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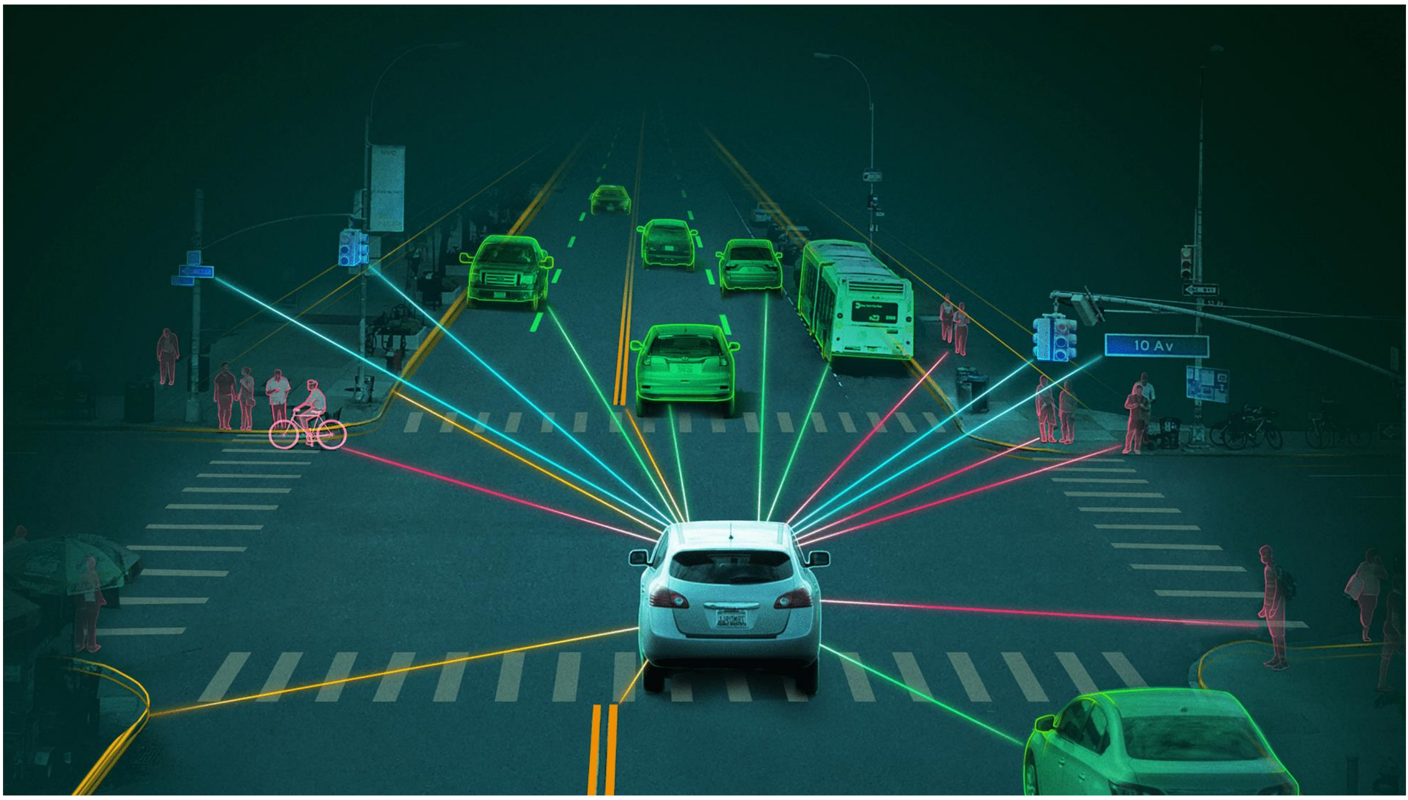

THE IMPACT OF AUTONOMOUS VEHICLES ON THE CAPACITY OF A WEAVING SECTION

HOW DIFFERENT SCENARIOS OF AUTONOMOUS VEHICLES, AND THE PENETRATION LEVEL THEREOF, INFLUENCE THE CAPACITY OF A 2 BY 2 WEAVING SECTION

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The impact of Autonomous Vehicles on the Capacity of a Weaving section

How different types of Autonomous Vehicles, and the penetration level thereof, influence the capacity of a 2 by 2 Weaving section

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Preface

In front of you, you can find the results of my Bachelor Thesis "The Impact of Autonomous Vehicles on the Capacity of a Weaving section: How different types of Autonomous Vehicles influence the capacity of a 2 by 2 Weaving section in Different Penetration Levels". This research was carried out within 10 weeks at the department Verkeersmanagement en -Prognoses at Goudappel.

I want to thank the supervisors of my research. First I would like to thank Leon Suijs and Mark van den Bos for their help and the feedback they have given. Their knowledge in VISSIM and the field of traffic has helped me understand the program and methods better and to keep on going when I was stuck. I would also like to thank my internal supervisor Oskar Eikenbroek for his help. He would always make the time to help, give feedback and gave useful insights on the literature and theoretical part of the subject. Besides my supervisors at Goudappel, I would also like to thank the department of Verkeersmanagement & -prognose for making me feel welcome and helping me when needed. The meetings and chats during lunch made the research more fun to do and gave me a chance to get to know the company. Finally, I want to thank Goudappel for the opportunity of doing my research within their company.

I hope you enjoy reading this research and if this research brings up any questions, it is possible to contact me via c.m.asbreuk@student.utwente.nl.

Carmen Asbreuk

Enschede, 30th of June 2023

Summary

Vehicles are evolving every day. They for example accelerate faster, drive more fuel efficient or get more supporting features compared to earlier models. These supporting features currently include automatic emergency braking, blind spot warning, lane centering, (adaptive) cruise control, automatic parking and many more. These features support the driver, but do not yet take over the task of driving. This aligns with level 0 to 2 of the SAE levels of automation (J.S. Choksey, 2021). From level 3 to level 5, the vehicles drive autonomously. This means that the systems in the vehicle completely take over and the 'driver' does not need to drive anymore. In levels 3 and 4 the vehicle can still request the driver to take over, in level 5 drives autonomous in all conditions. Currently, autonomous vehicles that take over the driving task in all circumstances are not yet allowed on the public road. Restrictions are attempted and expected to be disabled by testing and improving the autonomous vehicles (AVs) to than prove the consistency, reliability and advantages of the AV.

One of the advantages of AVs could be an increase in capacity. The capacity is the maximum number of vehicles passing a certain point within a certain time interval, often 1 hour, given certain circumstances. For this research motorway conjunction capacity is considered, which is the amount of vehicles driving away from the conjunction. If the capacity would be increased, current motorways can accommodate more vehicles.

To determine if an increase in capacity is a likely cause of AVs, this research focusses on a simulation and comparison of conventional and autonomous vehicles. To do this, 5 types of AVs are modelled based on different behavioural features. The first three types are typified by their aggressiveness. This aggressiveness is embodied in acceleration, headway time and more. The other two types focus on a specific feature: connected AVs and AVs driving in a platoon.

Each of these AV types will be simulated with 0%, 20%, 40%, 60%, 80% and 100% AV penetration rate, with the remaining percentage of vehicles driving conventional. The simulation will happen on a weaving section of 2 by 2 which has a length of 750 m. At both lanes the same amount of vehicles enter and for both half of the vehicles switch lanes. A weaving section has been chosen since it is a typical bottleneck on a motorway.

As mentioned, the 5 types of AVs are simulated through driving behavioural features. The altered features can be classified based on four different types of settings in the VISSIM traffic simulation software; *Wiedemann 99* parameters, *Other following* parameters, *Lane Change* parameters and *autonomous driving* features. Parameter changes have two main causes for the different types of Avs; first being due to the removal of human inconsistency and reaction times, second due to the human error being removed which leads lower risks. As a result of these alterations, vehicles can for example drive closer together. By altering the various parameters the 5 types of AVs were modelled.

These AV types together with the penetration rates form the scenarios, a combination of a defined AV type and a penetration rate of that type. These scenarios were run, through which the flow downstream of the conjunction was measured. Moreover, the average speed upstream was calculated for each 5 min interval. If there was conjunction, meaning the speed was lower than 50 km/h, the corresponding flow was taken as a capacity value. Since for a given scenario multiple capacity values are present, the median of this value is determined to be the overall capacity. The cumulative frequencies of the capacity values were also calculated and visualised to get a broader view of the consistency of congestion capacity.

The cumulative frequencies of the scenarios and the capacities show an inconsistency for both the 100% cautions and the 100% platoon scenario, the capacity values are drastically lower. This

contradicts the trend of the other penetration rates and can be explained by some unrealistic vehicle behaviour within the model. Next to this, two trends are spotted. First, AVs seem to have a positive influence on the capacity. Second, this increase in impact from the penetration rate on the capacity seems not linear but increases exponentially. This trend however cannot be stated with certainty.

The cautious AV barely influenced the capacity with only a maximum increase of 4% compared to the base scenario (conventional vehicles). The moderate AV already shows a bigger influence which is similar to the influence of the connected autonomous vehicle (CAV). They both lead to an increase in capacity of 35% at a 100% penetration rate. The aggressive and platoon AV show an even bigger impact with both scenarios having a +31% impact on the capacity at 80% penetration. When increasing the penetration rate further to 100%, the aggressive AV reaches the highest impact, 44%. This gives the general conclusion, that the capacity of conjunctions can be positively impacted by AVs. Important however is that the type of AV determines the extend of this positive impact, which ranges from 4% to 44% for the different types of AVs given a 100% penetration rate.

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Nomenclature

In the report different abbreviations, symbols, units and terms are used. In this chapter those are explained.

List of Abbreviations

Table 1 shows the used abbreviations.

Table 1 Abbreviations

Abbreviation	Meaning
AV	Autonomous vehicle
CAV	Connected autonomous vehicle
CIA	Capacity Infrastructure Motorways document from Rijkswaterstaat (Grontmij, 2015)
HGV	Freight traffic

List of Quantities and Units

Table 2 shows the used symbols and units in alphabetical order. The quantities and units used for the Wiedemann 99 model are shown were the model is also explained in 3.1.3. Driving characteristics of in Table 3. Similarly, the quantities and units for the standard deviation and variance those values are in Appendix D Variance in Figure 41.

Table 2 Quantities and Units

Quantity	Unit	Meaning of unit
Acceleration or deceleration	m/s2	Meter per squared second
Capacity (value) or flow	Veh/h	Vehicles per hour
Distance	m	Meter
Speed	Km/h	Kilometres per hour
Time	Sec, min or h	Seconds, minutes or hours

Terms

This report uses different terms, which have a debatable definition. These terms are defined below.

Capacity has many different definitions, which is mainly caused by the assumptions which are made to calculate it. For this report the congestion capacity is taken which means the amount of vehicles driving away from congestion. This also raises the question, what is congestion. The definition for this is taken from the *Capaciteitswaarden Infrastructuur Autosnelwegen*, which is when the average speed is below 50 km/h (Grontmij, 2015).

1. Introduction

Transport is a very important part of everyday life. It enables people to go to work, to do groceries, make recreational trips and to do much more. Cars are the dominant form of transport, with cars taking up 82.9 percent of passenger kilometres of inland transport in the European Union in 2018 (Car travel dominates EU inland journeys, 2020). This puts a strong connection between the economy and congestions in traffic (G. Weisbrod, D. Vary, G. Treyz, 2002).

Therefore, a large amount of money, time and effort is put into minimizing traffic congestions. This is often done by evaluating the current or expected future situation and the impact of the problem. Then improvements are designed and assessed in an ex-ante evaluation, for example using simulations. Lastly, a decision can be made on whether the road should be (re)constructed, adapted or kept the same. This is a long process starting with the initial research and concluded by the final road design. In the designs, future plans and trends are also taken into account, to ensure that the roads are durable.

This makes the (anticipated) future changes important within road designing. In fact, roads are typically not only designed to accommodate in a robust manner the current demand but also for the anticipated traffic, including induced traffic due to the increased capacity. Vehicles and the behaviour of their drivers also largely influence the optimal road design. This however changes slowly and is not as well-known. Currently, automation within vehicles is becoming more and more advanced and frequently used. The final stage of driving task automation is autonomous vehicles, which is also the subject of this research.

As stated, the exact influence of autonomous vehicles is still unknown, but may substantially impact road capacity. To give a range of how the capacity could change, different types of AVs will be compared in this research. The penetration of autonomous will increase from 0 to 100 percent, as a 100 percent penetration rate is expected (A. Talebia, 2018). When these different penetration rates are achieved is still uncertain, similar to the characteristics of the autonomous vehicles.

Autonomous vehicles must be able to drive on varying types of roads and will also have varying influences on different road aspects, like the capacity. For this research a weaving section is simulated. A weaving section was chosen because it is a key bottleneck in motorways. A weaving section can be interesting, mainly due to two driving behaviour characteristics: car following and lane changing. These characteristics represent how humans drive a vehicle, but can also be adjusted to represent how the system of an AV acts. The characteristics influence different aspects of road traffic, one of them is capacity. The capacity is the maximum amount of vehicles which can pass a certain point on a road, however it varies within different circumstances. There are two main types, free-flow capacity and congestion capacity. This research will focus on the second one, congestion capacity.

This research will firstly go into more detail of the research context after which the theoretical framework and methodology are discussed. Afterwards the results of the research will be shown. The report is concluded with a discussion, conclusion and recommendations for future research.

2. Research context

This chapter firstly describes the problem statement (section 2.1 Problem statement) which will be tackled in this report. Secondly, the objective of the research is displayed, in section 2.2 Research objective. After which the questions, including sub-questions are shown, in section 2.3 Research questions. The scope of the research is explained in section 2.4 Research scope. In section 2.5 the base model and the simulated weaving section are shown.

2.1 Problem statement

Making future predictions of capacities and how the road network should fit the demand can be difficult due to the changes in vehicles. A future expectation is the uptake of AVs to the global car fleet. AVs are expected to influence the capacity of roads, however there are still many uncertainties regarding their impact. The first uncertainty is how AVs will behave, which is why 5 types of AVs will be simulated in this research. These together will how the capacity can change.

The second uncertainty is the timeframe. When AVs first appear on roads this will only be in small numbers. However, after a while more and more vehicles will be autonomous. Therefore, the penetration rate of AVs on the road is expected to increase over time. How fast this process is going to take place is still uncertain. Estimations have been made, but also differ from each other. 75% percent AVs in 2040 and 70%-95% in 2070 has been estimated by multiple sources (K. Kim, 2015) (M. Lavasani, 2016). Talebia even assumes a 100% penetration rate of AVs by 2050 (A. Talebia, 2018). This shows that it is hard and maybe even impossible to state predictions with certainty.

2.2 Research objective

The objective of this research is to determine the influence of 5 types of AVs, and the penetration level thereof, on the congestion capacity of a typical 2 by 2 weaving section.

The research objective only tackles a small part of the problem stated. The problem stated the need of a prediction for the future, this research only predicts the changes happening and not when.

2.3 Research questions

This objective can be established by answering the following question:

- How do different types of AVs influence the capacity of a 2 by 2 weaving section considering different AV penetration levels?

To get the answer to this question, first 6 sub-questions need to be answered. The first one goes into the modelling of the AVs. For this research 5 different AV types are chosen. The last 5 go into each AV type separately:

- How do cautious, moderate, aggressive, aggressive including platoon and connected autonomous vehicles behave and how can this be translated into driving behaviour parameters in VISSIM?
- What is the capacity of a 2 by 2 weaving section with different penetration levels of cautious AVs?
- What is the capacity of a 2 by 2 weaving section with different penetration levels of moderate AVs?
- What is the capacity of a 2 by 2 weaving section with different penetration levels of aggressive AVs?
- What is the capacity of a 2 by 2 weaving section with different penetration levels of aggressive AVs with platooning?

- What is the capacity of a 2 by 2 weaving section with different penetration levels of CAVs?

The first sub-question will form the base for the definition of autonomous vehicles in VISSIM by finding the parameter values and differences between the types of AVs. VISSIM is a microsimulation model which simulates individual vehicles going through a certain network according to different values which can be altered by the user. In the program networks can be made using different types of roads and adding speed limits, parking places, vehicles, routes and much more. When the network is finished it can run the simulation even enabling multiple runs and random seed increment. Next to letting the vehicles drive, data can be collected using different methods in order to analyse various scenarios. When adding different features, it automatically picks certain value sets or lets the user chose the set. For example when adding a vehicle when a few different vehicle types are displayed. These sets can also be altered, which is what will be done for 'driving behaviours'.

After the behaviour of these vehicles has been estimated and implemented in VISSIM the other 5 sub-questions can be answered. The main question can be answered by comparing the capacities of the different types of AV and penetration levels. In addition, the shapes of the graphs showing the cumulative frequency of capacity values can be compared to see if the flow during congestion becomes more stable.

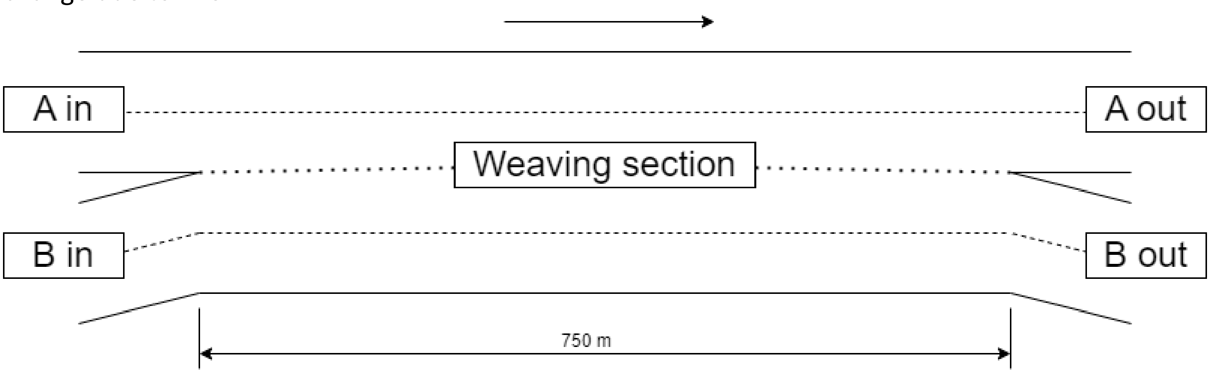
2.4 Research scope

Since this research has a limited amount of time, different boundaries have been set. These boundaries made sure that the research was finished in time.

The first boundary was already touched upon in Chapter 2.1 Problem statement. The statement showed a wish for future predictions. The research will only show how the capacity is likely to change in the future. These changes will not be connected to certain years.

The second boundary was already described in Chapter 2.2 Research objective. This objective already showed that the problem statement is too big to be solved within this research. The research is therefore only about one situation, a certain weaving section, and about the capacity. Not about the other indicates of traffic and other situations within the road network.

The influence of AVs is likely to stretch further than only driving behaviour. It could also affect the threshold to make a trip and route choice. These aspects are not included in the research. Also trends unrelated to AVs have an influence on traffic flows, examples are the popularity of other modes of transport and the increase of the population. All of these aspects are not taken into account which leads to the following assumption; the amount, length and routes of trips do not change due to AVs



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2.5 Weaving section

For the research a certain traffic situation is needed. As shown before, this will be a weaving section. Firstly a situation with bottleneck was needed. A bottleneck is a part of the road network where the capacity is lower than before, regularly causing congestion. A weaving section is an example of this on motorways. For this research a standard weaving section in the CIA is chosen. The CIA is a document containing different methods for finding capacities as well as capacities for many different situations, all trying to resemble the Dutch road network. Values from this document can be used to compare the 0% scenario. The weaving section is a part of the motorway network of the Netherlands and is shown in Figure 1.

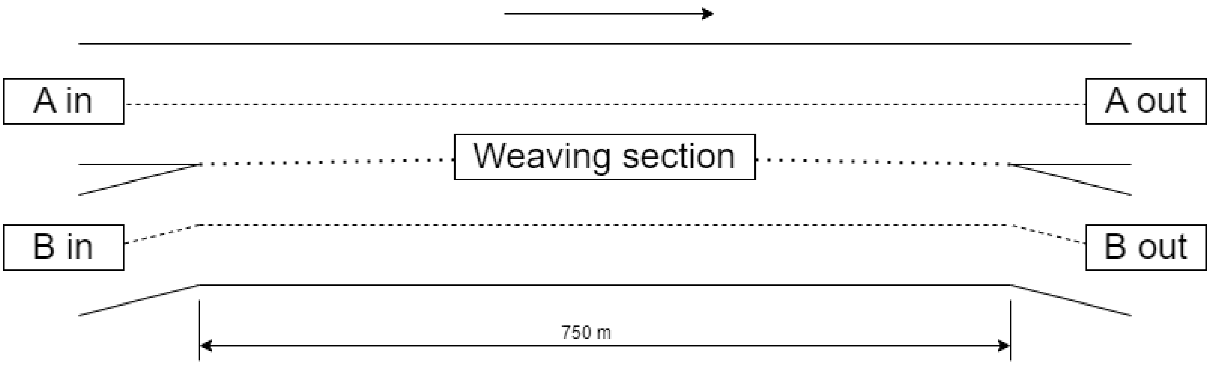

Figure 1 Road lay-out of weaving section

As can be seen in the picture the weaving section consists out of 2 roads of 2 lanes which are connected for 750 meters. From both lanes 50 percent of the vehicles will change to the other motorway. The motorway has a speed limit of 100 km/h, to represent the current motorway speed limit during the day. This differs from the CIA where the speed limit is 120 km/h. This however should not make a big difference since in this research the capacity is determined in congested situations, in which these speeds are not achieved. The fraction freight traffic of all of these flows is 15 percent.

3. Theoretical Framework

The previous chapter discussed the direction and topic of the research. With this, various topics related to AVs on motorways have been touched upon. These topics are further explained in this chapter. The chapter is divided in two parts; autonomous vehicles and capacity.

3.1 Autonomous vehicles

Autonomous vehicles are vehicles which do not need a driver. Due to the absence of human interference, AVs behave different than conventional (human driver) vehicles. This brings a many different changes of which driving behaviour changes are included in the research. Car following and lane changing are the two main aspects for weaving sections concerning driving behaviour (A. Kusuma, 2014), and therefore also for simulating AVs.

3.1.1. Levels of Automation

Figure 2 shows the different levels of driving automation, ranging from 0 to 5. Level 0 starts with a few support features. From level 3 the vehicle starts to drive autonomously, however only when engaged. In level 5 the vehicle can drive autonomous under every condition. Since it is unclear if level 3 would support weaving sections, level 4 and 5 are assumed for this research.

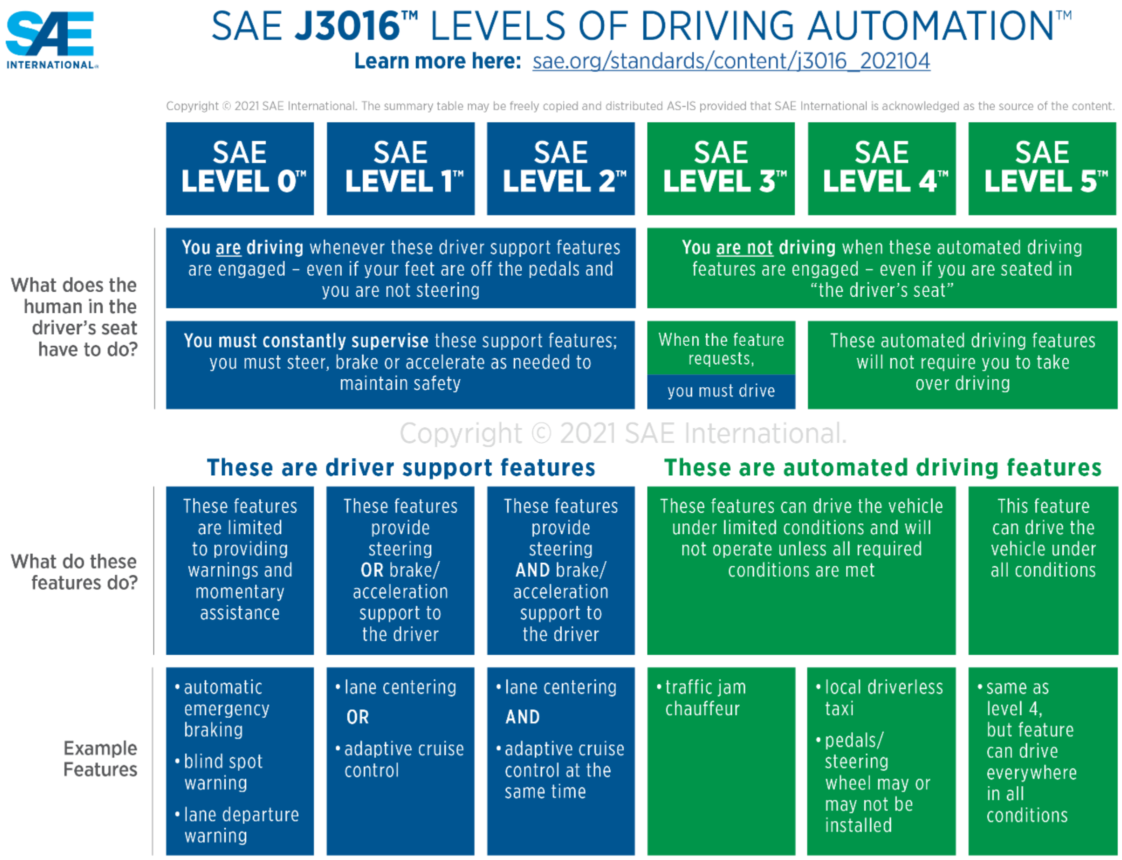

Figure 2 Degrees of automation (J.S. Choksey, 2021)

3.1.2. Types of AVs

The different levels of automation at the beginning mainly focus on the features of the automated vehicle and at the end in how many situations the vehicle can drive autonomously. This however does not directly relate to the differences in driving behaviour when they drive autonomously, which would be the difference between level 3 and 5. Therefore for this research another differentiation is chosen.

The first and most common differences in literature is in the aggressiveness, differentiating between AVs driving cautiously, moderately and aggressively. This difference is also already established in features like (adaptive) cruise control. It is amongst other things about how close an AV is driving to another AV (time gap or headway), how fast an AV switches lanes or how fast the AV accelerates. These three types of AVs are used as 3 types of AVs in this research, called cautious, moderate and aggressive AVs. The implementation and shapes of these AVs depend on different factors like responsibility, law and safety.

Driver characteristics at first seem to describe human driving behaviour. However for this research the human driving behaviour needs to be altered to resemble autonomous driving behaviour. To do this, differentiations are made within *car following*, *lane changing* and other parameters. AV characteristics are projected onto human driving behaviour to analyse the differentiations. The differentiations between the different AVs are comparable to the different human driving behaviours, therefore the same descriptions are used; cautious, moderate and aggressive.

An addition to changes in individual driving behaviour, vehicles can be platooning. Platooning is when vehicles find other vehicles with a similar speed. When they find a vehicle, they make sure to come close. When they are close to each other they act as one entity. The vehicles have the same speed and drive very close to one another (Cottingham, n.d.). Clustering of vehicles can also happen for conventional vehicles, however the difference is in actively looking for platooning possibilities and also act on it by for example driving closer to each other. Platooning is also an option in VISSIM and will be the one of the types of AVs in this research. Platooning shows properties which fall in line with aggressive driving behaviour like driving close to each other, therefore aggressive AV parameters will be the base for this AV type.

Vehicles can drive cooperative, this is about vehicles sharing what they are doing and are going to do and is a likely option for AVs. CAVs can drive close to each other, which is expected to massively increase the capacity of roads (X. Chang, H. Li, J. Rong, X. Zhao, A. Li, 2020). However, it is unclear if this is the case for a weaving section specifically. This is due to the different pelotons having to break up due a part of the vehicles switching lanes. How CAVs look like in the future is yet unclear. For this research it was assumed to be a separate type of AV. Next to this, the connected part is assumed to relate to the *car following*, which gets altered based on the vehicle at the front of the peloton. CAVs are the fifth AV type of this research. Platoon and connected AVs at first glance might seem similar, which they in large parts are. However the main difference is that platoon vehicles actively searches for other platoon vehicles and make larger platoons, where CAVs only react to the first vehicle in front if they encounter one by coincidence.

The 5 different types of AVs will be modelled using different options and altering different parameters in VISSIM. VISSIM is a microscopic multi-modal traffic flow simulation software, which unlike others has possibilities to model future vehicles. Standardized vehicle types with vehicle behaviour parameters are included in this software. Goudappel also has a few vehicle types with different parameters specifically for the Netherlands. Goudappel does not yet have AVs adjusted to the Dutch road network. However VISSIM does have general AVs, which is why AV related parameters will be combined with the weaving section vehicle behaviour type from Goudappel to get the different types of AVs for this research. Also, parameters from other researches will be compared to get the most realistic set of parameters for the 5 different types of vehicles.

3.1.3. Driving characteristics of AVs

To be able to conduct a simulation based research, AVs need to be simulated. For this VISSIM has various driving behaviour parameters. Most parameters are to replicate *car following*, *lane changing*, *following* and a few other parameters. Below the different parameters will be explained.

The first category is car following. To get a good perception of this, the Wiedemann 99 model can be used. This model describes what happens when you approach a car in front of you. This process is also visualised in Figure 3. At first the vehicles get closer to each other, until the following vehicle finds the space uncomfortable. At this point first a reaction time takes place, after which the vehicle brakes. Due to this the distance gets bigger again, after the appropriate distance has been reached the speed will again increase. This in- and decreasing of speed can happen a few times until the wanted speed and distance have been reached or until the following vehicle decides to pass the vehicle in front. In this process different parameters play a role, for example when to in- and decrease and how hard to brake.

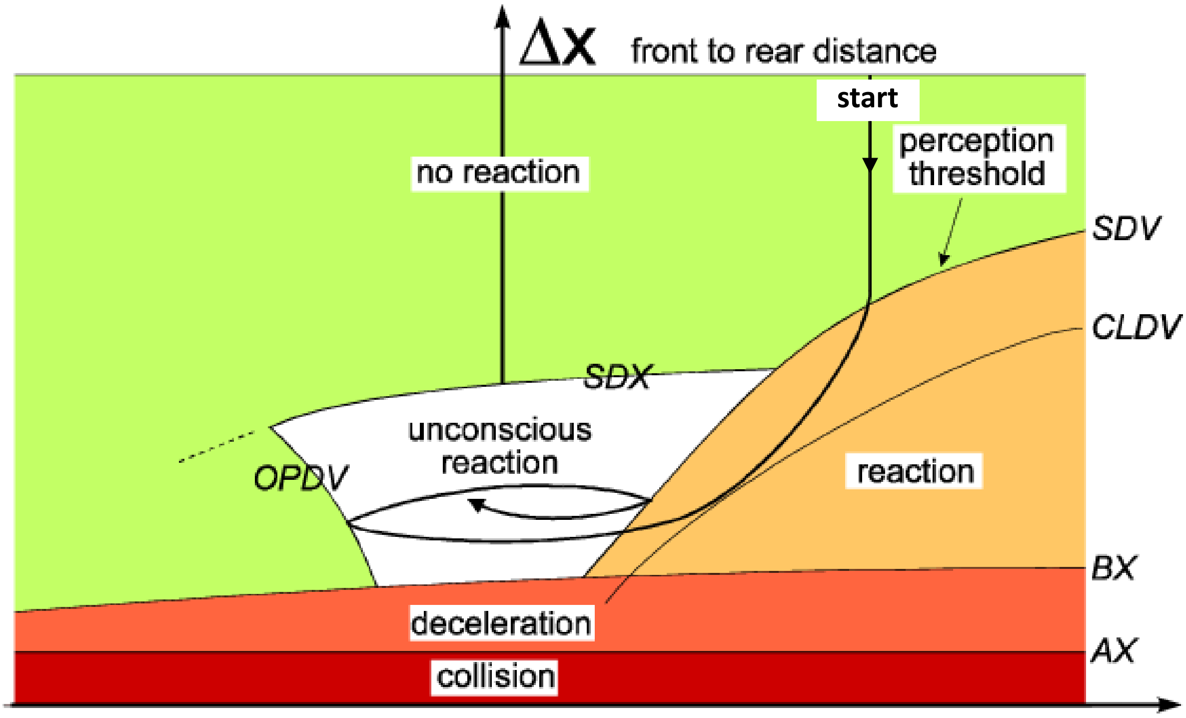

Figure 3 Wiedemann car following (B. Higgs, M.M. Abbas, A. Medina)

VISSIM uses two models of Wiedemann, Wiedemann 74 and Wiedemann 99. Wiedemann 74 was developed in 1974. In 1999 it was updated, this is the Wiedemann 99 model. In this update the physical and psychological aspects of drivers are better considered and some thresholds are defined better to simulate motorway traffic flow (Balich, 2019). The Wiedemann 99 model is standard for motorway traffic and Wiedemann 74 for urban traffic. Since this research is about a weaving section of two motorways, the Wiedemann 99 model will be used.

The Wiedemann 99 model has 10 parameters, these parameters are displayed and explained in Table 3.

Table 3 Wiedemann parameters

Parameter		Unit	Definition (PTV VISSIM, 2018)
CC0	Standstill distance	m	Average desired standstill distance between two vehicles
CC1	Spacing time	s	Time distribution of speed-dependent part of desired safety distance a driver allows before intentionally moving closer. This has two underlaying parameters, standard deviation and headway time. The standard deviation is typically 0, therefore headway time will be used in the remainder of the report.
CC2	Following variation	m	Restricts the distance difference or how much more distance a driver allows before intentionally moving closer
CC3	Threshold for Entering "Following"	s	Number of seconds before reaching the safety distance
CC4	Negative "Following" threshold	m/s	Negative speed difference during the following process, if this value is reached the vehicle lowers its speed
CC5	Positive "Following" threshold	m/s	Positive speed difference during the following process, if this value is reached the vehicle increases its speed
CC6	Speed Dependency of Oscillation	$(ms)^{-1}$	Influence of distance on speed oscillation while in following process
CC7	Oscillation acceleration	m/s^2	Oscillation during acceleration
CC8	Standstill acceleration	m/s^2	Desired acceleration when starting from standstill
CC9	Acceleration at 80 km/h	m/s^2	Desired acceleration at 80 km/h

Parameters CC2, CC4, CC5, CC6 and CC7 are expected to be different for AVs compared to conventional vehicles due to the human factor getting removed from the driving behaviour. The other parameters are also expected to change within the different 5 levels of automation, due to a less or more aggressive approach (Bruijl, 2019).

Next to car following, lane changes are also of big importance in this research. There are two reasons for lane changes, *necessary lane change* and *free lane change*. Necessary lane changes are made in order to stay on the route it was assigned to and free lane changes are to optimize its own trip and the one of others. For both reasons for lane changes different parameters describe when a change of lane is desired and if it is perceived as safe. This includes general behaviour where free lane selection and slow lane rule are the two options. In addition, settings like *advanced merging* and *vehicle routing decisions look ahead* can make a difference in if and how lane changes take place. The safety distance reduction factor is for example a factor which does not necessarily change due to automation itself, however it does change between the 5 types of automation. The moderate AV is likely to have a similar safety distance reduction factor, but the cautious AV has a higher one and the aggressive AV a lower one. Maximum deceleration for cooperative braking shows a similar pattern.

VISSIM also has regular following. This part of driving behaviour concerns itself with look ahead and look back distance, behaviour during recovery from speed breakdown, standstill distance for static obstacles and jerk limitation. Within these parameters the most interesting seems the number of interaction vehicles, which is regularly around 2, but increases for aggressive AVs. This is partly due to how advanced the vehicle is in terms of technology, but also due to what is needed. When a vehicle has settings which resemble aggressive driving more, the vehicle could be at more places and interact with more vehicles in one second or even two. Therefore a bigger picture of the surrounding vehicles is needed.

These factors represent the different driving behaviours for the AVs. They also show how they will be modelled and how they will differ from each other and conventional vehicles.

3.2 Capacity

Capacity is the maximum volume of vehicles that can pass a certain point or section of a road in a given timeframe. It cannot be directly observed, however it can be inferred using different methods. These methods all use different assumptions. These assumptions can be in surroundings and definitions. For example, the capacity volume can vary due to circumstances such as the weather. Since the capacity refers to the maximum amount of vehicles, regularly measurements in optimal conditions are picked, meaning no rain or heavy wind.

There are two ways within traffic engineering to define road capacity. First, capacity can be defined as the maximum volume of vehicles passing a point during a timeframe. The second way of defining capacity is the congestion capacity. This difference is illustrated in Figure 4. The flow is plotted against the density. The flow is the amount of vehicles passing a certain point in a set timeframe and the density is the amount of vehicles a specific part of a road network. In the graph, at first, the flow is increasing. At a certain point the demand exceeds the capacity which causes the flow to drop. This is called the capacity drop and is also the border between two types of capacity: free-flow capacity and congestion capacity. For the estimation of capacities, different methods are suited. As in this research the congestion capacity will be determined, the empirical distribution method will be applied as mentioned in the CIA. The flow can also be compared to the speed, giving the middle graph in Figure *5*. The graphs show the relation between flow, density and speed. The dotted line shows the border between free flow and congestion, however it does not show the capacity drop. In the left and middle graph the part related to congestion is marked red. As can be seen in the middle graph a lower speed, also lowers the flow.

The empirical distribution method has a two-parted measurement: upstream determination when congestion occurs and downstream measurement of the capacity values. According to the CIA-guideline congestion occurs when the average speed upstream of a bottleneck is below 50 km/h. The downstream measurements of capacity values are analyse in 5 minute intervals. When congestion occurs upstream, the downstream capacity values are incorporated in the capacity data set. This data set can be plotted to find a graph similar to Figure 6. Of this data set a median can be determined, which is considered to be the overall capacity. The shape of the graph shows if the congestion capacity might be more constant, meaning the vehicles driving away from the conjunction in similar manner during every interval.

A further explanation of the method and the results can be found in section 4.3 Capacity and Chapter 6. Results.

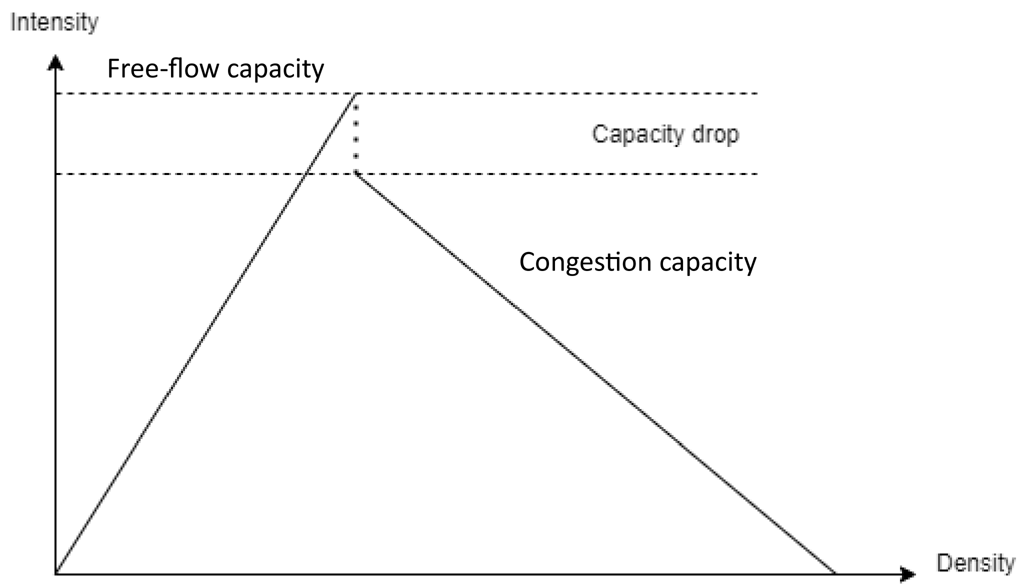

Figure 4 Capacity drop graph

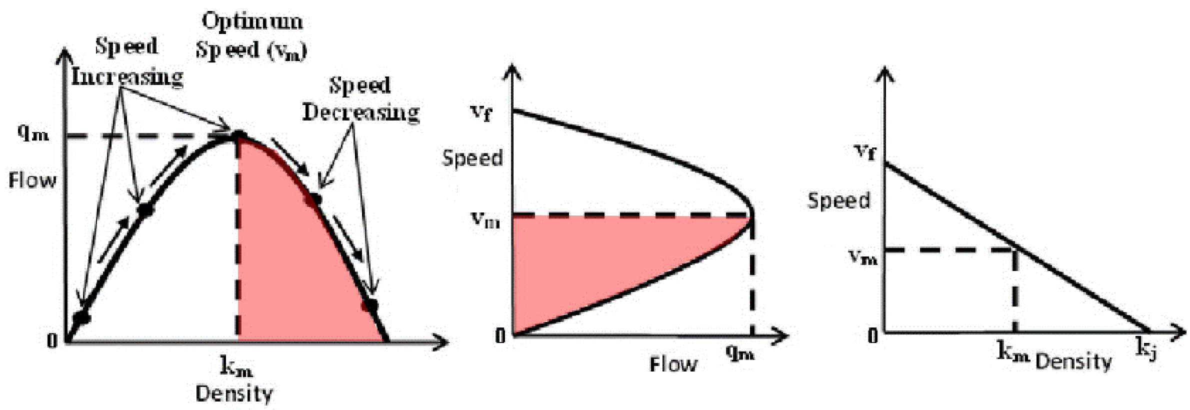

Figure 5 Relation between flow, density and speed. Note the lack of presence of the capacity drop (Zaidi, 2014)

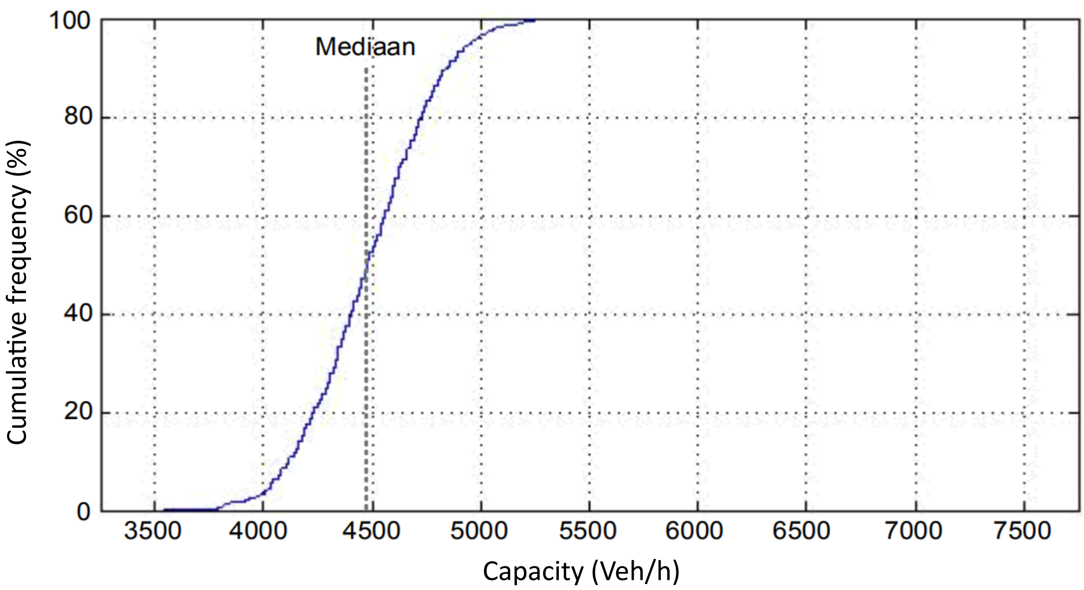

Figure 6 Cumulative frequency of capacity (Grontmij, 2015)

4. Methodology

To answer the research questions as articulated in Chapter 2, a methodology is needed. This consists of different steps and is visualized in the flow chart in Figure 7. Every box is a different step and will be explained below.

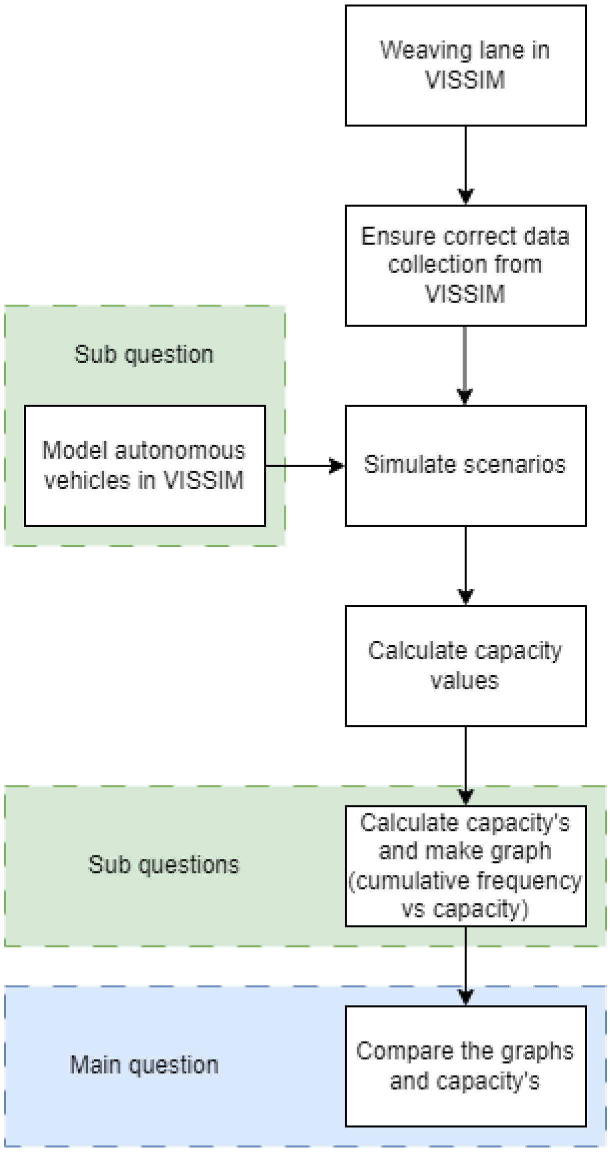

Figure 7 Flow chart of methodology

4.1 VISSIM model

To start simulating, a base model is needed. For this model the lay-out of the road was made and different features like vehicles, freight traffic, routes were added. Data collection points are also needed to collect the required data from the model. Data collection points are placed in VISSIM and collect different values at that certain point, for example the speed and amount of vehicles passing the point.

4.1.1 Weaving section in VISSIM

Simulating a weaving section in VISSIM is the first step which was taken. For the simulations, no specific study area was chosen. However, some specifications were selected. These specifications were based on the CIA from Grontmij from Rijkswaterstaat, as was explained in Chapter 2.5 .

The roads of the model are displayed in Figure 8. The network is quite simple and consists out of 2 roads, named A and B. The weaving section is when the two roads come together. The vehicles drive from left to right, so at the left-side the vehicles enter the model on road A in or B in. After a little more than 200 meters the two roads join. After another 750 meters the weaving section splits in A out and B out. All of the roads have a speed limit of 100 km/h and 80 km/h for freight traffic, since this is the current speed limit on motorways in the Netherlands.

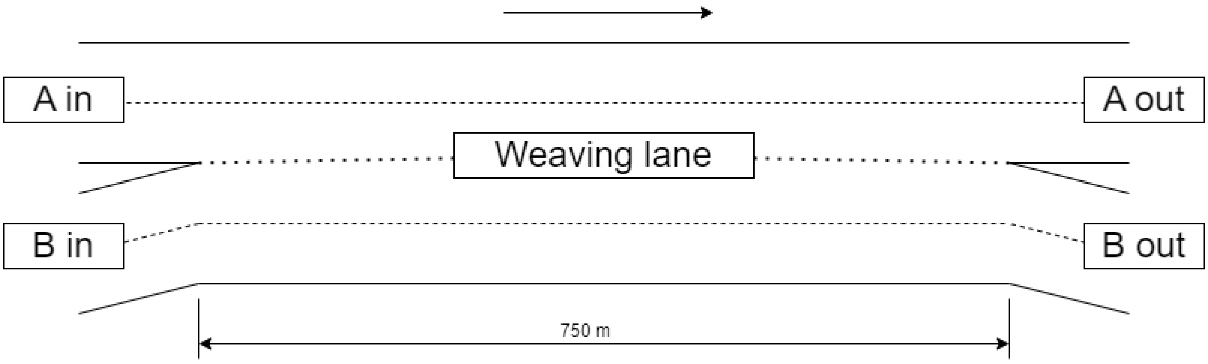

Figure 8 Copy of Figure 1: Road lay-out of weaving section

After the roads have been implemented in the model, vehicles have also been added. The vehicle inputs for A in and B in are both the same. The vehicle input increases in size within a run. This is done using time intervals. The vehicle input ranges from 5100 to 8700 veh/h taking steps of 300 veh/h. This is the input of one road, meaning the total input for the weaving section is double of the flows suggested before.

The vehicle input also changes between the scenarios, to get the correct type of AV and penetration rate. The percentage of freight traffic however is always 15. This gives the relative flows which are displayed in Table 4.

Table 4 Relative flows (%)

Penetration rate of AVs	Conventional car	Conventional HGV	AV car	AV HGV
0%	85	15	0	0
20%	68	12	17	3
40%	51	9	34	6
60%	34	6	51	9
80%	17	3	68	12
100%	0	0	85	15

As said, the vehicle input changes within the runs. These vehicles have a certain route to make. These routes have a starting point and a destination. For this research half of the vehicles switches roads. This means either going from A in to B out or B in to A out. In Table 5 the origin-destination matrix is given.

Table 5 Origin-Destination Matrix

	A out	B out
A in	50%	50%
B in	50%	50%

This was the first part of the model, however one more important function of VISSIM has to be correctly set up in order to make the different scenarios. This is making modifications and scenarios. Two types of modifications are made; types of AVs and the penetration rates of the AVs.

The modifications regarding penetration rate are adjusted by altering the vehicle composition according to Table 4. The modifications of the types of AVs are adjusted by changing the link behaviour type of the roads in the model. Link behaviour types describe how a vehicle acts on a specific part of the road, which can be differentiated for each vehicle type. The vehicles driving are: base vehicle, base HGV, AV and HGV AV. By adjusting the behaviour connected to the AV and HGV, the driving behaviour is changed for the specific AV type on that specific link. This was done for all links, matching the correct 'behaviour type' to the scenario.

The modifications than make different scenarios. This is displayed in Table 6. In the top row the different types of AVs are shown and at the lefthand column the penetration rates. Since the 0% scenario does not have AVs this one is valid for all 5 AV types as 0%. For the other penetration rates; 20%, 40%, 60%, 80% and 100 % the scenario cautious needs to be tested. The same goes for moderate, aggressive, platoon and connected. If a number is placed in a spot, the corresponding column and row show the modifications which make up the scenario. If a penetration rate is lower than 100 the remaining vehicles are conventional vehicles.

Table 6 Scenarios

	Cautious	**Moderate**	**Aggressive**	**Platoon**	**Connected**
0%			Scenario 1		
20%	Scenario 2	Scenario 7	Scenario 12	Scenario 17	Scenario 22
40%	Scenario 3	Scenario 8	Scenario 13	Scenario 18	Scenario 23
60%	Scenario 4	Scenario 9	Scenario 14	Scenario 19	Scenario 24
80%	Scenario 5	Scenario 10	Scenario 15	Scenario 20	Scenario 25
100%	Scenario 6	Scenario 11	Scenario 16	Scenario 21	Scenario 26

Furthermore standard values from Goudappel are used, in order to get a realistic view of the Dutch traffic. This mainly includes base data, of which driving behaviour is one part.

4.1.2. Ensure correct data collection from VISSIM

This is the second step and goes on from the road lay-out to make sure that data was correctly collected. To calculate the capacity, information from two places is needed. This is done using data points. These are placed according to the method, upstream and downstream. For upstream a point within the weaving section is picked. The downstream point is just after the bottleneck, which is this case is the separation of the two roads. The exact location of the data collection points are visualised in Figure 9.

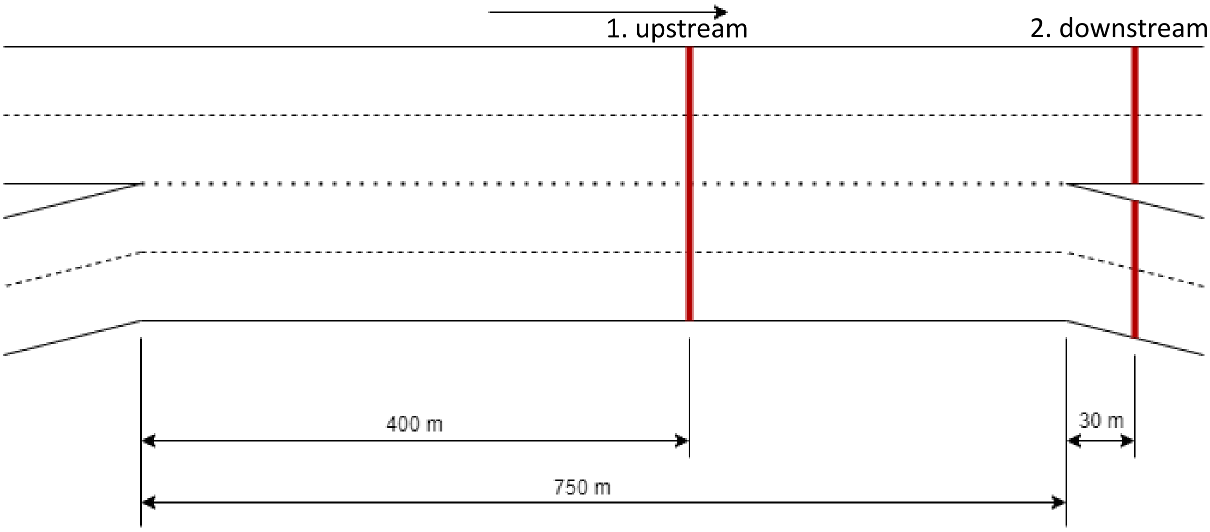

Figure 9 Collection points

The first collection point is placed to know when congestion occurs, which has been done by measuring if the average speed is below 50 km/h. This measurement takes place upstream, before the roads are split again. This can be done by measuring the speed of every car passing a certain point and collecting that data. The time frame also needs to be saved for the data processing.

The second part is getting the downstream data of the amount of vehicles leaving the congested weaving segments to get the capacity values. This can be done by measuring the amount of vehicles passing a certain point. This data is only required from the moments when the upstream speed is below 50 km/h, however this is easier to filter afterwards. Both data collections are done by using data collection points.

4.2 AVs

Since this research is about AVs, the next steps are about implementing AVs in VISSIM and simulating the different scenarios. It does not go into the actual values of the AVs, which is discussed in chapter 5. 5 Types of AVs.

4.2.1. Model AVs in VISSIM

For the autonomous vehicle simulation, 5 types of AVs are simulated in VISSIM. For cautious, moderate and aggressive the starting point is driving behaviour 'weaving section' from Goudappel, this was than adjusted by changing the car-following from Wiedemann 74 to Wiedemann 99. This also led to new parameters for which the correct values had to be found in order to resemble the AV types. Next to this regular following was altered by regulating the 'view' of the vehicle. The lane change parameters were fit to resemble the AV types in terms of changing lanes due to a higher speed and changing lanes to stay on their assigned route. Lastly AV options were picked, of which the main one for this research is platooning. For these adjustments literature research has been conducted and a comparison between standard driving behaviours in VISSIM was made. By combining this information, the three types of AVs (cautious, moderate and aggressive) can be modelled. Next to these AV types, platoon AV and CAV are also modelled. For both AVs the assumption was made that they have advanced software and a lot of input about the surrounding due to their features, to enable aggressive driving in a safe manner. Therefore aggressive was chosen to be the base of both AV types. By using the aggressive AV as a base and adding the option platooning in VISSIM, the platoon type of AV was modelled. For CAVs, the following behaviour is altered to moderate if the vehicle in front is not an CAV.

4.2.2. Simulate scenarios

When all settings are implemented in VISSIM, the 26 scenarios as stated in Table 6 were executed. Based on the simulations the effects of the various AV types given the various penetration rates can be analysed.

4.3 Capacity

After the model had run and the data was collected, the capacity was calculated. For this firstly the capacity values are needed. After this the capacities were calculated and the graphs have been made. Followed by the last step, comparing these graphs and values to get to a conclusion.

4.3.1. Calculate capacity values

The calculation of capacities will have to be conducted on all 6 levels of penetration and all 5 types of AVs. This leads to the 26 scenarios mentioned in Table 6, since the 0% only needs to be conducted once. The calculation consist out of different steps. These steps have to be repeated for every scenario and are displayed below.

1. Simulate the scenario with slowly increasing traffic flow. The flow was picked to cause congestion at half of the run time. The model has been run multiple times and with different random seeds in order to gain 100 congestion data points for each scenario.
2. Calculate the average speed of upstream vehicles for each 5 minutes.
3. Select the intervals where the speed was below 50 km/h
4. Find the amount of vehicles leaving the congestion during that interval
5. Multiply this amount with 12 to get veh/h

For each different scenarios this leads to one list of a minimum of 100 capacity values.

4.3.2. Calculate capacities and visualise cumulative frequency vs capacity)

This step is two-parted, both parts are a continuation from the previous step 4.3.1. Calculate capacity values. The graph can be seen as step 6. And the calculation of the capacity as step 7. Both steps are executed in Excel.

6. Set up ranges of capacity values and find the frequency of each range, plot this in a graph
7. Find the median

4.3.3. Compare the graphs and capacity's

For this last step different graphs need to be plotted together, to be able to compare not only the median, but also the slope of the graphs. Furthermore, conclusions can be made from the graphs and capacities, about the height and consistency of the capacity.

5. 5 Types of AVs

In this chapter the answer to the first sub-question will be found. The sub-question at hand is "How do cautious, moderate, aggressive, aggressive + platoon and connected autonomous vehicles behave and how can this be translated into driving behaviour parameters in VISSIM?". This will be done using 4 categories; Wiedemann 99, Other following parameters, lane change parameters and autonomous driving. At first it was found which parameters needed to be adjusted, after which the correct parameter values were estimated.

To find the set of parameters which needed to be adjusted, different driving behaviours were compared. These driving behaviours are; weaving section from Goudappel, motorway from VISSIM, cautious AV from VISSIM, moderate AV from VISSIM and aggressive AV from VISSIM. The parameters which differ can be sorted in 4 categories; *Wiedemann 99* parameters, *Other car following* parameters, *Lane change* parameters and *autonomous driving* features. Each of these categories contain different parameters which vary in value between two or more types of AVs. In Appendix B Reference driving parameters Figure 30 until Figure 33 show all of the used parameters as well as the reference parameter values for all of the 4 categories.

5.1 Wiedemann 99

The Wiedemann model consists out of 10 variables. These variables all have a different value for at least one type of AV. Two types of changes can be noted; difference only between the conventional vehicle and the AV, or a difference which also impacted by the specific type of AV. The exact values of the AVs and the base type of AV along with the source behind it are in Table 7. The conventional vehicle uses the parameters from Goudappel and is also used as a reference. The cautious, moderate and aggressive AVs are also shown. The platoon AV uses the values from aggressive AVs for the main part, therefore only the differentiations will be shared in the text. The same goes for CAV which is also based on aggressive AVs. In Appendix A , Table 16 the full table, including platoon and CAV is given.

The parameters which are the same for all AVs are; following variation (CC2), negative and positive following threshold (CC4/CC5), speed dependency of oscillation (CC6) and oscillation acceleration (CC7). All of these values do not show a big difference between the parameters from VISSIM, considered as general, and the parameters from Goudappel, considered as the Dutch parameters, therefore VISSIM was taken as the main source. The following variation is 0 for AVs, this is because AVs actively make sure to keep a certain distance from the leading vehicle. Where humans are not as constant. The negative and positive following threshold are both closer to 0 for AVs, this is due to AVs being more sensitive. The sensors are always monitoring and responding where humans only notice and/or respond at bigger differences. Oscillation is partly due to a vehicle and partly due to human driving behaviour. The speed dependency is human and therefore the value of AVs is 0 for this parameter. For oscillation during acceleration however, only a part of the factor is removed, which is also why the value is lowered and not 0.

The other 5 parameters do change between the different types of AVs and are more focussed on the aggressiveness of the driver. These parameters are standstill distance (CC0), Headway time (CC1), Following variation (CC2), and the acceleration at 0 and 80 km/h (CC8/CC9).

The standstill distance from Goudappel is lower than the one of VISSIM (1 m instead of 1.5 m). This hints that the standstill distance in the Netherlands is lower. This aligns with the level of automation 4/5 values from the report of Bruijl (Bruijl, 2019). Therefore the values of I. Bruijl are taken for the standstill distance.

The headway time from VISSIM and Goudappel are both 0.9 seconds. VISSIM assumes that this value stays the same for moderate AVs but decreases for cautious AVs and increases for aggressive AVs. I. Bruijl follows the same pattern, however he picks lower values in level of automation 4/5. For level 3 he has higher values. Since level 4/5 of automation is an AV, these values have been taken.

The threshold for entering following has a similar value within the standard values of VISSIM and Goudappel, therefore the types of AVs from VISSIM for AVs are assumed to also be applicable for the Dutch motorways.

Standstill acceleration becomes higher when driving more aggressive, going from 3 for cautious to 4 for aggressive. Bruijl and VISSIM both use these values, therefore they are assumed to be applicable for this research as well.

The standard acceleration at 80 km/h parameter from Goudappel and VISSIM are the same, which leads to believe that the parameters from VISSIM are applicable for AVs as well. Bruijl takes higher values for level of automation 4/5. Since this research is about the future and features like these are improving within vehicles, this higher acceleration is assumed.

Table 7 Wiedemann parameters for cautious, moderate and aggressive AVs

Parameters		Base	Cautious	Moderate	Aggressive	Source
CC0 (m)	Standstill distance	1	1,25	0,75	0,75	I. Bruijl & VISSIM
CC1 (s)	Headway time	0,9	1,3	0,6	0,3	I. Bruijl & VISSIM
CC2 (m)	Following variation	4	0	0	0	I. Bruijl & VISSIM
CC3 (s)	Threshold for entering following	-8	-10	-8	-6	VISSIM
CC4 (m/s)	Negative following threshold	-0,35	-0,1	-0,1	-0,1	VISSIM
CC5 (m/s)	Positive following threshold	0,35	0,1	0,1	0,1	VISSIM
CC6 (1/(ms)	Speed dependency of oscillation	11,44	0	0	0	VISSIM
CC7 (m/s^2)	Oscillation acceleration	0,25	0,1	0,1	0,1	VISSIM
CC8 (m/s^2)	Standstill acceleration	4	3	3,5	4	I. Bruijl & VISSIM
CC9 (m/s^2)	Acceleration at 80 km/h	1,5	1,5	1,5	2,25	I. Bruijl & VISSIM

5.2 Other following parameters

Other following parameters are not about interaction with other vehicles but focus on what environmental features a driver sees and takes into account when making a decision. Instead of seeing a vehicle uses visual recognition to than be able to process it and take it into account. It consists out of 3 parameters which together determine the input for driver decisions. The first one is the maximum look ahead distance and the second and third are the number of observed objects and vehicles. The cautious, moderate and aggressive AVs have the same values. The platoon and connected AVs also have the same values. The values can be found in Table 8.

The number of observed objects and vehicles are bounded by two things. The maximum look ahead distance and the number of observed objects/vehicles. If there are less objects or vehicles within the look ahead distance, the limit is defined by the look ahead distance. If there are more objects or vehicles, the number of observed objects or vehicles is the boundary.

The maximum look ahead distance is 250 meters according to both VISSIM and Goudappel. According to VISSIM this is also the case for cautious and moderate AVs, for aggressive AVs it is 300 meters. However, the look ahead distance is due to the quality of the observation of the surrounding, therefore aggressive is assumed to be similar to cautious and moderate. Only platoon and connected AVs are assumed to have this better view.

The number of observed vehicles is set at 5 for conventional vehicles at Goudappel and VISSIM. The standard values in VISSIM are lower for cautious and moderate AVs, namely 1, and higher for aggressive AVs which observes 8 vehicles. This partly corresponds with the research from Bruijl, he assumed that AVs observe 3 vehicles, so less compared to conventional vehicles. This value will also be assumed for the cautious, moderate and aggressive AVs. The platoon and connected AVs are both assumed to be 8, which is the value VISSIM also uses for aggressive.

The number of interaction objects is also set at 5 for both Goudappel and VISSIM. VISSIM assumes the number of observed obstacles to be slightly higher than the number of observed vehicles for AVs. This assumption will be kept by assuming 4 for cautious, moderate and aggressive vehicles and 10 for AVs with platoon or connection.

Table 8 Other following parameters

Parameter	Cautious, moderate, aggressive AV	Platoon, connected AV	Conventional
Max look ahead distance (m)	250	300	250
Number of observed objects (-)	4	10	5
Number of observed vehicles (-)	3	8	5

5.3 Lane Change parameters

Next to (car) following, lane changes constitute a significant part of driving. Lane changes are divided into two groups, necessary and voluntary lane changes. Parameters used to model necessary lane change are listed in Table 9 and not necessary lane changes in Table 10.

Most parameters from VISSIM comply with the parameters from Goudappel, in which case the AVs parameters from VISSIM are assumed to be applicable for the Netherlands as well. This is the case for; maximum deceleration trailing vehicle and accepted deceleration for own and trailing vehicle.

The maximum deceleration for the drivers own vehicle differs significantly between VISSIM and Goudappel. The cautious AV type from VISSIM is lower than the moderate and aggressive AV type. A higher value is more aggressive, which means that the VISSIM parameters are more aggressive. According to Kesting, the maximum deceleration of one's own vehicle is 4 m/s^2 (Kesting, 2006). This corresponds with the VISSIM data, where only the cautious AV has a lower value (3.5). These values will be assumed for this research.

The deceleration reduction distance of one's own vehicle is the same as the one of the trailing vehicle in all the standard values of Goudappel and VISSIM. According to VISSIM, 200 m is suited for motorways and 100 for arterial roads for conventional vehicles, they however use 100 and 80 for AVs. Goudappel uses 100 for both motorways and weaving sections. The value does not seem to be extremely different for AVs however it does depend on how careful a vehicle drives, therefore the cautious AV has a slightly lower value in comparison to moderate and aggressive, which are set at 100.

The safety distance reduction factor influences when a vehicle changes lanes. The maximum value is 1, and if this is the case the safety distance is not lowered in order to change lanes. When the value gets lower, with a minimum of 0.1, the safety distance is getting smaller. This increases the possibilities of a lane change. Whether the vehicle changes lanes is also dependent on the following distance. Goudappel takes a value of 0.1 for the reduction factor and VISSIM 0.6. The AVs from VISSIM all differ from each other. The cautious AV is 1, moderate 0.6 and aggressive 0.75. At first glance it might seem strange that aggressive has a higher value than moderate. However when taking the original safety distance into perspective, it can still be seen that the reduced safety distance is lower for aggressive AVs compared to moderate AVs, this can be seen in Table 17 in Appendix A Used driving behaviour parameters. This difference is significantly smaller than the difference between cautious and moderate. For this research the values from VISSIM are assumed to also be applicable for the Netherlands.

The maximum deceleration for cooperative braking ranges from -10 to -1 m/s^2. When the value gets further towards -10 m/s^2, the stronger the vehicle brakes and the higher the chance of changing lanes. VISSIM uses the value 3 m/s^2 for motorways and lowers it to 2.5 m/s^2 for cautious AVs. It is increased to 6 m/s^2 for aggressive AVs. These values however, are all significantly lower than the value from Goudappel, which is 9 m/s^2. This value is used for both motorways and weaving sections. This value is higher than the maximum braking of most street vehicles (Sawicki, 2013) . Therefore this seems unlikely behaviour at an motorway and the values from VISSIM are assumed to be correct.

Cooperative lane change is not included in conventional vehicles according to both VISSIM and Goudappel, it is however likely to be a feature in AVs. VISSIM assumes no cooperative lane change for cautious AVs but does for the other AVs. The same assumption has been made for this research.

Table 9 Necessary lane change parameters

Parameter	**Cautious**		**Moderate**		**Aggressive**		**Conventional**	
	Own	Trailing	Own	Trailing	Own	Trailing	Own	Trailing
Maximum deceleration (m/s^2)	-3.5	-2.5	-4	-3	-4	-4	-3	-3
-1m/s^2 per distance	80	80	100	100	100	100	100	100
Accepted deceleration (m/s^2)	-1	-1	-1	-1	-1	-1.5	-1	-0.5

Table 10 Not necessary lane change parameters

Parameters	Cautious AV	Moderate AV	Aggressive AV	Platoon and connected AV	Conventional
Safety distance reduction factor	1	0,6	0,75	0,75	0,1
Maximum deceleration for cooperative braking (m/s^2)	-2,5	-3	-6	-9	-9
Cooperative lane change	No	Yes	Yes	Yes	No

5.4 Autonomous driving

Autonomous driving is a relative new feature within VISSIM and has three options. The first one is enforce absolute braking distance. The second feature is implicit stochastics and the last one is platooning. For the first two little research was found, which is why the values from VISSIM copied. The last one platooning was used for the platooning AV, the used values can be found in Table 11.

Table 11 Autonomous driving settings

Setting	Cautious AV	Moderate AV	Aggressive AV	Platoon AV	CAV	Conventional
Enforce absolute braking distance	Yes	No	No	No	No	No
Use implicit stochastics	No	No	No	No	No	Yes
Platooning	No	No	No	Yes	No	No

6. Results

After the different AVs were modelled, the data was collected and the capacities have been calculated. This was done for all 26 scenarios. First the different types of AVs will be shown, the base scenario will be included in all of them. The first one, cautious will be more elaborate and also includes a more elaborate explanation of the method. In Appendix C all of the graphs excluding capacity are shown. Below the graphs a table with the capacities and percentual changes is given. After the types of AVs have been analysed separately, the data of the different AVs will also be compared to each other. Ending with a more extensive elaboration on the standard deviation and variety of the capacities.

6.1 Capacity of Cautious AVs

After the model has more than 100 of capacity values for each scenario. Intervals of 400 veh/h were made. For each interval the values within and below were counted. This is to get the cumulative capacity values. For the base scenario and all of the cautious AV scenarios this gave the values displayed in Table 12. Left the capacity value is shown and on top the scenarios. Each number represents the amount of 5 min intervals with a lower capacity value than the capacity value given in the left column. As can be seen none of the scenarios have a capacity value below 2000 veh/h and none above 6400 veh/h. Between the different columns some different values can be spotted. Amongst these values are the ending values which are not due to a difference in capacity value, but due to a different amount of capacity values in total. This makes comparing difficult. This difference in the ending number is due the amount of times congestion appeared within a 5 minute interval.

Table 12 Cautious AV cumulative capacity values (absolute values)I

Capacity-value	Base	20% cautious AV	40% cautious AV	60% cautious AV	80% cautious AV	100% cautious AV
2000	0	0	0	0	0	0
2400	0	1	0	0	0	11
2800	0	17	0	0	0	93
3200	0	17	0	0	1	158
3600	0	18	0	0	4	168
4000	0	18	0	0	10	171
4400	0	18	0	0	19	172
4800	7	20	1	0	24	173
5200	80	88	69	58	54	173
5600	117	143	158	151	152	173
6000	123	148	165	165	172	173
6400	123	149	168	168	173	173
6800	127	149	168	168	173	173
7200	127	149	168	168	173	173
7600	127	149	168	168	173	173
8000	127	149	168	168	173	173
8400	127	149	168	168	173	173
8800	127	149	168	168	173	173
9200	127	149	168	168	173	173
9600	127	149	168	168	173	173

Due to the different ending values, the relative numbers were compared. All intervals are ending with 100 percent and for all of the intervals before the percentage of the final number is calculated. These numbers give the graph in Figure 10. As can be seen the base scenario and the scenarios up to 80% cautious AV are all very close. The 100% AV scenario however is not. To determine if this is realistic, a penetration rate of 90% and 95% have been simulated as well. These results can be found in Figure 11. The two added lines are dotted and show results similar to the 100% penetration rate.

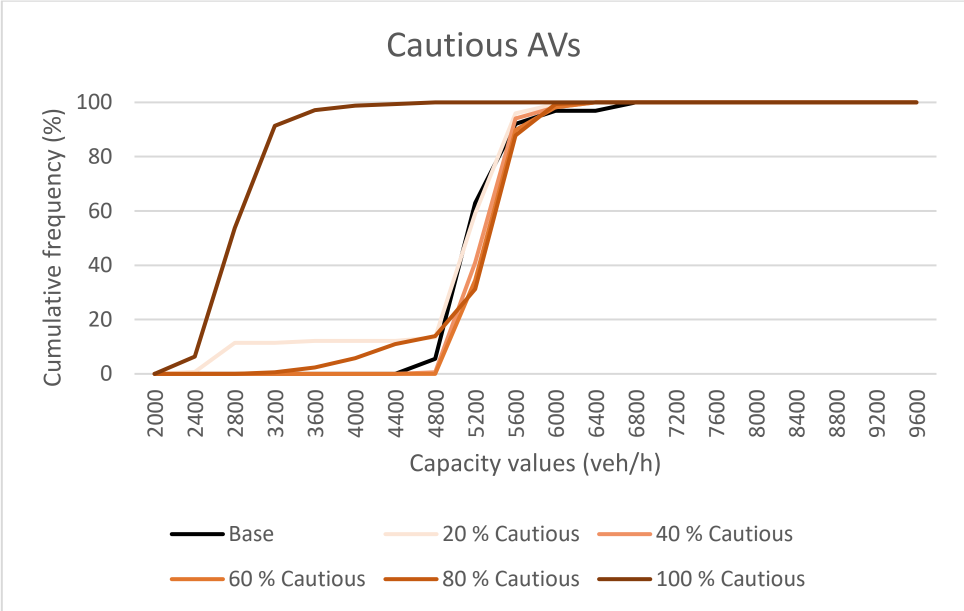

Figure 10 Cautious AV cumulative frequency graph

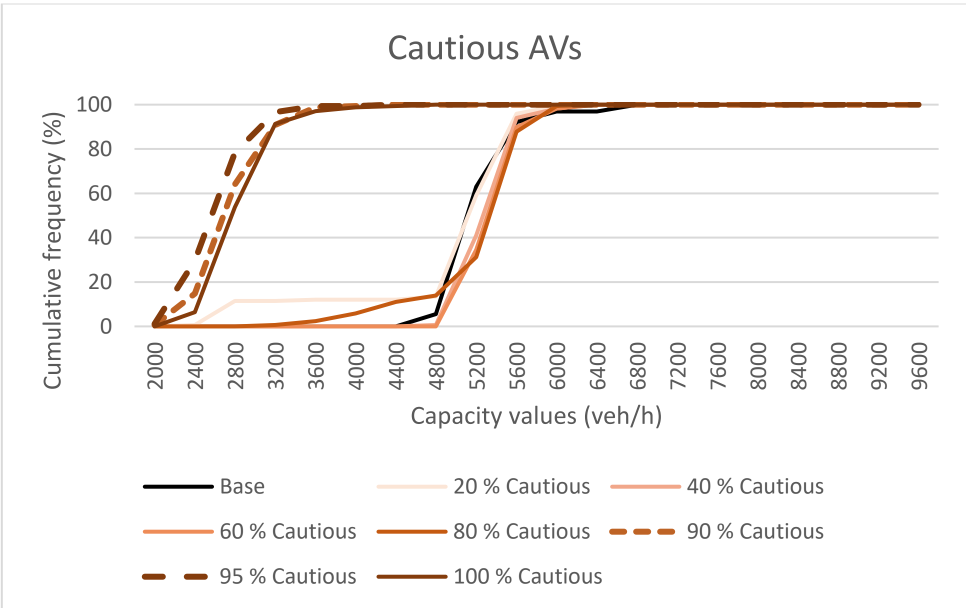

Figure 11 Cautious AV cumulative frequency graph including 90% and 95% penetration rate

The reason for this divergent value seems to be due to the low speeds. In Table 13 the average speed during congestion is given. In the table it can be seen that the speed slowly drops and is drastically lower for the 100% cautious AV scenario. This is likely to be the cause or a part of the cause since 90% and 95% penetration rate show similar results to 100% penetration rate. In Figure 4 and Figure *5* in Chapter 3.2 Capacity fundamental graphs show the relation between flow and, speed and capacity. The negative relation for congestion capacity between speed and capacity explains the relation which can be seen in the 100% cautious AV scenario. Since the results of 3 scenarios show similar results, it does not seem to be a flaw within the specific scenario. The cause of the low speed is the interaction between the vehicles, which gets AVs 'stuck' within the network or lets them decelerate unnecessarily. This leads to blocked roads and therefore an instant slow speed congestion. This behaviour has barely happened with the scenarios with other penetration rates. The strange behaviour of these AVs is yet unexplained.

Table 13 Average speed during congestion for base and cautious AV scenarios

	Base	20% cautious AV	40% cautious AV	60% cautious AV	80% cautious AV	100% cautious AV
Speed (m/s)	48,09	47,55	46,61	44,29	37,01	9,23

Now that the outlier has been accounted for, the other lines look quite similar. They differ slightly but all have their mayor increase on the same spot. At this point the lines are slightly apart, but they do not show a logical order. This would, for example, be starting with a low penetration rate of AVs at the left and increasing towards the right. Therefore, the capacities will be calculated next after which a graph with a smaller range of capacity values is shown.

The capacity is median. This is the number which is in the middle when the list is sorted from low to high. If the data set is uneven, this returns one number which is the median. If it is even, it returns two values of which the average is taken. The capacities are displayed in Table 14. Here it can also be seen that all scenarios are relatively similar, except for 100% cautious AV.

Table 14 Capacities of cautious AV scenarios

	Base	20% cautious AV	40% cautious AV	60% cautious AV	80% cautious AV	100% cautious AV
Capacity (veh/h)	5118	5160	5241	5280	5322	2748

These values are the median of more than 100 capacity values. The cumulative capacities already show the values to differ quite a lot. This could be due to the random seed or the interval within the run. This deviation between the values can be calculated and expressed as a standard deviation. The formula is displayed and explained in Appendix D Variance and standard deviation. The calculation revolves around the difference between the average and one value out of the set. Comparing every value one by one. This standard deviation can be added and subtracted from the capacities displayed in Table 14. This gives the range of how the actual capacity could deviate from the capacity calculated. These ranges are given in Figure *12*. The orange line shows the capacities as displayed in Table 14 and the vertical black lines show the possible deviation. As can be seen, the deviations can be quite big, showing most values to not be significant. Only the 100% penetration rate shows a significant result, mainly due to the low capacity and not due to the significantly lower deviation.

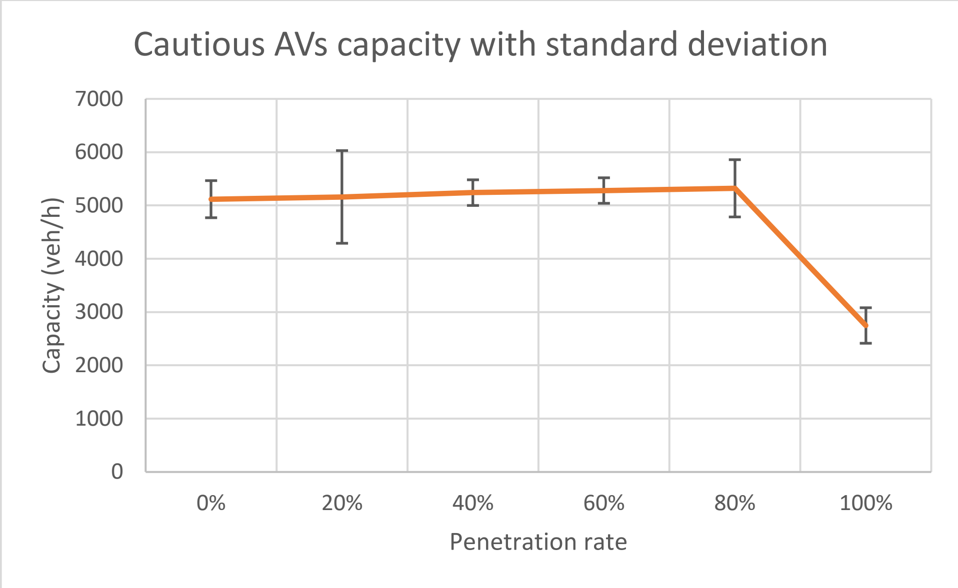

Figure 12 Cautious AVs capacity with standard deviation

Figure 10 is a zoomed in graph of the cumulative frequencies of the cautious scenarios, the 100% cautious AV data was left out of this graph since the capacity is not within the range of the x-axis. The capacities were added to the graph, to take a closer look at the results. The graph is still looks quite unorganised when looking at the cumulative frequencies. The median however show a clearer trend, showing that cautious AVs slowly increase the capacity at a quite constant pace. Only between the line of 20% and 40% AVs a bigger increase is spotted. However when looking at both Figure *12* and Figure 13, no significant results were found.

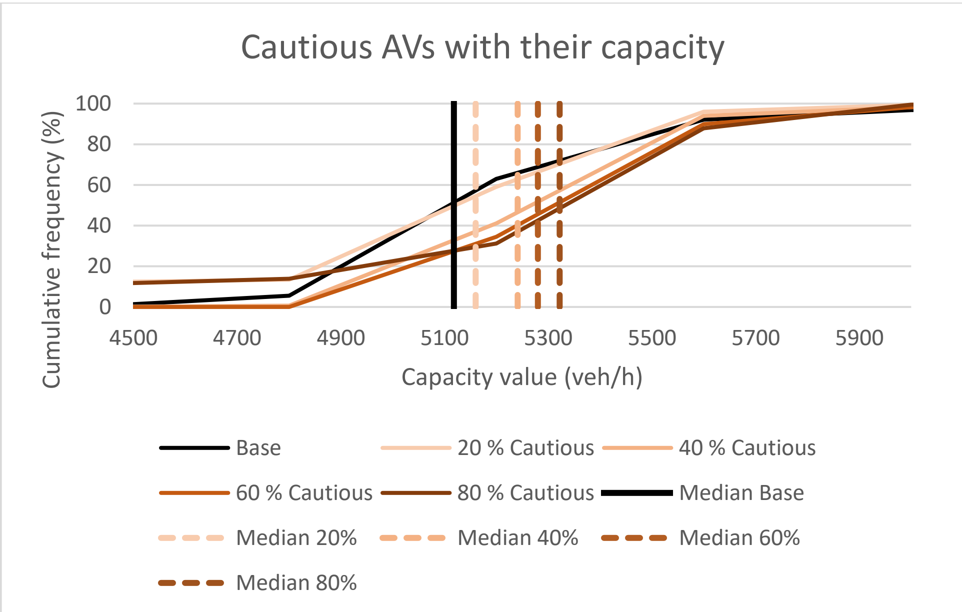

Figure 13 Cautious AVs with their capacity

6.2 Moderate AVs

For moderate AVs the same steps have been taken. The steps gave the graph displayed in Figure 14. The first base line starts to rise the quickest. After that the lines start to increase from low penetration rate AV to high. This is result corresponds the expectation that, AVs have a positive influence on the capacity. When looking at the capacities it looks like an increasing effect is at hand.

This can also be seen in Figure 15, where the medians were plotted. In this line a curve can be spotted. This shows this increasing impact. The exact values of the medians can be found in Table 18 in Appendix C Cumulative frequency graph. The graph also shows the standard deviation. The deviation, unlike for cautious AVs, do show a significant difference. The ranges do not overlap between most scenarios. Meaning it is not certain that 20% penetration rate is an improvement compared to only conventional vehicles, 60% however is. This ensures a positive influence. The shape of the graph is however still uncertain since differently sloped and curved lines could fit within the ranges.

Next to the location of the lines in Figure 14, the slope of the graph can also be noted. The slope is the biggest for the base scenario and slowly decreases when increasing the penetration. This shows the base scenario to relatively have the most values within one or two intervals. Where this is more spread out for the 100% penetration rate. This trend along the different scenarios, does not fall in line with the standard deviation. This difference is in the values considered. For the slope it matters how many capacity values are within one or two intervals. If a value is not within those boundaries, it does not matter how much it deviates. For the standard deviation, the values furthest from the average count the heaviest. Therefore the two indicators can show completely different results.

To conclude moderate AVs have a positive influence, which possibly is exponential. Next to this the capacity values seem to spread out more, when increasing the penetration rate of moderate AVs.

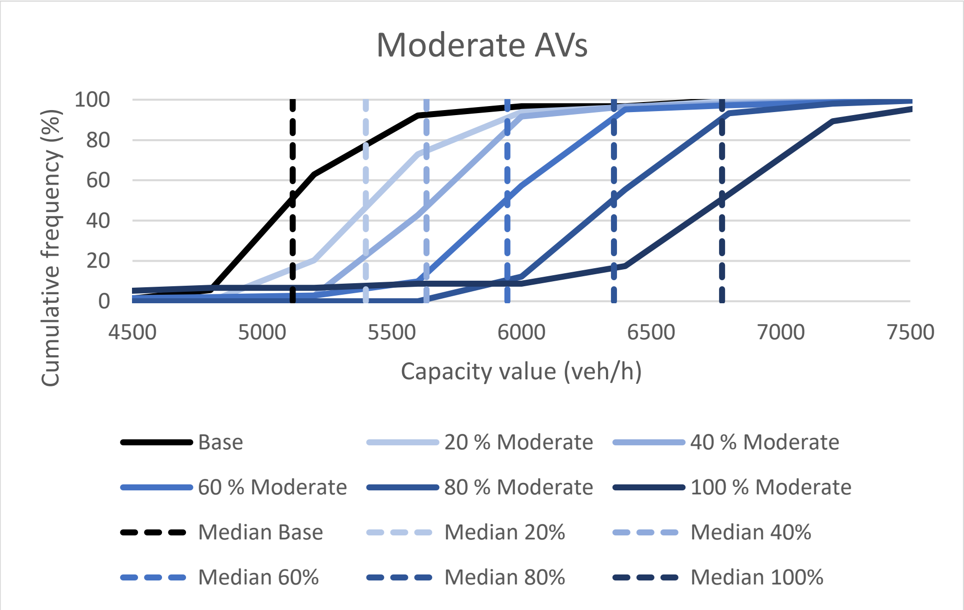

Figure 14 Moderate AVs with their capacity

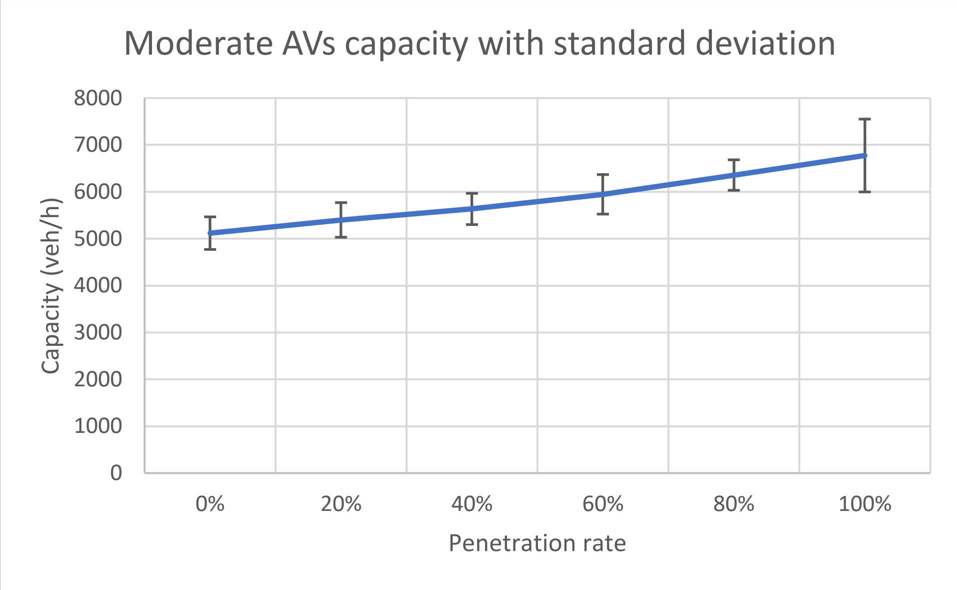

Figure 15 Moderate AVs median

6.3 Aggressive AVs

The results of aggressive AVs look similar to the moderate AVs, as can be seen in Figure 16. The AVs show to have a positive influence on the capacity. Figure 17 shows the capacity and their standard deviation. The capacity shows to increase with every increase of penetration rate. The trend within the increase however is different from moderate. It at first increases slower and from 40% penetration rate starts to show an exponential trend. The deviations are quite constant along the line and show significant results, meaning the aggressive AVs having a positive influence on the capacity of a weaving section. The deviations however are too big to make conclusions about the trend within the increase of capacities.

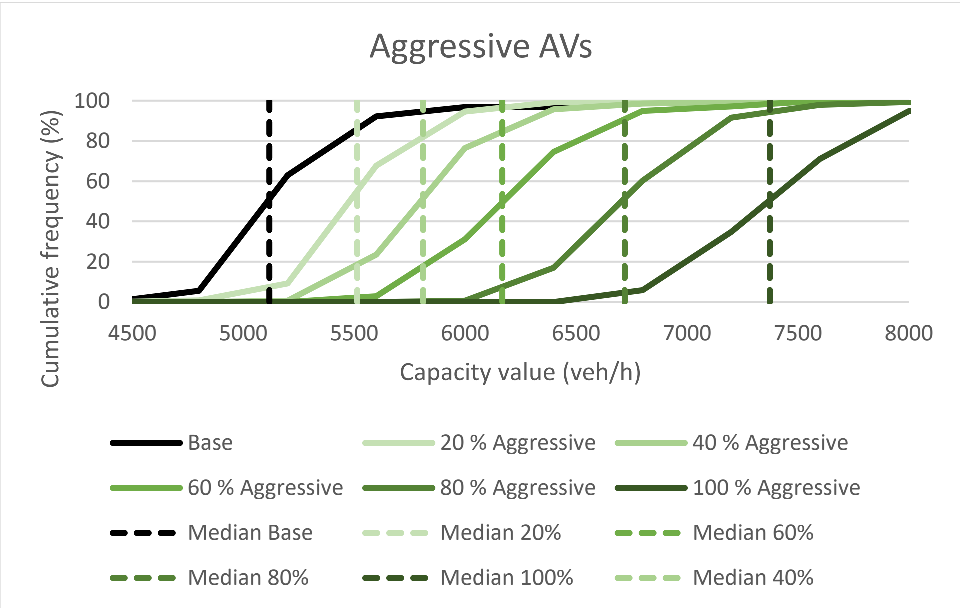

Figure 16 Aggressive AVs with their capacity

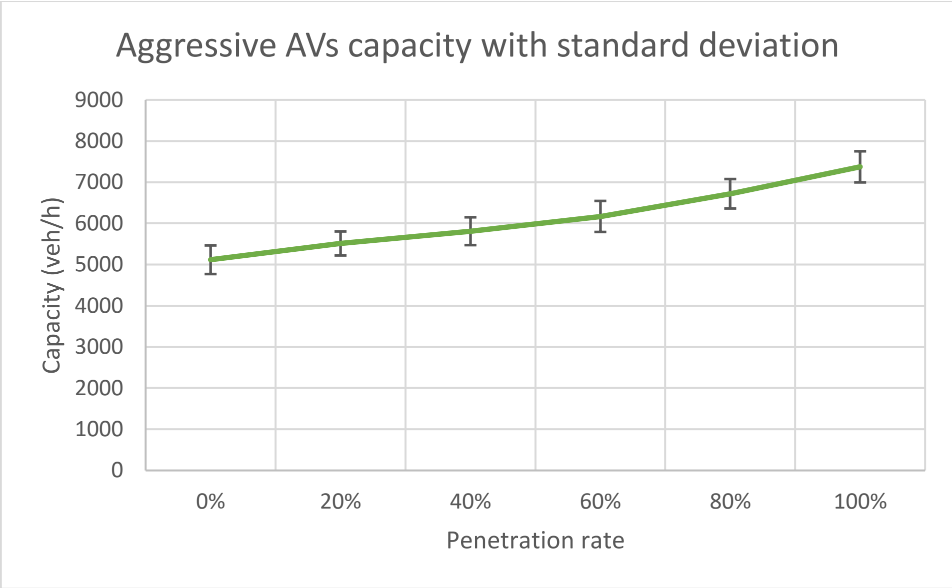

Figure 17 Aggressive AVs capacity with standard deviation

6.4 Platoon AVs

Figure 18 shows two things which were also noted in previous scenarios. The first one is the 100% scenario which is an outlier, similarly to the cautious AVs. Here the outlier, as well as the positive influence, shows to be significant. The outlier does still seem to show a mistake within the simulation. The cause is again due to the vehicles driving at a very low speed. To confirm this, a 90% and 95% penetration rate scenario were executed and added in Figure 19 by the dotted lines. The 90% and 95% penetration rate are almost identical, also coming close to the 100% penetration rate scenario. Similar to the cautious AVs, vehicles started to show unrealistic behaviour by decelerating unnecessarily and getting stuck trying to switch lanes. This behaviour is the cause of the low capacity, however the cause for the behaviour is was not found.

The second notable thing can be seen best in Figure 20 and Figure 21 were the capacity again shows to rise with an increase of AVs and similar to the aggressive AV the increase in penetration rate is not constant. The slopes of the graphs in Figure 20 seem to decrease when reaching higher penetration rates, this difference is however quite small. Similar to the moderate and aggressive AVs, a positive influence is certain due to the deviation of the results not showing overlap on all scenarios.

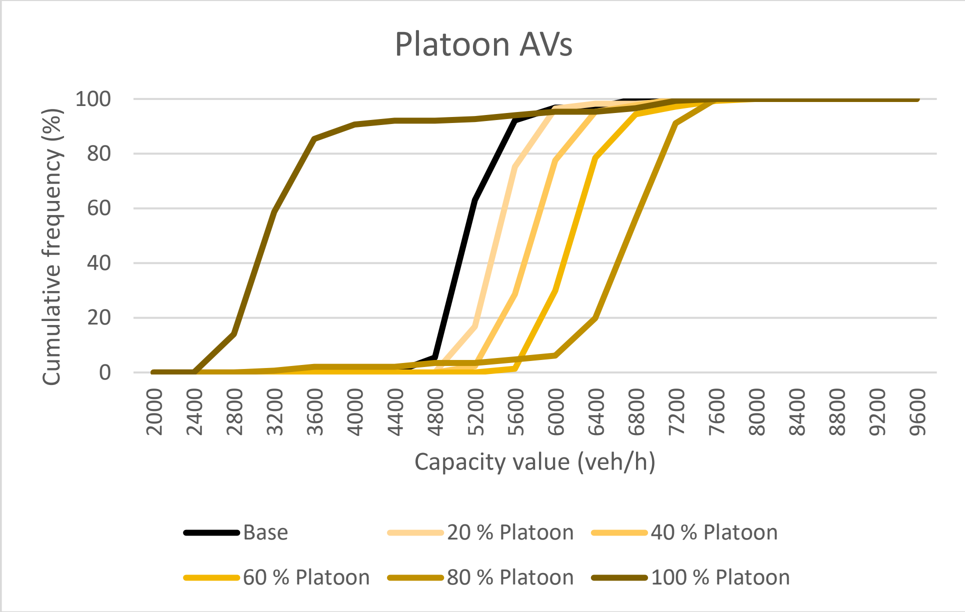

Figure 18 Platoon AV cumulative frequency graph

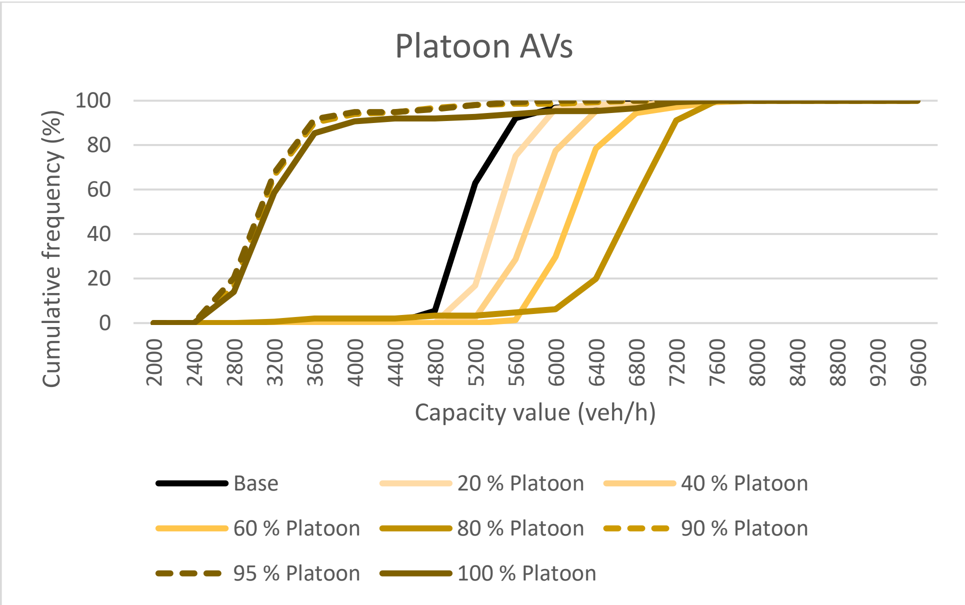

Figure 19 Platoon AV cumulative frequency graph including 90% and 95% penetration rate

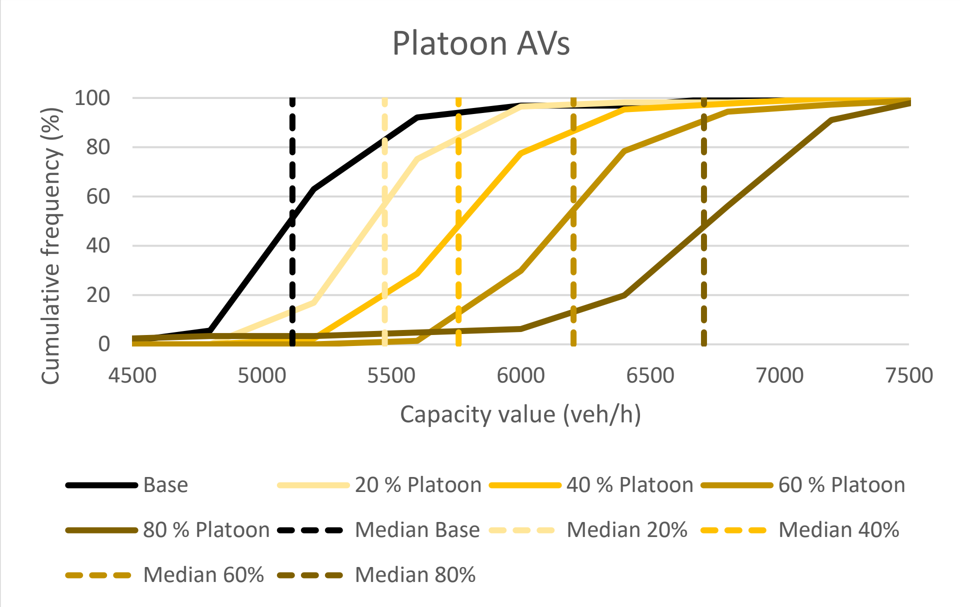

Figure 20 Platoon AVs with their capacity

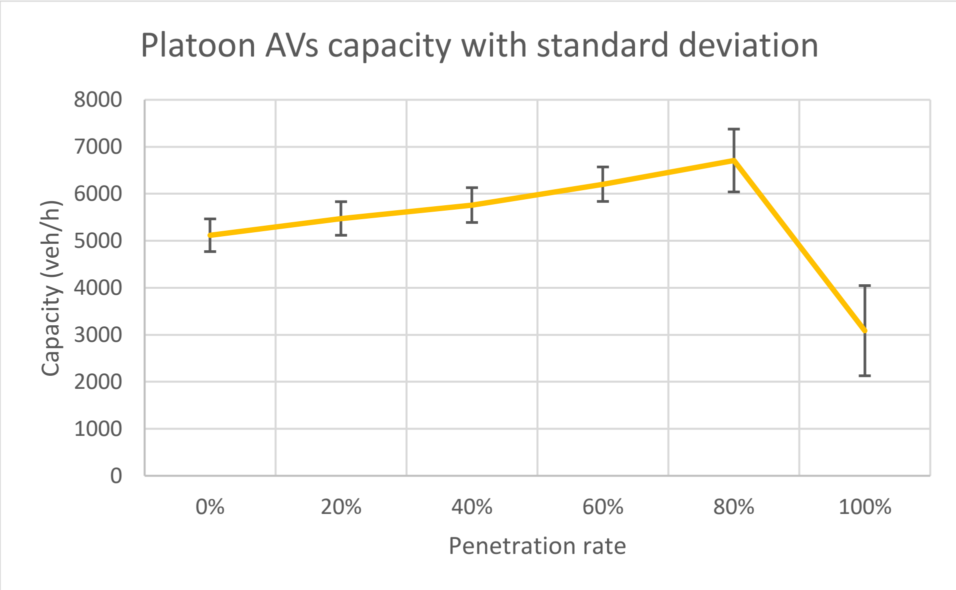

Figure 21 Platoon AVs capacity with standard deviation

6.5 CAVs

CAVs again show a similar trend. Which is increasing the capacity and doing it with a non-linear trend. This can be seen in Figure 22 and Figure 23. The standard deviation of the 100% penetration rate is bigger than the standard deviations of the other scenarios. Nevertheless the results show significant results. Meaning CAVs similar to previous AV types, have a positive influence on the capacity. The slopes of the graphs in Figure 22, are not showing a clear trend, unlike the previous AV types. The shapes look less different and more random, this could be due to the chosen interval. It shows for the 20% CAV scenario a big increase between 5200 and 5600 veh/h, the higher interval shows only a small increase. In contrast the 60% CAV scenario shows a big increase in two following intervals. It could be the case that a large part of these values could fit within one interval if it would be 5800 – 6200 instead of 5600 – 6000 and 6000 – 6400. Therefore, no conclusions can be made about the slope of the graph.

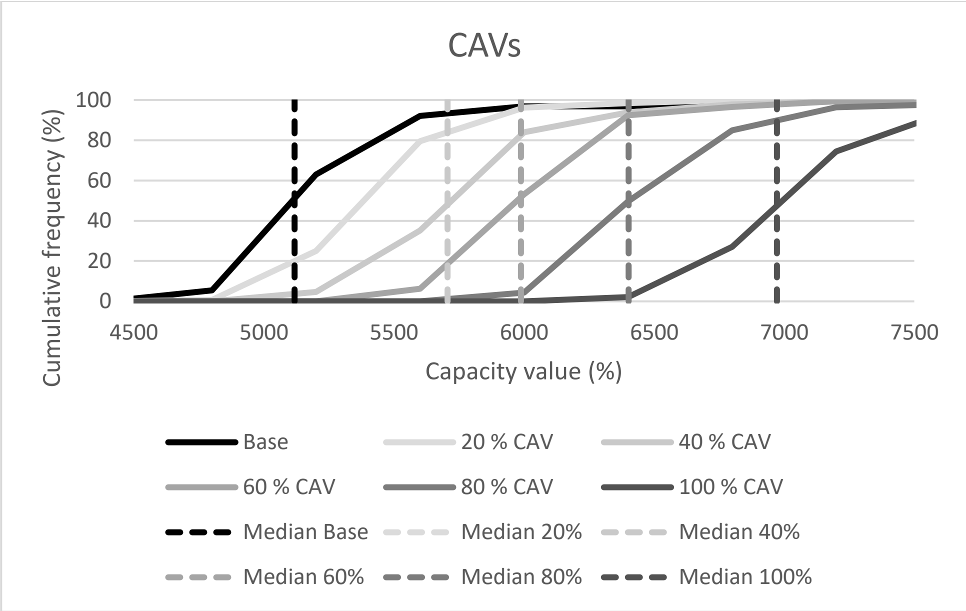

Figure 22 CAVs with their capacity

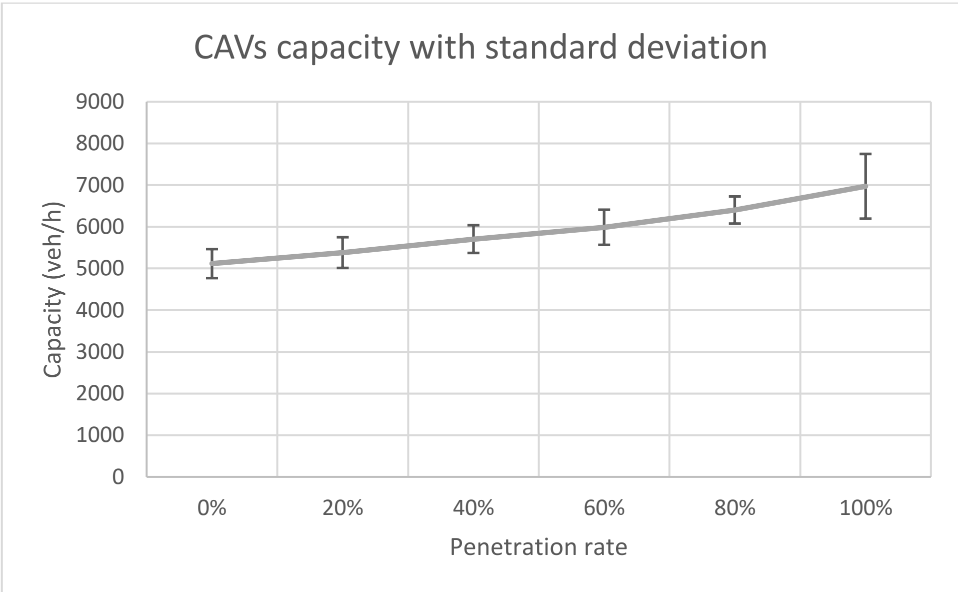

Figure 23 CAVs capacity with standard deviation

6.7 Comparison 40% and 80% scenarios

Next to knowing the effect of the different AVs, it is also useful to compare them to each other. This will be done for 40% and 80% penetration rates of AVs. Since a 100% penetration rate of AVs has two unlikely graphs this comparison would be less useful, therefore 80% and half of that are compared.

Firstly the 40% AVs were compared. In Figure 24 the result is shown. Two clusters of lines can be seen. Firstly the base and cautious scenario, which was also noted before. Secondly the moderate, aggressive, platoon and connected AVs are close to each other. The cautious, moderate and aggressive AVs are in order of least to most aggressive which is logical since more aggressive vehicles for example drive closer together or accelerating quicker. Next the CAV is between the moderate and aggressive scenario. This is again can be reasoned since the CAV behaves as a moderate or aggressive vehicle, depending on the vehicle in front. The platoon AV has a smaller influence on the capacity compared to the aggressive scenario, this might be due to platooning vehicles acting like a barrier for vehicles which want to switch lanes. However this is not certain.

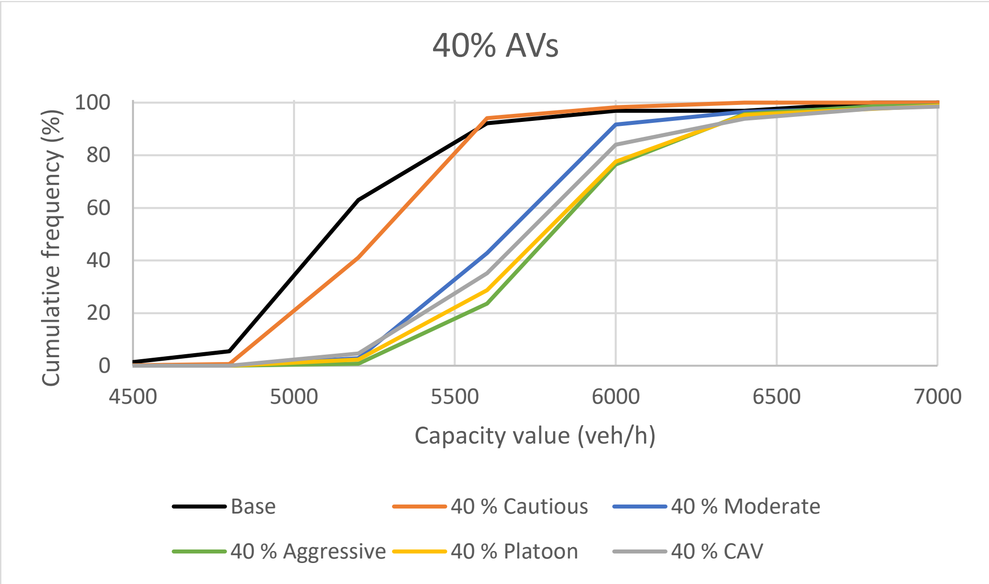

Figure 24 40% AVs comparison cumulative frequency

Figure 25 shows the different AVs with an 80% penetration rate. Here the same two clusters can be spotted, however they are further apart. The cautious AVs show again not to have a big influence on the capacity of a weaving section. The moderate and aggressive AVs are further apart but still show similar relations. The CAV has come closer to the moderate scenario instead of the aggressive scenario. This was expected to be the other way around, since the chance of having another CAV in front is bigger and therefore the chance of acting as an aggressive vehicle also becomes bigger. The platoon vehicle still is almost identical to the aggressive AVs, this would mean that the advantages and disadvantages of platooning weigh each other out.

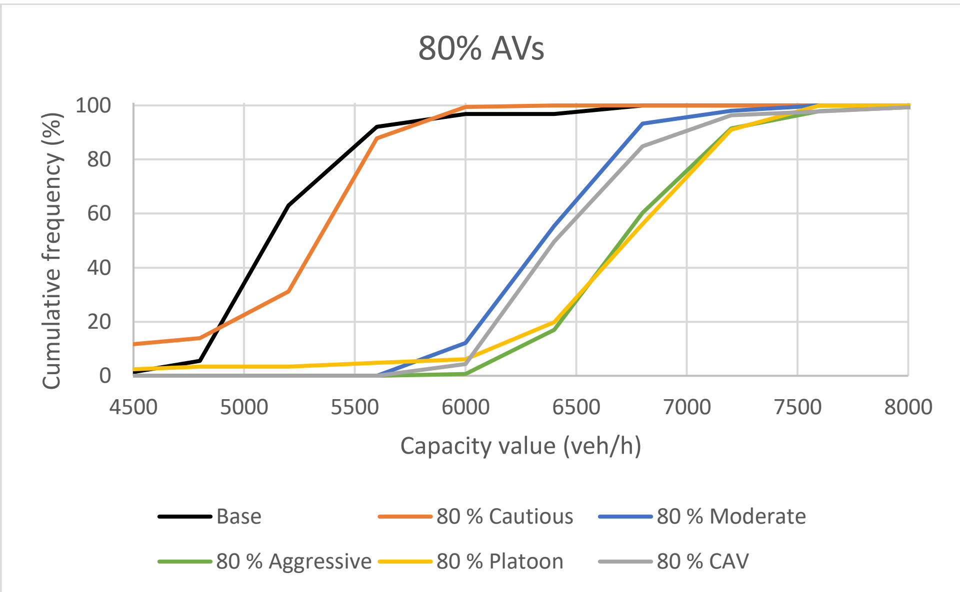

Figure 25 80% AVs comparison cumulative frequency

6.8 Comparison capacities all scenarios

Figure 26 shows the capacities and percentual changes along the different penetration rates. All of the lines start with 0%, which is the base scenario. After this the cautious AV line stays relatively horizontal, until it drops for the 100% scenario. The other lines all significantly go up. The moderate and connected AV have a similar line. The platoon and aggressive AV have the most impact and are similar until 80%, after which the platoon AV line drops. This shows that aggressive AVs have the biggest impact on the capacity of a weaving section, the addition of platoon to aggressive AVs does not have a big impact.

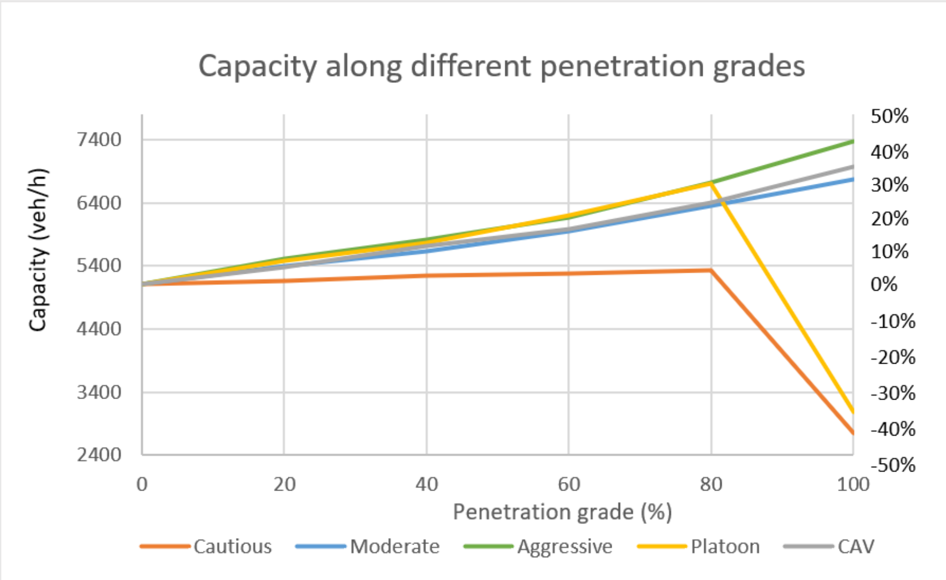

Figure 26 Capacity along different penetration rates

6.9 Standard deviation and variety capacity values

Next to the capacities and slopes of the graphs, the deviation and variety could show us some more about the results. The variance and standard deviation were calculated for all scenarios. Both give an indication of the variety in the data set and have their main focus on the big outliers.

The deviations have already been used to show the significance of the capacities, however it could also show more. In the previous chapters the slope has already been considered, focussing on the values in the middle of the set. However, a similar comparison could be done for the values near the edges of the set. To compare these, in this section the deviation will be discussed however in Appendix D Variance together with the calculations of both the variance and the standard deviation is given.

The standard deviation is shown in Figure 27. The cautious AV has a varying standard deviation across all of the penetration rates. At 20% a peak is spotted; this is likely due to the intervals with a flow of between 2400 and 2800 veh/h. This can also be seen in Figure 10, were this shows an increase, after which the line is low again. This is due to one of the 9 runs and therefore might be an error. If this is the case could be known and the impact could be lowered by executing more runs. At 80% a similar small peak can be found. This is again mainly due to one run, were the flows were mainly below 4400 veh/h. This is however closer to the average, as can also be seen in the standard deviation.

Moderate and platoon show a constant beginning but increase after 60% and 80%. For 100% moderate AVs and 80% platoon AVs this cause is the same as for cautious. For 100% platoon AVs the cause is different. The variance is not in the lower values but the higher ones. Here the first one to three values of every run are drastically higher.

The aggressive and connected AV show similar results and are also constant along the different penetration rates.

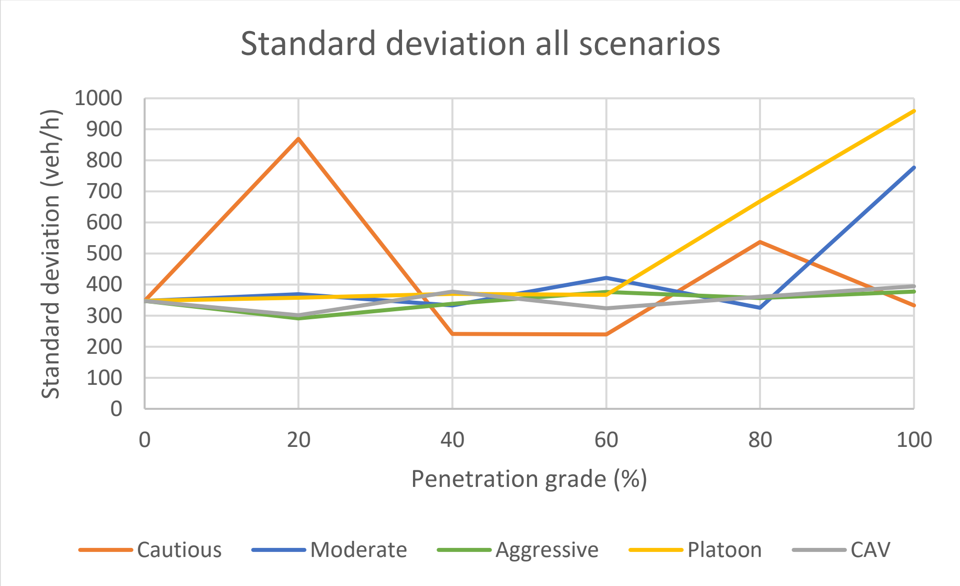

Figure 27 Standard deviation all scenarios

By not taking into account the variables, which were described above to be the reason for outliers. The following graph is made, Figure 28 Standard deviation all scenarios after adjustments.

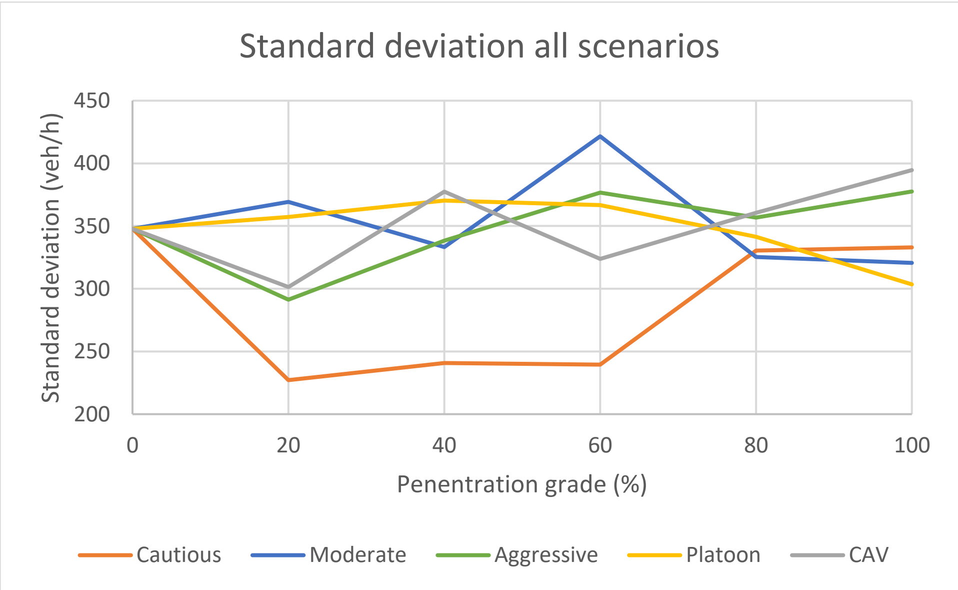

Figure 28 Standard deviation all scenarios after adjustments

To see if these changes make a big influence, the capacities are placed in Table 15. The differences are quite minimal and below two percent. Next to that minimal changes have also been spot in other scenarios, which therefore could be due to the random seed. Therefore, these changes will not be used in the rest of the report.

These graphs show the standard deviation, which means it looks at differences between the different runs. This can be due to a random seed and for example vehicles switching lanes effortlessly in contrast with vehicles blocking one or two lanes trying to manoeuvre to the right lane. It could also be due to inconsistencies in other areas of the model. Vehicles always accelerating and decelerating in the same manner and removing other aspects which normally vary for each vehicle. One driver accelerates quicker than the other and maybe even quicker during some trips and time frames. Next to this, one vehicle can accelerate quicker than the other. By giving modelling each vehicle to act in the exact same way, some deviation might be removed from the equation. Giving a lower overall deviation. In Figure 28 cautious, moderate and platoon AVs show a lower deviation at 100% penetration. Aggressive and CAV however increased with 100% penetration rate compared to the 0% penetration rate. Due to the deviation of a few scenarios massively changing by removing the outliers, it is too little data to make conclusions out of it. Next to this the lines vary along the penetration rates, not showing a clear trend leading up to the 100% penetration rate.

Table 15 Capacities before and after changing outliers

	Capacity before (veh/h)	**Capacity after (veh/h)**	**Difference (veh/h)**
Cautious 20%	5160	5184	24
Cautious 80%	5322	5343	21
Moderate 100%	6774	6807	33
Platoon 80%	6708	6741	33
Platoon 100%	3087	3045	42

7. Discussion

The research has encountered different decisions and aspects which led to discussion. These aspects are described below.

First of all, the data which was collected was enough since outliers did not mayorly impact the results as was found in 6.9 Standard deviation and variety capacity values. However the 100% Platoon AV and 100% cautious scenario, showed big changes between two intervals, as for platoon 100% can be seen in Appendix E Capacity values 100% Platoon AV. This shows that a capacity can change drastically over 5 minutes. This might be partly due to an increase in flow from 10 minutes before the measurement instead of 5 minutes. Therefore, waiting longer while increasing the flow to the next step might also give more values along the line of going from a small to a big congestion and therefore along the different speeds.

For this research the CIA was used and the best method according to the manual was executed for congestion capacity. There are however many different methods. These methods could have been better compared to choose the best suited method. Also, more methods could have been executed to be able to compare them. Possible flaws could be filtered this way.

Similarly, the program VISSIM was chosen right at the start. This is program is suited for the research, however FOSIM in theory would have suited better. FOSIM is developed to simulate Dutch motorways, while VISSIM is developed to simulate both motorways and urban traffic situations. This is likely to make a difference due to the underlaying methods and values. This difference for example surfaces with the capacity drop, which has proven to be smaller in VISSIM compared to FOSIM. The choice for VISSIM was made at the start based on previous experiences with the software and the ability of the software to include autonomous vehicles in a rather simple manner. FOSIM might however have been the better option, due to its focus on the Dutch motorway system. Since this research also simulates a weaving section resembling a standard situation within the Dutch motorway network.

The program VISSIM was as mentioned partly chosen for its driving behaviour options, which includes cautious, moderate and aggressive AVs. This was very useful, but the parameters may have had too much influence. By finding the differences between parameters from conventional motorway vehicles from VISSIM, the three AV types from VISSIM and weaving lane behaviour from Goudappel, the interesting parameters were determined. If the parameters from VISSIM and Goudappel fell in line, in terms of conventional motorway vehicles, the parameters from VISSIM for AVs were considered likely to be correct. Meaning only a few were also compared to literature review. More research could have gone into these assumptions, whilst considering a wider range of sources.

This research is about vehicles in the future, this means that real-life observations are not possible. There are however some test for AVs. These tests could have given an indication as to whether the model and output of the research are correct. These tests would probably be in a different environment, so a complete comparison or validation would not be possible. The model could have been altered to the situation of the test to see if similar results show up. If this were the case, at least some of the results would have been verified.

Wiedemann has made two models, one in 1974 and one in 1999. The version from 1999 was an improvement which was best suited for motorways (Balich, 2019). It is however unclear if this is also the case for weaving sections. These doubts are due to the high number of lane changes.

In the research 5 different types of AVs were simulated. These types vary on different parameters. The results showed differences between the types of AVs however it also could have been useful to know which parameters influence the capacity the most, this could be done by a sensitivity analyses. It would give a better explanation as to why the vehicles behave differently. This explanation has now been done by logically reasoning, however this leads to possible positive and negative influences. Of which the relative and actual size are unknown. Instead an actual number to be able to compare them would have given clearer causes for the results.

For this research only one weaving section was simulated. This gives an image of a very specific situation. It would be helpful to know if it is also the case for other weaving sections, and preferably even more traffic situations. This helps to get a bigger picture and also adds to the knowledge gab illustrated in 2.1 Problem statement. Adjusting the weaving section could be done by altering the relative flows, the length of the weaving section and the amount of lanes of one or both motorways.

The network of the model consists out of 2 lanes entering, a weaving section and two lanes going out. The two lanes going in are fairly short, being only 200 m. Traffic flows take longer to get into the rhythm of slower vehicles driving right and being able to pass on the left side. Also platoons might take longer to form which means that the current situation mainly has platoons who are forming within the weaving section. This is not realistic which is why the incoming lanes should be longer for better platooning analysis.

Autonomous vehicles are expected to always make the same decisions in similar circumstances. This is realistic, since a self-driving system goes through the same methods each time to reach a decision. With this it is however also assumed that all AVs drive the same, meaning all manufacturers offer the same system. This is not realistic. For some values it might be close, for example when regulations state a minimum and manufacturers have found the optimal value to be lower. Even in this case manufacturers will likely include a small safety to ensure passing possible test. This is currently also happening with speed: when the speedometer displays a speed of 100 km/h, it might actually be 95 km/h to ensure the manufacturer will not get sued. Similar aspects are expected for autonomous vehicle settings, therefore keeping a difference between different vehicles. When the optimal value is within limits, vehicles could even be further apart, all aiming for a different value. This could have been done by for example including spreads in the exact parameter values. These driving behaviours would than drive together on the road, just like the different types of vehicles and freight traffic do in the model used for this research.

The scenarios cautious and platoon AV with 100% penetration rate showed some strange results, leading to a closer look at the final part of the increase of penetration by also simulating a 90% and 95% penetration rate scenario. These showed to be in line with 100% penetration rate. However they still made a huge gap between the 80% and 90% penetration rate results. An extra scenario of 85% penetration rate could have helped with this. Also for the relation between the different capacities and the penetration rate, more scenarios could have helped. However for this the main improvement would be more runs to gather more data.

8. Conclusion

The research question is "How do different types of AVs influence the capacity of a 2 by 2 weaving section in different penetration levels?". The sub-questions will be answered first to than answer this main question.

How do cautious, moderate, aggressive, aggressive + platoon and connected autonomous vehicles behave and how can this be translated into driving behaviour parameters in VISSIM?

The behaviour of AVs is different in two aspects. Firstly, the removal of the human features like reaction time and inconsistency. Secondly, by being able to remove inconsistency, human error also gets removed. This leads to possibilities like driving closer to each other.

This was translated by altering parameters within the following categories; *driving behaviour parameters*, *other following parameters*, *lane change parameters* and *autonomous driving settings*. The exact values can be found in Appendix A Used driving behaviour parameters. The scenarios with penetration rate of 90%, 95% and 100% for cautious and platoon AV however showed some flaws in the driving behaviour, the reason is unclear.

What is the capacity of a 2 by 2 weaving section with different penetration levels of cautious, moderate, aggressive, platoon and connected AVs?

All of the capacities are displayed in Figure 29. The capacities show a minor change for cautious, except for the big decrease at the end which is due to unexplainable driving behaviour. The moderate AVs show an increase in capacity along the penetration rates. For aggressive AVs this increase is even bigger. The platoon AVs follow the same trend but similarly to cautious, have a dip at the 100% scenario due to strange driving behaviour. The CAVs show similar influences as the moderate AVs.

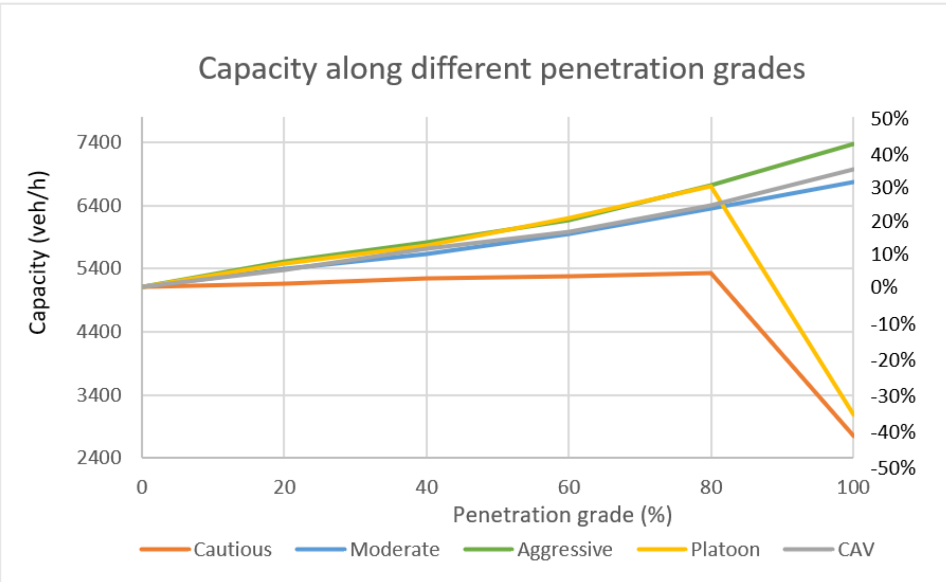

Figure 29 Copy of Figure 26 Capacity along different penetration rates

This leads to the main question:

How do different types of AVs influence the capacity of a 2 by 2 weaving section in different penetration levels?

In general, the different types of AVs have a positive influence on the capacity of the weaving section. The size of the impact does change. Cautious AVs stay relatively low, with the highest influence of 4% as visible in Figure 29, this influence is not significant unlike the other types of AVs. Aggressive AVs have the biggest influence with 44%. Aggressive AVs also influence the capacity the most in the other penetration rates, only the penetration rate of 60% is the exception, platoon AVs have a slightly higher capacity. This leads to the conclusion that the influence of aggressive AVs on the capacity is the highest and the future influence can go up to a 44% increase in capacity for this specific weaving section.

9. Recommendations

This research does not solve the entire problem and most definitely is not the final piece of research needed on this topic. Therefore, three main recommendations follow from this research. The first one concerns the retrieval of the AV parameters . Second is the variation in traffic network. The third is related to the broader theme of the influence of AVs. The first two have already been briefly mentioned in chapter 7. Discussion, but will also be shortly explained below.

Since the research showed big differences between the different scenarios and the platoon option did not show the expected results, more extensive research in the parameters of AVs would improve the research. For example the platoon option and the two underlaying parameters.

Next to this the network could be expanded. This could be by modelling another weaving section or adjusting small things in the weaving section itself, like the length or the number of lanes. The expansion could also go more into other traffic situations, like motorway ramps and exits. But also non-motorway settings, like roads with a 50 km/h speed limit and roundabouts. These would maybe require a different car following model (Wiedemann 74).

Lastly, in the beginning it was already suggested that AVs could influence the threshold to make a trip and to make longer trips. This could cancel out the positives of the AVs as it would increase traffic demand, but as stated is still uncertain. It would however be good to know whether or not AVs would benefit the road network, as people might move further away from their employer or services, more trips by car or freight traffic becoming more popular.

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Appendix A Used driving behaviour parameters

The used driving behaviour parameters for the Wiedemann model are shown in Table 16. After that, in Table 17 the safety distance reduction factors and headway times are shown and multiplied to give an impression in the reduction factors.

Table 16 Wiedemann 99 parameters for all 6 behaviour types

Parameters		**Base**	**Cautious**	**Moderate**	**Aggressive**	**Platoon**	**CAV**	
							Base	CAV
CC0 (m)	Standstill distance	1	1,25	0,75	0,75	0,75	0,75	1.25
CC1 (s)	Headway time	0,9	1,3	0,6	0,3	0,3	0,6	0.3
CC2 (m)	Following variation	4	0	0	0	0	0	
CC3 (s)	Threshold for entering following	-8	-10	-8	-6	-6	-6	
CC4 (m/s)	Negative following threshold	-0,35	-0,1	-0,1	-0,1	-0,1	-0,1	
CC5 (m/s)	Positive following threshold	0,35	0,1	0,1	0,1	0,1	0,1	
CC6 (1/(ms))	Speed dependency of oscillation	11,44	0	0	0	0	0	
CC7 (m/s^2)	Oscillation acceleration	0,25	0,1	0,1	0,1	0,1	0,1	
CC8 (m/s^2)	Standstill acceleration	4	3	3,5	4	4	3,5	5.25
CC9 (m/s^2)	Acceleration at 80 km/h	1,5	1,5	1,5	2,25	2,25	1,5	2.25

Table 17 Safety distance reduction factor taking into account the headway time

	Cautious AV	**Moderate AV**	**Aggressive AV**
Headway time (s)	1,5	0,9	0,6
Reduction (-)	1	0,6	0,75
Multiplication (s)	1,5	0,54	0,45

Appendix B Reference driving parameters

In Figure 30 until Figure 33 the referenced driving parameters are given divided in the 4 sub-categories; Wiedemann 99, Other car following parameters, Lane change parameters and autonomous driving. At the left of the tables the parameters can be found, in the middle the used parameters for the AVs, right the referenced parameters. The column, basis Goudappel is used as the base. The three partly red bars indicate that two values are different. The bar between cautious and moderate indicates a difference between those two values. The same goes for the bar between moderate and aggressive. The bar right of the base, indicates a difference between the base and moderate AV.

			1. Cautious	2. Normal	3. Aggressive	4. Aggressive + platoon	5. CAV		Basis VISSIM	Basis Goudappel	Cautious	Normal	Aggressive	I. Bruijl						
	Parameters						Basis	CAV						Basis	I3 C	L3 I	L3 A	L4/5 C	L4/5 I	L4/5 A
Wiedemann 99	CC0 (m)	Standstill distance	1,25	0,75	0,75	0,75	0,75	1,25	1,5	1	1,5	1,5	1	1	1,5	1,25	1	1,25	0,75	0,75
	CC1 (s)	Headway time	1,3	0,6	0,3	0,3	0,6	0,3	0,9	0,9	1,5	0,9	0,6	0,9	1,8	1,3	0,9	1,3	0,6	0,3
	CC2 (m)	Following variation	0	0	0	0	0		4	4	0	0	0	4	5	2	3	3	2	1
	CC3	Threshold for entering following	-10	-8	-6	-6	-6		-8	-8	-10	-8	-6							
	CC4	Negative following threshold	-0,1	-0,1	-0,1	-0,1	-0,1		-0,35	-0,35	-0,1	-0,1	-0,1							
	CC5	Positive following threshold	0,1	0,1	0,1	0,1	0,1		0,35	0,35	0,1	0,1	0,1							
	CC6	Speed dependency of oscillation	0	0	0	0	0		11,55	11,44	0	0	0							
	CC7 (m/s2)	Oscillation acceleration	0,1	0,1	0,1	0,1	0,1		0,25	0,25	0,1	0,1	0,1							
	CC8 (m/s2)	Standstill acceleration	3	3,5	4	4	3,5	5,25	3,5	4	3	3,5	4	4	0,25	3	3,5	3,5	3,5	4,5
	CC9 (m/s2)	Acceleration at 80 km/h	1,5	1,5	2,25	2,25	1,5	2,25	1,5	1,5	1,2	1,5	2	1,5	1	1,25	1,5	1,5	1,5	2,25

Figure 30 Reference Wiedemann 99 parameters

			1. Cautious	2. Normal	3. Aggressive	4. Aggressive + platoon	5. CAV		Basis VISSIM	Basis Goudappel	Cautious	Normal	Aggressive
	Parameters						Basis	CAV					
Other car following parameters	(m)	Max look ahead dist	250	250	300	300	300		250	250	250	250	300
		N of obs objects	4	4	4	10	10		5	5	2	2	10
		N of obs vehicles	3	3	3	8	8		5	5	1	1	8

Figure 31 Reference other following parameters

	Parameters		1. Cautious	2. Normal	3. Aggressive	4. Aggressive + platoon	5. CAV		Basis VISSIM	Basis Goudappel	Cautious	Normal	Aggressive
							Basis	CAV					
Lane Change parameters	m/s2	Maximum deceleration own	-3,5	-4	-4	-4	-4		-4	-3	-3,5	-4	-4
	m/s2	Maximum deceleration trailing vehicle	-2,5	-3	-4	-4	-4		-3	-3	-2,5	-3	-4
	m	- 1 m/s2 per distance own	80	100	100	100	100		200	100	80	100	100
	m	- 1 m/s2 per distance trailing vehicle	80	100	100	100	100		200	100	80	100	100
	m/s2	Accepted deceleration own	-1	-1	-1	-1	-1		-1	-1	-1	-1	-1
	m/s2	Accepted deceleration trailing vehicle	-1	-1	-1,5	-1,5	-1,5		-0,5	-0,5	-1	-1	-1,5
		Safety distance reduction factor	1	0,6	0,75	0,75	0,75		0,6	0,1	1	0,6	0,75
	m/s2	Maximum deceleration for cooperative braking	-2,5	-3	-6	-9	-9		-3	-9	-2,5	-3	-6
		Advanced merging	Yes	Yes	Yes	Yes	Yes						
		Vehicle routingdecisions look ahead	No	No	No	No	No						
		Cooperative lane change	No	Yes	Yes	Yes	Yes		No	No	No	Yes	Yes

Figure 32 Reference lane change parameters

	Parameters		1. Cautious	2. Normal	3. Aggressive	4. Aggressive + platoon	5. CAV		Basis VISSIM	Basis Goudappel	Cautious	Normal	Aggressive
							Basis	CAV					
Autonomous driving		Enforce absolute braking distance	Yes	No	No	No	No		No	No	Yes	No	No
		Use implicit stochastics	No	No	No	No	No		Yes	Yes	No	No	No
		Platooning	No	No	No	Yes	No		No	No	No	No	No

Figure 33 Reference autonomous parameters

Appendix C Cumulative frequency graph

In this appendix the different cumulative frequency graphs are given. They are separated by the type of AV and displayed in Figure 34 until Figure 38. Underneath Table 18 gives all of the different capacities. Table 19 shows the change between the corresponding scenario and the base scenario in percentage.

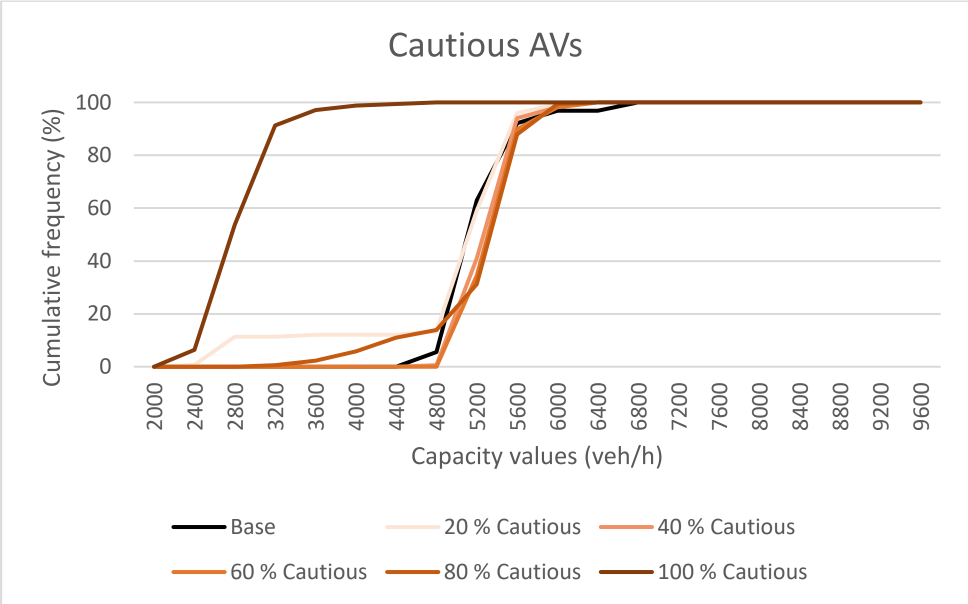

Figure 34 Cautious AV cumulative frequency graph

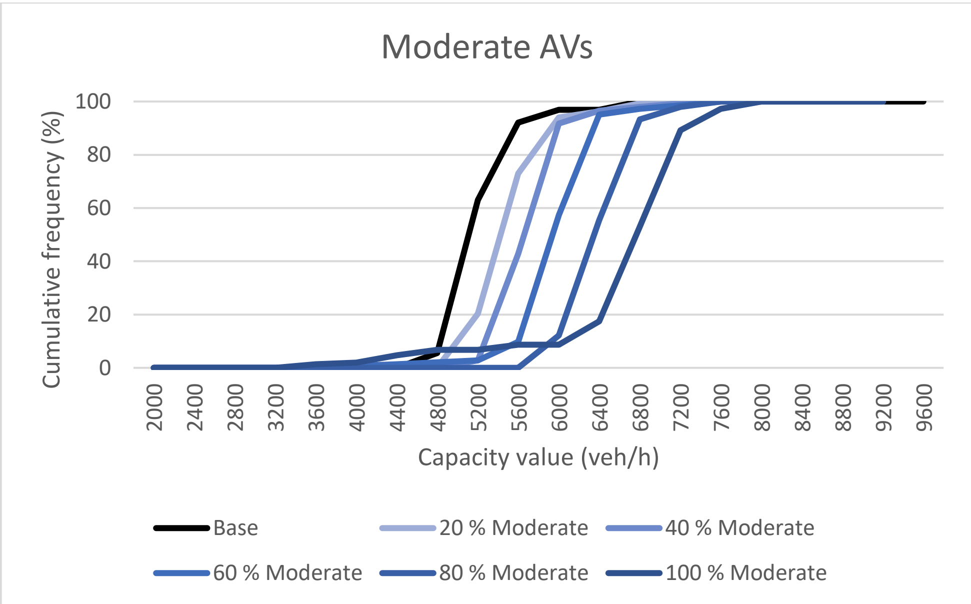

Figure 35 Moderate AV cumulative frequency graph

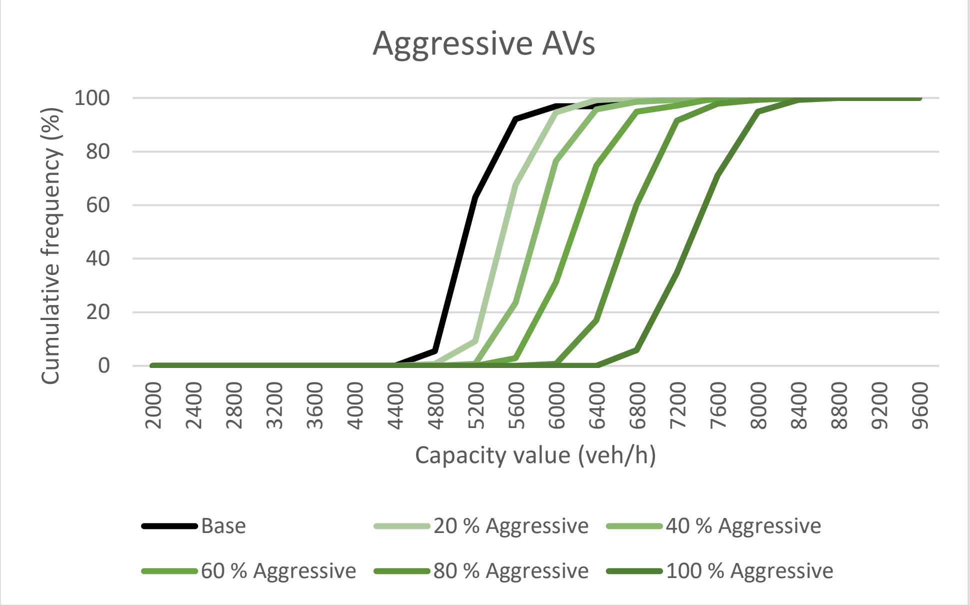

Figure 36 Aggressive AV cumulative frequency graph

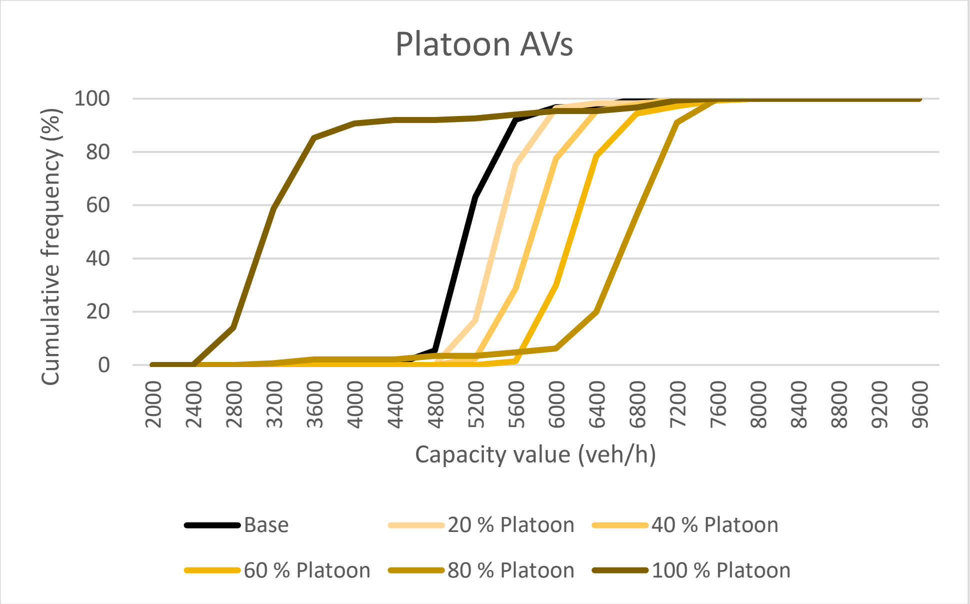

Figure 37 Platoon AV cumulative frequency graph

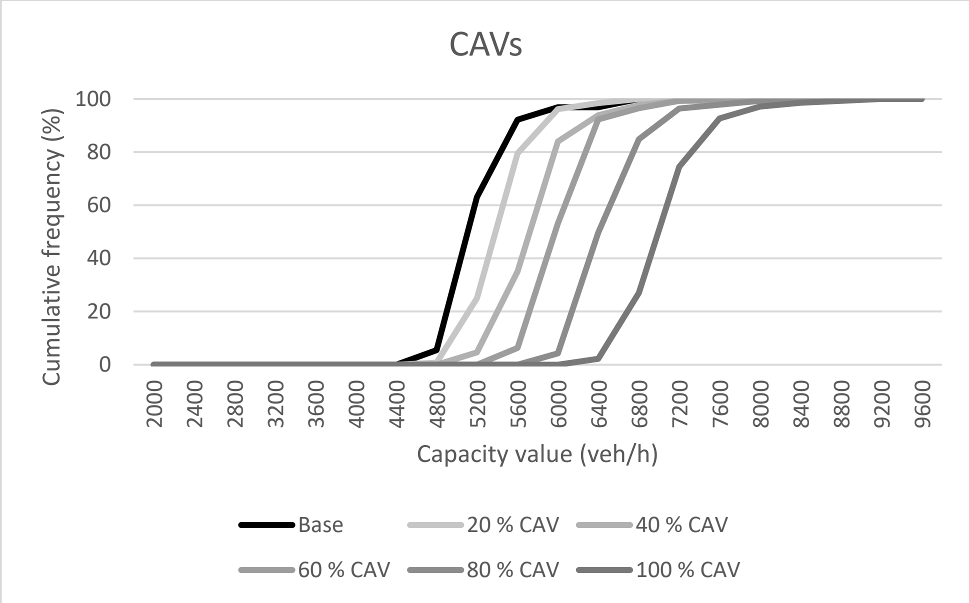

Figure 38 CAV cumulative frequency graph

Table 18 Capacities (veh/h) of all scenarios

	Cautious	Moderate	Aggressive	Platoon	Connected
0%			5118		
20%	5160	5400	5514	5474,831	5382
40%	5241	5634	5811	5760	5706
60%	5280	5946	6168	6204	5988
80%	5322	6357	6720	6708	6402
100%	2748	6774	7374	3087	6972

Table 19 Change in capacity along different penetration rates (%)

	Cautious	Moderate	Aggressive	Platoon	Connected
0%			0		
20%	0,82	5,51	7,74	6,97	5,16
40%	2,40	10,08	13,54	12,54	11,49
60%	3,17	16,18	20,52	21,22	17,00
80%	3,99	24,21	31,30	31,07	25,09
100%	-46,31	32,36	44,08	-39,68	36,23

Appendix D Variance and standard deviation

In Figure 39 the variance of all scenarios is given before the adjustments, Figure 40 shows them after. Below the two graphs, in Figure 41, the used calculation of the variance and standard deviation is given.

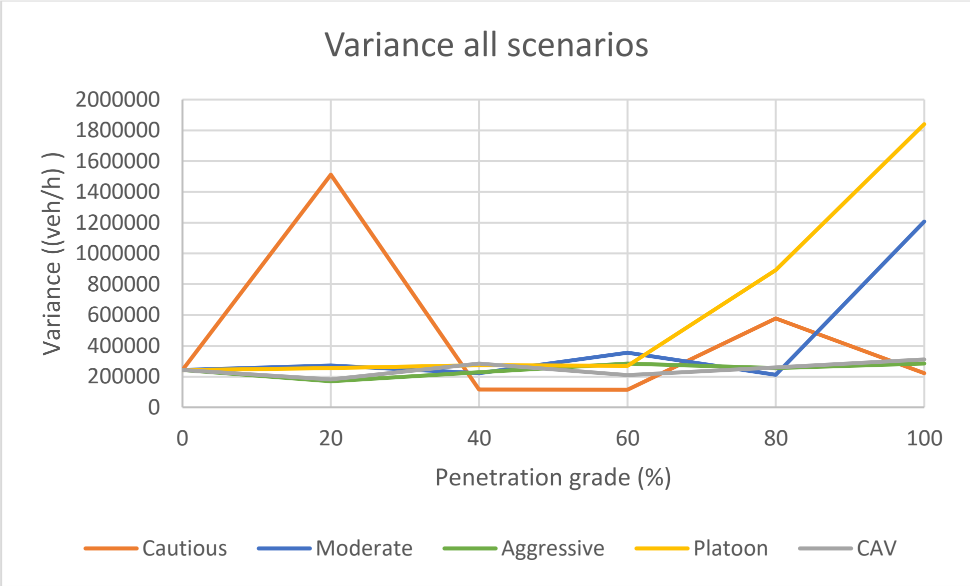

Figure 39 Variance all scenarios

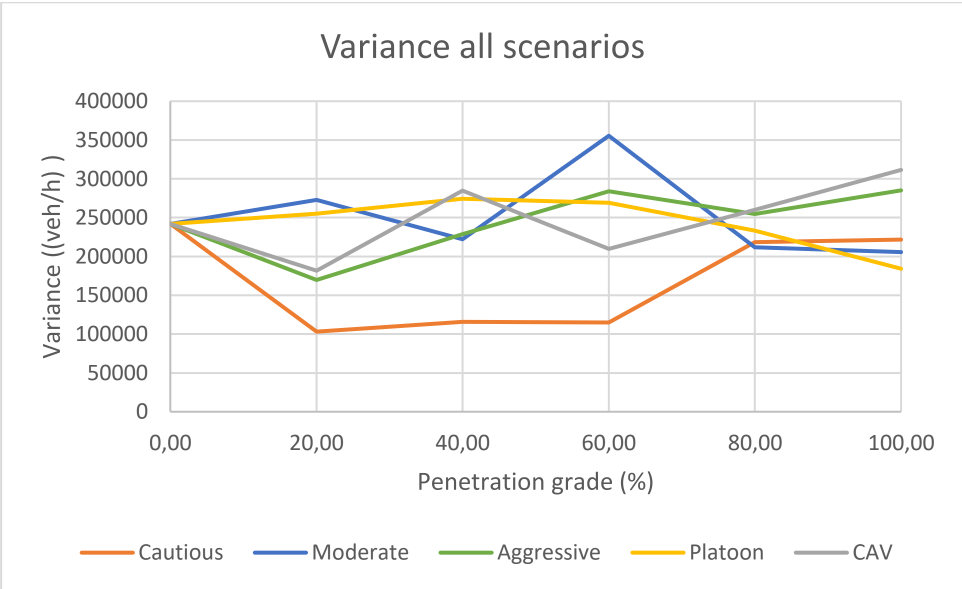

Figure 40 Variance of all scenarios after the adjustments

The variance and standard deviation largely use the same formula. The average is calculated. After this every capacity value is compared to the average, by finding the difference. All of these differences are summed to than be divided by the sample size minus one. This is the variance. The standard deviation is the square route.

Sample

Variance

$$S^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}$$

Standard Deviation

$$S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}}$$

S = standard deviation

n = sample size

x = value from data set (going from 1st number to the last number)

x = average from data set

Figure 41 Formula Variance and standard deviation (Variance and Standard Deviation, n.d.)

Appendix E Capacity values 100% Platoon AV

This table shows at the top the number of the run the values come from. The numbers in the table are all capacity values in veh/h. The heat map shows green values on top and the quick transition from green to yellow and orange/red.

Table 20 Capacity values 100% Platoon AV

1	2	3	4	5	6	7	8	9
				6936				
7008	6600	7464		7158	6738			
4368	5052	3888	5736	5274	6822	5796	4368	5406
3132	2940	3048	3846	3534	3936	3696	2784	3732
2496	2856	3294	2904	2514	2634	2754	2700	3420
3696	3348	3504	3612	2922	3054	3312	2808	3192
2616	3024	3006	2844	2964	2808	2640	3036	3396
3156	2964	2736	3318	3552	2868	3588	3138	3456
2850	2844	3780	2922	3420	3084	2784	3402	2784
2730	3048	3294	2952	3210	3048	2820	3174	3156
2880	3276	3432	2928	3288	3150	3018	3114	3108
3060	3054	2946	3216	3378	2982	3072	3402	3048
2838	3066	2976	3402	3228	3336	3318	2940	3048
3216	3132	3072	2694	3318	2988	2928	2910	3006
3270	3048	3012	3456	3462	3090	2916	2544	2982
3012	3276	3522	3030	2880	3486	2592	2988	2664
3408	2646	3282	3090	2748	3276	2880	3216	3084
2808	2730	3306	3600	2724	3264	3048	3108	2586