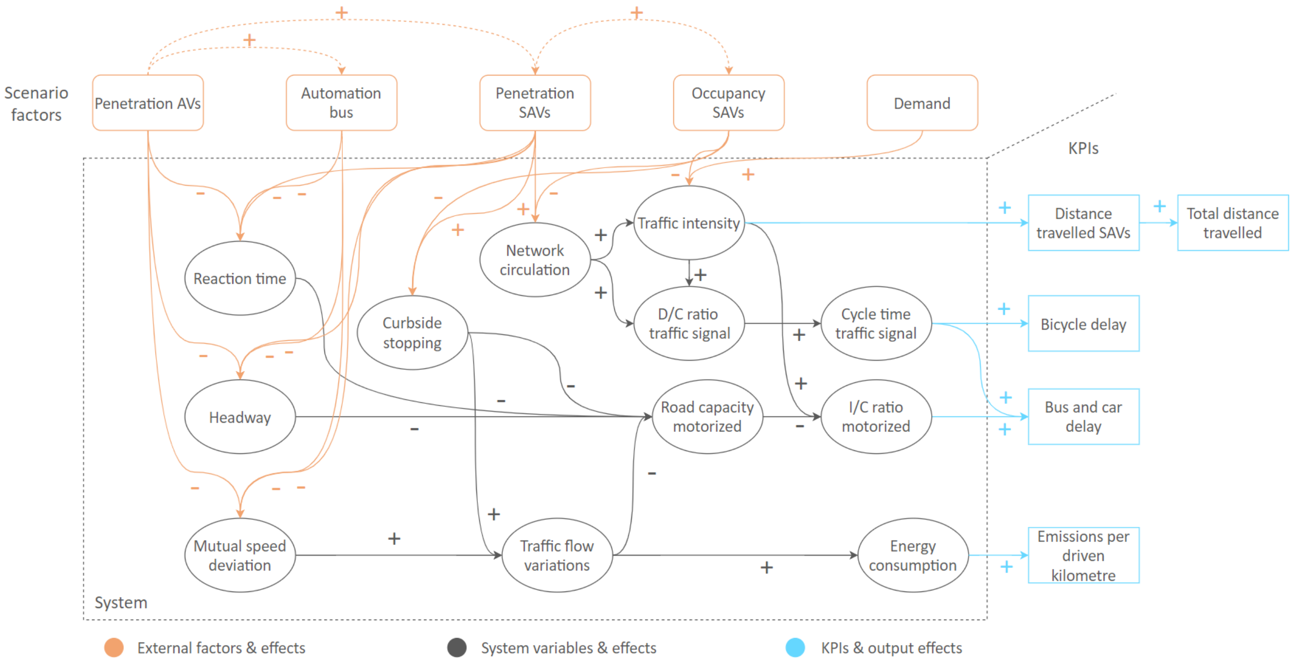

Fig. 1 Causal diagram

results. After model verification, model validation and determining the experimental set-up, results could be retrieved.

4.2 Design studies

To reduce the expected negative effects of SAVs while still providing them access to surrounding real estate, the municipality might need to undertake action. However, in the transition period, it is desirable to keep adaptations to the road infrastructure to a minimum and limit the height of investments. Therefore, two easy-to-implement designs were defined and their effectiveness was tested. The first is a design where the main road is expanded by one lane on the curbside, which then becomes a dedicated lane for SAVs and buses. SAVs may stop on this lane wherever they want. The second is a design where kiss & ride facilities are built on the roadside of the lower level roads, diverting SAVs from the main road.

It was expected that the first design may have a positive effect on congestion, because the capacity of the road is increased and the problem of SAVs stopping on the road, forming bottlenecks for other vehicles, is solved. Further, is was expected that the distance driven by SAVs could be reduced, because they can drop-off their passengers centrally in the network. However, it was also expected that a negative effect may be an increased amount of weaving movements on the main road, and the SAVs still using low capacity links to make U-turns on the main road. The second design was expected to have a positive influence on the congestion by leading the SAVs away from the main road, preventing usage of low capacity links, and mandating them to stop on the side of the road, thereby not forming bottlenecks for other road users. However, this design was expected to increase the distance that SAVs drive, as they are sent to decentral locations.

The designs were implemented in the simulation models of the four scenarios with different penetration rates of SAVs: scenarios 1 (20/3), 2 (50/25), 3 (80/50) and 7 (100/100). In these simulation models, the road infrastructure and vehicle routing was slightly changed. However, the changes were only minor, as these are easy-to-implement solutions. After defining the experimental set-up, results could be retrieved.

5 Results

To get a full grip on the congestion effects, results were retrieved from the model in terms of average vehicle delays, distance driven and emissions. Vehicle delays were measured by looking at the difference between each car's "ideal" travel time and the actual travel time over four representative routes. These were routes with both a high amount of traffic and a high usage of the entire network. To check whether differences in delay could not be attributed to a possible increase or decrease in intensity on the network, the total distance driven by all vehicles was reported and compared between cases. Further, average emissions per kilometre driven were retrieved with the help of the Enviver Pro module, to verify that differences in delay were due to differences in turbulence of the traffic flow as a result of the driving behaviour of AVs and SAVs. The idea behind this being that an increase in traffic flow turbulence causes an increase in energy consumption of all vehicles, which can be measured by means of measuring the emissions per kilometre.

It was found that in all cases, high or low delays came paired with high or low emission levels per driven kilometre, and the total distance driven hardly ever differed significantly. Therefore, it could be concluded that the delay values found purely represent the congestion effects of the driving behaviour shown by AVs and SAVs. The delay values for non-SAV motorized vehicles as well as SAVs are presented for each scenario and each design in table 3. Further, the propagation of the vehicle delay over the entire morning peak period is displayed in figure **??**. In this table and figure, a distinction is made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because the SAVs spend more time in the network by default, because they need to drop off passengers. Combining these vehicles with other vehicles, would give a distorted idea of the effects.

Table 3 Scenario and design results for vehicle delays of non-SAVs and SAVs

	Non-SAV mean delay (mm:ss)			**SAV mean delay (mm:ss)**		
Scenario/design	**None**	**Dedicated lanes**	**K&R-facilities**	**None**	**Dedicated lanes**	**K&R-facilities**
1: 20/3	02:20	02:36	02:32	03:43	04:27	04:05
2: 50/25	02:55	02:50	02:50	04:00	04:22	03:49
3: 80/50	02:28	02:11	01:59	03:35	03:41	03:06
4: 0/0	04:00	-	-	-	-	-
5: 50/0	01:31	-	-	-	-	-
6: 100/0	01:16	-	-	-	-	-
7: 100/100	06:15	05:50	03:36	09:15	09:52	04:36

5.1 Effects of AVs

The results confirmed the suspicion that an increase in the amount of AVs on the road reduces congestion significantly. This could be concluded from low delays in scenarios 5 (50/0) and 6 (100/0) with AVs but no SAVs as compared to scenario 4 (0/0) with neither AVs nor SAVs. Additionally, the emissions values in this scenario were much lower, indicating less energy consumption per kilometre and the total distance driven remained the same. This implies that the reduction in delay is truly an effect of less turbulent, more efficient driving behaviour of AVs.

5.2 Effects of SAVs

The presence of SAVs, however, yielded less positive results. Scenarios with realistic amounts of SAVs in addition to AVs (scenarios 1, 2 and 3) still showed a reduction of delay as compared to scenario 4 with no AVs and SAVs, but not as much as the scenarios without SAVs. Furthermore, scenario 2 (50/25) performed significantly worse than scenario 1 (20/3) with regards to vehicle delay. Scenario 7 (100/100) where all travellers made use of SAVs took the crown in terms of high delays. In this scenario, the delays were so high that not all vehicles had been able to enter the model by the end of the simulation period. When checking the distances and emissions, to see whether these delays were due to an increase in intensity or due to the on-road driving behaviour of the SAVs, it could be seen that the total distance had not significantly changed between scenarios and the emissions per kilometre had significantly deteriorated. This confirmed the suspicion that the delays were a result of the driving behaviour. As mentioned in the literature review, urban roads are designed for conventional cars to provide a certain combination of throughput and access, depending on the road level. As AVs provide a higher level of throughput and SAVs provide a higher level of access, but neither in the way that conventional cars do, solutions are needed to help restore the balance.

5.3 Effects of designs

After implementing the two designs in four scenarios with varying penetration rates of SAVs, it was found that the dedicated lanes design was unsuccessful in reducing the delays and emissions, even though the distance driven by SAVs was significantly reduced with this design. Even though this design implied an increase in the road's capacity, the increase in weaving movements and the increase in U-turns taken on the main road had a negative effect on the vehicle delays and emissions to the extent that the values for these KPIs remained statistically equal for the non-SAV motorized vehicles. The delays for the bus even increased with this design. This is due to the fact that the SAVs share the dedicated lane with the bus, which can therefore be held up by stopping SAVs.

The K&R design, on the other hand, turned out to be an effective measure to reduce delays caused by SAVs. However, this was only the case when the penetration rate of SAVs was higher than 25% of travellers. Effects that this design had on the distance travelled and emissions were only noticeable in the extreme scenario of 100% market penetration of SAVs. The positive effects associated with this design can be attributed to the fact that the SAVs are led away from the main road, where less traffic is hindered and where they stop on the side of the road. Additionally, the amount of U-turns made on the main road, using low capacity links, are kept to a minimum. This way, the traffic lights can easily process the queues that form.

6 Conclusions

Following the results from the scenario studies and the design studies, it could be concluded that cities with similar networks like the case study (ie. an urban main road where high traffic flow is combined with accessibility functions and interactions with other traffic is controlled by signalized intersections), can count on AVs to have a positive influence on the traffic flow here, reducing congestion. However, SAVs, which are likely to gain popularity together with AVs, can have a negative influence on road congestion by forming blockages, causing turbulence in traffic flow and causing queues on low capacity links. These results not only confirm the relationships that were proposed in the conceptual model, but also emphasize the conflict that is present on urban roads between the throughput function and the access function.

The research pointed out that these negative effects can be reduced by facilitating the SAVs with a fine-meshed network of kiss and ride-facilities on the sides of the underlying road network. However, the results suggest that this will only become effective at higher penetration rates of SAVs. As the research already detects negative effects at lower penetration rates, it is advisable to perform more research on solutions that will work when less than 25% of travellers or less are using SAVs. The results of this research suggest that effective solutions can be found in diverting the SAVs away from the main roads, to preserve its throughput function.

Besides the above mentioned recommendations that specifically target the problems found in this research, it is advisable for municipalities to be cautious and closely monitor the situation when it comes to AVs an SAVs in their city. As these are new technologies and concepts, many other unexpected problems could occur like the ones found in this research. Furthermore, technological developments and market adoption are moving at a fast pace. Adopting a wait-and-see attitude in this could prevent the city from being able to benefit from these new mobility concepts or could even be potentially harmful. Therefore, it is advisable to pay attention to the impacts of (S)AVs in all future infrastructure plans.

6.1 Limitations

However, before interpreting the results of this research as a universal truth, its limitations should be taken into account. These can be found mainly in the forecasting, and the conceptualization and specification of the model.

There are many uncertainties when it comes to the technological and market developments of (S)AVs. Therefore, assumptions had to be made with regards to the demand effects and the driving behaviour of these vehicles. From the sensitivity tests, the model was found to be especially sensitive to the base demand and the AV headways. If these factors turn out to have a higher value in reality, this could have negative effects on congestion. The industry and mobility market should be closely monitored to see how these assumptions will relate to reality.

A model is always a simplified version of reality. Therefore, reductions have to be made. With each reduction, a piece of information is lost. Important reductions made in this research relate to the translation of demand forecasts and market penetration into OD matrices, the behaviour of AVs, and the network usage of SAVs.

Finally, the use of the case limits generalization of the results to parts of cities with similar networks. The effects of AVs on congestion and emissions could, for instance, be very different for a network with single lane roads, direct interaction with cyclists and unsignalized intersections.

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