THE IMPACT OF AUTOMATED VEHICLE LANES ON HIGHWAY TRAFFIC FLOW

Bachelor Thesis

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Summary

Automated vehicles (AVs) are vehicles which will be able to take over human driving tasks in the future. ‘Roads filled with automated vehicles could also cooperate to smooth traffic flow and reduce traffic congestion’ (NHTSA). For instance, these vehicles will be expected to drive closer to each other, and therefore increase the road capacity (Morando, 2018). It is likely that within a few decades self-driving vehicles are a part of the roadway system. In the transition period automated and conventional vehicles will share the same road. Many studies suggest that the interactions between regular and autonomous vehicles can reduce their potential efficiency (Talebpour, 2017) (Wei,2013). A possible measure to separate these different types of vehicles on highways, are automated vehicle lanes (AV lanes). The focus of this report is to research what the impact of dedicated lanes for automated vehicles is on the highway traffic flow efficiency.

At first the characteristics of the driving performance of automated vehicles have been analysed. The focus has been on longitudinal and lateral movement of vehicles. Many studies suggest that the driving performance of automated vehicles will be more assertive, the vehicles will react faster and therefore, drive closer to other vehicles. This means that the characteristics of the car-following- and lane change behaviour of automated vehicles will have different values compared to conventional vehicles.

Fully-automated vehicles are not commercially available now. Therefore, a simulation is needed to measure the impact of AV lanes. Traffic simulation programme PTV Vissim has been used to simulate a highway with an on-ramp with conventional and automated vehicles. The AVs are simulated by adapting the driving performance parameters based on the analysis on vehicle characteristics. The simulation consists of two experiments in which different scenarios are simulated. Performance indicators are used to analyse and evaluate the data of each scenario. These indicators are: travel time, vehicle density, average speed and queue discharge rate.

The first simulation experiment is focused on the impact of the market penetration rate (MPRs) of automated vehicles. For the MPRs of 25, 50 and 75% an AV lane was added for the most left lane. One important simulation result is that the MPR of automated vehicles has a positive effect on the traffic flow efficiency. On the other hand, implementing an AV lane has a negative effect, especially for a market penetration of 25%. The variable of the second simulation experiment is the total number of driving lanes. As expected, the impact of one AV lane gets smaller, when the total number of driving lanes gets larger. The results indicate that implementing two AV lanes has a very negative influence on the traffic flow efficiency. This is because the positive impact of AVs, higher road capacity due to smaller headway, do not cover the negative impact on conventional vehicles when the number of driving lanes for these vehicles gets smaller.

Based on this research, it can be concluded that dedicated lanes for automated vehicles do not positively benefit the traffic flow. Therefore, automated vehicle lanes are not a solution to improve the integration of AVs on highways.

Contents

1 Introduction

This introduction consists of the following parts: firstly the problem is explained, followed by the scope, objective and research questions. The structure of the overall report is explained by a reading guide at the end of this chapter.

1.1 Problem statement

An evolution is currently happening in the automotive industry. Many car companies are developing automated vehicles which will improve comfort by reducing the number of human driving tasks. An automated vehicle is called full-automated when it reaches SAE-level 5. SAE, standing for the Society of Automotive Engineers, categorizes the intelligence level and automation capabilities of vehicles, ranking through 0 to 5 (Gigabit, 2018) One of the reasons why automated vehicles are developed, is the improvement of safety. For instance the vehicle would be able to react faster than a human due to sensors, cameras and radar. Roads filled with automated vehicles could also cooperate to smooth traffic flow and reduce traffic congestion (NHTSA). Automated vehicles are designed to be more efficient in traffic, and that could benefit energy consumption and emissions as well.

It is expected that automated vehicles will perform differently in traffic than conventional vehicles, for instance the headway, the distance between two vehicles, will decrease. This means that cars would drive closer to each other, and therefore increase the road capacity. It is likely that within a few decades self-driving vehicles are a part of the traffic network. Fully automated vehicles are expected to be commercially available within a time window of twenty years (between 2025 and 2045) (Milakis, 2015). Before traffic will consist of merely automated vehicles, conventional and automated vehicles will both use the same road, which is called the transition period. In this period the market penetration rate (MPR) of automated vehicles, the number of automated vehicles compared to conventional vehicles, will increase.

Many studies suggest that the interactions between regular and autonomous vehicles can reduce their potential efficiency (Talebpour, 2017) (Wei,2013). A solution to decrease the number of interactions between conventional and automated vehicles, is separating the two types of vehicles. Therefore, dedicated lanes for automated vehicles (AV lanes) are a possibility to improve the efficiency of automated vehicles. There are two different ways of implementing AV lanes: adding an extra lane or prohibiting conventional vehicles of using specific lanes. The first option would be very costly and ineffective after the transition period has ended. The second option is more feasible, because big changes on the infrastructure will not be necessary. AV lanes could be indicated by introducing specific road signs or changing road design elements for AV lanes. These AV lanes could have an impact on the overall traffic flow efficiency, this problem will be researched in this report. One of the reasons is that conventional vehicles will have less lanes to drive on and negatively influence the road capacity on the regular lanes. Especially at on- and off-ramps automated vehicles will be forced to change lane and impact the overall highway traffic flow.

1.2 Scope

It is important to determine the scope of the research, because of the limited amount of time. Therefore, the research must focus on specific parts of the problem. The problem is about automated vehicles, which is a very broad subject. The automated vehicles, which will be part of the simulation, will have the characteristics of a vehicle with SAE-level 4 or 5. These levels are called high- and full automation, the SAE-levels are listed in appendix 1. Full-automated vehicles can perform all driving functions in all circumstances. High automated vehicles can perform these driving tasks in certain circumstances. That is the significant difference of these different levels of automation. The reason for researching these high levels is because the driving performance of these automated vehicles will differ the most compared to conventional vehicles.

Freight traffic will not be in the research scope, because it would make the research more complex and not feasible in the available amount of time. The scope will be on driving performance and traffic flow efficiency of automated vehicle lanes. More subjects about the implementation of automated vehicles, for instance traffic safety, road design and emissions will not be in the research scope. It has been mentioned in the problem statement that the focus will be on highway traffic flow.

1.3 Objective & research questions

The objective of this research is to understand the impact of automated vehicle lanes on highway traffic flow. This will be done by simulating a highway with and without automated vehicle lanes. It is still unclear how automated vehicles will integrate in the roadway system, therefore it is important to understand what the impact of these automated vehicles will be on the traffic flow efficiency. This research could contribute to further research on the implementation of automated vehicles in the future.

A research question is needed to find a solution of the problem which has been introduced in the problem statement. At the end of this research the following main research question will be answered in the conclusion:

What is the impact of automated vehicle lanes on the highway traffic flow efficiency?

The research question is divided in to three sub-questions. These three sub-questions are more specific and give a clear view of the research approach:

1. Which driving performance characteristics of automated vehicles are different compared to conventional vehicles?
2. How does an AV lane influence the traffic flow for different market penetration rates of automated vehicles?
3. What is the relation of AV lanes and the total number of driving lanes on the traffic flow?

The first question will be answered based on an analysis about the driving performance of automated vehicles. The second and third question will be answered based on two simulation experiments. The main research question will be answered based on the analysis about automated driving behaviour and the results of the simulation.

1.4 Reading guide

This report starts by explaining the research approach in chapter 2, methodology. The following chapter consists of an analysis about the difference in driving behaviour of automated vehicles and conventional vehicles. Chapter 4 is about the traffic flow simulation; the model and experiment results per performance indicator are explained in this chapter. In chapter 5 the simulation results are discussed and further research is recommended. The main research question is answered in chapter 6 by a conclusion. The report ends with a list of references and appendices.

2 Methodology

The methodology of this report is elaborated in this chapter. The simulation programme which will be used for this research is explained at first. The analysis and simulation experiments are followed. The traffic flow efficiency is measured by performance indicators. The final part of this chapter consists of a flowchart which gives an overview of the research approach.

2.1 Simulation programme

The impact of AV lanes is researched by a simulation in PTV VISSIM. In this programme, there are two possibilities of modelling automated vehicles. Figure 1 below shows that these vehicles can be internally- and externally modelled. The combination of internally- and externally modelling creates a better approximation of the driving behaviour of automated vehicles, however externally modelling is a difficult process due to a significant amount of programming. Therefore, this research will only consist of internally modelling of AVs, adapting the default driving parameters.

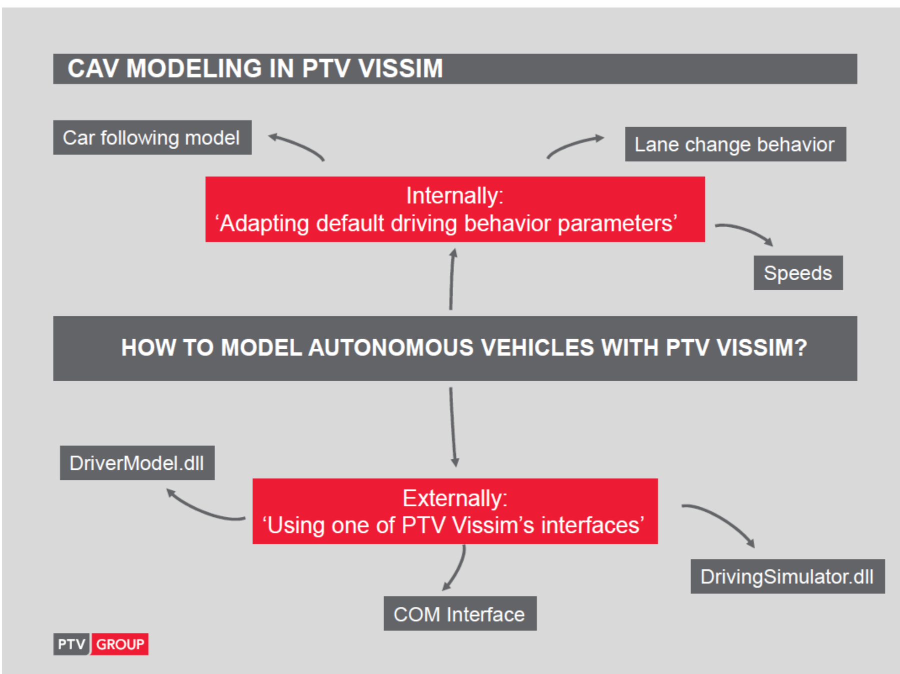


Figure 1: Modelling of automated vehicles in PTV VISSIM

2.2 Analysis

This part of the research consists of an analysis about the driving performance of automated vehicles. The characteristics of AV driving performance, longitudinal and lateral movement, are elaborated. The used set of parameters to simulate automated vehicles are explained in this chapter. The answer of the first research question consists of the differences in driving performance of conventional and automated vehicles.

2.3 Simulation model & experiments

The simulation model consists of a highway with an on-ramp. Depending on the scenario, the highway consists of three or more driving lanes. A traffic flow of conventional and automated vehicles is simulated on this highway. The traffic demand increases with 1500 vehicles per hour per time interval (900 s). The simulation period gets longer when the number of lanes increases. The goal of the simulation is to create congestion in the model. The impact of AV lanes on the traffic flow efficiency is measured by different performance indicators. In chapter 2.4 the performance indicators are further explained. The impact of AV lanes is simulated by two different experiments which are explained here below:

- Experiment 1: **Market penetration rate**
  In the first experiment, it is determined at which market penetration rate AV lanes are beneficial for the overall traffic flow. The road section consists of three driving lanes with an on-ramp. The market penetration rate (MPR) of automated vehicles is a variable in the model. Five MPRs are simulated in the model: 0-25-50-75-100%. This report is focussed on the impact of AV lanes; therefore, an AV lane on the left driving lane is added for the MPRs of 25, 50 and 75%. It does not make sense to add an AV lane when there would be no automated vehicles, or the traffic flow would be fully-automated.

- Experiment 2: **Number of driving lanes**
  The goal of the second experiment is to understand the impact of AV lanes for different number of driving lanes. The number of driving- and AV lanes are variables for this experiment. The total number of driving lanes ranges from three till five driving lanes. For each number of driving lane one AV lane is added on the left lane. The highway is also simulated with two AV lanes when the highway consists of four or five driving lanes. On the other hand, the market penetration rate of automated vehicles is not variable in this scenario. It chosen to have a MPR of 50%, because this rate is the mean value. Also, it is not feasible to simulate it for different MPRs due to available amount of time.

2.4 Performance indicators

The traffic flow efficiency is measured by the following indicators:

- Travel time (s):
- Vehicle density (number of vehicles/km)
- Speed (km/h)
- Queue discharge rate (number of vehicles/h)

The values of the different indicators are the average value of ten simulation runs for each scenario. The average travel time of each scenario is measured of the highway, the on-ramp is not included in the travel time measurement. Macroscopic models of traffic flow relate three fundamental variables: speed (v), flow (q) and density (k) in the form q = k*v (Atkins, 2016). The vehicle density, queue discharge rate and speed are measured 750 m after the on-ramp. This distance has been chosen because this distance is the turbulence length downstream of an on-ramp with a design speed of 120 km/h (Rijkswaterstaat, 2017).

2.5 Approach

The research methodology has been explained in this chapter. To get a clear overview of the approach of this research a flowchart is pictured in figure 2 here below.

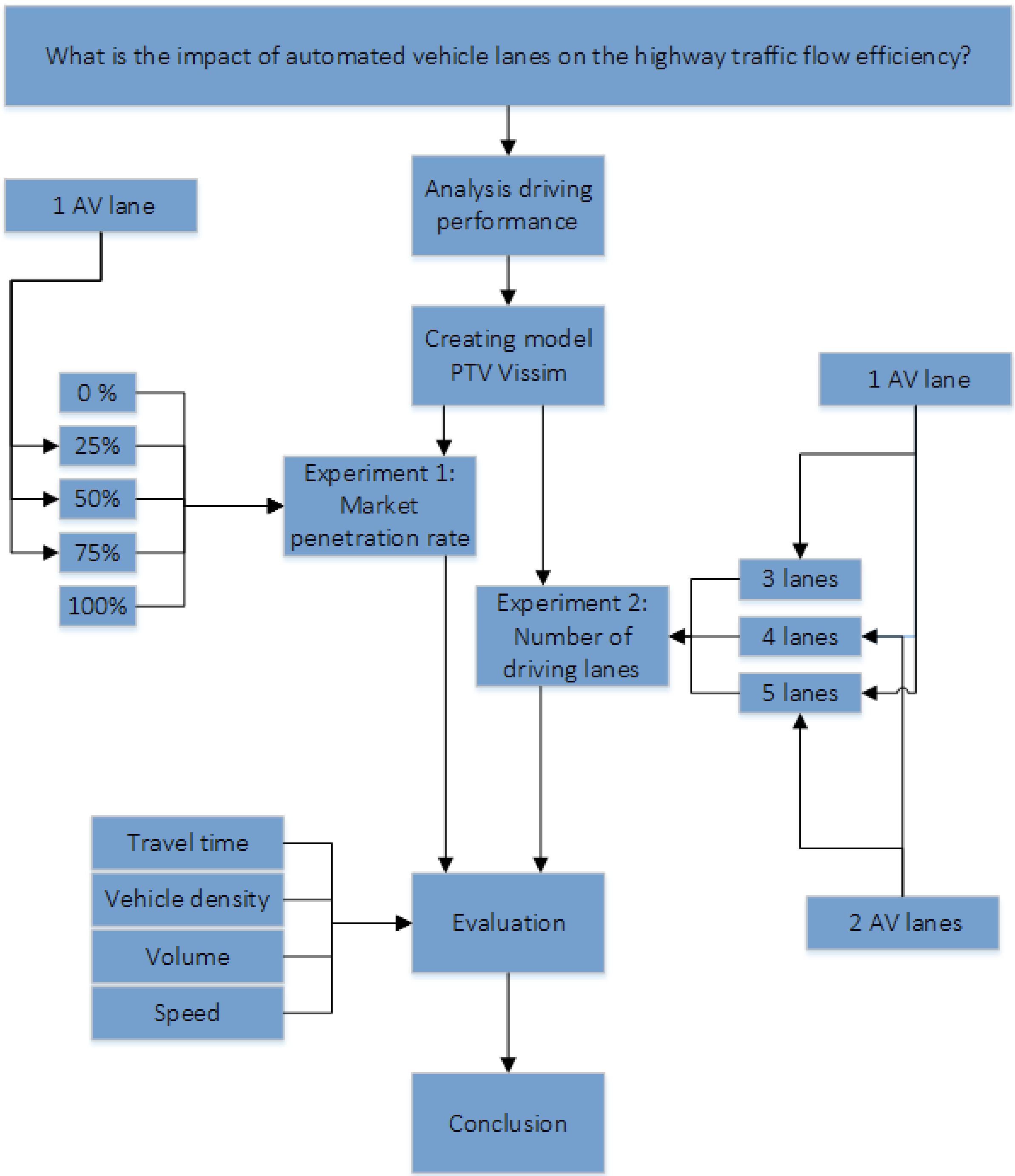


Figure 2: Methodology flowchart

3 Driving performance of automated vehicles

In this chapter the driving performance of automated vehicles is analysed. At first the driving parameters for the traffic microsimulation are explained. Next, the difference in longitudinal and lateral movement of automated- and conventional vehicles are explained. The first sub-question is answered at the end of this chapter.

3.1 Simulation parameters

As mentioned in the methodology, automated vehicles can be modelled in PTV Vissim by adapting the default driving parameters. Table 1 below shows the driving performance parameters of conventional – and automated vehicles which will be used in the simulation. This set of parameters are determined based on research about the impact of connected and autonomous vehicles on traffic flow (Atkins, 2016). Other researches use the same set of parameters of this report to simulate automated vehicles. Based on that information, it is concluded as a reliable source of data. In that research many different sets of parameters are given, based on different scenarios: single-lane link, multi-lane link, signalised junction, roundabout and multi-lane link with merge. The aim of this report is to simulate a highway with an on-ramp. Therefore, the parameters of the multi-lane link with merge have been chosen. These parameters change the longitudinal and lateral movement of automated vehicles which is elaborated in the next part.

Table 1: Driving performance parameters of conventional- and automated vehicles

Driving performance parameters	Unit	Conventional vehicle	Automated vehicle
Standstill distance	m	1.50	0.50
Headway time	s	0.90	0.50
Following variation	m	4	0
Negative following threshold	m/s	-0.35	0
Positive following threshold	m/s	0.35	0
Speed dependency of oscillation	1/m*s	11.44	0
Oscillation acceleration	m/s^2	0.25	0.45
Standstill acceleration	m/s^2	3.50	3.90
Acceleration at 80 km/h	m/s^2	1.50	1.90
Observed vehicles		2	10
Min. headway	m	0.50	0.20
Safety distance reduction factor		0.60	0.30
Cooperative lane change		No	Yes

The definitions of the driving performance parameters according to Vissim are given in appendix 2.

3.2 Longitudinal movement

The simulation programme uses a traffic flow model which is called Wiedemann 99. Wiedemann's traffic flow model assumes that there are basically four different driving states for a driver: Free driving, approaching, following and braking. (PTV Vissim, 2018). This explains the longitudinal movement of vehicles in the simulation programme. Two key factors should be considered in modelling the car-following behaviour of autonomous vehicles: (1) their ability to constantly monitor other vehicles in their vicinity, which can result in a deterministic behaviour in dealing with other drivers' behaviour; and (2) their ability to react almost instantaneously to any changes in the driving environment. (Mahmassani, 2016). Parameters for AVs reflect more assertive behaviours, such as shorter standstill distance and shorter safety distance, lower headway and following variation. (Morando, 2018). These statements explain the longitudinal movement of automated vehicles. The gaps between automated vehicles are smaller compared to vehicles which are controlled by humans (figure 3).

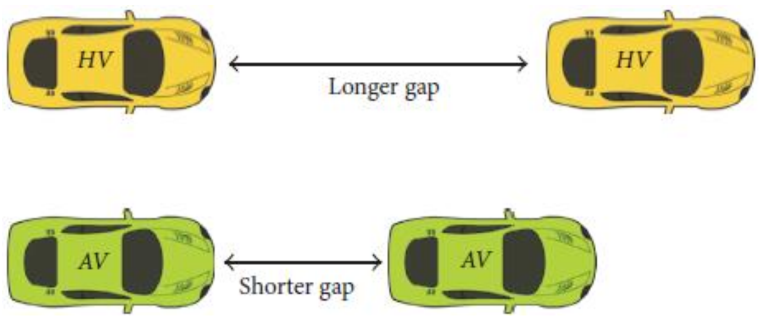


Figure 3: Longitudinal movement of vehicles controlled by humans and automated vehicles

3.3 Lateral movement

Lateral movement of vehicles consists of changing lane and merging. Merging is entering a major road from a minor road, for instance an on-ramp. There are two types of lane changing behaviour replicated – necessary lane changes (for example, due to routing) and free lane changes (to take advantage of higher speeds and greater lane capacity). Lateral movement incorporates longitudinal behavioural change in that the desired safety distance (standstill distance + headway time * speed) must be achieved/maintained as part of the manoeuvre. (Atkins, 2016). Table 1 shows that the safety distance is smaller for automated vehicles, this means that automated vehicles can merge into smaller gaps between vehicles.

Sub-question 1: Which driving performance characteristics of automated vehicles are different compared to conventional vehicles?

Answer: The driving performance of automated vehicles can be described as more assertive and direct compared to conventional vehicles. Due to automated technologies, like radar, sensors, and connectivity with other vehicles, automated vehicles are able to react faster than humans. This contributes that automated vehicles drive closer to other vehicles, smaller gaps and following variation. This results in higher road capacities due to automated vehicles.

4 Simulation

The impact of automated vehicles lanes is researched by a traffic simulation in Vissim. At first the simulation model and programme setup are explained in detail. In the following section the results of two simulation experiments, market penetration rate and number of driving lanes, are displayed for each performance indicator: travel, vehicle density, speed and queue discharge rate. The second and third sub-question are answered at the end of each experiment. An overview of the two experiments is given by a table of the capacity factors compared to the base scenario for the different market penetration rates and number of driving lanes.

4.1 Model & programme setup

The simulation model (figure 4) is explained in this section. At first a 3-lane highway is drawn with the function ‘Links’ in PTV Vissim. The width of the lanes is set to 3.50 meters and the design speed of the highway is set to 120 km/h. An on-ramp is added and connected to the highway. The length of the on-ramp is set to 250 m, which is the length of an on-ramp for a design speed of 120 km/h according to *‘Richtlijn Ontwerp Autosnelwegen’* (Rijkswaterstaat, 2017). The total length of the highway is 2750 meters. The vehicles are generated two kilometres before the on-ramp, because the model needs some area to settle after the vehicle input. The traffic flow is measured 750 meters after the bottleneck, as mentioned in the methodology. The travel time is measured over the total length of the highway. For the second experiment a highway of four and five driving lanes is simulated by adding one or two extra lanes on the left.

The vehicle input consists of two types of vehicles, automated - and conventional vehicles. Conventional vehicles are simulated by the vehicle type ‘Car’. Automated vehicles are added to the model by changing the parameters of ‘Driving behaviour’. These parameters are explained in the previous chapter about driving performance of automated vehicles. Figure 4 shows the two types of vehicles on the highway. The automated - and conventional vehicles have different colours, red and black. An AV lane is implemented by editing the link settings for the most left lane. By selecting the function: ‘Blocked vehicles classes: Car’, conventional vehicles did not enter the left lane.

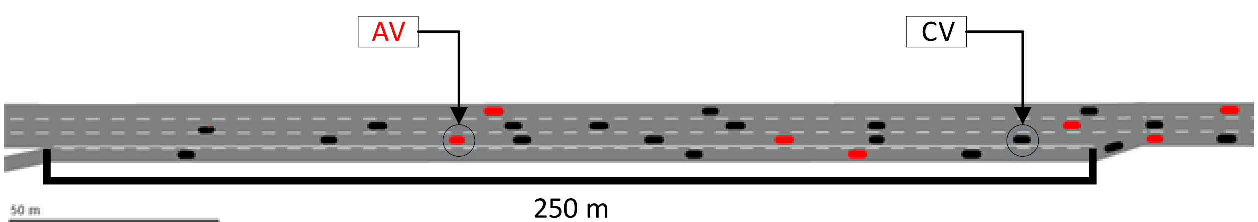


Figure 4: Model in PTV Vissim with automated and conventional vehicles

4.1.1 Traffic demand

At two locations vehicles enter the model, two kilometres before the on-ramp on the highway and at the start of the on-ramp. The number of vehicles on the highway is not constant over time but increases per time interval. The graph (figure 5) shows the traffic demand over time. The demand increases with 1500 vehicles per hour per time interval, it is set to 900 seconds. The simulation period gets longer when the number of lanes increases. The goal of the simulation is to create congestion in the model. Congestion arises when the traffic demand gets larger than the road capacity. Therefore, the simulation ends one-time interval after the theoretical capacity has been reached. For instance, the capacity of a 3-lane highway with on-ramp is 7240 vehicles per hour, according to *'Capaciteitswaarden Infrastructuur Autosnelwegen'* (Rijkswaterstaat, 2015). The graph shows that the simulation for 3 lanes ends at 5400 seconds with a traffic demand of 9000 vehicles per hour. The simulation periods for 4 lanes and 5 lanes, are determined to be 7200 and 9000 seconds.

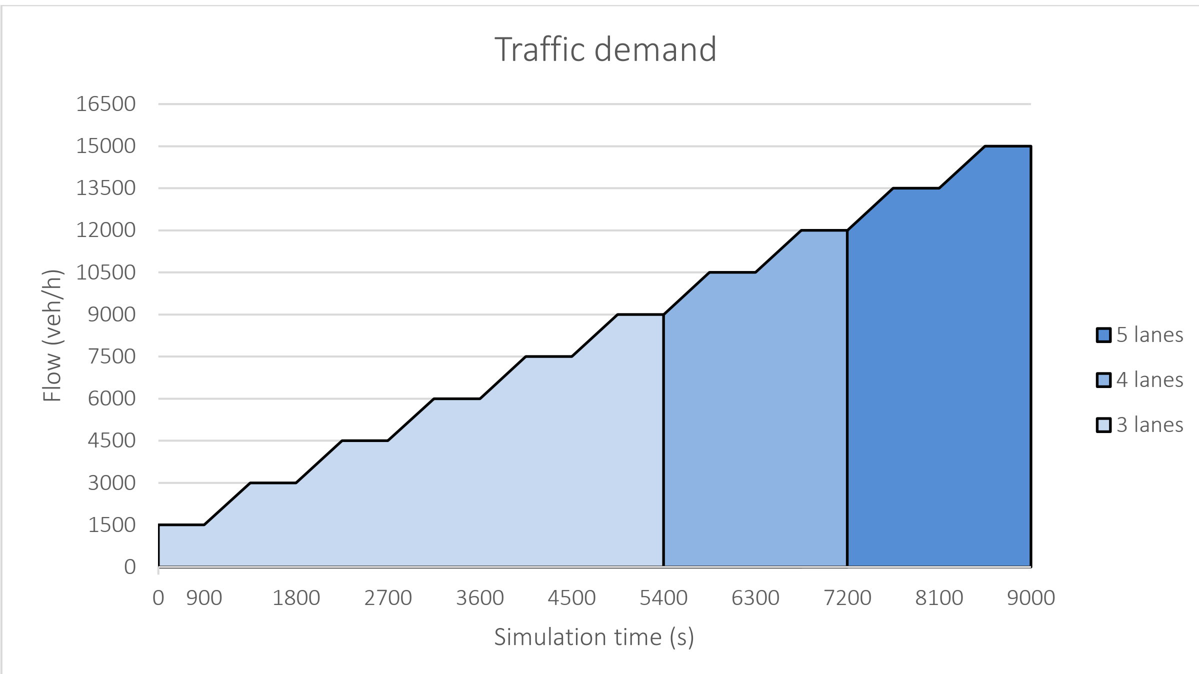


Figure 5: Traffic demand for 3-4-5 driving lanes

The vehicle input on the on-ramp is set to 1000 vehicles per hour. This value is constant for the different time intervals and scenarios.

4.1.2 Output

The output of the simulations runs consists of four traffic flow performance indicators: travel time, vehicle density, speed and queue discharge rate. These indicators have been explained in the methodology. The number of runs is set to ten runs per simulation. It is ideally to have more simulation runs to get more precise results. The more simulation runs per scenario, the smaller the standard deviation will be. Due to the limited amount of time ten runs are chosen.

4.2 Experiment 1: Market penetration rate

The simulation results of experiment 1 are shown in this chapter, which is divided into four parts. Each part indicates a different performance indicator. At first the impact of the market penetration rate on the traffic flow is shown. Five scenarios are simulated with market penetration rates ranging from 0 till 100%. This is followed by a comparison of implementing an AV lane for different MPRs (25-50-75%). At the end of this chapter the second sub-question is answered.

4.2.1 Travel time

The graph (figure 6) indicates the average travel time of the vehicles for different market penetration rates. It is clear to see that the travel time has the largest value for the lowest MPR. The travel time gets smaller, when the number of automated vehicles increases. The mean values and standard deviations of this graph are shown in table 7 in appendix 3.

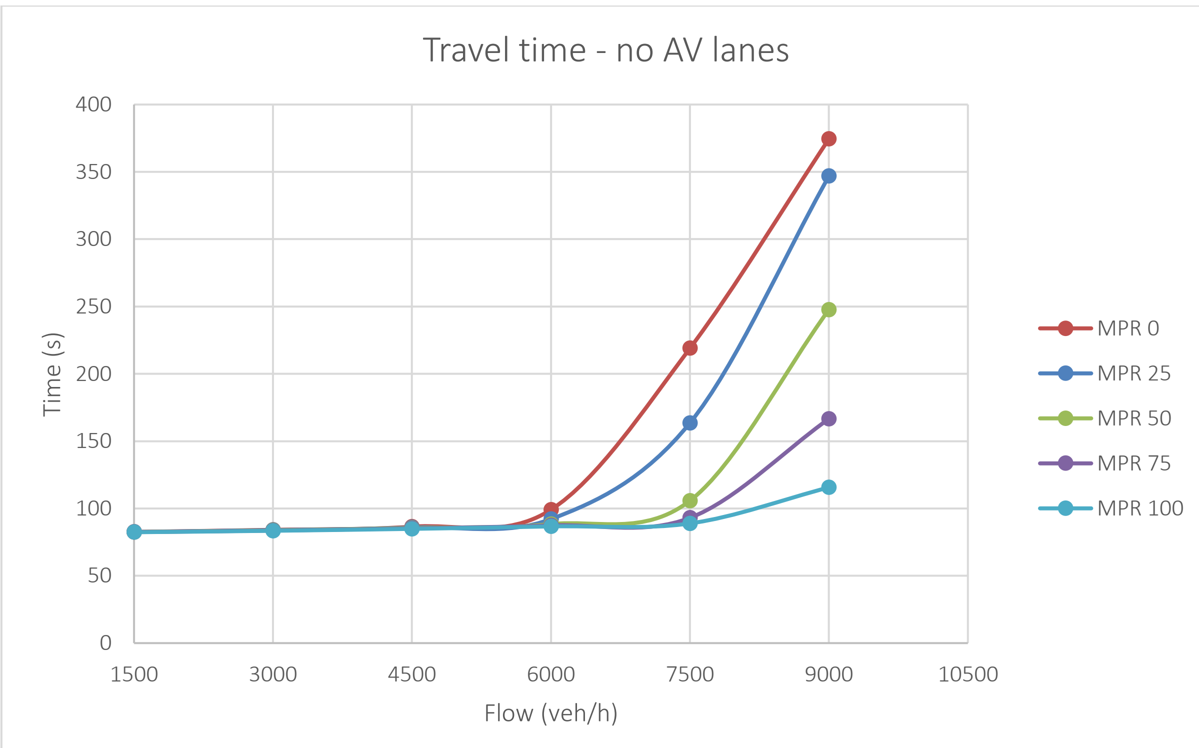
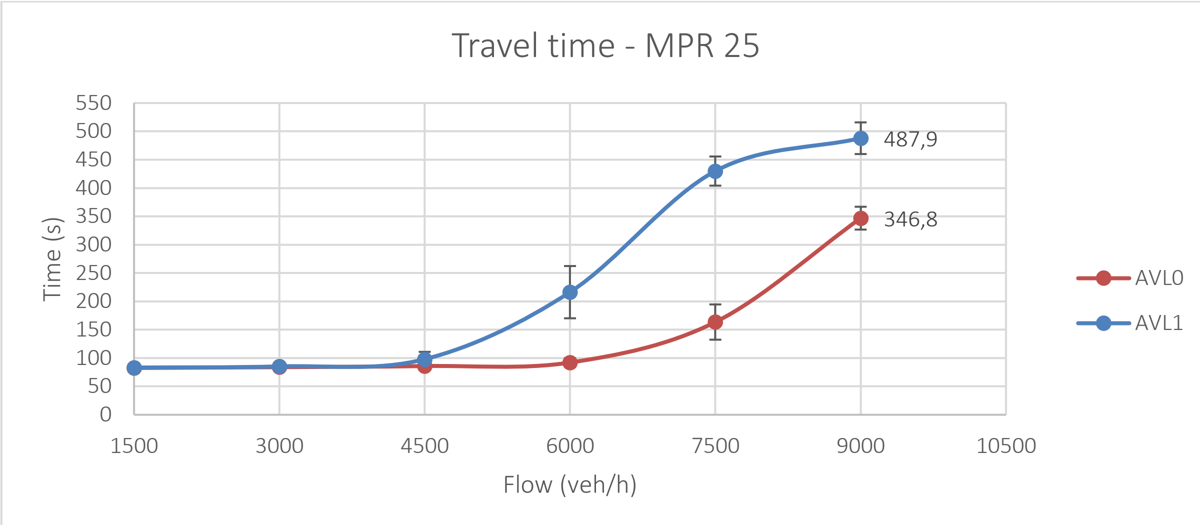
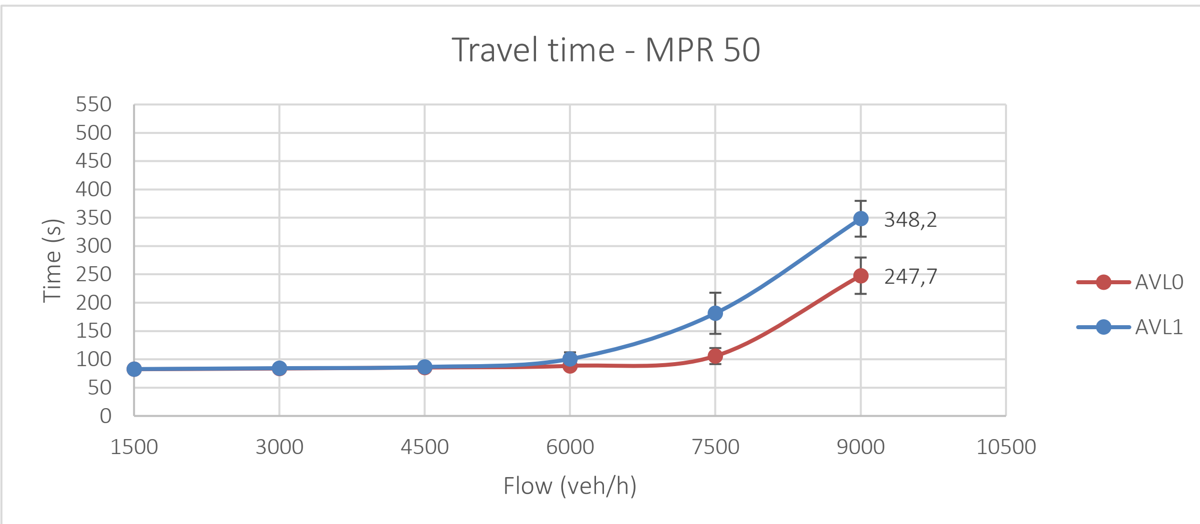
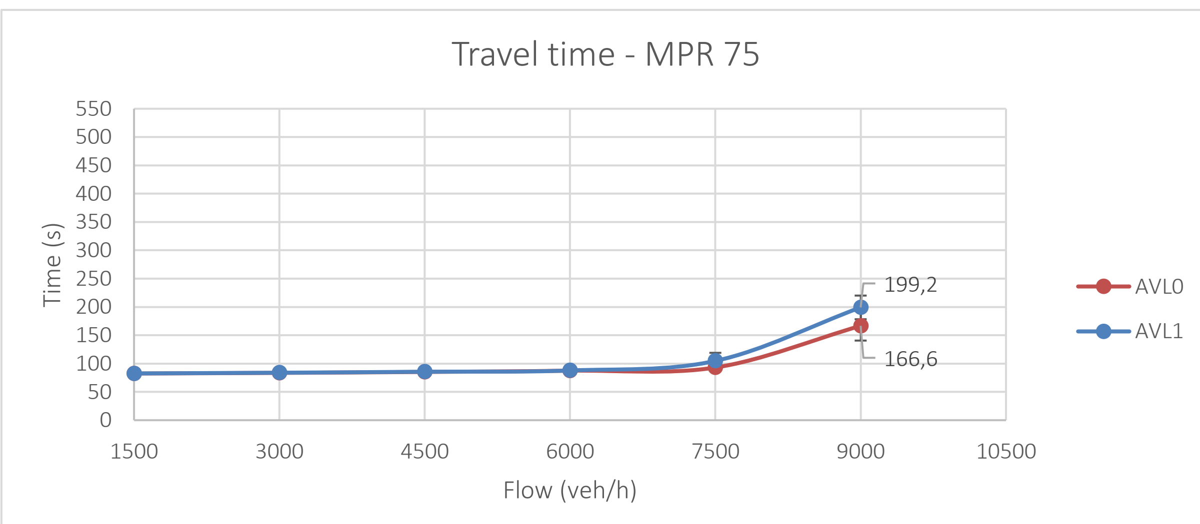


Figure 6: Travel time no AV lanes (MPR 0-25-50-75-100%)

On the next page three graphs (figures 7-8-9) are shown with the travel time of MPR 25, 50 and 75%. For these scenarios the most left lane is converted into an AV lane. The term AVL0 means no AV lane is added. AVL1 means that one AV lane is added to the highway. The travel time when an AV lane is added, is larger compared to no AV lane. The difference in travel time gets smaller for higher MPRs. The mean values and standard deviations of these graphs are shown in tables 8,9 and 10 in appendix 3.







Figures (7-8-9): Travel time (MPR 25-50-75) no AV lane vs 1 AV lane

4.2.2 Vehicle density

Figure 10 shows the average vehicle density for each scenario. The number of vehicles per kilometres increases when the market penetration rate of automated vehicles increases. The vehicle density has similar values, free flow, until a flow of 6000 vehicles per hour. At that point the maximum vehicle density is reached for the scenario when there are no and 25% automated vehicles on the road. The vehicle density increases for other three scenarios after this intensity. The mean values and standard deviations of this graph are shown in table 11 in appendix 4.

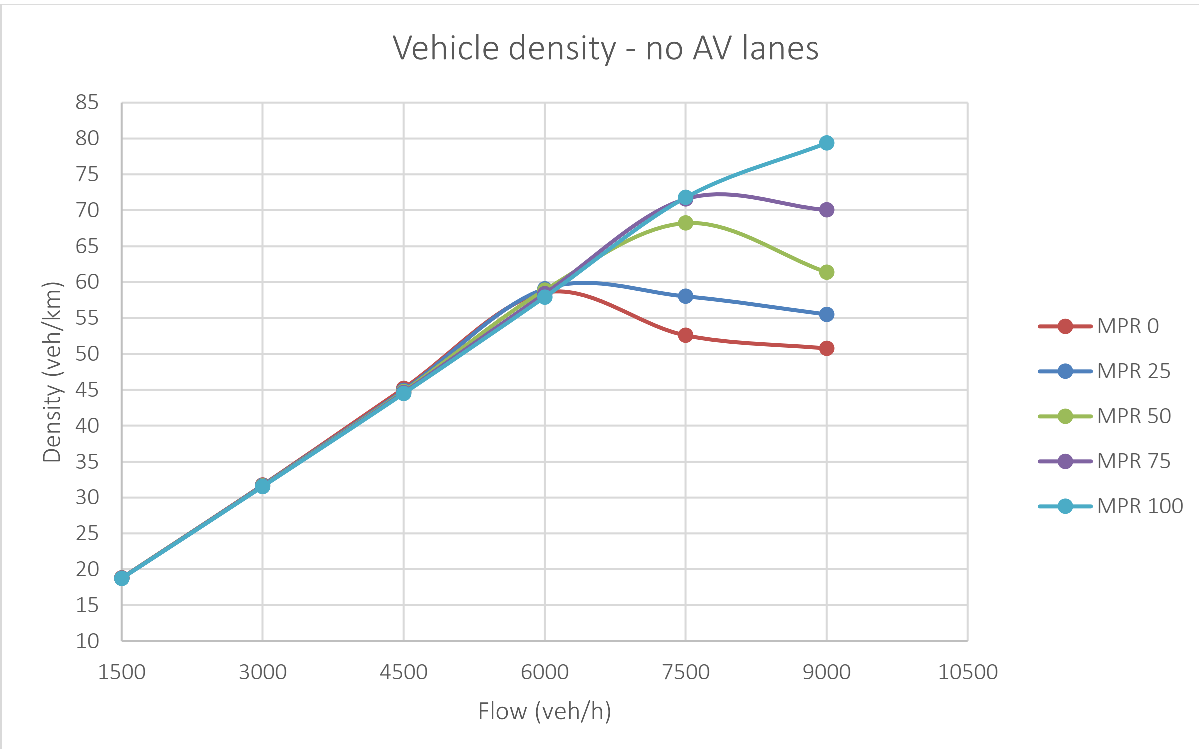
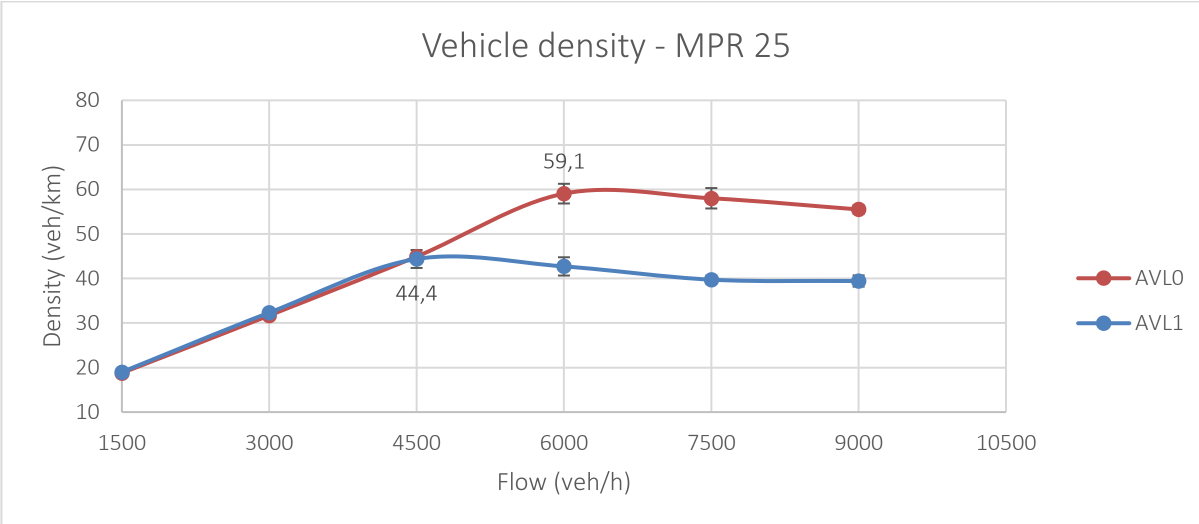
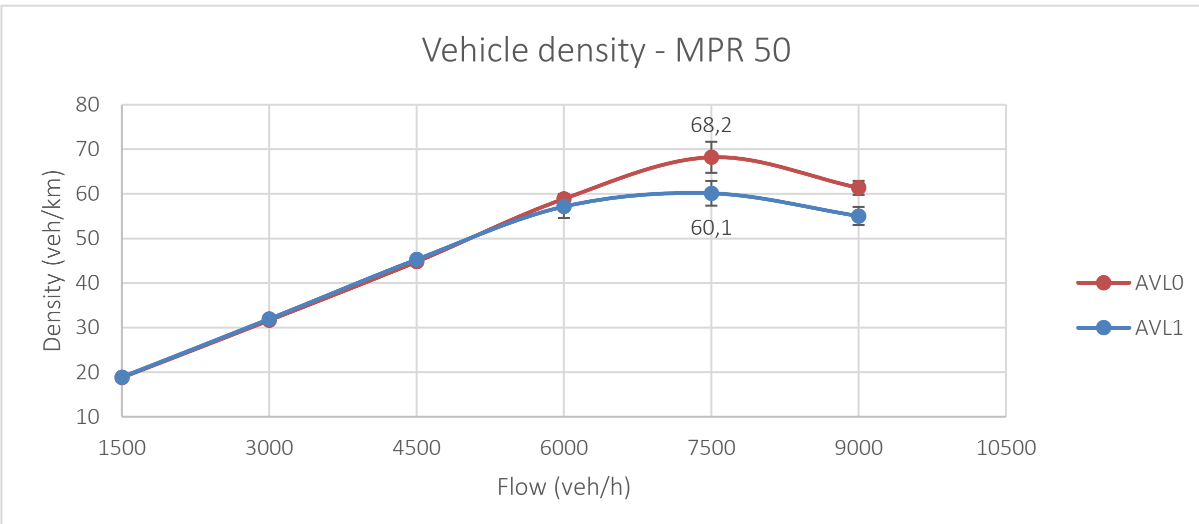
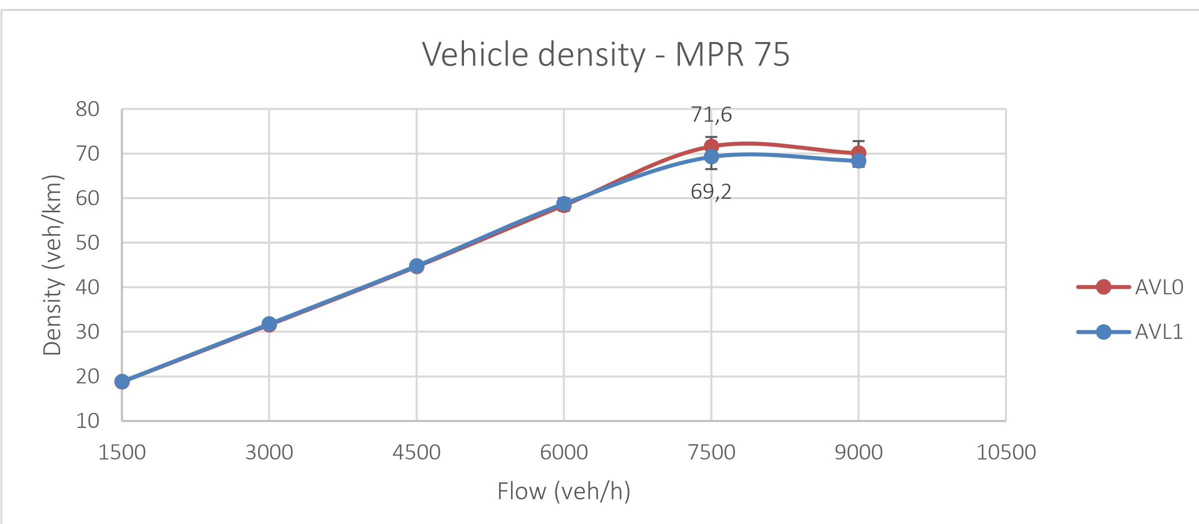


Figure 10: Vehicle density no AV lanes (MPR 0-25-50-75-100%)

On the next page three graphs (figures 11-12-13) are shown with the vehicle density of MPR 25, 50 and 75%. For these scenarios the most left lane is converted into an AV lane. The figures show that an AV lane does not improve the vehicle density. The labels indicate the maximum density for each scenario. Like travel time, the difference in vehicle density gets smaller when the market penetration rate gets larger. The mean values and standard deviations of these graphs are shown in tables 12,13 and 14 in appendix 4.







Figures (11-12-13): Vehicle density (MPR 25-50-75) no AV lane vs 1 AV lane

4.2.3 Speed

The next performance indicator which is evaluated is the average speed after the bottleneck. This graph (figure 14) is not as clear as previous graphs. The average speed decreases over time until 6000 vehicles per hour. At that point the average speed of MPR 0 and 25 increases again. The average speed of the other scenarios keeps on decreasing. When congestion arises, the average speed reaches it minimum. When there is congestion for an amount of time the average speed 'recovers' a bit, and that creates a reverse peak. So, congestion has not started for the scenario of MPR 100. Like the previous performance indicators, it can be concluded that the highest market penetration rate has a positive impact on the traffic flow. The mean values and standard deviations of this graph are shown in table 15 in appendix 5.

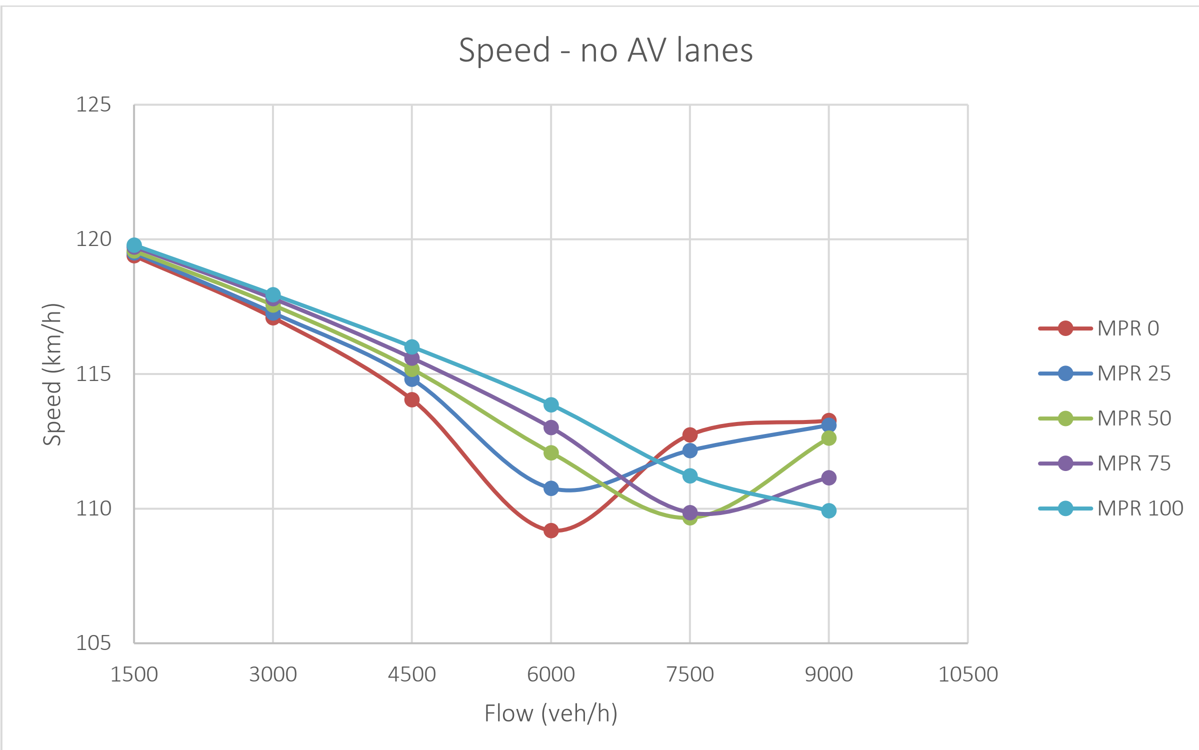
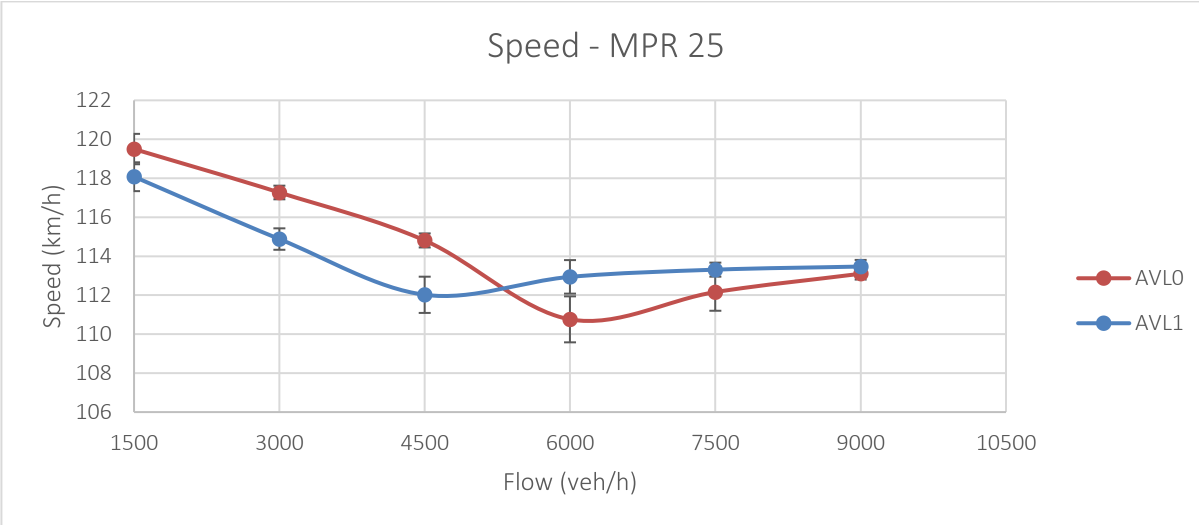
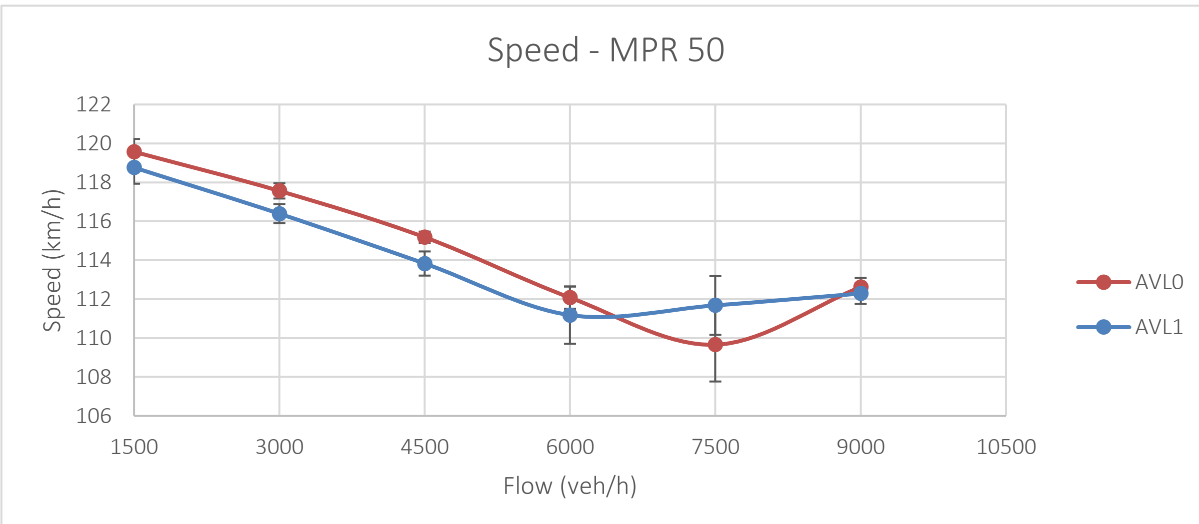
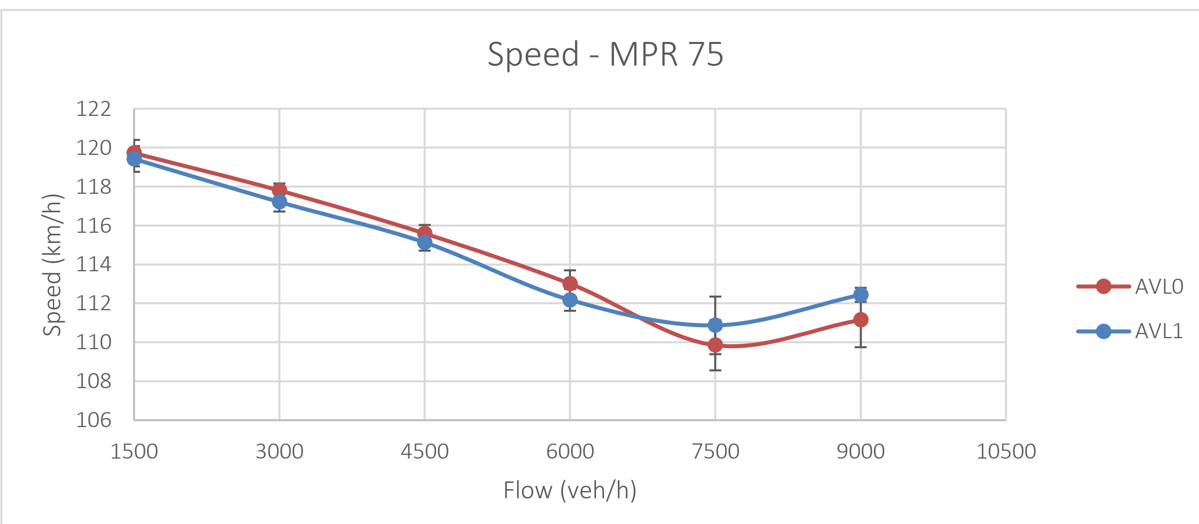


Figure 14: Speed no AV lanes (MPR 0-25-50-75-100%)

On the next page three graphs (figures 15-16-17) are shown with the average speed of MPR 25, 50 and 75%. For these scenarios the most left lane is converted into an AV lane. The average speed for the scenarios with an AV lane is lower when there is free traffic flow. The differences between the scenarios gets smaller, as the market penetration gets larger. Congestion arises at an earlier stage for market penetration rates of 25 and 50%. The mean values and standard deviations of these graphs are shown in tables 16,17 and 18 in appendix 5.







Figures (15-16-17): Speed (MPR 25-50-75) no AV lane vs 1 AV lane

4.2.4 Queue discharge rate

This performance indicator gives an indication of the road capacity after the bottleneck. Figure 18 shows the queue discharge rates for the five different scenarios with no AV lanes. The value on the x-axis is the input flow at the beginning of the highway. The y-axis indicates the flow at the end of the highway, after the on-ramp where 1000 vehicles per hour are added to the traffic flow. The peak of each line indicates the maximum queue discharge rate. The graph shows that MPR 100 has the largest capacity after bottleneck. This capacity is 36% larger than the capacity of MPR 0, which is a significant difference. The mean values and standard deviations of this graph are shown in table 19 in appendix 6.

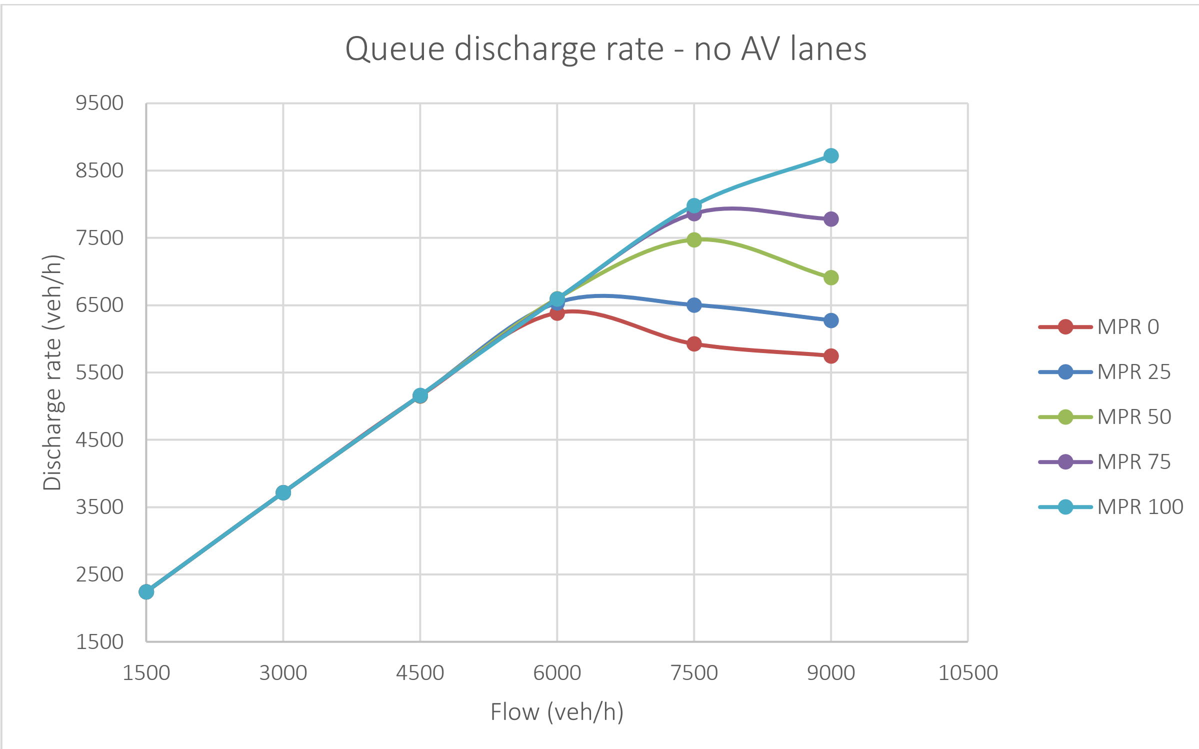
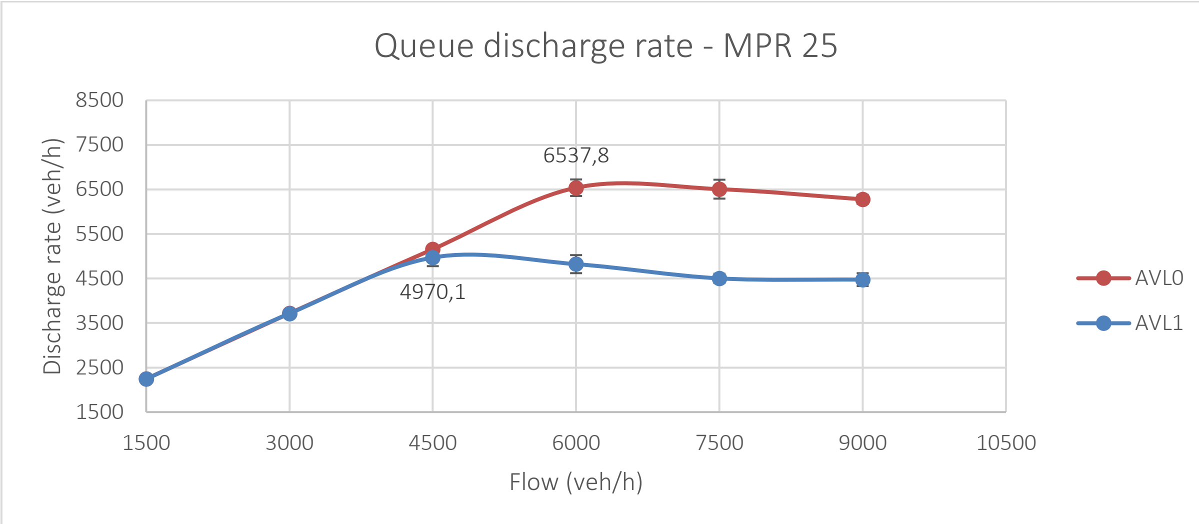
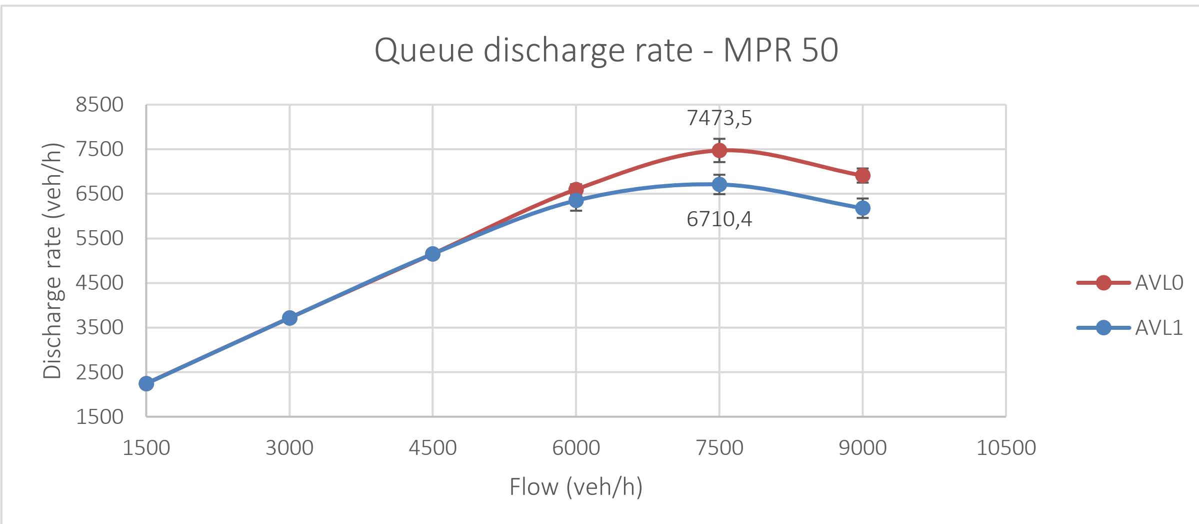
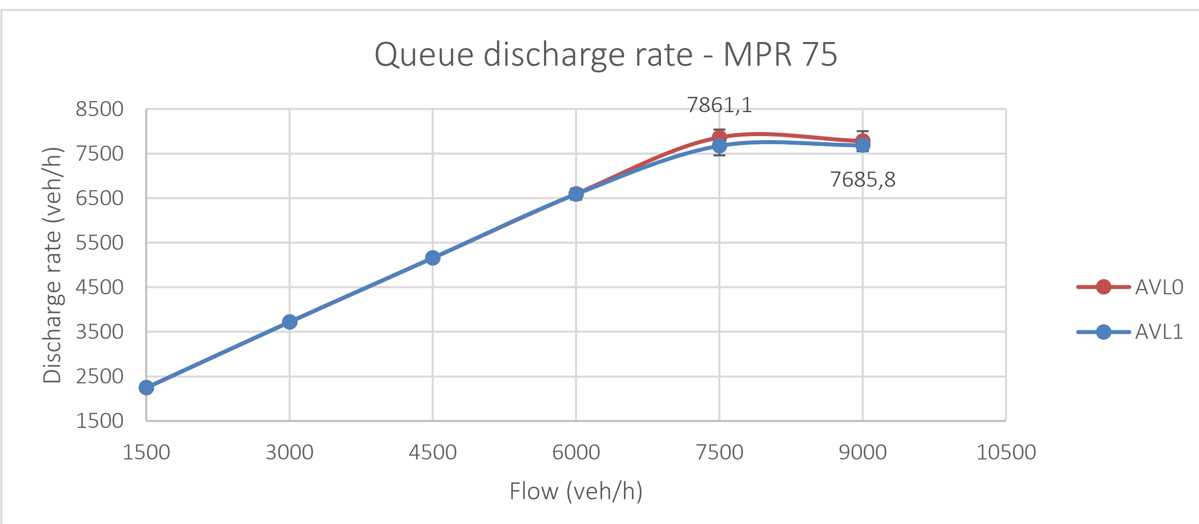


Figure 18: Queue discharge rate no AV lanes (MPR 0-25-50-75-100%)

On the next page three graphs (figures 19-20-21) are shown with the queue discharge rate of MPR 25, 50 and 75%. For these scenarios the most left lane is converted into an AV lane. The three graphs show that the discharge rate, capacity after the bottleneck, is smaller for each scenario with an AV lane. The difference in capacity gets smaller when the market penetration rate of automated vehicles gets higher. The mean values and standard deviations of these graphs are shown in tables 20,21 and 22 in appendix 6.







Figures (19-20-21): Queue discharge rate (MPR 25-50-75) no AV lane vs 1 AV lane

Based on the results of this experiment the following sub-question can be answered:

Sub-question 2: How does an AV lane influence the traffic flow for different market penetration rates of automated vehicles?

Answer: An AV lane does not improve the traffic flow efficiency for all scenarios. A market penetration rate of 25% has a large negative impact on the traffic flow, congestion arises at an earlier stage and capacity drops significantly. This is because a big part of the traffic flow (75%) have one lane less to drive on. When the market penetration rate increases the negative effect decreases, but a positive effect does not occur. However, as mentioned in the answer to the first sub-question, the road capacity increases when the number of automated vehicles becomes larger. This effect is not strengthened by separating automated and conventional vehicles with AV lanes.

4.3 Experiment 2: Number of driving lanes

The goal of the second simulation experiment is to the research what the influence of the total number of lanes is, when an AV lane is implemented. The same four performance indicators are used for this experiment. The experiment consists of three scenarios: three, four and five driving lanes. For each of these scenarios an AV lane is added on the most left lane. For the scenarios with four and five driving lanes, two AV lanes are added. The market penetration rate of the scenarios is set to 50%. The scenario with three driving lanes is displayed with graphs in experiment 1, therefore a table of results is shown in this part. At the end of this chapter the third sub-question is answered.

4.3.1 Travel time

The two graphs below (figures 22 and 23) show the average travel time for four and five driving lanes. The travel time of two AV lanes is significantly longer compared to the other scenarios, and the travel time increases heavily at an earlier stage (7500-9000 veh/h). Compared to three lanes with an AV lane (table 2), the impact is less negative for four and five driving lanes. There is not a significant difference in the impact of an AV lane on four and five driving lanes. The mean values and standard deviations of these graphs are shown in tables 23 and 24 in appendix 7.

Table 2: Travel time 3 driving lanes no and 1 AV lane

	3 lanes AVL0		3 lanes AVl1	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,5	0,39	82,8	0,43
3000	83,8	0,22	84,3	0,28
4500	85,6	0,2	86,5	0,23
6000	88,4	0,74	100,5	11,8
7500	105,8	14,1	181,3	36,3
9000	**247,7**	32,1	**348,2**	31,6

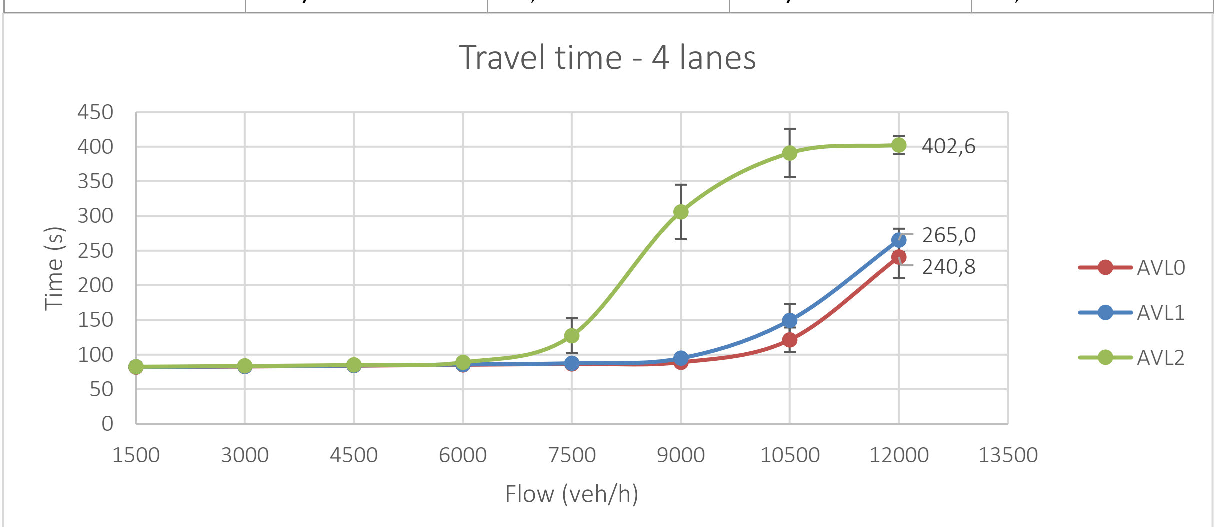


Figure 22: Travel time 4 driving lanes no -, 1 AV lane and 2 AV lanes

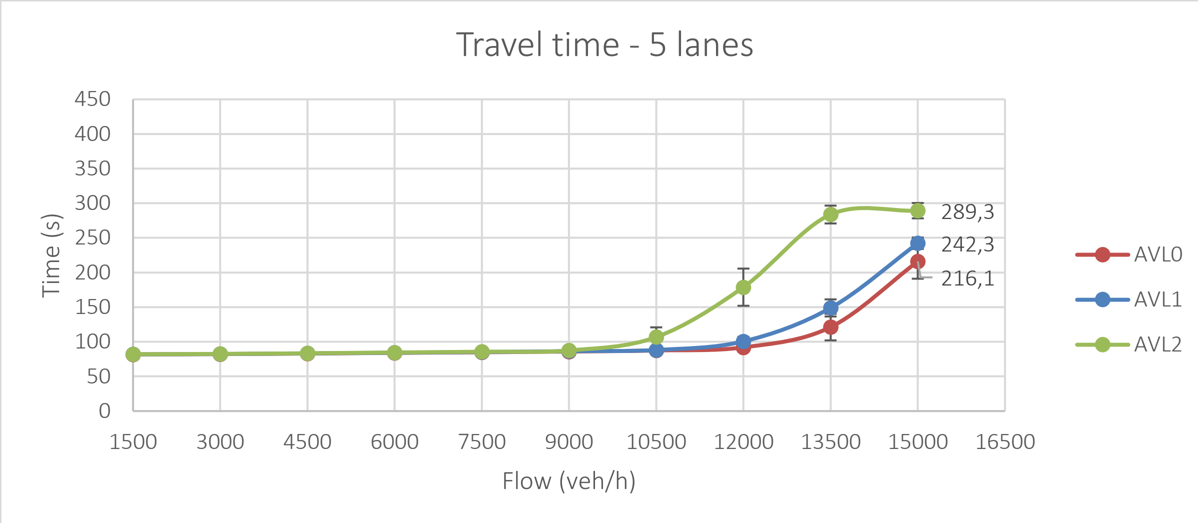


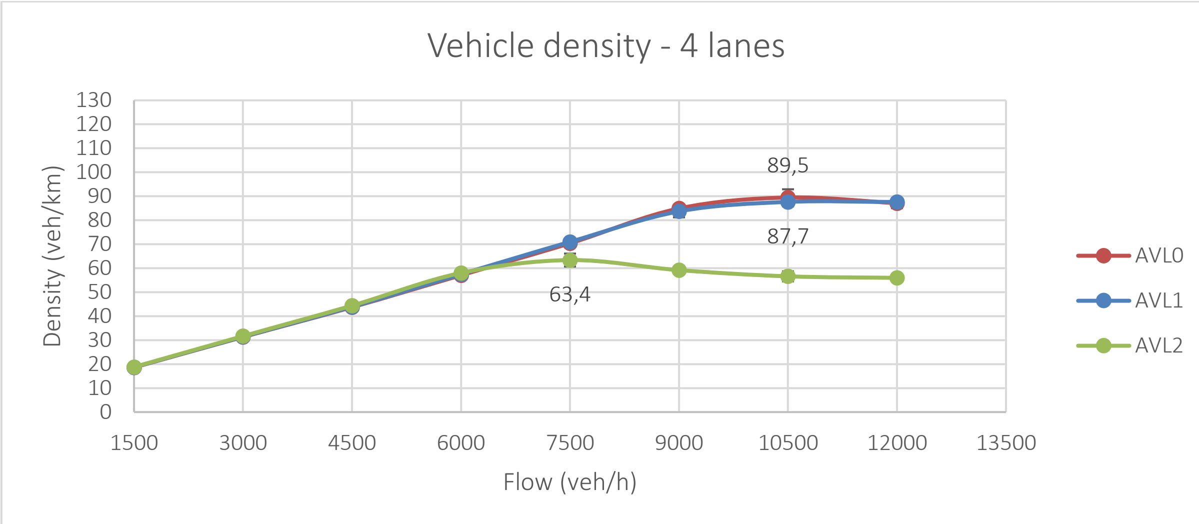
Figure 23: Travel time 5 driving lanes no -, 1 AV lane and 2 AV lanes

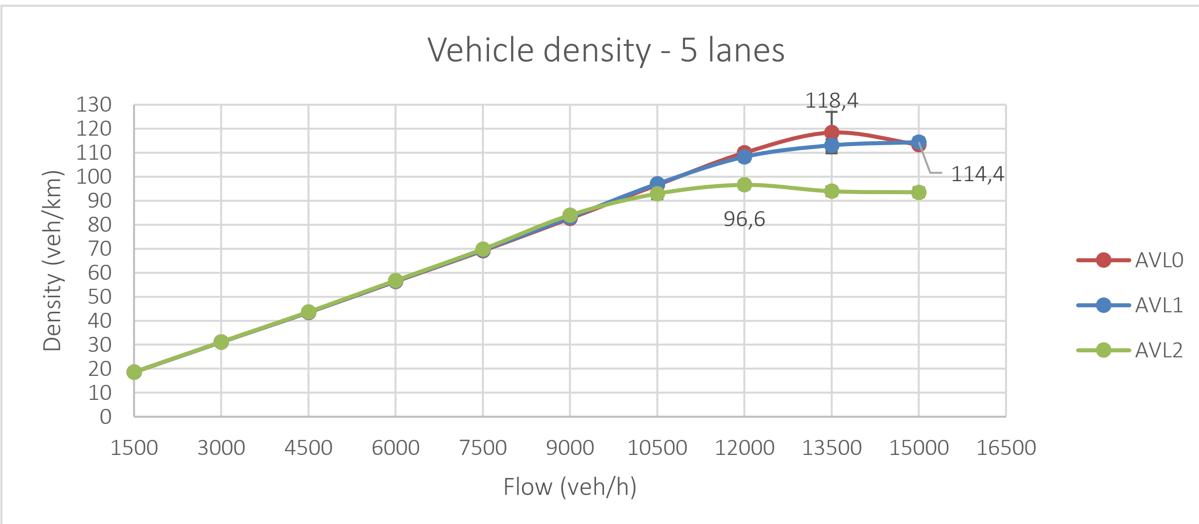
4.3.2 Vehicle density

The number of vehicles per kilometres is the definition of vehicle density. The vehicle densities of the second simulation experiment is shown in table 3 and figures 24 and 25. The scenarios of one AV lane get nearly similar results as no AV lane for four and five driving lanes. The difference in vehicle density is larger for the three lanes scenario. The scenario of two AV lanes gives similar results as for travel time, for both four and five lanes the vehicle density has much lower values. Based on these values, it can also be concluded that 2 AV lanes have a negative impact on the road capacity. The mean values and standard deviations of these graphs are shown in tables 25 and 26 in appendix 8.

Table 3: Vehicle density 3 driving lanes no and 1 AV lane

	3 lanes AVL0		**3 lanes AVl1**	
Flow(veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,8	0,58	18,9	0,59
3000	31,6	0,40	31,9	0,49
4500	44,8	0,60	45,3	0,70
6000	58,9	1,1	57,1	2,6
7500	**68,2**	3,5	**60,1**	2,8
9000	61,4	1,6	55,0	2,1





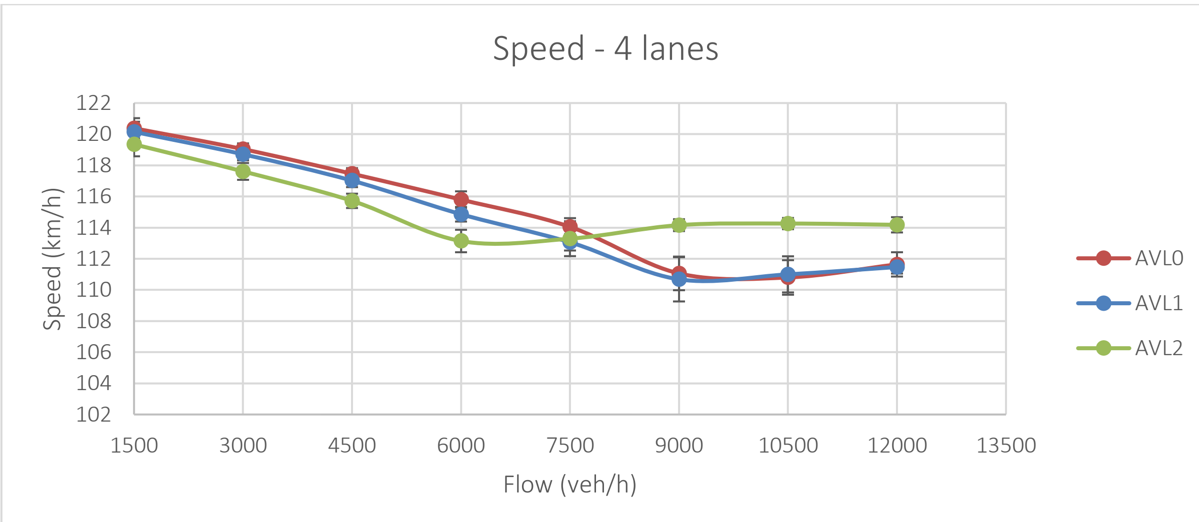
Figures 24-25: Vehicle density 4&5 driving lanes no -, 1 AV lane and 2 AV lanes

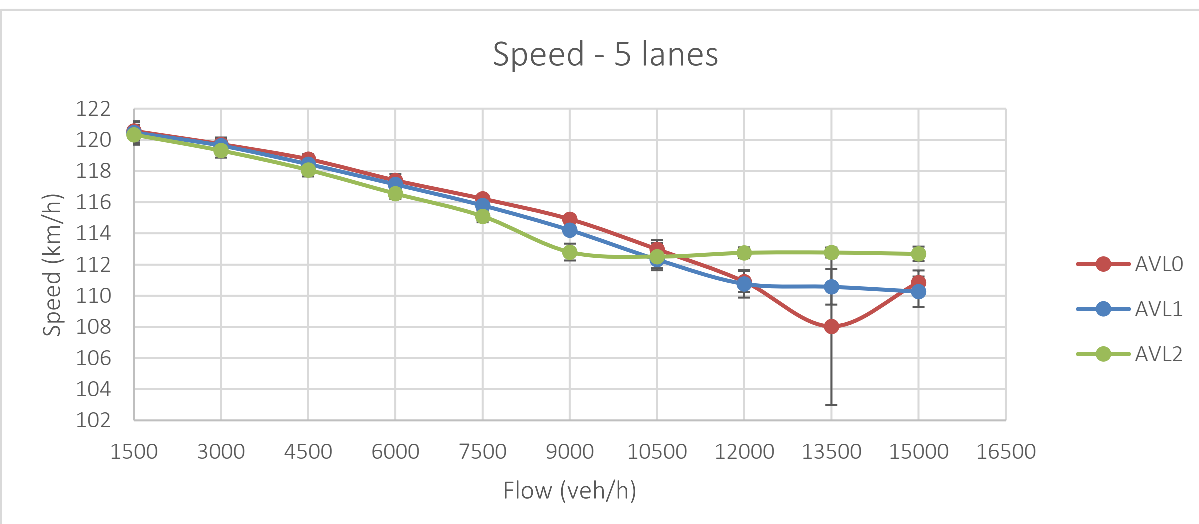
4.3.3 Speed

The average speed is measured 750 meters after the bottleneck for this simulation experiment as well. The results of this experiment is shown in table 4 and figures 26 and 27. The results of the two AV lanes scenario shows that congestion arises earlier compared to the other scenarios, due to the reverse peak. The average speed of four driving lanes has nearly the same values for no and one AV lane. For the scenario of five driving lanes with no AV lane there is a big standard deviation, (5,1 km/h), at the point of 13500 vehicles per hour. Therefore, it is not possible to conclude what the difference is between no- and one AV lane for five driving lanes, due to the large standard deviation. The mean values and standard deviations of these graphs are shown in tables 27 and 28 in appendix 9.

Table 4: Speed 3 driving lanes no and 1 AV lane

	3 lanes AVL0		3 lanes AVl1	
Flow(veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	119,6	0,66	118,8	0,83
3000	117,6	0,39	116,4	0,49
4500	115,2	0,29	113,8	0,62
6000	112,1	0,57	111,2	1,5
7500	109,7	1,9	111,7	1,5
9000	112,6	0,48	112,3	0,53





Figures 26-27: Speed 4&5 driving lanes no -, 1 AV lane and 2 AV lanes

4.3.4 Queue discharge rate

The number of vehicles per hour after the bottleneck is defined as the queue discharge rate. In table 5 and figures 28 and 29 the discharge rates are given for the different scenarios. For one AV lane the difference in capacity is much smaller for the scenarios of four and five driving lanes compared to the scenario of three driving lanes. These scenarios nearly have the same capacity. The scenario of two AV lanes has a negative impact on the discharge rate, the maximum value is much lower, and because of that it is reached at an earlier stage. The mean values and standard deviations of these graphs are shown in tables 29 and 30 in appendix 10.

Table 5: Queue discharge rate 3 driving lanes no and 1 AV lane

	3 lanes AVL0		3 lanes AVl1	
Flow(veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2244,1	61,1	2243,1	59,9
3000	3717,6	47,6	3715,9	49,7
4500	5155,1	63,7	5153,0	60,0
6000	6599,0	115,5	6350,2	228,8
7500	**7473,5**	261,0	**6710,4**	217,8
9000	6910,6	158,5	6178,0	217,6

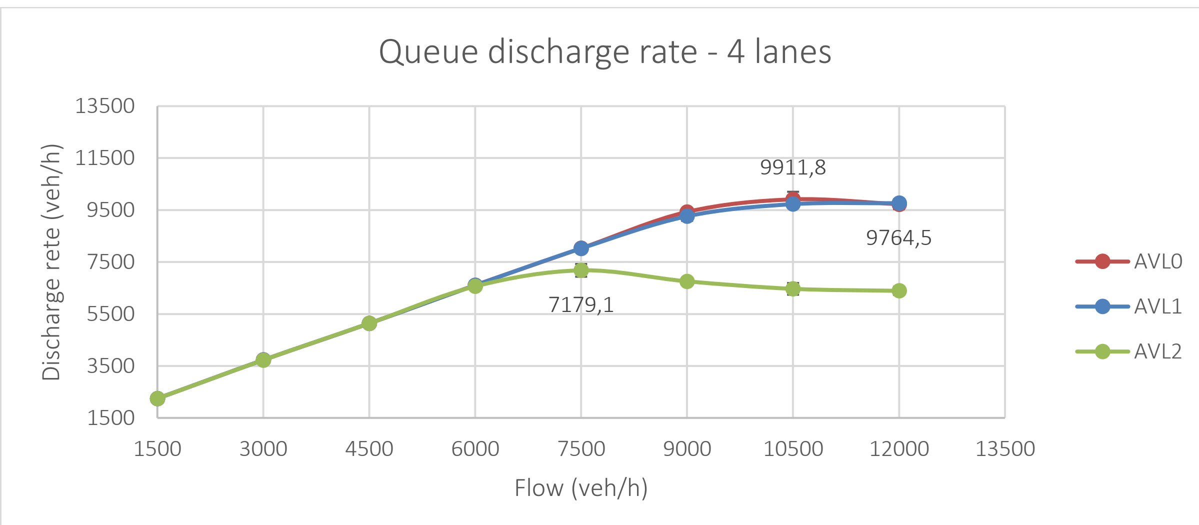


Figure 28: Queue discharge rate 4 driving lanes no -, 1 AV lane and 2 AV lanes

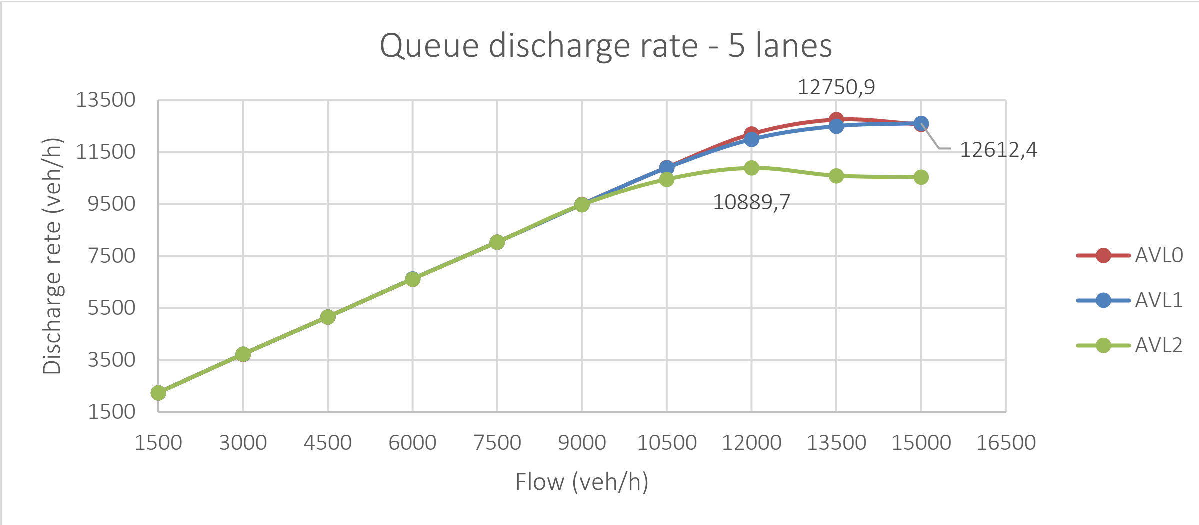


Figure 29: Queue discharge rate 5 driving lanes no -, 1 AV lane and 2 AV lanes

Based on the previous experiment the following sub-question can be answered:

Sub- question 3: What is the relation of AV lanes and the total number of driving lanes on the traffic flow?

Answer: The converging of one driving lane into an AV lane has a negative impact on the traffic flow for a total of three driving lanes. For the scenarios of four and five driving lanes this negative effect decreases, but for none of the scenarios an AV lane improves the traffic flow. The effect becomes smaller because conventional vehicles can utilize more lanes. The implementation of two AV lanes has a highly negative impact on road capacity and travel time. This is because the positive impact of AVs, higher road capacity due to smaller headway, do not cover the negative impact on conventional vehicles when the number of driving lanes for these vehicles decreases.

4.4 Road capacity factors

The two simulation experiments are focussed on market penetration rate and number of driving lanes. In this chapter these two experiments are combined to get a good overview of the impact of AV lanes. The starting point of this overview is the queue discharge rate of each scenario. The reason for using this indicator instead of speed and travel time, is that these indicators do not have specific maximum values for each scenario. Comparing vehicle densities could be a valid option as well, however road capacity is a starting point for designing road sections, therefore the discharge rate after a bottleneck, is evaluated.

Queue discharge rate indicates what the maximum capacity is of a certain scenario. When the number of driving lanes increases, the queue discharge rate increases as well. Therefore, the discharge rates are divided to a baseline measurement, the discharge rate of a market penetration rate of 0%. In appendix 11 a table is placed with the road capacities of all scenarios. Table 6 shows the road capacity factors of the different scenarios. The scenarios of four and five driving lanes with MPRs of 25 and 75% are not simulated, and therefore these rows are empty is this table. Based on the results of the two experiments, assumptions of these factors can be made. The road capacity factors could be around 1,00 for MPR of 25%, and 1,20 for MPR of 75%. Further research will be needed to confirm these assumptions.

Based on the road capacity factors the following can be concluded:

- The road capacity increases when the MPR gets higher.
- Capacity does not improve when one AV lane is implemented.
- The negative impact of one AV lane becomes smaller, for higher number of driving lanes.
- Adding two AV lanes has a highly negative effect on capacity.

Table 6: Road capacity factors

	3 lanes		4 lanes			5 lanes		
	AVL0	AVL1	AVL0	AVL1	AVL2	AVL0	AVL1	AVL2
MPR 25	1,02	0,78						
MPR 50	1,17	1,05	1,16	1,14	0,84	1,19	1,17	1,01
MPR 75	1,23	1,20						

In appendix 12 a table is shown with vehicle density factors, which give nearly similar results.

5 Discussion

In this report a traffic microsimulation has been performed to research the impact of automated vehicles lanes on the traffic flow. The simulation results show that these lanes do not improve the overall traffic flow. In this chapter the results are discussed.

First of all, automated vehicles have been simulated in VISSIM by adapting driving parameters of conventional vehicles. The Wiedemann model is a psycho-physical car following model, which is based on human driving behaviour. As mentioned in the report, these set of parameters are the results of an extensive research, but it is not assured whether these parameters approximate the future driving performance of automated vehicles. Also, the automated vehicles in the simulation were not connected with each other, for instance when a congestion appeared, the automated vehicles before the bottleneck were not warned. Therefore, they responded similar as conventional vehicles to the congestion. Externally - instead of nor internally modelling could have resulted in a more reliable results. Interactions between AV's and other vehicles can be simulated with these additional modules, however due to the limited amount of time and knowledge of this modules, this was not feasible.

The simulation results consists of the mean of ten simulation runs. If higher precision is required, this number should have been higher, for instance 30 simulation runs. Also, more experiments could have been simulated, instead of only market penetration rate and number of driving lanes. Possible simulation experiments could have been freight traffic rate and AV lane policies. For instance, the automated vehicles were not forced to use the AV lane, when an AV lane was implemented some AVs still used the conventional lanes. These scenarios could have contributed to different conclusions.

The impact on the different vehicle types was not included in this report, because in the simulation data significant differences between CVs and AVs were not visible. A possible reason for this effect is the assumed driving performance of automated vehicles. The simulation results were counterintuitive, because it was expected that for some scenarios, high MPRs or large number of driving lanes, AV lanes would improve the traffic flow, because the number of interactions between the two types of vehicles would be much smaller. Further research is needed to confirm or refute these results, in the short term this could be done by more extensive simulations of AV lanes. In the long term, tests of automated vehicles with dedicated lanes on highways might be an option to determine the possible effects of these lanes on the traffic flow efficiency.

6 Conclusion

In this document three sub-questions have been answered which form the base for answering the main research question. The goal of this report is to research the impact of automated vehicle lanes on highway traffic flow efficiency. Based on this research, it can be concluded that dedicated lanes for automated vehicles do not positively benefit the traffic flow. By analysing the driving performance of automated vehicles, it was concluded that automated vehicles have a more assertive behaviour in lateral and longitudinal direction. This has a positive impact on the traffic flow, which was confirmed in the first simulation experiment. When the number of automated vehicles increases, the road capacity increases as well. This effect is not improved by separating automated vehicles from conventional vehicles. The two factors which determine this impact are the market penetration rate and total number of driving lanes. When there is a small amount of automated vehicles (25%), an AV lane arises more congestion, because for a majority of the vehicles the number of driving lanes has decreased. For higher MPRs (75%), the impact of an AV lane is less negative and has nearly similar efficiency compared to no AV lane. When the number of driving lanes increases (four and five driving lanes), the negative impact of an AV lane becomes smaller, but none of the performance indicators is affected in a beneficial way. Therefore, automated vehicle lanes are not a solution to improve the integration of AVs on highways.

References & figures

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Figures

- Figure cover sheet, retrieved from: https://unsplash.com/photos/d271d_SOGR8
- Figure 1: PTV Vissim & connected autonomous vehicles, retrieved from: http://www.sfbayite.org/wp-content/uploads/2017/04/1%20VISSIM_CAV_SFITE_April2017.pdf
- Figure X : Morando, M. ,2018. *Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures*

Appendices

The list of appendices are listed here below.

- Appendix 1: SAE-levels
- Appendix 2: Driving performance parameters definitions
- Appendix 3: Market penetration rate - Travel time
- Appendix 4: Market penetration rate – Vehicle density
- Appendix 5: Market penetration rate - Speed
- Appendix 6: Market penetration rate – Queue discharge rate
- Appendix 7: Number of driving lanes – Travel time
- Appendix 8: Number of driving lanes – Vehicle density
- Appendix 9: Number of driving lanes – Speed
- Appendix 10: Number of driving lanes – Queue discharge rate
- Appendix 11: Road capacity of all scenario
- Appendix 12: Vehicle density factors

Appendix 1: SAE-levels

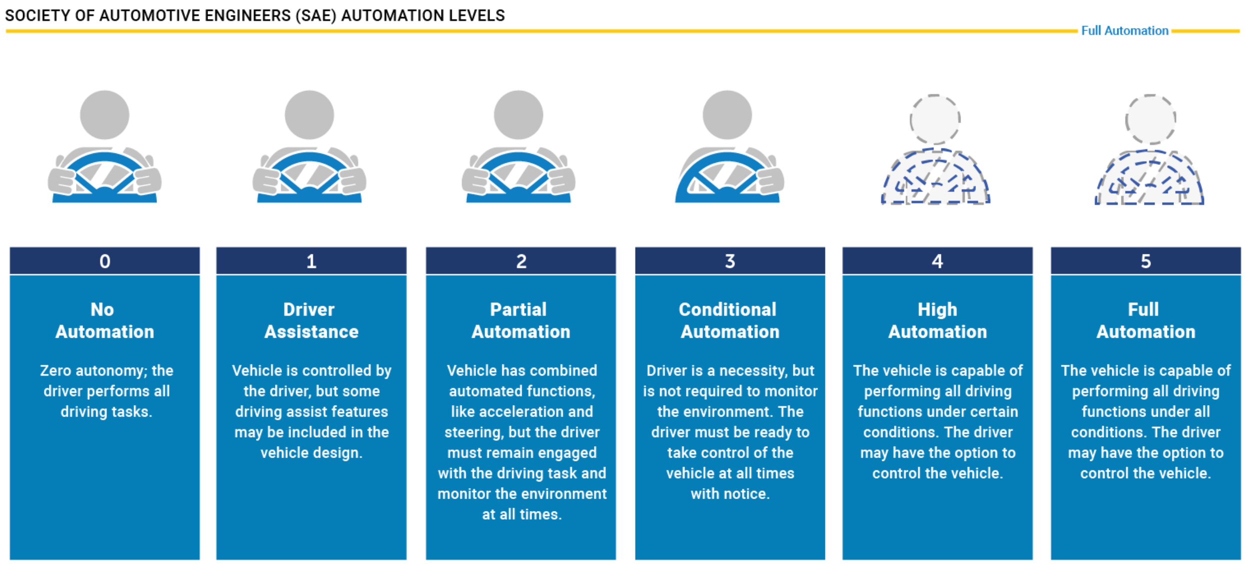

Figure 30: Levels of automation

- Level 0: No Automation - Zero autonomy, the driver performs all driving tasks.
- Level 1: Driver Assistance - Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.
- Level 2: Partial Automation – Vehicle has combined automated functions, like acceleration and steering, but the driver must remain engaged with the driving task and monitor the environment at all times.
- Level 3: Conditional Automation: Driver is a necessity, but is not required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.
- Level 4: High Automation: The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle.
- Level 5: Full Automation: The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

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Appendix 2: Driving performance parameters definitions (PTV VISSIM)

- **Standstill distance (m):** The average desired standstill distance between two vehicles.
- **Headway time (s):** Time distribution of speed-dependent part of desired safety distance. Based on the time distribution, the following distance for a vehicle is calculated. This is the distance in seconds which a driver wants to maintain at a certain speed. The higher the value, the more cautious the driver is. The safety distance is defined in the car following model as the minimum distance a driver will maintain while following another vehicle.
- **Following variation (m):** It restricts the distance difference (longitudinal oscillation) or how much more distance than the desired safety distance a driver allows before he intentionally moves closer to the car in front.
- **Negative following threshold (m/s):** Defines negative speed difference during the following process. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
- **Positive following threshold (m/s):** Defines positive speed difference during the following process.
- **Speed dependency of oscillation:** Influence of distance on speed oscillation while in following process. Value 0: The speed oscillation is independent of the distance. Larger values: Lead to a greater speed oscillation with increasing distance.
- **Oscillation acceleration (m/s2):** Oscillation during acceleration
- **Standstill acceleration (m/s2):** Desired acceleration when starting from standstill (limited by maximum acceleration defined within the acceleration curves).
- **Acceleration at 80 km/h (m/s2):** Desired acceleration at 80 km/h (limited by maximum acceleration defined within the acceleration curves).
- **Observed vehicles:** The number of observed vehicles or number of certain network objects affects how well vehicles in the link can predict other vehicles' movements and react accordingly.
- **Min. headway (m):** The minimum distance between two vehicles that must be available after a lane change, so that the change can take place (default value 0.50 m). A lane change during normal traffic flow might require a greater minimum distance between vehicles in order to maintain the speed-dependent safety distance.
- **Safety distance reduction factor:** is taken into account for each lane change. It concerns the following parameters:
  - The safety distance of the trailing vehicle on the new lane for determining whether a lane change will be carried out.
  - The safety distance of the lane changer itself.
  - The distance to the preceding, slower lane changer

During the lane change Vissim reduces the safety distance to the value that results from the following multiplication: Original safety distance * safety distance reduction factor. The default value of 0.60

reduces the safety distance by 40%. Once a lane change is completed, the original safety distance is taken into account again.

- **Cooperative lane change:** If vehicle A observes that a leading vehicle B on the adjacent lane wants to change to his lane A, then vehicle A will try to change lanes itself to the next lane in order to facilitate lane changing for vehicle B. For example, vehicle A would switch from the right to the left lane when vehicle B would like to switch to the left from a merging lane to the right lane.

Appendix 3: Market penetration rate - Travel time

Table 7: Travel time MPR 0-25-50-75-100

	MPR 0		MPR 25		MPR 50		MPR 75		MPR 100	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,6	0,38	82,6	0,39	82,5	0,39	82,4	0,38	82,4	0,38
3000	84,1	0,21	84,0	0,24	83,8	0,22	83,6	0,24	83,4	0,23
4500	86,5	0,32	85,9	0,25	85,6	0,20	85,2	0,22	84,9	0,18
6000	99,1	14,1	92,1	7,7	88,4	0,74	87,5	0,43	86,7	0,30
7500	219,0	35,9	163,5	31,1	105,8	14,1	93,0	5,2	88,9	1,17
9000	374,5	11,2	346,8	20,2	247,7	32,1	166,6	26,0	115,6	16,8

Table 8: Travel time MPR 25 no- and 1 AV lane

	MPR 25 AVL0		MPR 25 AVL1	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,6	0,39	83,3	0,54
3000	84,0	0,24	85,4	0,42
4500	85,9	0,25	98,0	13
6000	92,1	7,7	216,3	46,1
7500	163,5	31,1	429,9	25,7
9000	346,8	20,2	487,9	27,9

Table 9: Travel time MPR 50 no- and 1 AV lane

	MPR 50 AVL0		MPR 50 AVL1	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,5	0,39	82,8	0,43
3000	83,8	0,22	84,3	0,28
4500	85,6	0,2	86,5	0,23
6000	88,4	0,74	100,5	11,8
7500	105,8	14,1	181,3	36,3
9000	247,7	32,1	348,2	31,6

Table 10: Travel time MPR 75 no- and 1 AV lane

	MPR 75 AVL0		MPR 75 AVL1	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,4	0,38	82,6	0,36
3000	83,6	0,24	83,8	0,28
4500	85,2	0,22	85,6	0,29
6000	87,5	0,43	87,8	0,69
7500	93,0	5,2	104,7	14,3
9000	166,6	26,0	199,2	20,9

Appendix 4: Market penetration rate - Vehicle density

Table 11: Vehicle density MPR 0-25-50-75-100

	MPR 0		**MPR 25**		**MPR 50**		**MPR 75**		**MPR 100**	
Flow (veh/h)	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1500	18,8	0,60	18,8	0,60	18,8	0,58	18,8	0,59	18,7	0,59
3000	31,7	0,43	31,7	0,43	31,6	0,40	31,6	0,42	31,5	0,39
4500	45,2	0,61	44,9	0,65	44,8	0,60	44,6	0,68	44,5	0,64
6000	58,5	3,4	59,1	2,2	58,9	1,1	58,4	1,2	57,9	1,1
7500	52,6	2,1	58,0	2,3	68,2	3,5	71,6	2,1	71,8	1,3
9000	50,8	0,58	55,5	0,99	61,4	1,6	70,0	2,8	79,4	2,8

Table 12: Vehicle density MPR 25 no- and 1 AV lane

	MPR 25 AVL0		MPR 25 AVL1	
Flow (veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,8	0,6	19,0	0,58
3000	31,7	0,43	32,3	0,51
4500	44,9	0,65	44,4	2,0
6000	59,1	2,2	42,7	2,1
7500	58,0	2,3	39,7	0,94
9000	55,5	0,99	39,4	1,3

Table 13: Vehicle density MPR 50 no- and 1 AV lane

	MPR 50 AVL0		MPR 50 AVL1	
Flow (veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,8	0,58	18,9	0,59
3000	31,6	0,40	31,9	0,49
4500	44,8	0,60	45,3	0,7
6000	58,9	1,1	57,1	2,6
7500	68,2	3,5	60,1	2,8
9000	61,4	1,6	55,0	2,1

Table 14: Vehicle density MPR 75 no- and 1 AV lane

	MPR 75 AVL0		MPR 75 AVL1	
Flow (veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,8	0,59	18,8	0,58
3000	31,6	0,42	31,7	0,43
4500	44,6	0,68	44,8	0,68
6000	58,4	1,2	58,7	1,3
7500	71,6	2,1	69,2	2,7
9000	70,0	2,8	68,4	1,3

Appendix 5: Market penetration rate – Speed

Table 15: Speed MPR 0-25-50-75-100

	MPR 0		MPR 25		MPR 50		MPR 75		MPR 100	
Flow (veh/h)	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1500	119,4	0,79	119,5	0,78	119,6	0,66	119,7	0,68	119,8	0,73
3000	117,1	0,31	117,3	0,35	117,6	0,39	117,8	0,36	118,0	0,39
4500	114,1	0,53	114,8	0,36	115,2	0,29	115,6	0,44	116,0	0,46
6000	109,2	2,3	110,8	1,2	112,1	0,57	113,0	0,69	113,9	0,55
7500	112,7	1,0	112,2	0,96	109,7	1,89	109,9	1,3	111,2	0,87
9000	113,3	0,27	113,1	0,30	112,6	0,48	111,2	1,4	109,9	1,5

Table 16: Speed MPR 25 no- and 1 AV lane

	MPR 25 AVL0		MPR 25 AVL1	
Flow (veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	119,5	0,78	118,1	0,74
3000	117,3	0,35	114,9	0,55
4500	114,8	0,36	112,0	0,93
6000	110,8	1,2	112,9	0,86
7500	112,2	0,96	113,3	0,36
9000	113,1	0,30	113,5	0,34

Table 17: Speed MPR 50 no- and 1 AV lane

	MPR 50 AVL0		MPR 50 AVL1	
Flow (veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	119,6	0,66	118,8	0,83
3000	117,6	0,39	116,4	0,49
4500	115,2	0,29	113,8	0,62
6000	112,1	0,57	111,2	1,5
7500	109,7	1,9	111,7	1,5
9000	112,6	0,48	112,3	0,53

Table 18: Speed MPR 75 no- and 1 AV lane

	MPR 75 AVL0		MPR 75 AVL1	
Flow (veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	119,7	0,68	119,4	0,66
3000	117,8	0,36	117,2	0,49
4500	115,6	0,44	115,1	0,42
6000	113,0	0,69	112,2	0,56
7500	109,9	1,3	110,9	1,5
9000	111,2	1,4	112,4	0,36

Appendix 6: Market penetration rate - Queue discharge rate

Table 19: Queue discharge rate MPR 0-25-50-75-100

	MPR 0		MPR 25		MPR 50		MPR 75		MPR 100	
Flow (veh/h)	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1500	2243,5	60,4	2244,1	61,1	2244,1	61,1	2244,1	61,1	2244,5	60,5
3000	3716,6	48,0	3716,9	48,0	3717,6	47,6	3718,3	48,1	3718,7	46,9
4500	5153,5	62,0	5156,8	63,6	5155,1	63,7	5157,3	64,8	5160,5	60,2
6000	6386,7	262,2	6537,8	186,2	6599,0	115,5	6595,1	110,5	6593,7	109,3
7500	5926,2	190,3	6505,2	212,3	7473,5	261,0	7861,1	177,1	7983,2	132,9
9000	5749,4	57,2	6276,9	101,9	6910,6	158,5	7781,8	219,4	8721,0	219,9

Table 20: Queue discharge rate MPR 25 no- and 1 AV lane

	MPR 25 AVL0		MPR 25 AVL1	
Flow (veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2244,1	61,1	2242,3	58,6
3000	3716,9	48,0	3714,2	51,4
4500	5156,8	63,6	4970,1	193,4
6000	6537,8	186,2	4822,1	202,8
7500	6505,2	212,3	4502,0	105,2
9000	6276,9	101,9	4473,9	144,0

Table 21: Queue discharge rate MPR 50 no- and 1 AV lane

	MPR 50 AVL0		MPR 50 AVL1	
Flow (veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2244,1	61,1	2243,1	59,9
3000	3717,6	47,6	3715,9	49,7
4500	5155,1	63,7	5153,0	60,0
6000	6599,0	115,5	6350,2	228,8
7500	7473,5	261,0	6710,4	217,8
9000	6910,6	158,5	6178,0	217,6

Table 22: Queue discharge rate MPR 75 no- and 1 AV lane

	MPR 75 AVL0		MPR 75 AVL1	
Flow (veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2244,1	61,1	2243,6	60,4
3000	3718,3	48,1	3720,3	49,6
4500	5157,3	64,8	5155,9	62,4
6000	6595,1	110,5	6587,3	122,2
7500	7861,1	177,1	7671,8	213,1
9000	7781,8	219,4	7685,8	133,7

Appendix 7: Number of driving lanes – Travel time

Table 23: Travel time 4 lanes no-, 1 AV lane and 2 AV lanes

	4 lanes AVL0		4 lanes AVL1		4 lanes AVL2	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	82,0	0,36	82,1	0,37	82,5	0,41
3000	82,8	0,23	83,0	0,25	83,5	0,36
4500	84,0	0,21	84,2	0,25	85,1	0,29
6000	85,3	0,34	85,7	0,31	88,8	4,17
7500	86,7	0,32	87,6	0,75	127,3	25,4
9000	88,8	0,58	94,6	4,79	305,9	39,3
10500	121,3	17,8	149,3	23,5	391,0	35,0
12000	240,8	30,6	265,0	16,7	402,6	13,1

Table 24: Travel time 5 lanes no-, 1 AV lane and 2 AV lanes

	5 lanes AVL0		5 lanes AVL1		5 lanes AVL2	
Flow (veh/h)	Mean (s)	Std (s)	Mean (s)	Std (s)	Mean (s)	Std (s)
1500	81,8	0,37	81,9	0,39	82,0	0,38
3000	82,3	0,25	82,4	0,25	82,6	0,27
4500	83,1	0,14	83,3	0,19	83,5	0,21
6000	84,1	0,24	84,3	0,26	84,6	0,24
7500	85,0	0,27	85,3	0,24	85,7	0,26
9000	86,0	0,08	86,5	0,37	87,6	0,75
10500	87,5	0,69	88,2	0,59	106,9	14,0
12000	92,0	4,9	100,6	6,55	178,8	26,8
13500	121,2	19,2	148,9	12,4	283,7	12,9
15000	216,1	25,1	242,3	8,3	289,3	11,1

Appendix 8: Number of driving lanes – Vehicle density

Table 25: Vehicle density 4 lanes no-, 1 AV lane and 2 AV lanes

	4 lanes AVL0		4 lanes AVL1		4 lanes AVL2	
Flow(veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,7	0,59	18,7	0,58	18,8	0,60
3000	31,3	0,54	31,4	0,54	31,7	0,60
4500	43,7	0,69	43,9	0,69	44,4	0,70
6000	57,1	1,3	57,5	1,2	58,0	1,2
7500	70,4	0,93	71,0	0,88	63,4	2,7
9000	84,9	1,3	83,7	2,49	59,2	1,1
10500	89,5	3,4	87,7	1,9	56,6	2,1
12000	87,1	2,1	87,6	1,2	56,0	1,5

Table 26: Vehicle density 5 lanes no-, 1 AV lane and 2 AV lanes

	5 lanes AVL0		5 lanes AVL1		5 lanes AVL2	
Flow(veh/h)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)	Mean (veh/km)	Std (veh/km)
1500	18,5	0,59	18,6	0,59	18,6	0,58
3000	31,1	0,80	31,1	0,83	31,2	0,84
4500	43,4	0,86	43,5	0,86	43,7	0,88
6000	56,3	1,1	56,5	1,2	56,8	1,2
7500	69,1	0,93	69,4	0,99	69,8	0,93
9000	82,6	1,1	83,0	1,1	84,0	1,4
10500	96,5	0,82	97,0	1,1	92,9	2,29
12000	110,0	1,9	108,3	1,9	96,6	1,8
13500	118,4	8,6	113,1	2,5	93,9	2,0
15000	113,4	1,4	114,4	2,0	93,5	2,1

Appendix 9: Number of driving lanes – Speed

Table 27: Speed 4 lanes no-, 1 AV lane and 2 AV lanes

	4 lanes AVL0		4 lanes AVL1		4 lanes AVL2	
Flow(veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	120,4	0,65	120,2	0,65	119,4	0,77
3000	119,0	0,37	118,7	0,39	117,6	0,54
4500	117,5	0,36	117,0	0,42	115,7	0,46
6000	115,8	0,53	114,9	0,47	113,1	0,72
7500	114,1	0,56	113,1	0,53	113,3	1,1
9000	111,1	1,1	110,7	1,4	114,2	0,38
10500	110,8	1,1	111,0	1,2	114,3	0,36
12000	111,6	0,78	111,5	0,42	114,2	0,49

Table 28: Speed 5 lanes no-, 1 AV lane and 2 AV lanes

	5 lanes AVL0		5 lanes AVL1		5 lanes AVL2	
Flow(veh/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)	Mean (km/h)	Std (km/h)
1500	120,6	0,62	120,5	0,66	120,3	0,64
3000	119,7	0,43	119,6	0,46	119,3	0,45
4500	118,8	0,31	118,4	0,31	118,1	0,42
6000	117,4	0,39	117,1	0,39	116,6	0,35
7500	116,2	0,24	115,8	0,35	115,1	0,39
9000	114,9	0,15	114,2	0,26	112,8	0,54
10500	113,0	0,58	112,3	0,56	112,5	0,88
12000	110,9	0,68	110,8	0,88	112,8	0,35
13500	108,0	5,1	110,6	1,1	112,8	0,32
15000	110,9	0,77	110,3	0,97	112,7	0,47

Appendix 10: Number of driving lanes – Queue discharge rate

Table 29: Queue discharge rate 4 lanes no-, 1 AV lane and 2 AV lanes

	4 lanes AVL0		**4 lanes AVL1**		**4 lanes AVL2**	
Flow(veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2245,1	64,5	2244,9	64,5	2243,8	64,9
3000	3728,2	65,0	3728,9	63,9	3726,4	65,2
4500	5137,4	73,3	5139,0	64,6	5137,7	64,9
6000	6609,5	127,1	6603,4	123,0	6565,5	109,8
7500	8028,6	83,8	8023,9	88,1	7179,1	244,7
9000	9429,1	127,5	9262,5	178,1	6756,7	119,8
10500	9911,8	293,0	9728,1	128,5	6467,9	226,5
12000	9726,0	189,8	9764,5	130,5	6390,3	158,2

Table 30: Queue discharge rate 5 lanes no-, 1 AV lane and 2 AV lanes

	5 lanes AVL0		**5 lanes AVL1**		**5 lanes AVL2**	
Flow(veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)	Mean (veh/h)	Std (veh/h)
1500	2234,7	65,9	2234,7	66,0	2233,6	65,6
3000	3719,2	92,6	3720,8	94,8	3720,4	92,8
4500	5157,3	93,7	5151,9	93,6	5154,4	92,9
6000	6612,7	123,7	6617,3	124,3	6614,2	123,4
7500	8035,1	101,3	8034,8	99,1	8032,3	101,0
9000	9491,9	125,5	9483,8	128,7	9474,2	125,3
10500	10906,2	99,7	10894,3	105,2	10452,6	188,2
12000	12196,4	171,9	11991,6	150,0	10889,7	186,9
13500	12750,9	366,8	12499,6	151,5	10591,5	199,1
15000	12564,4	116,0	12612,4	122,7	10534,4	218,6

Appendix 11: Road capacity of all scenarios

Table 31: Road capacity of all performed scenarios

	3 lanes		4 lanes			5 lanes		
	AVL0	AVL1	AVL0	AVL1	AVL2	AVL0	AVL1	AVL2
MPR 0	6386,7		8568,4			10738,6		
MPR 25	6537,8	4970,1						
MPR 50	7473,5	6710,4	9911,8	9764,5	7179,1	12750,9	12612,4	10889,7
MPR 75	7861,1	7685,8						

Appendix 12: Vehicle density factors

Table 32: Vehicle density factors off all scenarios

	3 lanes		4 lanes			5 lanes		
	AVL0	AVL1	AVL0	AVL1	AVL2	AVL0	AVL1	AVL2
MPR 25	1,01	0,76						
MPR 50	1,17	1,03	1,15	1,12	0,81	1,22	1,18	1,00
MPR 75	1,22	1,18						