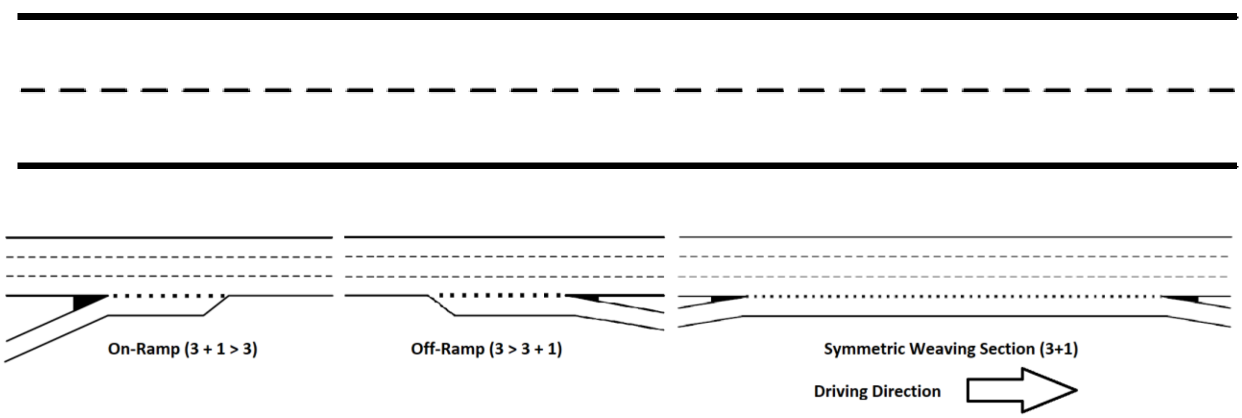
Autonomous and Cooperative Vehicles
&
Highway Capacity

A theoretical model approach for vehicle automation and communication on Dutch highway road segments, focused on non-platoon based car-following behavior.

Master Thesis in Transport Engineering and Management



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Autonomous and Cooperative Vehicles & Highway Capacity

A theoretical model approach for vehicle automation and communication on Dutch highway road segments, focused on non-platoon based car-following behavior.

By

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Pictures cover page
Bottom left: Autonomous vehicle on a highway, Bosch (2017)
Top and middle: Road Segments, Edited from Rijkswaterstaat and Grontmij (2015)

SUMMARY

Autonomous driving is one of the main current developments in the field. Many aspects, including the technology and systems used to achieve autonomous driving, human interaction, safety, reliability and security as well as the effects on traffic, are involved. This study focuses on the effects on capacity of multiple levels and penetration rates of automated driving on Dutch highways. Automated driving consists of many forms and levels, with and without communication, that can be achieved on the short term as well as the long term.

The capacities and network design according to the Dutch highway manual, are the base for the microscopic traffic simulation model VISSIM, in which longitudinal and lateral movements are parameterized.

The network, namely 8 road segments, and driving behavior parameters are modeled and calibrated for 2 reference subscenarios, one for straight road segments (2-6 lanes) and one for merging and diverging road segments (an On-Ramp, an Off-Ramp and a Symmetrical Weaving Section). MATLAB is used to control the VISSIM simulations and change input. Validation is done with measured data of a Dutch highway. Alteryx and MATLAB are used to (pre)process the data and to produce output in the form of tables, boxplots and other figures. In total 1300 simulations have been executed in VISSIM during 100 hours of net simulation time and many more for preprocessing, processing and presenting output. Five main scenarios for vehicle automation are studied:

- Adaptive Cruise Control (ACC)
- Cooperative Adaptive Cruise Control (CACC)
- Autonomous Vehicles (AV)
- Cooperative Autonomous Vehicles (CAV)
- Cooperative Autonomous Vehicles with fixed desired speed (CAV+)

The simulations show a drop in capacity of 5-10% for road segments with straight lanes for scenarios with 100% market penetration of ACC in comparison to the reference scenario, while scenarios with 100% cooperative vehicles (both CACC and CAV) show an increase of around 10% to over 20% in capacity in comparison to the modeled reference. Scenarios with autonomous vehicles without communication show a small increase in capacity for these road segments. An On-Ramp shows similar results, though the capacity increase of cooperative vehicles is limited to around 10%. An Off-ramp barely shows any differences between scenarios in comparison to reference, only 100% ACC shows a drop of about 3% and the scenarios with 100% cooperative autonomous vehicles show an increase of 3.1% (CAV) to 7.3% (CAV+). Last, the Symmetrical Weaving Section is very difficult to calibrate properly. However, the cooperative scenarios again show higher capacities than the other scenarios, but since the road segment has not been modeled properly in the reference scenario, conclusions must be drawn very carefully.

Scenarios with high capacities have high (left lane) speeds for higher intensities and approximate equal lane shares near congestion later or not even at all. This can be explained by the deviation in speed per lane. The scenarios with high capacities show less deviation in (mean) speed on the left lane between different intervals, as well as much smaller left lane standard deviation in speed within 5-minute intervals.

To conclude, vehicle automation is likely to decrease capacity in the short-term since vehicles equipped with ACC use larger headways than human drivers, while in the long-term it will increase capacity since autonomous vehicles can use smaller headways and have smaller speed deviations, especially on the left lane. Communication between vehicles is hereby more important than vehicle automation itself.

SAMENVATTING

Geautomatiseerd rijden is één van de belangrijkste huidige ontwikkelingen in verkeer en vervoer. Veel aspecten daarvan, waaronder de technologie en systemen die gebruikt worden voor geautomatiseerd rijden, menselijke interactie, verkeersveiligheid, betrouwbaarheid en veiligheid in het algemeen, alsmede de effecten op het verkeer, zijn van belang. Dit onderzoek focust op de effecten van meerdere niveaus en penetratiegraden van geautomatiseerd rijden, op de capaciteit van Nederlandse snelwegen. Vele vormen en niveaus behoren tot geautomatiseerd rijden, met of zonder communicatie. Dit geldt voor zowel de lange als de korte termijn.
De capaciteiten en het ontwerp van het netwerk zoals deze zijn beschreven in het handboek Capaciteitswaarden Infrastructuur Autosnelwegen vormen de basis voor het microscopisch verkeerssimulatiemodel VISSIM, waarin longitudinale en laterale bewegingen worden beschreven met behulp van parameters.
Het netwerk, namelijk 8 wegsegmenten, alsmede parameters voor het rijgedrag zijn gemodeleerd en gekalibreerd voor 2 deelscenario’s, één voor normale wegsegmenten (2 tot 6 rijstroken) en één voor invoegend en uitvoegend verkeer (toerit, afrit en symmetrisch weefvak). MATLAB wordt gebruikt om de VISSIM-simulaties aan te sturen en instellingen te veranderen. Voor de validatie wordt gemeten data van een Nederlandse snelweg gebruikt. Alteryx en MATLAB worden gebruikt voor de voorbewerking en verwerking van de data en het produceren van resultaten in de vorm van tabellen, boxplots en andere figuren. In totaal zijn er 1300 simulaties in VISSIM uitgevoerd. Dit duurde ongeveer 100 uur aan netto simulatietijd en nog vele uren meer voor het voorbewerken, verwerken en presenteren van de resultaten. Vijf hoofdsceneario’s voor geautomatiseerd rijden zijn onderzocht:

- Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC), Autonomous Vehicles (AV), Cooperative Autonomous Vehicles (CAV) en Cooperative Autonomous Vehicles met vaste wenssnelheid (CAV+)

De simulaties resulteren in een capaciteitsafname van 5 tot 10% voor ACC met 100% marktpenetratie op normale wegsegmenten ten opzichte van de referentie. Tegelijkertijd hebben coöperatieve voertuigen (zowel CACC als CAV) een capaciteitstoename van 10 tot meer dan 20% in vergelijking met de referentie. Deelscenario’s met autonome voertuigen zonder communicatie, tonen slechts een kleine capaciteitstoename. Een toerit heeft vergelijkbare resultaten, maar de capaciteitstoename voor coöperatieve voertuigen blijft beperkt tot ongeveer 10%. De verschillende scenario’s geven nauwelijks verschillen voor een afrit, alleen 100% ACC heeft een afname van ongeveer 3% en de scenario’s met 100% coöperatief autonome voertuigen hebben een toename van 3.1 (CAV) tot 7.3% (CAV+). Tenslotte is gebleken dat het weefvak lastig te kalibreren is. Desondanks geven de coöperatieve scenario’s hogere capaciteiten dan de andere scenario’s, maar aangezien het weefvak niet goed kon worden gemodelleerd moet men voorzichtig zijn met het trekken van conclusies.
Scenario’s met hoge capaciteiten hebben hoge snelheden (op met name de linkerrijstrook) bij hoge intensiteiten. Ook hebben deze scenario’s pas bij hogere intensiteiten een gelijke verdeling van het aantal voertuigen per rijstrook of wordt deze helemaal niet gelijk bij congestie. Dit wordt verklaard met de verschillen in snelheid per rijstrook: Scenario’s met hoge capaciteiten hebben kleinere snelheidsverschillen op de linkerrijstrook, zowel tussen verschillende als binnen meetintervallen.
Concluderend, voertuigautomatisering verlaagt capaciteiten op de korte termijn doordat voertuigen met ACC grotere volgafstanden aanhouden dan menselijke bestuurders, maar verhoogt het de capaciteit op lange termijn, omdat autonome voertuigen kleinere volgafstanden hanteren en snelheidsverschillen, met name op de linkerrijstrook, kleiner zijn. Communicatie tussen voertuigen is hierbij belangrijker dan het automatiseren van voertuigen zelf.

PREFACE

The general idea of a subject for a master thesis study has emerged at the dinner after the Business Course about the “Blankenburgverbinding” of Witteveen+Bos in Deventer in June 2016. During dinner several topics of interest were discussed with Otto Schepers, head of Business Unit Traffic and Roads at Witteveen+Bos. Since there were many mutual topics of interest, Otto Schepers and yours truly agreed to meet again at the Witteveen+Bos office in Amsterdam to specify the topic. The meeting in Amsterdam included Robbert Verweij, the company supervisor. After discussing several options, highway capacity and the use of autonomous vehicles was chosen as the main topic. During the preparation of this thesis, this also resulted in researching Advanced Driver Assistance Systems and Cooperative Vehicles and the current situation as a reference. Witteveen+Bos uses the microscopic traffic simulation software VISSIM to model traffic. Actual measured data from the Dutch highway network can be loaded into VISSIM at nearly real-time speed (a delay in the order of magnitude of minutes).

This thesis could not be executed without the help of many people. I would like all of them in general and the following people and organizations in particular.

First, I would like to thank the main supervisor Eric van Berkum for his expert knowledge in traffic and transport engineering.

Second, the daily supervisor Tom Thomas. He was always concerned with my thesis as well as my well-being in general. In the cases I was stuck he helped me to get back on track and came up with possible steps to continue the study, especially during calibration and .

Third, the company supervisor Robbert Verweij. Even though we were often physically apart, he was always helpful either by email or by making time to meet in person whenever necessary, and he was always willing to think along with me. I could not have wished for a better company supervisor.

Next, without a subject and a host company I could not have executed this study at all. Therefore, I would like to thank Otto Schepers for giving me the opportunity to do this study, as well as for facilitating my visit to the IAA 2017 car exhibition and New Mobility World congress.

In addition to Robbert and Otto I would like to express my appreciation to other colleagues at the host company: Aries for sending me related theses and discussing relevant parts, Sander for calculations in Python to verify reference input and all other colleagues from Witteveen+Bos from Business Units *Traffic and Roads* and *Urban Development* in Amsterdam as well as in Deventer for showing their interest and having enjoyable lunch breaks together.

I am also grateful to the PTV Group as well as Alteryx for providing me thesis student licenses of their software.

Then I would like to thank my sister Katja for her feedback on writing the thesis and last but not least, I would like to thank my parents for their support during my entire studies.

CONTENTS

NOMENCLATURE

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System(s)
ADS	Automated Driving System
Alteryx	Alteryx Designer, Repeatable Workflow for Self-Service Data Analytics Software
Automated Driving	Collective name of different forms of automated driving, i.e. ACC, ADAS, ADS, AV, CACC & CAV
AV	Autonomous Vehicle(s)
CACC	Cooperative Adaptive Cruise Control
Capacity	Median value of intensities at the 5-minute interval before congestion in vehicles per hour
Congestion	Congestion starts at the moment when one vehicle has a speed below 50 km/h on a detector
CAV	Cooperative Autonomous Vehicle(s) (in literature sometimes also Connected Autonomous Vehicle(s)) [1]
CF	Car-Following
CIA	(Handboek) Capaciteitswaarden Infrastructuur Autosnelwegen, Dutch Highway Capacity Manual
COM-interface	A COM-interface can be used to control a program from another program: In this study MATLAB has been used to control VISSIM
DAB	Dicht Asfalt Beton, Dutch non porous asphalt
DCP	Data Collection Point, a detector in VISSIM
DDT	Dynamic Driving Task
HGV	Heavy Goods Vehicle(s)
MATLAB	A programming language and software for matrix and array mathematics
NDW	Nationale Databank Wegverkeersgegevens, Dutch National Database for Traffic Information
NHTSA	National Highway Traffic Safety Administration (United States of America)
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
RS	Random Seed(s), used in the Monte Carlo simulations in VISSIM
SAE	The Society of Automotive Engineers, currently SAE International
SDRF	Safety Distance Reduction Factor, factor of the time headway (CC1) in VISSIM, used to temporarily allow a shorter headway for lane changes
VC	Vehicle Composition(s), the combination of market penetration per vehicle automation and the corresponding set of driving vehicle behavior
VI	Vehicle Input, number of vehicles entering a road segment in vehices per hour
VISSIM	PTV Vissim, a microscopic multi-modal traffic flow simulation software package developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. Derived from "Verkehr In Städten - SIMulationsmodell" (German for "Traffic in cities - simulation model")
ZOAB	Zeer Open Asfalt Beton, Dutch porous asphalt

[1] Connected is in general Vehicle to Infrastructure or Vehicle to Network, while Cooperative usually means Vehicle to Vehicle. In this study it is assumed both as far as modeling allows and is called cooperative.

1 INTRODUCTION

Advanced driver assistance systems, autonomous vehicles, self-driving cars, vehicles auto-pilot, driverless cars, they are all over the news. Some are cooperative or connected, some are not. There are many names and many forms of automated driving, some with communication with other vehicles, road-side infrastructure, a network or even pedestrians or cyclists, while others are without. One thing is certain, automated driving, in at least some of the forms, will be part of future, and in a way is already part of the present. However, this will also have major consequences for many aspects related to driving. Many studies are carried out on those different aspects, but how do different levels and penetration rates of automated driving affect capacity on Dutch highways?

This chapter gives the inducement of this study by giving a general overview of related topics and the resulting research gap. Next, a reading guide is given to view the different parts of the thesis. The chapter ends with the research outline, which includes the problem definition, the goal and the research questions.

1.1 INDUCEMENT

Which aspects are important for automated driving? Many studies discuss the technology used in the vehicles, i.e. Levinson et al. (2011), Broggi et al. (2013) and Hobert et al. (2015), or human interaction with it, i.e. Engström et al. (2006). Numerous other studies are related to the safety, reliability and cybersecurity of used systems (Adell, Várhelyi, & Fontana, 2011; Althoff, Althoff, Wollherr, & Buss, 2010; Fagnant & Kockelman, 2015; Kyriakidis, Happee, & de Winter, 2015; Ozguner, Stiller, & Redmill, 2007; Tettamanti, Varga, & Szalay, 2016), while other do look into specific traffic or driving characteristics. i.e. Khodayari, Ghaffari, Ameli, and Flahatgar (2010).

All these aspects are important and very interesting. However, this study focusses on the traffic engineering aspects of autonomous and cooperative driving by evaluating capacity at several road segments and multiple values of several longitudinal and lateral vehicle behavior aspects. Safety aspects are only taken into account as boundary conditions, rather than aspects to study or vary on directly.

While some of the studies address traffic engineering aspects are focused on urban environments, i.e. Seif and Hu (2016), many are focused on platooning of HGV (Bergenhem, Shladover, Coelingh, Englund, & Tsugawa, 2012; Gehring & Fritz, 1997; Nowakowski, Shladover, Lu, Thompson, & Kailas, 2015), passenger vehicles on highways (Ali, Garcia, & Martinet, 2015; Piao & McDonald, 2008; Sancar, 2017) or even platooning in urban settings (Lioris, Pedarsani, Tascikaraoglu, & Varaiya, 2016).

There are studies that do have a view on the effects of automated and cooperative driving on capacity. However, those are in most cases focused on one scenario and often limited in studying the effects on capacity; either Adaptive Cruise Control (ACC) (Kesting, Treiber, Schönhof, Kranke, & Helbing, 2007), Cooperative Adaptive Cruise Control (CACC) (Nowakowski, O'Connell, Shladover, & Cody, 2010; Wolterink, Heijenk, & Karagiannis, 2010) or (Cooperative) Autonomous Vehicles ((C)AV) (Bierstedt et al., 2014; Bohm & Häger, 2015; Endsley, 2017) or in a rare case on two scenarios (Qing & Sengupta, 2003; Shi & Prevedouros, 2016).

In addition, there are studies looking into automated driving on the Dutch highways, but in general they do consider only one scenario (R. Hoogendoorn, van Arem, & Hoogendoorn, 2014; Van Arem, Van Driel, & Visser, 2006), are for specific conditions (de Waard, van der Hulst, Hoedemaeker, & Brookhuis, 1999) or too dated to represent current and future technology properly (VanderWerf, Shladover, Kourjanskaia, Miller, & Krishnan, 2001). As far as studies do look into multiple scenarios including several penetration rates in the Netherlands, findings are still based on different models and often on non-Dutch contexts, i.e. Milakis, Snelder, Van Arem, Van Wee, and Homem de Almeida Correia (2015).

As far as mentioned studies find, capacity increase of automated driving ranges from 0 to +400% for 100% (cooperative) automated driving (Table 1). Vehicle automation which is not cooperative barely shows any improvements, except for a relatively dated study with +33% in capacity (Chang & Lai, 1997), while cooperative vehicles show very large improvements. This is especially the case for platooning.

Table 1: Change in capacity due to vehicle automation and communication

Study	Type of vehicle automation	Change in capacity
Bierstedt et al. (2014)	Conservative ACC Intermediate ACC Aggressive ACC Cooperative	Negative (few %) ~0% Positive (few %) (up to) +100%
Chang and Lai (1997)	Not cooperative	+33%
Fernandes and Nunes (2012)	Very high cooperation (72 km/h), platooning	+186-414%
Ni, Li, Andrews, and Wang (2010)	Cooperative	+20-50%
Shladover (2011)	ACC CACC CACC Platooning	~+0% ~+100% (up to) +200%
Shladover, Su, and Lu (2012)	Not cooperative Cooperative	+1-4% +97%
Tientrakool, Ho, and Maxemchuk (2011)	Not cooperative (100 km/h) Cooperative (100 km/h)	+40% +270%

Since literature study shows a large range in capacity changes and most studies look into a limited number of scenarios and market penetrations, there is thus a research gap of: modelling different levels and penetrations rates of automated and cooperative driving on highways in equal boundary conditions, especially specifically on Dutch highways without platooning. Therefore a new study was necessary and thus this study has been carried out.

This study looks into vehicle automation in multiple scenarios: on the short term without communication (ACC) and with communication (CACC), as well as on the long term without communication (AV) and with communication (CAV). Finally, also the effect of fixing the desired speed to the maximum speed is studied in the final scenario in order to see how differences in speed affect capacity at several road segment types. Since market penetration of CACC, AV and CAV, will gradually increase from the relative near future (large percentage of ACC) to a potential final stage (100% CAV), those three scenarios are split into multiple subscenarios with different percentages of market penetration.

This way, policy makers and engineers can make decisions based on both short and long term expectations and can follow estimates for market penetrations of different levels of vehicle automation.

1.2 READING GUIDE

The study looks into the effect of automated vehicles on highway road capacity. This can be done on numerous ways. One can vary on many aspects of the use of autonomous vehicles in general as well as on highways in specific. The literature study of the Theoretical Framework addresses what there is already known in this research field and what still needs to be studied (Chapter 2), since varying on all aspects and studying or modeling all would be too time-consuming for this study or not even be possible at all. Next, in chapter 3, the used research methodology and implementation of the modeling are given as a basis to carry out the study in an orderly manner. A validation is then carried out in order to: check the validity of the intermediate results, find any errors and improve the model for final simulations. The results of these final simulations are presented and briefly described in chapter 4. The most important findings are furtherly analyzed in chapter 5. Finally, conclusions and discussion per research question and any recommendations are in given in chapter 6. All chapters from the theoretical framework to the additional analysis, are each summarized at the end of the respective chapter as well.

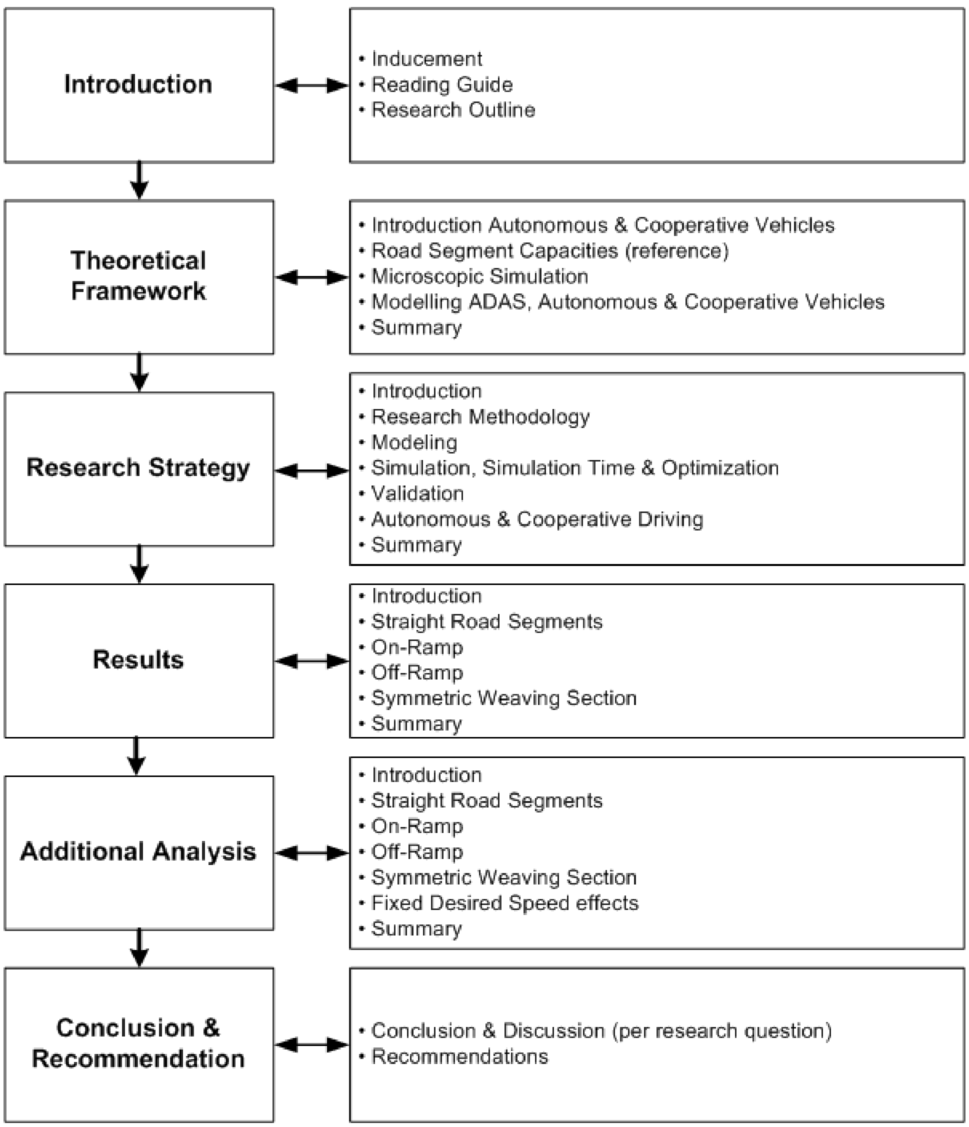

Figure 1: Report structure

1.3 RESEARCH OUTLINE

This research outline extracts the most important parts of the inducement into a problem, goal and research questions. First the main problem is described. Second, to solve this problem the goal of this study is formulated and third, four research questions are developed in order to achieve the goal.

1.3.1 Problem Definition

The development of advanced driver assistance systems and potentially the arrival of fully cooperative and autonomous vehicles will have effects on traffic networks all over the world and in particular in the Netherlands. The effects are expected to be the largest in areas which are congested in the current situation.

Secondly, ADAS and autonomous vehicles seem to have the greatest potential on highways on a shorter period in time in comparison to urban networks.

Third, effects on capacity of bottlenecks on a network scale are leading since bottlenecks affect total travel times more than capacities of single road segments. However, it is very interesting to know how the capacities of single road segments change. This way bottleneck locations might change when automated and cooperative vehicles reach significant market penetration rates.

Fourth, effects on capacity of ADAS and especially cooperative and autonomous vehicles are still subject of study and are not sufficiently developed to be used on a macroscopic scale.

Therefore, the study area is a combination of a varied range of road segment types on the Dutch highway network on a microscopic scale, and multiple levels and market penetration rates of vehicle automation. Both road segments where congestion happens frequently in the current situation, and straight road segments are addressed.

1.3.2 Goal

This problem results in the following goal:

Goal

To determine the effects on capacities of ADAS, autonomous and cooperative vehicles on common road segments of the Dutch highway network, focused on non-platoon based car-following behavior.

1.3.3 Research Questions

In order to achieve this goal several research questions are formed to determine capacities of reference in practice, of the reference in the model, of automated and cooperative driving and compare them to each other:

Question 1

What is the current capacity for road segments types relevant for the Dutch highway network (i.e. according to CIA)?

In order to study the (relative) effects of vehicle automation on highway capacity, it is necessary to know the current capacity of some of the most important road segments on Dutch highways to compare any results to as well as to help calibrate a reference scenario in the model. Therefore, the current capacity of the following road segments need to be known:

- "Straight" Road Segments (2-6 lanes)
- On-Ramp merger 3+1 > 3
- Off-Ramp 3 > 3+1
- Symmetric Weaving Section 3 + 1

Question 2

What is the capacity for those types of road segments in the used traffic model (VISSIM) and how do they compare to the theoretical reference?

- How can parameters in the model be calibrated to fit the CIA values for the reference scenario?
- How do modeled and CIA capacities compare?

Since modeling and calibrating the model to reference data will approximate theoretical or measurements in practice, but the model will not exactly match those, question 2 is asked in order to study the capacity values of the model for the reference scenario. By answering the subquestion, the tools are provided to find the answer to the main question.

Question 3

What is the modeled capacity of these road segments with several levels and penetration rates of autonomous and cooperative vehicles, and how do they compare to the reference?

Question 3 is the most important question to reach the goal of this study. In order to study the (relative) effects of different levels and penetration rates of automated vehicles on Dutch highway capacity, it is necessary to determine the capacity of the different levels of vehicle automation:

- ACC
- CACC
- Autonomous Vehicles
- Cooperative Autonomous Vehicles
- Cooperative Autonomous Vehicles with fixed desired speed

By determining the capacities of the different levels of vehicle automation, in combination with the answer to question to, it is also possible to answer the second part of the question. By dividing the values found for vehicle automation by the reference values, the ratios can be determined for each road segment.

Question 4

What is the effect of vehicle automation on traffic conditions in comparison to the reference situation?

The final question is question 4. Question 4 is the extension of question 3 in order to get more insight in traffic conditions of automated driving in addition to capacities of question 3. In order to do so the following traffic conditions are studied:

- Lane share
- Lane intensity
- Mean Speed
- SD Speed

The distribution over lanes (lane share) and the mean speeds are the focus of this question. Lane intensity and the standard deviation in speed are used to study lane share and mean speed respectively, in more detail.

2 THEORETICAL FRAMEWORK

2.1 INTRODUCTION AUTONOMOUS AND COOPERATIVE VEHICLES

In the previous chapter the subject and research question have been defined. This chapter addresses all definitions with the relevant literature.

2.1.1 Levels

Though people may say there is either a human driver or it is an autonomous vehicle, automation of driving is more nuanced. From no automation with solely a human driver to full driving automation, there is a whole spectrum of applications in between. To structure this, the Society of Automotive Engineers (SAE International), has developed a standard with the following table containing 6 levels (0 – 5) as a summary (Figure 2). However, these levels should be taken informative rather than normative (SAE International, 2016). These levels of automated driving seem to be the standard in the field and is therefore used in this study as well.

Level	Name	Narrative definition	DDT: Sustained lateral and longitudinal vehicle motion control	DDT: OEDR	DDT fallback	ODD
Driver* performs part or all of the *DDT						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 2: SAE's levels of automated driving (SAE International, 2016)

The National Highway Traffic Safety Administration used to have a slightly different system to categorize the automation of driving in their policy in 5 levels, namely level 0 to 4 (National Highway Traffic Safety Administration, 2013), but adopted the SAE levels more recently as well and uses the SAE levels in their current policy (National Highway Traffic Safety Administration, 2016).

2.1.2 Current state of autonomous driving

Currently, many vehicles in developed countries have advanced driver assistance systems (ADAS). However, a human driver is still primarily necessary for part of the driving tasks in most cases (level 1) or has to actively pay attention for "*object and event detection and response"* (OEDR, level 2) (SAE International, 2016). Level 2 is the current state of the art, which is available on some new vehicles, while level 3 is currently being tested (Litman, 2014, 2017).

In research and development, vehicles can currently drive autonomously in an controlled environment and can drive autonomously in the real-world in *a variety of lighting, weather and traffic conditions. Challenges including narrow roads, crosswalks, and intersections governed by traffic light are now manageable. However it remains necessary for a safety driver to be present at all times, and we are not yet able to driver for hours on end without occasionally switching to manual control due to unexpected events* (Levinson et al., 2011). There are also experiments going on in order to let autonomous vehicles drive in both structured and unstructured environments, though this is under development (Kolski, Ferguson, Bellino, & Siegwart, 2006). This shows that autonomous driving is still at an advanced level 2, level 3.

2.1.3 Cooperative driving

However, there is more to autonomous driving than the levels stated by SAE International. An important element for driving in the future is cooperative, sometimes called connected, driving[2]. Though people may think autonomous vehicles are communicating with each other, autonomous driving and cooperative driving are two different aspects. Cooperative can be seen as an extension of autonomous driving and can have large advantages over solely autonomous driving. Piao and McDonald state that cooperative driving has great potential to improve traffic safety and efficiency (Piao & McDonald, 2008), while Calvert and colleagues found that *the application of Cooperative Adaptive Cruise Control* (CACC) *has great potential to improve traffic flow and suppress negative effects of congestion largely through shockwave damping* (Calvert, Broek, & Noort, 2011). Another study confirms this. Highly automated vehicles equipped with Cooperative Adaptive Cruise Control at relatively low penetration rates (0-20%) show an increase in throughput up to 4.3% and reduce shockwave speed of congestion (Motamedidehkordi, Margreiter, & Benz, 2016). Gordon and Lidberg also found that CACC is much more stable than ACC (Gordon & Lidberg, 2015). Similar results are found by Qing and colleagues where CACC takes less breaking effort at all penetration rates (Qing, Hedrick, Sengupta, & VanderWerf, 2002).

2.1.4 Important aspects of ADAS and autonomous driving

Many aspects related to ADAS and autonomous driving are important. One can vary many aspects during modeling ADAS and autonomous driving. This can be done by, but is not limited to: varying the level of autonomous driving, communication with other vehicles or infrastructure, penetration rate, traffic rules, theoretical function of used systems within the level of autonomous driving, type of road segments or combination of segments or network, reliability of used systems, operating used system and system settings, weather conditions, infrastructure condition and fraction of heavy vehicles.

[2] In literature, cooperative often means communication from vehicle to vehicle (V2V), while connected usually refers to communication with Infrastructure or Network (V2I /V2N). In this study it is assumed both are present.

Though autonomous driving is a technical subject, there is an important human aspect as well. As Helbing and Treiber conclude, many aspects of traffic dynamics can be understood and reproduced by simulations. Though some might need psychological aspects as well (Helbing & Treiber, 2002). One of the aspects related to humans is the Human Machine Interface (HMI) where people can give input to systems in a car. Engström and colleagues found that HMI design and HMI integration have great influence on the use ADAS of drivers and related safety effects (Engström et al., 2006).

Another aspect is cost of used systems. Many systems that have to be very reliable, are very expensive. Therefore, Broggi et al. (2013) studied the effects of multiple sensors for autonomous vehicles in order to find more cost efficient and easy to implement systems to reduce the cost and invasiveness of ADAS.

The safety and reliability of used systems (Adell et al., 2011; Althoff et al., 2010; Ervin et al., 2005; Fagnant & Kockelman, 2015; Ozguner et al., 2007; P. Fancher et al., 1998) and cyber security, i.e. vulnerability for hacks of the software of autonomous and cooperative and remote control by unauthorized persons (Kyriakidis et al., 2015; Tettamanti et al., 2016) are of great importance and concern of people as well. Though important, most of the aspects concerning safety are either not relevant for capacity or are an effect of traffic engineering aspects.

However, as stated before, this study focusses on the traffic engineering aspects of autonomous and cooperative driving by evaluating capacity at several road segments and multiple values of several longitudinal and lateral vehicle behavior aspects. Safety aspects are only taken into account as boundary conditions, rather than aspects to study or vary on directly. To start with, the following section addresses the capacities of several conditions in the current situation of the Dutch highway network.

2.2 Road segment Capacities

Since this study aims at, among other steps, determining road segment capacities for (different levels and different penetration rates of) autonomous and cooperative vehicles on highways, there has to be a reference as a starting point and to compare to. In general, this can be done in several ways. One could use a framework, rule of thumb or experts' general estimates. Alternatively one could use measured data. Finally, one could use modeled data. Since the first part of this framework looks at different general types of road segments, using general values is preferred over (i.e. measured) using data from a specific situation. Therefore, the Dutch Highway Capacity Manual (Handboek CIA in Dutch) has been chosen for this study, since it contains general values in the Dutch context.

2.2.1 CIA Method

In this framework the data from the CIA and a paper about recent developments and its history are used as a starting point for the current situation (Heikoop & Henkens, 2016; Rijkswaterstaat & Grontmij, 2015). The values of the CIA are based on multiple measurements of several implementations per road segment type. The amount of used implementations differs from 3 to 7 per type of road segment (used for the values in Table 2 and Table 3). Next, these values are not static values but they are given certain conditions. The CIA uses standard conditions as described in the following subsection (§2.2.2). For any deviations of the standard conditions, the CIA uses several correction factors.

The CIA describes several methods to determine capacities. For discharge flow capacities, the empirical distribution method is recommended. Next, they mention the Brilon-method for free-flow capacities and elaborate on the FOSIM-method. The Brilon-method only takes the period of time directly before congestion into account, while the FOSIM-method a larger period of times uses.

2.2.2 CIA Assumptions

The CIA consist of values for standard conditions. Below is described which conditions are fixed or assumed. Anything that differs in road segments, in both the type and number of lanes, as well as correction factors in comparison to the standard conditions, is elaborated on in the next subsection.

The following conditions are considered as standard:

- A maximum speed of 100 and 120 km/h
- Standard width of a full lane at Dutch highways (120 km/h) is 3.50m
- Given certain traffic movement and traffic composition[3]
- Capacities in motor vehicles per hour (Capacity is the median value of a set measurements at the 5-minute hourly intensity where one vehicle reaches a speed below 50km/h)
- 15% heavy vehicles
- Free-flow capacities
- Design as meant by guidelines for highways
- No large objects near road (i.e. sound barriers)
- No distracting objects or events next to the road
- Without steep slopes (<2.5%) or long gentle slopes
- By daylight and dry weather (less than 2 mm/h rainfall)
- Road pavement (ZOAB) in good condition
- Including traffic signaling
- No other traffic management measures

2.2.3 Variation

The CIA varies in different types of road segments and in number of lanes. These are summarized in the following subsection. Next, variations in environmental factors are elaborated upon. Third, the effects of traffic factors on capacity are briefly discussed. Fourth, all other aspects in the CIA that can vary are listed to get a full overview. They are not considered necessary for the master thesis study, but can be used in future work to adjust the reference scenario, so one can easily see that there is information in the CIA. Finally, combining different correction factors is discussed.

2.2.3.1 Capacity of standard road segments

In general there are two main types of road segments, straight road segments with a fixed number of lanes and weaving sections. In addition there are many other types which relate to these first two. The following (sub)types of road segments are listed in the CIA and are summarized in this subsubsection:

- Straight road segment (Figure 3, top left), on-ramp merger (top right) and lane termination
- Off-ramp (bottom left)
- Weaving section (bottom right)

[3] Range of values given in 2.2.3.1 for weaving, full tables in Appendix (Table 28 to Table 30) for specific traffic movement and composition

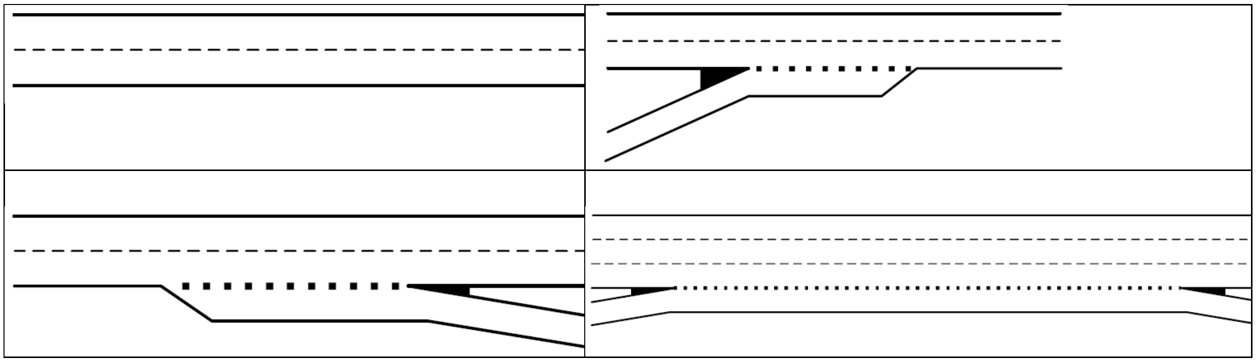

Figure 3: Examples of standard road segments: Straight road segment of 2 lanes (top left), On-Ramp merger of 2 + 1 lanes (top right), Off-ramp of 2 + 1 lanes (bottom left) and Symmetric Weaving Section of 3 + 1 lanes (bottom right), Edited from (Rijkswaterstaat & Grontmij, 2015)

The general capacities of the following other road segment types are outside the scope of this study, but are briefly addressed in Appendix A:

- Merger (general)
- Merge Taper
- Fork
- Interchanges
- Main lanes and parallel roads
- Extra lane
- Expressways and secondary networks

Straight road segment, on-ramp merger and lane termination

In Table 2 the capacities per number of lanes are shown for straight road segments. Situations with an extra merging lane joining the main road segment or an extra lane upstream (lane termination) have about equal capacities since the downstream capacity is normative and merging effects are limited.

Table 2: Highway capacity of road segments, …, at 15% heavy vehicles (Rijkswaterstaat & Grontmij, 2015)

Road segment	Merging lane	Lane termination	Capacity [veh/h][4]	Notes
1 lane			1,900	Length > 1,500 m
1 lane		From 2 to 1 lane	2,100	Length < 1,500 m
2 lanes	2 lanes + merging lane	From 3 to 2 lanes	4,300	
3 lanes	3 lanes + merging lane	From 4 to 3 lanes	6,200	
4 lanes	4 lanes + merging lane	From 5 to 4 lanes	8,200	
5 lanes	5 lanes + merging lane	From 6 to 5 lanes	10,250	
6 lanes	6 lanes + merging lane	From 7 to 6 lanes	12,000	
7 lanes	7 lanes + merging lane	From 8 to 7 lanes	13,500	

As can be seen by comparing Table 3 to 2 and 3 lanes in Table 2, peak hour lanes generate about half to full capacity of a standard extra lane. Right hand peak hour lanes generate only about half the extra capacity of a full lane due to the fact that not all drivers are using the extra lane and especially heavy vehicles have to change to right peak hour lane which can be significantly smaller. Since left hand lanes

[4] CIA definition of Capacity: Number of vehicles per hour based on a 5-minute interval, from 5 minutes before to the moment that one vehicle has a speed below 50km/h at a single detector.

are mainly used by cars and not by heavy vehicles and are also mainly used for overtaking, the width of the peak hour lane at the left hand side has less influence on the capacity than at the right hand side. As the table shows, 2 lanes plus a 3.10 meter wide peak hour lane (left) has only a capacity drop of 100 vehicles an hour in comparison to 3 full lanes.

Table 3: Highway capacities (in veh/h) of road segments (with peak hour lane), at 15% heavy vehicles (Rijkswaterstaat & Grontmij, 2015)

Road segment	Width peak hour lane	Capacity
2 lanes + peak hour lane right	Smaller cross section than standard	5,300
2 lanes + peak hour lane left (plus lane)	3.10 meter	6,100
2 lanes + peak hour lane left (plus lane)	2.5 – 2.75 meter	5,800

Off-ramp

In general an Off-ramp has the same capacity as a straight road segment with the same number of (main) lanes. However, in the two cases given below the capacity is lower than for a straight road segment. The absolute capacity is very situation dependent. Therefore, actual values cannot be given.

- Congestion at intersection at end of off-ramp; standing or slow moving traffic causes delays at main lanes of highway with reduced capacity as a result
- Large fraction of vehicles to off-ramp, capacity of exit lane may be assumed lower than on main highway lane due to exiting movements and lower speed at exiting lane; upstream of exiting lane (on main lane) might have high intensity at right lane due to presorting behavior with possible congestion as a result

Weaving section

Table 4 shows the capacity giving the total number of lanes at the road segment for symmetric and asymmetric weaving[5]. Capacity depends on the number of lanes and on the amount of weaving vehicles. In general the following holds:

- More lanes means higher capacity (a lot of weaving about 1,000 veh/h, limited weaving about 2,000 veh/h)
- More weaving movements means lower capacity, especially with a large number of HGV

However, many weaving movements might outweigh the effects of an extra lane, as can be concluded from the minimum capacity of 5 and 6 lanes. A more detailed table is given in Appendix A (Table 28).

Table 4: Total Capacity (vehicles / hour) for symmetric and asymmetric weaving configurations

Total number of lanes[6]	Symmetric	Asymmetric
2	1,750	-
3	4,520 – 5,590	3,880 – 6,020
4	5,620 – 7,690	4,640 – 8,280
5	6,790 – 9,710	5,690 – 10,270
6	6,250 – 11,710	6,580 – 11,150

[5] The number of lanes upstream and downstream are equal, i.e. both 2+1, both 2+2, both 3+1 etc.
[6] The total number of lanes, i.e. 5+1, 4+2 and 3+3 are all examples of 6 total lanes. Also multiple weaving percentages are included per configuration.

2.2.3.2 Environmental Factors

Environmental factors can be of great influence on capacity. However, since this study addresses capacity at standard conditions, any effects on capacity caused by environment factors according to CIA are only briefly described in Appendix A.

2.2.3.3 Traffic factors

The CIA considers two types of traffic factors to adjust road capacity to: The traffic composition (fraction of heavy vehicles) and familiarity with the local situation.

Traffic composition (fraction of heavy vehicles)

To correct for a different traffic composition than standard the CIA advices to use the reduction factors in Table 5. Since 15% is taken for the standard situation in 2.2.3.1, one should use the corresponding factors (bold band) to adjust for a different traffic composition.

Table 5: Reduction factors traffic composition at PCE of 2.0 (Rijkswaterstaat & Grontmij, 2015)

From % heavy vehicles	To % heavy vehicles (at a passenger car equivalent factor of 2.0)						
	0%	5%	10%	15%	20%	25%	30%
0%	1.00	0.95	0.91	0.87	0.83	0.80	0.77
5%	1.05	1.00	0.95	0.91	0.88	0.84	0.81
10%	1.10	1.05	1.00	0.96	0.92	0.88	0.85
15%	1.15	1.10	1.05	1.00	0.96	0.92	0.88
20%	1.20	1.14	1.09	1.04	1.00	0.96	0.92
25%	1.25	1.19	1.14	1.09	1.04	1.00	0.96
30%	1.30	1.24	1.18	1.13	1.08	1.04	1.00

Familiarity with local situation

Exact numbers are unknown, but the CIA mentions a reduction of 10 to 25% for drivers who are unknown with the situation. It is clear that the effect can be significant and can vary strongly.

2.2.3.4 Other factors & Combining factors

Above, all factors which are currently found relevant for the master thesis study are described in the paragraphs above. If any other factors will have a part in future research, the CIA also describes other factors. An overview of those in given in Appendix A. All factors described in section 2.2, as well as mentioned appendix, can be used to correct the capacity values to certain conditions. They may be combined. However, if too many are combined they may not be accurate.

2.3 Microscopic Simulation

To understand a traffic or transport system one can use only real-world data. However, in some cases this is either impossible and in most other cases this is very expensive. Therefore, simulation software is a good alternative. In general there are three levels of modeling: macroscopic, mesoscopic and microscopic. Macroscopic is most useful for very large networks and transport planning. Microscopic is much more accurate and very useful for detailed studies, but it is too slow and therefore time consuming for very large networks. In between, there are mesoscopic models. For this master study detailed effects are important. Since there is limited microscopic data of the subject, macroscopic models cannot be properly developed yet because they require findings from microscopic studies. Therefore, a microscopic simulation package has been chosen to model autonomous vehicles on highway segments.

There are several software packages for Microscopic simulation of traffic in general. For example, Higgs and colleagues mention AIMSUN, SISTM, DRACULA, VISSIM, CORSIM and PARAMICS (Higgs, Abbas, & Medina, 2011). In the book *Fundamentals of Traffic Simulation*, VISSIM, AVENUE, Paramics, Aimsun, MITSIMlab, SUMO, DRACULA, Dynameq, DynaMIT and METANET are discussed (Barceló, 2010). For the Dutch case, FOSIM, a functional but graphically limited, modeling package. It is developed together with and recommended by the Dutch highway authority Rijkswaterstaat, since it is calibrated on the Dutch highways (Rijkswaterstaat & Grontmij, 2015). Next to FOSIM, the CIA also mentions three of the packages Higgs et al. mentioned: AIMSUN, VISSIM and PARAMICS. More recently, videogames like Grand Theft Auto 5 (GTA5) are being used to simulate autonomous driving and to teach the Artificial Intelligence how to drive in an environment of wide variety. Though processing computer vision and training autonomous cars, is much more efficient in videogames such as GTA5 than in other simulations or real-world tests (Richter, Vineet, Roth, & Koltun, 2016), the use of videogames in the master thesis study is found unusable since the context is very different.

2.3.1 Software choice

VISSIM seems to be one of the leading software packages in the field since it is often used for, amongst others, capacity on freeways and highways (Choa, Milam, & Stanek, 2004; Gomes, May, & Horowitz, 2004; Laufer, 2007; Leyn & Vortisch, 2015; Mehar, Chandra, & Velmurugan, 2014; Miller, 2009; Saka, Jeihani, & James, 2008)

Although autonomous vehicles are a relatively new subject in the field, autonomous vehicles are also being modeled in VISSIM in both an urban setting (Le Vine, Zolfaghari, & Polak, 2015; Zhang, 2017) as well as on highways or freeways (Aria, Olstam, & Schwietering, 2016; Bierstedt et al., 2014; Xie, Zhang, Gartner, & Arsava, 2017).

Despite Rijkswaterstaat recommends the use of FOSIM in the context of Dutch highways (Rijkswaterstaat & Grontmij, 2015), it is decided together with the company supervisor to use VISSIM. The host company uses both FOSIM and VISSIM, but VISSIM is more extensive and has a COM-interface[7] which can be used to test a set of special simulations (Fellendorf & Vortisch, 2010). Using this COM-interface has been found very useful, since it is used in the master thesis study. One of the programs that can, and has been, used to control VISSIM via the COM-interface, is MATLAB (Tettamanti & Horváth, 2015), since the latter has already been known. VISSIM is used often in this research field and is therefore considered a suitable package.

[7] A COM-interface can be used to control a program from another program: In this study MATLAB has been used to control VISSIM

Therefore, VISSIM has been chosen for simulation and its algorithms are studied into more detail in the following sections. To study the effect of autonomous driving on highway capacity by modeling it on a network in a microscopic simulation software package, several vehicles characteristics, both longitudinal as well as lateral, need to be quantified. However, there are many companies, both tech as automobile companies, that are developing autonomous vehicles, and they each have their own way of implementing algorithms to automated driving. Though Google (Waymo), Uber and Tesla are often in the news, they are not the top companies. Navigant Research determined the top 10 given in Table 6 (2017):

Table 6: Top 10 companies for autonomous vehicles (Navigant Research, 2017)

1	Ford	2	GM	3	Renault-Nissan Alliance	4	Daimler	5	Volkswagen Group
6	BMW	7	Waymo	8	Volvo/Autoliv/Zenuity	9	Delphi	10	Hyundai Motor Group

Ideally, one would implement all algorithms into a model based on their respective market share. However, the used model is limited by its parameters and not all algorithms of all companies can directly be put into the model. This is given the assumption all companies share their algorithms in the first place, which is very unlikely. In addition, future algorithms are not known and cannot be used either way. Therefore the study needs to be executed with any data that is available. To do so, the first step consists of evaluating the parameters used in models that are necessary for the current (non-autonomous) situation as well as for modeling automated and cooperative vehicles.

2.3.2 Modeling in VISSIM in general

As many traffic modeling packages, VISSIM uses link as nodes as explained in more detail by Fellendorf and Vortisch (2010):

Roadway networks are usually represented by graphs with nodes located at inter-sections and links placed on road segments. Nodes are needed if (a) two or more links merge, (b) links cross each other, (c) one link splits into two or more links, and (d) the characteristics of a road segment change.

- *Vehicle category-like modes (mandatory)*
- *Vehicle length or distribution of vehicle lengths (mandatory)*
- *Distributions of technical and desired acceleration and deceleration rates as a*
- *function of speed (mandatory)*
- *Maximum speed or distribution of maximum speeds (mandatory)*
- *Vehicle width (optional)*
- *Color and 3D model or distribution of colors and 3D models (optional)*
- *Vehicle weight or distribution of vehicles weights (optional)*
- *Emission class or distribution of set of emissions (optional)*
- *Variable and fixed cost of vehicle usage (optional)*

In VISSIM, the longitudinal and lateral driving behavior is divided into: Following (including look settings), Lane change, Lateral (mainly within a lane), Signal Control and Meso. The latter two are considered as not relevant for the Dutch highways on this scale are therefore left as is. The others aspects of driving behavior are described in the following (sub) sections.

2.3.3 Longitudinal movements: Car-Following

Car-Following (CF) is the behavior related to driving within a lane relative to a leading vehicle. However, there are multiple ways do model this. Many Car-Following models have been developed: Saifuzzaman and Zheng (2014) refer to Barceló (2010) by stating: "*A large number of Engineering CF models have been developed in an attempt to describe CF behavior under a wide range of traffic conditions, ranging from free-flow to extreme situations. Some of these models have been used in commercial packages of microscopic traffic simulations*".

By referring to Higgs and colleagues this can be confirmed as they give several examples (Higgs et al., 2011): "*Micro-simulation software packages use a variety of car-following models including Gipps' (AIMSUN, SISTM, and DRACULA), Wiedemann's (VISSIM), Pipe's (CORSIM), and Fritzsche's (PARAMICS)*".

Since VISSIM is likely to be used (see Software choice), this subsection focusses on the car-following parameters of Wiedemann (1974) and in particular Wiedemann (1999), which are used in VISSIM. As Aghabayk and colleagues explain VISSIM uses two car-following models: Wiedemann (1974) and Wiedemann (1999). The first is more suitable for urban arterial roads and the latter one is more suitable for freeways (Aghabayk, Sarvi, Young, & Kautzsch, 2013). Since highways are most similar to freeways the focus lies on the Wiedemann 99 model.

In either model there are four driving modes:

- Free driving
- Approaching
- Following
- Breaking

These are all determined by six thresholds:

- AX: the desired distance between two stationary vehicles
- BX: the minimum following distance which is considered as a safe distance by drivers
- CLDV: the points at short distances where drivers perceive that their speeds are higher than their lead vehicle speeds
- SDV: the points at long distances where drivers perceive speed differences when they are approaching slower vehicles
- OPDV: the points at short distances where drivers perceive that they are travelling at a lower speed than their leader
- SDX: The maximum following distance indicating the upper limit of car-following process

These thresholds, as well as the trajectory of a single vehicle, are visually shown in Figure 4. When a driver is driving in the free driving state (green) and perceives speed differences at long distances when approaching slower vehicles (SDV) it goes to the approaching driving mode (orange). When he realizes at short range that his speed is higher than his lead vehicle he (continues to) decelerate (CLDV) until he realizes he is driving slower than the lead vehicle (OPDV) and accelerates a little. This keeps oscillating around the point of a comfortable following distance and zero speed difference (white).

With ADAS and autonomous vehicles is it expected that SDV is more fixed (in comparison to human drivers) at the distance of the range of its sensors (a more horizontal line in the figure). Since speed differences are likely to be perceived more accurate the reaction can be smoother and the oscillation process will be limited (OPDV closer to Y-axis and the white area smaller). The following distance can be closer to BX as well. For cooperative ACC in comparison to ACC and especially CAV in comparison to AV, the white area can approach a single point at [ΔV=0, BX] since speeds are communicated between vehicles. In that case AX and BX can also lay closer together.

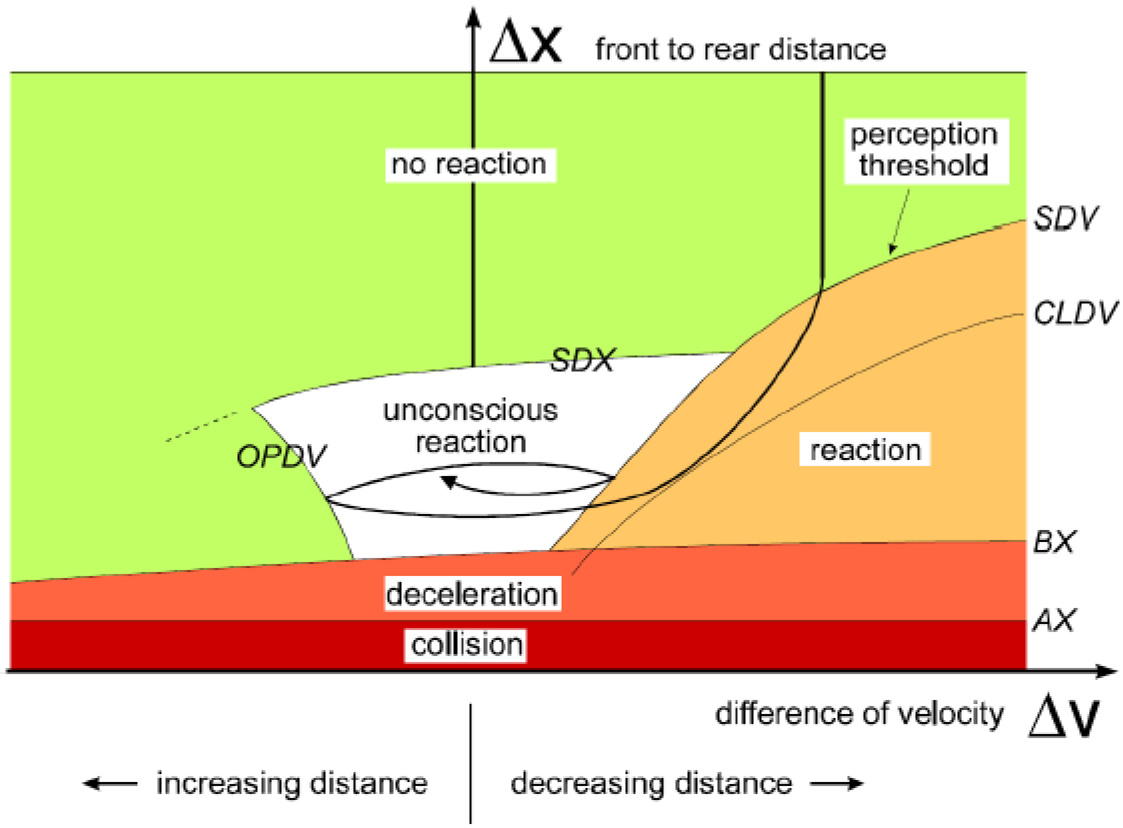

Figure 4: Car-following behavior of WIEDEMANN Thresholds and one vehicle trajectory (Hoyer & Fellendorf, 1997)

The model uses 10 parameters for car-following, CC0 to CC9 (Table 7), which are used in six equations and three acceleration conditions (Figure 5) that quantify the behavior of Figure 4.

Table 7: Wiedemann Car-following parameters

Parameter name	Parameter meaning	Unit
CC0	Standstill Distance	m
CC1	Headway Time	s
CC2	Following Variation	m
CC3	Threshold for Entering 'Following'	
CC4	Negative 'Following' Theshold	
CC5	Positive 'Following' Theshold	
CC6	Speed dependency of Oscillation	
CC7	Oscillation Acceleration	m/s^2
CC8	Standstill Acceleration	m/s^2
CC9	Acceleration at 80 km/h	m/s^2

In the box of car-following model parameters, there exist ten parameters (CC0-CC9). The first seven parameters (CC0-CC6) are used to determine the car-following thresholds and the rest have different roles. The relation between the parameters and thresholds are defined by Equations 1 to 6.

$$AX = L + CC0 \qquad Eq.(1)$$

where L is the length of the lead vehicle

$$BX = AX + CC1 \times v \qquad Eq.(2)$$

where v is equal to subject vehicle speed if it is slower than the lead vehicle; otherwise, it is equal to lead vehicle speed with some random errors. The error is determined randomly by multiplying the speed difference between the two vehicles by a random number between -0.5 and 0.5.

$$SDX = BX + CC2 \qquad Eq.(3)$$

$$(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4 \qquad Eq.(4)$$

where Δx is the space headway between the two successive vehicles calculated from front bumper to front bumper.

$$CLDV = \frac{CC6}{17000} \times (\Delta x - L)^2 - CC4 \qquad Eq.(5)$$

$$OPDV = -\frac{CC6}{17000} \times (\Delta x - L)^2 - \delta . CC5 \qquad Eq.(6)$$

where δ is a dummy variable which is equal to 1 when the subject vehicle speed is greater than CC5 and 0 else.

The CC7 parameter defines the actual acceleration during the oscillation process; The CC8 parameter defines the desired acceleration when starting from standstill condition; and the CC9 parameter determines the desired acceleration at the speed of 80 km/h.

Figure 5: Wiedemann Car-Following equations in VISSIM (Aghabayk et al., 2013)

Next to the ten parameters in the CF-model it also uses look settings for the minimal and maximal (*ahead* as well as *back*) distance for leading and following vehicles to be taken into account.

2.3.4 Lateral movements

Next to the movements in driving direction there are movements perpendicular to the driving direction. These lateral movements are structured in 3 types in VISSIM (Fellendorf & Vortisch, 2010)

- Lane selection
- Lane changing
- Continuous Lateral Movement

Lane selection
As long as a driver does not need to take a mandatory lane change, the lane with the best interaction is chosen. This is only executed when three conditions are fulfilled (Fellendorf & Vortisch, 2010):

- The driver is currently not in free-flow conditions
- The adjacent lane has better downstream conditions (free-flow or higher time-to-collision than current lane)
- The is an acceptable gap upstream on the target lane

The value of an acceptable gap depends on calibration and for mandatory lane changes it is as well a function of the distance to point of divergence.

Lane change
Lane change parameters are relevant in the first step of lane change: Lane change happens when the driving mode in Wiedemann's model car-following model is different than free, the interaction situation on the other lane is better (free of higher time-to-collision) and lane change is possible considering vehicles upstream as described at lane selection (Fellendorf & Vortisch, 2010). Details of lane change parameters in VISSIM can be found in Table 36 in Appendix B.

Continuous Lateral Movement
Continuous lateral movement is less relevant on Dutch highways since there is a good lane structure and the amount of vehicles next to each other within a single lane is very limited (rarely 2 motorcycles). Therefore, the driving behavior settings of the lateral tab, are kept at default values for this study.

2.3.5 Sensitivity

Several studies (Bohm & Häger, 2015; Oud, 2016) have looked into the sensitivity of several parameters of VISSIM. First, from the study Bohm & Häger it can be concluded that all researched parameters are significant for at least high flow conditions in the Swedish case. Though the AV settings at low flow conditions seem to have a negative impact on traffic flow (Table 8), the same settings have a positive impact on traffic at high flow conditions (Table 9). Since this thesis of the Dutch case looks into highway capacity and high flow conditions, all mentioned parameters seem to be significant.

Table 8: Numerical resulting values for the key indicators during low flow (Bohm & Häger, 2015)

Simulation	Changed parameter	Delay [s]	Number of stops	Speed [km/h]
1	Base Scenario	44.02	1.04	63.4
2	Look ahead/back distance	45.99	1.11	62.93
3	Observed vehicles	46.42	1.12	62.73
4	Smooth closeup	45.34	1.03	63.13
5	Standstill distance	46.95	1.14	62.62
6	Headway time	45.38	1.08	63.09
7	Following variation	46.18	1.12	62.79
8	Thresholds	45.93	1.10	62.85
9	Speed dependency of oscillation	45.67	1.07	62.85
10	Acceleration	44.78	1.10	63.15
11	Standstill acceleration	45.63	1.11	62.95
12	Acceleration at 80 km/h	46.74	1.12	62.73
13	All parameters	44.59	1.01	63.16

Table 9: Numerical resulting values for key indicators for high vehicle flow (Bohm & Häger, 2015)

Simulation	Changed parameter	Delay [s]	Number of stops	Speed [km/h]
1	Base scenario	173.9	9.43	40
2	Look ahead/back distance	125.6	5.84	46.44
3	Observed vehicles	131.2	6.38	45.57
4	Smooth closeup	113.6	4.32	48.27
5	Standstill distance	115.2	4.86	48.1
6	Headway time	113.4	4.32	48.37
7	Following variation	123.4	7.07	46.75
8	Thresholds	124.7	5.52	46.57
9	Speed dependency of oscillation	112.3	5.05	48.6
10	Oscillation acceleration	123.5	5.99	46.75
11	Standstill acceleration	136.3	7.24	44.86
12	Acceleration at 80 km/h	132.6	6.65	45.37
13	All parameters	76.2	3.37	55.37

The study of Oud (2016) looked into five parameters and their significance. At least three of them are significant according to Oud (Table 10). Though the other two parameters are barely significant according to Oud, they are significant in the study of Bohm and Häger.

Table 10: Results from initial test run (Oud, 2016)

Parameter	Scale of effect	Suggested direction of change
Look ahead distance	Barely significant	Unclear
Observed vehicles	Barely significant	Unclear
Desired headway (CF)	Very significant	Increase
Free driving time	Very significant	Increase
Safety distance reduction factor	Moderately significant	Increase

Therefore, all parameters are considered to be significant when adjusted individually. This would make sense, since it VISSIM is a model which is extensive and needs a lot of computational power. Including parameters when they would not be relevant for the simulation results, would be unnecessary and a waste a computational power. Since it would be very time-consuming to also test the significance of single parameters in a combination of multiple adjusted parameters, it is more useful to limit the number of input values, i.e. the number of scenarios, than to focus on excluding parameters.

2.4 MODELING ADAS, AUTONOMOUS AND COOPERATIVE VEHICLES

In order to model different scenarios in automated driving, it is necessary to find values for the parameters in the microscopic model of systems that are likely to be used. Therefore, for all parameters, CF-parameters look settings, lane change and lateral parameters, relevant literature is described below.

This section briefly describes the main literature used for the modeling of automated and cooperative driving. Four main categories are studied. First, two ADAS categories are mentioned: Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC). Both are systems for partial vehicle automation on the relatively short term. ACC is without communication and is thus not cooperative, while CACC has communication and is cooperative. In addition to ACC and CACC, literature for vehicle automation on the long term is mentioned. Again one category without communication, Autonomous Vehicles (AV) and one with communication, Cooperative Autonomous Vehicles (CAV).
In the research strategy, the relevant literature is described per category of vehicle automation in order to implement the driving behavior in the model (section 3.6).

Per parameter, the relevant literature to model the driving behavior is given below. Some of the studies provide information about multiple categories:

CC0 Standstill Distance

Bierstedt et al. use 1.5, 1.25 and 1.0 m for standstill distance as conservative, intermediate and aggressive ACC settings respectively, while Bohm & Häger use 1.0m for (C)AV. Motamedidehkordi et al. mention the range for standstill distances to be 1 to 4m. However, the default setting in VISSIM is 1.5m and automation of driving is expected to cause smaller standstill distances. Therefore it is assumed 1.5m is feasible for default and ACC settings, 1.25m for CACC and 1.0m for AV and CAV.

CC1 Headway Time[8]

Though time headway feels like one of the most important parameters in relation to capacity it is also the one literature has no clear answer for, since estimates have a large range of values for automation of driving.

Literature shows that manual driving has a minimal time headway about 0.66 s while the comfortable time headway varied from 0.94 to 1.00 s (Taieb-Maimon & Shinar, 2001) which seems be similar to the default value in VISSIM (0.9 s). However, preferred time headways of ACC are relatively uncertain. ACC time headways with an average of 1.54 s (±0.41) have been found (Nowakowski et al., 2010) while Bierstedt et al. use 1.2, 0.8 and 0.6 s for following variation as conservative, intermediate and aggressive ACC settings respectively. Piao & McDonald state that ACC needs a slightly larger headway time in order to regain control for the driver than when driving manually, indicating that ACC time headways should be larger than the default 0.9 s of VISSIM.

However, CACC time headways seem to be much smaller than ACC, i.e. 0.71 s (±0.13) (Nowakowski et al., 2010).

Time (and distant) headways for autonomous cars (in a simulator) were found to be relatively large for *Fixed follow risk* of 1.8-1.9 s and 1.85-2.00 s for *Free follow risk*, while 1.65-1.71 s for *Fixed follow comfort* and 1.80 -1.98 s for *Free follow comfort* were found (Siebert, Oehl, Bersch, & Pfister, 2017).

[8] Setting in VISSIM is called Headway Time, while literature in general speaks of time headway

However another study uses a time headway of 1.4 s between platoons or 0.3 s within platoons for CAV (Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014) and Bohm & Häger use 0.5 s for (C)AV (2015). Aria, Olstam & Schwietering (2016) even use 0.3 s for CAV (highly AV). This might be because by the time of AV are common, people will be used more to ACC than they are now.

There are many different values found, this might be explained by variation in circumstances. According to Risto & Martens (2014), simulators and instrumented vehicle show similar headway times, while there is an overestimation of headway based on time and an underestimation based on distance (Risto & Martens, 2014; Taieb-Maimon, 2007). Women seem to be overestimating time headway while distance headway and number of vehicles seem to be similar for both genders (Taieb-Maimon & Shinar, 2001). Other research seems to find results which can be linked to these deviations. Hou and colleagues concluded that most human drivers prefer using distance headways over time headways and this will be an important aspect for the acceptance of autonomous vehicle technology (Hou et al., 2014) Therefore it is assumed that a distribution around 0.9 s is feasible for default, a distribution around 1.2 s for ACC settings, a distribution around 0.75 s for CACC, 0.9 s fixed for AV and 0.5 s fixed for CAV.

CC2 Following Variation

Bierstedt et al. use 4, 3 and 2m for following variation as conservative, intermediate and aggressive ACC settings respectively (2014), while Bohm & Häger assume 1 m for (C)AV. Therefore it is assumed 4 m is for feasible default, 3 m for ACC settings, 2 m for CACC and AV and 1 m for CAV.

CC3 Threshold for entering 'Following'

A few different values have been found for entering following. One study uses -11 as threshold (Motamedidehkordi, Benz, & Margreiter, 2016) while others use -16, -12 and -8 for acceleration at standstill as conservative, intermediate and aggressive ACC settings respectively (Bierstedt et al., 2014). Therefore it is assumed that -8 is feasible for default, -12 for ACC, CACC and AV and -16 is for CAV.

CC4 & CC5 Negative and Positive 'Following' Threshold

Different values for the negative and positive following thresholds have been found as well: Some use (-)0.1 for the negative and positive following threshold of (C)AV or AV (Bohm & Häger, 2015; Motamedidehkordi, Benz, et al., 2016) while others use (-)0.6, (-)0.35 and (-)0.1 as conservative, intermediate and aggressive ACC settings respectively (Bierstedt et al., 2014). Therefore it is assumed that -0.35 is feasible for default as well as ACC, CACC and AV and CAV.

CC6 Speed Dependency of Oscillation

Since systems can use a fixed speed, the speed dependency of oscillation is 0 for both ACC (Bierstedt et al., 2014) as well as for (C)AV (Bohm & Häger, 2015), therefore speed dependency of oscillation is 11.44 for default and 0 for ACC, CACC, AV and CAV.

CC7 Oscillation Acceleration

Bierstedt et al. use 0.4, 0.25 and 0.1 m/s^2 for oscillation acceleration as conservative, intermediate and aggressive ACC settings respectively, while 0.25 is VISSIM's default value. Therefore, it is assumed that 0.25 m/s^2 is feasible for default and ACC and 0.1 m/s^2 for CACC, AV and CAV.

CC8 Standstill acceleration

Bierstedt et al. use 3, 3.5 and 4 m/s^2 for acceleration at standstill as conservative, intermediate and aggressive ACC settings respectively while Bohm & Häger use 4 m/s^2 for (C)AV. Therefore it is assumed that 3.5 m/s^2 is feasible for default, ACC, CACC and AV and 4 m/s^2 is for CAV.

CC9 Acceleration at 80 km/h

Bierstedt et al. use 1, 1.5 and 2 m/s^2 for acceleration at 80 km/h as conservative, intermediate and aggressive ACC settings while Bohm & Häger use 2 m/s^2 for (C)AV. Therefore it is assumed that 1.5 m/s^2 is feasible for default, ACC, and CACC and 2 m/s^2 is for AV and CAV[9].

Look ahead distance & Look back distance

Next to previous CF-parameters, there are several look settings in VISSIM. The minimum look ahead (and back) distance is about 150m for CACC (Qing & Sengupta, 2003) and *highly automated ADAS* (Laquai, Duschl, & Rigoll, 2011), while the maximum look ahead and look back distance can be 200 or 250 m (Laquai et al., 2011; Wolterink et al., 2010). For CAV, literature is less consequent: Bohm & Häger use a minimum of 0 m and a maximum of 300/500 m as look ahead distance and a minimum of 0 m and maximum of 100/300 m as look back distance for (C)AV, while it also can be many kilometers due to vehicle-to-vehicle or vehicle-to-infrastructure communication (Laquai et al., 2011). Therefore it is assumed that minimum and maximum look ahead/back distances vary from 0 and 250/150m (Default and ACC) to 150 and 200 m (CACC and AV) to 5000 and 5000 m (CAV).

Observed vehicles

Different settings for the number of observed vehicles have been found ranging from 6-8 (Aria et al., 2016) observed vehicles (no clear distinction between AV and CAV) and 10 observed vehicles for (C)AV (Bohm & Häger, 2015). Though, when there is a vehicle-to-vehicle and vehicle-to-infrastructure network many more vehicles can be communicated, however, the maximum number of observed vehicles in VISSIM is 10. Therefore it is assumed that 2 is feasible for default, 10 is for CAV and 8 is for the rest.

Cooperative lane change (CLC)

This setting can be checked and unchecked. In accordance with literature (Aria et al., 2016). it is assumed that cooperative vehicles (CACC & CAV) are best modeled with this setting checked while other vehicles (default, ACC, AV) are best modeled with this setting unchecked.

Other lane change parameters & Lateral Parameters

Decelerations in order to allow lane changes are assumed to be similar in automated driving as manual driving since the forces caused by deceleration will remain to have the same impact on the human body. Though passenger comfort is also depending on vertical (and horizontal) vibrations, i.e. as stated by Kruczek and Stribrsky (2004), Wu, Lui and Pan state that there is little research done on longitudinal deceleration (2009) and passenger comfort while discomfort by braking is a daily occurrence. In the work of Luo, Liu, Li and Wang it seems that the maximum acceleration has a similar magnitude for ACC as it has for the preceding vehicle (2010). This supports the assumption of that automating of vehicles will not change a lot in the maximum decelerations of vehicles, though vehicles might have lower average decelerations caused by smaller speed differences and better response times.

The lateral parameters as stated in VISSIM are related to lateral movements within a lane and the use of a single lane by multiple vehicles next to each other. Since this is very rare in the Dutch case, these are considered irrelevant for modeling automated driving and are therefore not studied any further.

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[9] Per parameter it is estimated whether the estimates of Bohm & Häger's are more suitable for AV, CAV or both in comparison to other literature. This might results in different corresponding values of ACC, CACC, AV and CAV per parameter.

2.5 SUMMARY

To summarize this chapter, the most important findings of this part are listed below:

- Autonomous Driving consists of multiple levels of automated driving: From no vehicle automation to fully autonomous driving (0 to 5 as described by the SAE). The levels are based on the number of automated tasks, the role of the human driver and the conditions vehicle automation is enabled. However, the can be differences between manufacturers within a level as well.
- Though related, vehicle automation and communication (cooperative / connect vehicles) to other vehicles, road-side infrastructure, a network or even other modalities are different developments.
- Many different aspects of automated driving are studied in literature:
    - Systems and technologies
    - Safety, reliability, cybersecurity
    - Traffic engineering, i.e. effects on capacity
- This study focuses on the latter: the effects of vehicle automation and communication on capacity and related traffic conditions
- Standard conditions are assumed and correspond as much as possible to the Dutch Highway Manual (CIA), including: daylight, dry weather, 15% HGV, 120 km/h speed limit.
- VISSIM is one of the leading software packages in the field for both highway traffic in general and vehicle automation in particular. In addition, VISSIM is available at the host company and the company supervisor has experience with it. Therefore, VISSIM has been chosen in this study.
- The microscopic model consists of Car-Following, Lane Selection & Lane Change behavior.
- Car-following parameters are found most important and all potentially significant.

In addition to the overview above, this chapter also answers the first research question:
Question 1: What is the current capacity for road segments types relevant for the Dutch highway network (i.e. according to CIA)?

Table 11: CIA Capacities of studied Road Segments

Road Segment	Capacity (vehicles per hour)
Straight 2 lanes	4,300
Straight 3 lanes	6,200
Straight 4 lanes	8,200
Straight 5 lanes	10,250
Straight 6 lanes	12,000
On-Ramp 3+1-to-3	≤6,200
Off-Ramp 3-to-3+1	≤6,200
SW 3+1	6,840

3 Research Strategy

3.1 Introduction

In order to structure the study, a research methodology has been developed. The following section describes the elements that are part of this methodology and how they are related. In the section after, the most important parts of the modeling, calibration and validation of the reference scenario are described. After validation of the reference scenario, the input for the actual study, namely the model input to study the effects of different levels and penetration rates of vehicle automation and communication, are given and founded. Finally, this chapter is summarized by a short overview of the most important aspects in the conclusion.

3.2 Research Methodology

The research methodology as schematically visualized in Figure 6, consists of five main categories:

- Literature (green)
- The microscopic traffic model VISSIM (red)
- MATLAB as a tool to give input to VISSIM as well as for data-analysis (Orange)
- Alteryx Designer for data-preparation (Blue)
- The thesis (Yellow)

In addition to these five categories, there are uncategorized elements used to pass information from one category to another (white).

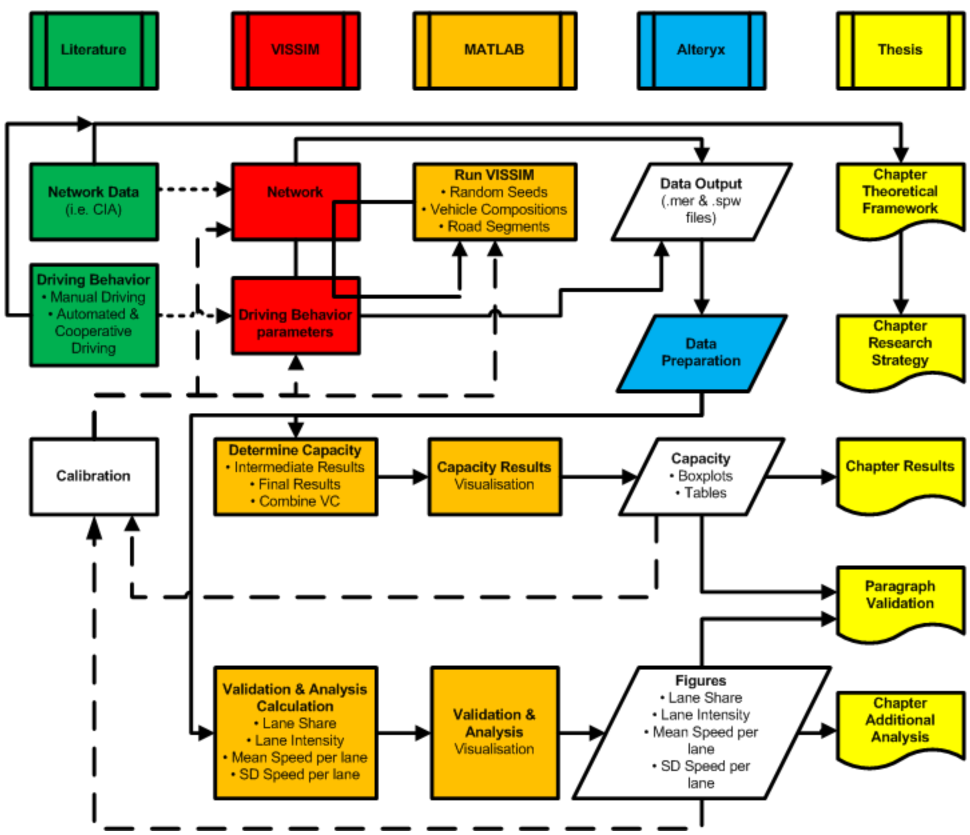

Figure 6: Schematic overview of the Research Methodology

The first part of the research methodology consists of the literature as described in the theoretical framework. The useable input for the used microscopic traffic model, VISSIM, is then extracted from the literature as described later in this chapter. The model can be split into two main elements:

- Network (§3.3.2)
- Driving behavior (§3.3.3)

The MATLAB script “Run_VISSIM.m” (Appendix F & Script attachment I) has been used to run several Monte Carlo Simulations in VISSIM by using the COM-interface. All eight road segments are simulated simultaneously. Each VC has been run per random seed consecutively. VISSIM has been set to produce raw output files for these simulations (.mer & .spw files). The files are basically semi-column-separated data files as text with some extra information at the beginning of the files. The files are then preprocessed in Alteryx to remove unnecessary columns and combine multiple random seeds and save to .csv-files (Appendix G). The csv files have then been processed in multiple MATLAB scripts for determining the capacity and producing tables and boxplots (Appendix H and Script III) as well as producing figures for the validation by lane share, lane intensity, mean and SD speed per lane (Appendix J and Script V). This has been repeated until the calibration was finished. After calibration and optimization of the speed of the model (§3.4), the model has been validated (§3.5).

After validation, the same process from Running VISSIM from MATLAB to producing boxplots and tables for the capacity as well as the figures of lane share, lane intensity, mean and SD speed, has been repeated for the final results (Chapter 4) and Additional Analysis (Chapter 5).

Afterwards, everything described above is used to answer the research questions of chapter 1 by the conclusion and discussion, and final recommendations are given (Chapter 6).

3.3 Modeling

In the previous section the overview of the research methodology has shown that the modeling consists of two main parts: The network and the driving behavior. The modeling consists of a default scenario for the current driving behavior which acts as a reference and 5 main scenarios of vehicle automation. All scenarios are simulated on 8 different road segments. First the default scenario has been implemented in VISSIM and has been used to calibrate the model. Both the network and the driving behavior are described in this section.

3.3.1 Calibration

The calibration of models is important to approximate real-world traffic states (Aghabayk et al., 2013). However, an extensive calibration is too time consuming to do for the many different parameters used in this study in combination with the lack of data to calibrate upon for most of the scenarios. Alternatively, the network (§3.3.2) and parameter values (§3.3.3) found during the literature study, are used as input for initial calibration. Initial results are then validated and recalibrated until validation indicates proper calibration. Final simulations of the reference scenario for 3 straight lanes are again validated and compared to a reference data set (§3.5).

3.3.2 Network Design, Capacity & Vehicle Input

First, eight road segment types are modeled individually as a reference; five types of straight lanes and three types of merging and diverging segments as shown in Table 12.

Table 12: Road segments and respective capacities

Road Segment Type	Number of Lanes	Length Main Section	Lane Width	Capacity according to CIA (veh/h)
"Straight"	2	-	3.50 m	4,300
"Straight"	3	-	3.50 m	6,200
"Straight"	4	-	3.50 m	8,200
"Straight"	5	-	3.50 m	10,250
"Straight"	6	-	3.50 m	12,000
On-Ramp merger	3+1 > 3	300 m	3.50 m	≤ 6,200
Off-Ramp	3 > 3+1	250 m	3.50 m	≤ 6,200
Sym. Weaving Section (75%, 23%)[10]	3+1	700 m	3.50 m	6,840

3.3.2.1 Road Segment lay-out

Each road segment consists of the following parts as can be seen in Figure 7 and Figure 8:

- Pre-Input
- Transition
- Main Section
- Downstream Section (merging and diverging segments only)

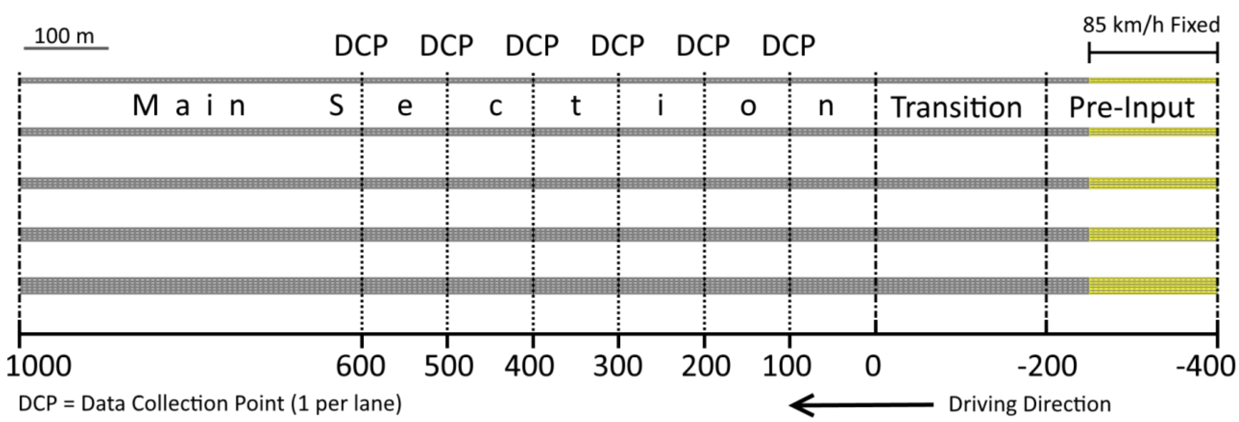

Figure 7: Network Model of 2 (top) to 6 (bottom) straight lanes

[10] 75% weaving of O2 (right hand lane) to D1 (left hand lanes, main lanes) and 23% weaving from O1 to D2

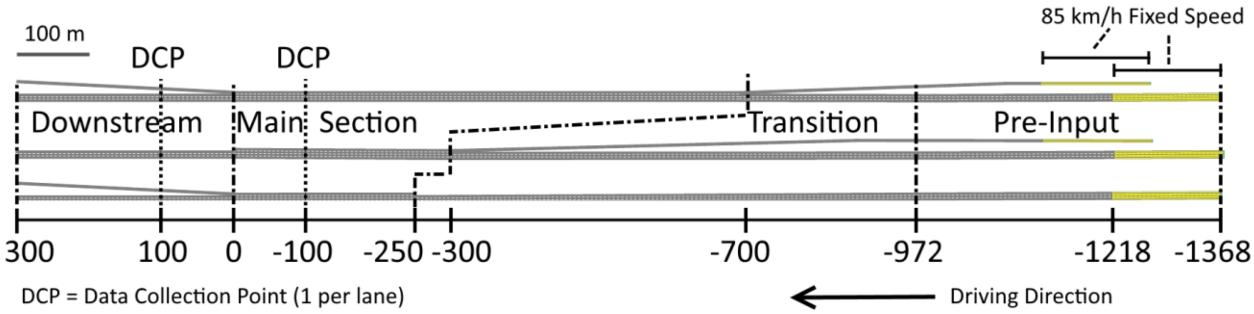

Figure 8: Network Model of Symmetric Weaving Section (top), On-Ramp merger and Off-Ramp (bottom)

Pre-input sections and transition sections have been added in order to have a stable traffic flow enter the network since VISSIM puts vehicles with pseudorandom interval on the network. Without the pre-input sections and transition sections, simulations generate large deviations in capacity over the different random seeds. This is due to the way VISSIM puts vehicles on the network, since vehicles enter the network at their desired speed. When vehicles with a high desired speed (i.e. fast passenger vehicle) are put onto the network shortly after a vehicle with a low desired speed (i.e. HGV), disturbances occur directly after the vehicle input. This happens because the way relaxion is modeled in VISSIM, is suitable for driving on the network, but is not for entering the network. Though adding pre-input sections and transition sections resolves most of the problem, it is not perfect since there might still be minor disturbances and there are small differences to the situation where vehicles would enter a road segment in practice. Appendix E gives details about the simulations during calibration and thus gives more information about the details of this phenomenon.

Network Assumptions
In order to be able to compare capacities to CIA, the modeling is as similar to CIA as possible. However, in few cases CIA is either unclear or it is not possible in VISSIM to exactly match the CIA design characteristics of the road segments:

- Road segments are assumed according to CIA as much as possible
  - Capacities as shown in Table 35 in Appendix B
    - Capacity is defined as the median value of measurements of a 5-minute interval directly prior to congestion (one vehicle below 50 km/h at a detector)
  - Physical Dimensions: Segment lengths, lane width, detector locations as in Table 12, Figure 7 and Figure 8 as well as in Table 33 & Table 34 in Appendix B)
    - Diagonal parts of merging and diverging lanes are modeled as half their length with full width in VISSIM

- Vehicle Input of merging lanes are assumed half of a single main lane since CIA has no information on upstream vehicle shares
  - Vehicle Input of an On-Ramp with 3 main lanes and 1 merging lane is set 6:1 respectively (details in the next subsubsection: §3.3.2.3)
  - Vehicle Input of a Symmetric Weaving Section with 3 main lanes and 1 merging/diverging lane is set to 6:1 respectively (details can be found in the next subsubsection: §3.3.2.3)

- The exit percentage of the Off-Ramp is determined by VISSIM's default algorithm since CIA does not provide any values

- The Symmetric Weaving Section has 75% weaving of Origin 2 (O2,right hand lane) to Destination 1 (D1, left hand lanes, main lanes) and 23% weaving from O1 to D2, according to the intermediate value in CIA

3.3.2.2 Vehicle Detection

The detector locations (Data Collection Points, DCP) are placed at every 100 m in the main sections of the straight road segments as shown earlier in this chapter (Figure 7) and 100 m upstream and 100 downstream of the end of the main section for merging and diverging road segments (Figure 8). More detector locations would determine congestion earlier. However, each added detector slows the simulations. In addition, this matches the number of detector locations in practice, since they are limited as well. These locations have been chosen to be similar to the detectors on the Dutch highway network[11] as well as to limit simulation, preprocessing and processing time.

3.3.2.3 Vehicle Input

The start value of the vehicle input (VI) has been set to round values in the range of ⅔ to ¾ of the CIA capacity and is increased by 1/60 at the end of every minute (Table 13). At the end of the simulation, which lasts 3600 seconds (1 hour), the VI has therefore a value of 119/60th of it's start value. These values have been chosen in order to have congestion somewhere in the middle of each simulation and also have later scenarios of vehicle automation reach congestion within the same range of VI and simulated time.

Table 13: Vehicle Input per road segment

Road Segment Type	Number of Lanes	Capacity according to CIA (veh/h)	Start VI [t = 0 s] (veh/h)	Interval duration [s]	VI Increase per Interval [t=t+60 s] (veh/h)	Final Vehicle Input [t = 3600 s – 60 s] (veh/h)
"Straight"	2	4,300	3,000	60	50	5,950
"Straight"	3	6,200	4,500	60	75	8,925
"Straight"	4	8,200	6,000	60	150	11,900
"Straight"	5	10,250	7,500	60	225	14,875
"Straight"	6	12,000	9,000	60	300	17,850
On-Ramp merger	3+1 > 3	≤ 6,200	3,000 500	60	50 50/6	5,950 991 ⅔
Off-Ramp	3 > 3+1	≤ 6,200	4,500	60	75	8,925
Sym. Weaving Section (75%, 23%)[12]	3+1	6,840	3,000 500	60	50 50/6	5,950 991 ⅔

[11] As found in CIA and NDW data
[12] 75% weaving of O2 (right hand lane) to D1 (left hand lanes, main lanes) and 23% weaving from O1 to D2

3.3.2.4 Simulation in location and time

In this subsection, the network including the different sections of each road segment and detector locations, as well as the vehicle input over time have been described separately. However, they influence each other. The way in which they influence each other, is described in this subsubsection.

Since the network is 1 – 1.5 km long and vehicles drive at (nearly) their desired speed[13] at the start of the simulation, it takes about 1 minute to fill the network (entire left part of the xt-diagram in Figure 9).

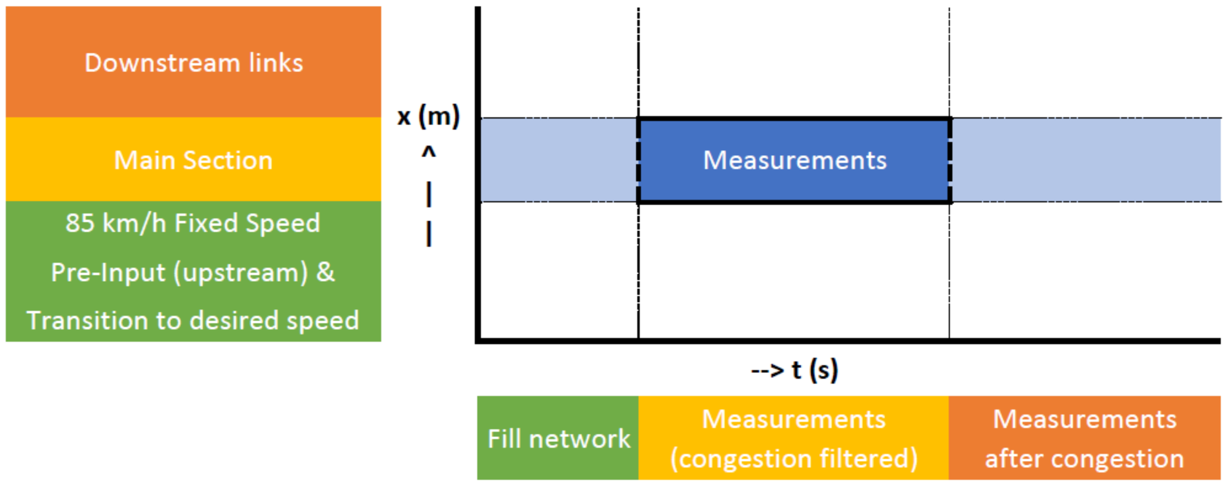

Figure 9: The xt-diagram of a single simulation

Each simulation is run for one simulated hour with increasing VI as described in previous subsection; Capacity as well as other traffic conditions are determined afterwards. Both are used in the validation as well as the study of automated driving (chapter Results and chapter Additional Analysis respectively).

Capacity is determined by taking the median value of all random seeds (RS) of a Vehicle Composition (VC, see §3.3.3 and §3.6.1 and onwards for details) of a 5-minute interval directly prior to congestion (one vehicle below 50 km/h at a detector). This pre-congestion interval can be at a range in time within the simulation of 3600 s. However, as described in previous subsection, the VI has been chosen in such a way that the pre-congestion interval lies somewhere in the middle of the simulation. Nevertheless, there are a few random seeds where this might not be the case. This is overcome by using a 5-95% interval to determine the range of values found and using the median value to determine capacity. Using the median value meets the definition of CIA.

Next, for Validation of the reference scenario as well as the Additional Analysis, the simulated hour of each RS is divided into twelve 5-minute intervals to determine further traffic conditions. By using 5-minute intervals, the intensities are all comparable to CIA and the capacities found. The studied traffic conditions are:

- Vehicle Distribution (Lane Share)
- Lane Intensity
- Mean Speed
- SD Speed

[13] 85 km/h for HGV, higher for passenger vehicles

The focus lies on Lane Share and Mean Speed, while the other two are used to study these in more detail. These four are chosen since they are best comparable with the reference data set for the validation.

These four are studied for each road segment and each VC. Since congested intervals should not influence the results, the measurements of interval after the congestion moment of each RS are filtered. By combining the spatial dimension segment (y-axis in Figure 9) where the detectors lie in the main section of each road segment, with the temporal dimension (x-axis in Figure 9), this results in the data points which are covered by the dark blue rectangle in the middle of the figure "Measurements". The left lighter blue rectangle is also included in these data points, but corresponds with low intensity data points while data points around capacity have most importance in the Validation and Additional Analysis. The data points covered by the left light blue rectangle therefore do not influence any findings and conclusions. The data points covered by the right lighter blue rectangle are filtered in general. However, in some cases these data points do have valuable information, especially for the Validation. Therefore, two figures for all road segments and each VC are made for each of the four traffic conditions: one with congestion intervals filtered and one without. This results in a total of 832 figures[14].

Since it is not feasible to present all figures, the figures of the Lane Share and Mean Speed of the most interesting road segments and the vehicle compositions with 100% market penetration (see §3.6.1) are presented with congestion filtered. In addition, specific figures with deviant results are added in the cases they are considered to give extra information and add value to the study. The most important figures of other road segments are put in Appendix K.

3.3.3 Driving Behavior

The modeling of the network has been described in previous subsection. In this subsection the second part of the modeling, namely the driving behavior in the default scenario for reference is covered. First, the parameters and their values in the default scenario for straight lanes are described and second, the differences in the default alternative, which is used as the reference for the merging and diverging road segments. Default scenarios in VISSIM (0 and 0b) should give similar results as the theoretical CIA capacities of researched road segments (Table 12). All results of the validation as well as the final simulations are compared to these values.

HGV are always modeled equal to passenger vehicles as in the default scenario except for their desired speed distribution. This is done in order to keep them as a constant and not let HGV driving behavior influence the results, since this study looks into the vehicle automation of passenger vehicles with a focus on non-platoon car-following behavior[15].

[14] 8 road segments, 13 VC, 4 traffic conditions, with and without congestion filtered (8 * 13 * 4 * 2 = 832)
[15] HGV parameter settings are also kept constant (equal to default scenario with HGV desired speed) at the scenarios with vehicles automation and communication

3.3.3.1 Scenario 0: Default (VC1)

VISSIM has default values for the Wiedemann 99 CF-parameters, look settings, lane change parameters and lateral parameters. These are used as values for parameters in the base scenario as far as the literature study did not provide better values (Table 14). Two changes to VISSIM's default values have been made: The time headway and the desired speed.

Table 14: VISSIM parameter settings for the default scenario (manual driving)

		Scenario	Default (0): VC1	Default Alternative (0b): VC2
		Market penetration of passenger vehicles	[1]*85%	[1]*85%
		Market penetration HGV	15%	15%
Longitudinal Parameters	CC0	Standst. dist. (m)	1.5	1.5
	CC1	Headway t. (s)	**~Triangular (0.6, 1,2, 0,9)**	~Triangular (0.6, 1,2, 0,9)
	CC2	Following Var.	4	4
	CC3	TH for entering following	-8	-8
	CC4	Neg. following TH	-0.35	-0.35
	CC5	Pos. following TH	0.35	0.35
	CC6	Speed dep. Osc.	11.44	11.44
	CC7	Osc. Acc. (m/s2)	0.25	0.25
	CC8	Standst. acc. (m/s2)	3.5	3.5
	CC9	Acc. At 80km/h (m/s2)	1.5	1.5
Look settings	Look ahead distance	Min (m)	0	0
		Max (m)	250	250
	Look back distance	Min (m)	0	0
		Max (m)	150	150
	Observed vehicles	#	2	2
Desired Speed[16]	Desired Speed Distribution	CDF of desired speeds: μ, σ (km/h)	**114.18, 11.71**	114.18, 11.71
Lane change Parameters	Cooperative Lane Change	Checked (C) / Unchecked (UC)	UC	UC
	Safety Distance Reduction Factor	Factor to CC1 headway	0.6	**0.4**
	Other		VISSIM Default	VISSIM Default
Lateral Parameters	All		VISSIM Default	VISSIM Default

[16] Desired Speed distribution for HGV is set to μ=85 km/h and σ=2.5 km/h for all scenarios

First, the time headway has been altered from a fixed 0.9 seconds to a triangular distribution with minimum 0.6, maximum 1.2 and modus 0.9 seconds since not all drivers maintain an equal time headway. The triangular distribution is used as an approximation to the normal distribution since it is easier to implement in VISSIM.
Second, the desired speed distribution has been set to values for the Dutch highway network. Since the theoretical framework only shows a desired speed distribution for a speed limit of 130 km/h, while the model simulates the traffic situation for a speed limit of 120 km/h, the found distribution has to be corrected. This can be done in numerous ways but it is likely to be in the range of 120/130 times the distribution of 130 km/h ("slow") and the distribution of 130km/h minus 3 km/h ("fast")[17]. These are shown in Figure 10.
Therefore, both are modeled for the default scenario to find the most realistic distribution to use in the final simulations (see also §3.5 Validation). The slow distribution has μ=114.18 km/h and σ=11.08 km/h approximately, while the fast distribution has μ=120.7 km/h and σ=11.71 km/h approximately. During calibration (Appendix E), the slow distribution has been found best and has therefore been chosen for the final simulations. HGV are modeled with a desired speed distribution of μ=85 km/h and σ=2.5 km/h approximately. All exact distributions as put into VISSIM can be found in Appendix D.

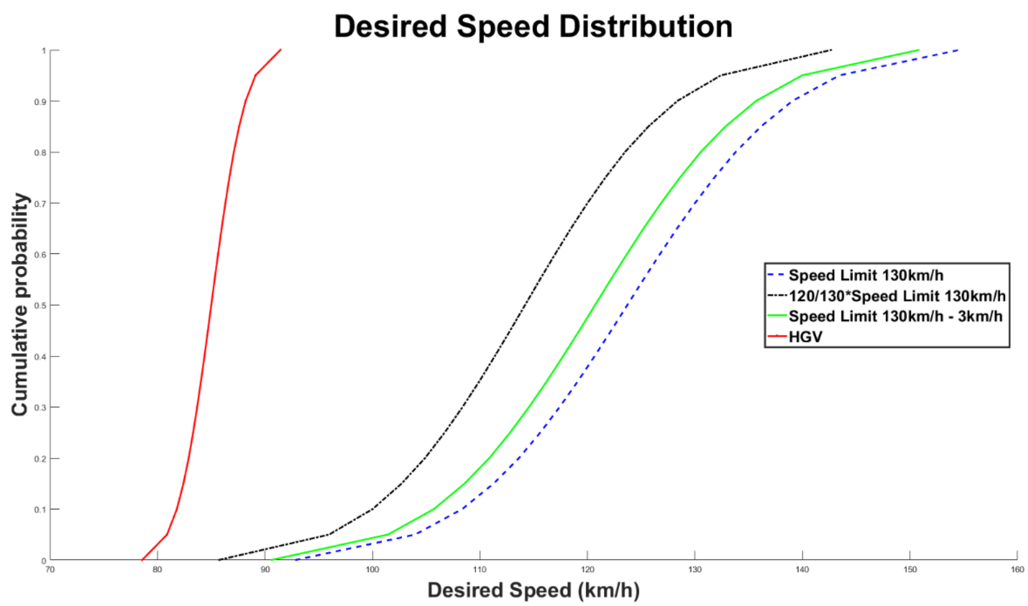

Figure 10: 120km/h Speed limit desired speed distribution based on 130 km/h speed limit

3.3.3.2 Scenario 0b: Default Alternative (VC2)

Scenario 0b is equal to the default scenario except for one setting, namely the safety distance reduction factor (SDRF). This parameter is set to 0.4 in the default alternative instead of default 0.6, which means that temporarily shorter headways (as factor of the normal car-following headway) are accepted for lane changes. During calibration the capacities found for the merging and diverging road segments, especially the symmetric weaving section, were found very low (Appendix E, Figure 44). This has been caused by vehicles failing to change lanes and coming to a standstill at the end of the merging or weaving section. Since vehicles in VISSIM only anticipate on a mandatory lane change to a limited extend since they will not exceed their desired speed and only partially lower their speed to find a gap. Bosdikou (2017) and de Baat (2015) show that a SDRF of 0.05 up to 0.50 can be used to calibrate

[17] See Appendix D for explanation

weaving sections. However, this is a measure that only partially makes sense in actual driving, since people will accept shorter headways to avoid missing their exit or having to stop and the end of the merging lane, but is also used as a workaround to the lack of proper anticipation modeling in VISSIM. Based on simulations during calibration (Appendix E) and the fact that the lower end values (0.05 – ~0.20) are very unrealistic in practice, a SDRF of 0.4 has been chosen for the reference of merging and diverging segments.

3.4 Simulation, Simulation Time and Optimization

Each vehicle composition can be run multiple times as a Monte Carlo simulation in order to reduce random errors. Monte Carlo techniques are frequently used in traffic simulation in general, i.e. Yan, Gu, Hu, and Engstrom (2013), as well as for calibration and validation in VISSIM (Park & Schneeberger, 2003), calibration of freeway capacity in VISSIM (Miller, 2009), recovery time on freeways in VISSIM (Saka et al., 2008) and for the combination of VISSIM and cooperative and autonomous vehicles in particular (Xie et al., 2017) and is therefore considered as a useful method to reduce random effects.

In general, as many runs as possible is optimal. As a starting point, the order of 100 to 1000 runs in total seems to be standard in the field (Miller, 2009; Saka et al., 2008). During a large part of the study this was not feasible due to simulation speed and therefore the time runs would take to be simulated.

Simulation Speed

Since simulation speed has been an issue since the beginning of the study, speed optimizations have been done in order to reach a desired sample size. At the point of the final simulations the following speed optimizations have been done:

- Reduced the simulation resolution in VISSIM from the initial maximum of 20 back to the default value of 10 time steps per second (**speed x2**)
- Changed the intensity increase from outside the random seed to inside the random seed via the COM-interface in MATLAB, resulting in initially 12 steps (every 5 minutes in 1 simulated hour) and lastly 60 steps (every minute in 1 simulated hour) so only 1 run is necessary per RS per VC instead of an amount of runs equal to the number of steps (**speed x12-x60**)
- Using RAW data instead of direct output via COM-interface in order to save desired model output. Initially (with at that moment part of the road segments modeled) this made the simulations twice as fast, an educated guess by experience of later simulations is likely to be an improvement of three to five times of the simulation speed (**speed x2-x5**).
- By using a private notebook (HP Pavillion with an Intel i7-6700HQ CPU and 16GB of RAM) in a later stage (when a personal license for VISSIM was arranged) instead of the company notebook (HP ProBook with an Intel i3-4005U CPU and 4GB of RAM) an intermediate test of 12 runs (12 vehicle compositions x 1 random seed) the private notebook took 49 instead of 82 minutes (**speed x1,67**)

This means a total speed increase of the order of magnitude of 100x to 1000x has been achieved during the study. Any further improvements are very difficult to achieve.

Simulation time of the final results is over 3.5 days for a total of 1300 runs (Appendix F). This means all speed optimizations have enabled the Monte Carlo simulation to have 100 runs per Vehicle Composition. All these results are presented in chapter 4 and furtherly analyzed in chapter 5.

3.5 VALIDATION

Validation of the VISSIM model is based on three main aspects: Capacity, vehicle distribution over the lanes and the speed distribution. Since capacity is a central element in this study, the capacity of the modeled reference scenario should be similar to the capacity on the Dutch highways. Therefore capacity is being validated for all road segments. The CIA capacities are taken as a reference since this study looks into the Dutch highway network and is strongly set to CIA conditions in order to make a fair comparison.

However, since many different traffic conditions can still lead to similar capacities, more traffic characteristics should be included to validate the traffic model. Namely, CIA is mainly used for road design and does not directly look into differences between lanes, over time within the measurement interval or individual vehicles. Literature shows, i.e. W.J. Schakel (2015), that validation can be done by comparing vehicle distribution over lanes as well as speeds per lane to the amount of traffic. In the example this is done by density. However, instead of density, intensity is chosen since this is a lot more suitable for the data available as well as for the reference data.

For the validation of the latter two, a data set of measured data of the A2 is taken as a reference for validation (Thomas, 2018). Since the available data set only includes data of three straight lanes, three straight lanes is the only road segment that is used for validation of vehicle distribution and speed distribution. In order to fairly compare data of the microscopic traffic model with the measured data, the lane distribution as well as the mean speeds are set to their respective 5-minute hourly intensity for intensities in the range of 4,000 to 6,500 vehicles per hour. In this way the for this study relevant intensities of medium high intensity up to capacity values are validated for speed and lane share.

3.5.1 Capacity

Table 15 shows that scenario 0 (VC1) has similar capacities as the theoretical CIA capacities for straight lanes, especially 2 and 6, while scenario 0b (VC2) better matches CIA for the merging and diverging road segments. This means that the only difference in the two VC, namely the Safety Distance Reduction Factor (SDRF), has a large influence on capacity. Between a SDRF of 0.6 (VC1), meaning less aggressive lane changing than a SDRF of 0.4 (VC2), there can be differences of 5 to 10% in capacity as the table shows. The less aggressive lane changing of VC1 better suits the straight road segments (S2 – S6), while more aggressive lane changes of VC2 give a better representation of vehicles in merging and diverging road segments. During calibration this seemed to be the case and therefore both reference scenarios were included in this study. From a logical point of view, this also makes sense: For straight lanes a more stable traffic flow with fewer disturbances by aggressive lane changes, will have a higher capacity than a less stable one with more disturbances, while earlier lane changes at mandatory lane changes in merging and diverging prevent more full blockages at the end of a merging section.

However, a remark must be made: Anticipating traffic behavior in such situations is not realistically modeled in VISSIM and changing the SDRF is the best found solution to that problem. Other studies found low SDRF values during calibration for weaving sections as well (Baat, 2015; Bosdikou, 2017). This confirms that a lower SDRF, and thus more aggressive lane changing during merging and diverging, is more suitable for calibrating those road segments, while less aggressive lane changing is more suitable for calibrating straight road segments. VC1 should thus be taken as a reference for straight road segments and VC2 for merging and diverging road segments.

Table 15: Capacity and 5 and 95% modeled intensity values (100 simulations per VC)

Segment	CIA Capacity	VC1	VC1 5p_value	VC1 95p_value	VC2	VC2 5p_value	VC2 95p_value
S2	4,300	4,218	3,594	4,602	4,056	3,390	4,560
S3	6,200	5,676	4,566	6,282	5,376	2,112	5,988
S4	8,200	7,488	6,408	8,268	7,032	4,608	7,860
S5	10,250	9,648	8,364	10,356	9,000	5,538	9,804
S6	12,000	11,940	10,518	12,780	11,082	9,438	12,258
On-Ramp 3+1-to-3	≤6,200	5,406	3,894	6,408	5,682	4,896	6,432
Off-Ramp 3-to-3+1	≤6,200	5,886	4,740	6,840	6,306	5,130	6,978
SW 3+1	6,840	4,848	3,738	6,144	5,634	4,140	6,930

In the table above the 5 and 95% values found are included to show the differences between different random seeds of simulations with the same settings. In general, the values lie about 10-20% from the capacity (median value). Though the capacities found are not equally well for all road segments, the values found are in an acceptable margin and are difficult to improve without calibrating all road segments separately. In the next subsections, the driving behavior is validated as well by the vehicle distribution over lanes as well as by the speed per lane.

3.5.2 Vehicle distribution over lanes (3 straight lanes)

To validate the driving behavior in the model, the vehicle distribution, namely the fraction of vehicles per lane relative to the intensity, is compared to the reference data. Since determining capacity is the main goal of this study, only high intensities up to capacity are relevant. Therefore, intensities of 4000, which is about 65% of the theoretical CIA capacity of 6300 veh/h, up to intensities of the congestion interval[18] are taken into account.

Figure 11 on the next page shows the fits of scenario 0 (VC1) and scenario 0b (VC2) and the data points of the reference data set (A2). All corresponding points of the original data can be found in Appendix E (Figure 48 to Figure 50). Both scenarios have very similar distributions over the lanes. Both have, except for near-capacity intensities, a few percent more vehicles on the left lane and a few percent less vehicles on the middle lane than in the A2 reference, while in both cases the right lane is very similar to the reference. Though the slight differences between VISSIM and the A2, in general the lane distribution for both scenarios is still similar to the one of the A2 since the right lane is nearly equal and has the lowest lane share (for studied intensities), the middle lane has highest lane shares for intensities around 4,000, while the left lane has highest lane share for high (>5,000 veh/h) intensities.

[18] Not a fixed number since capacity depends on the respective conditions, different per measurement (random seed in VISSIM)

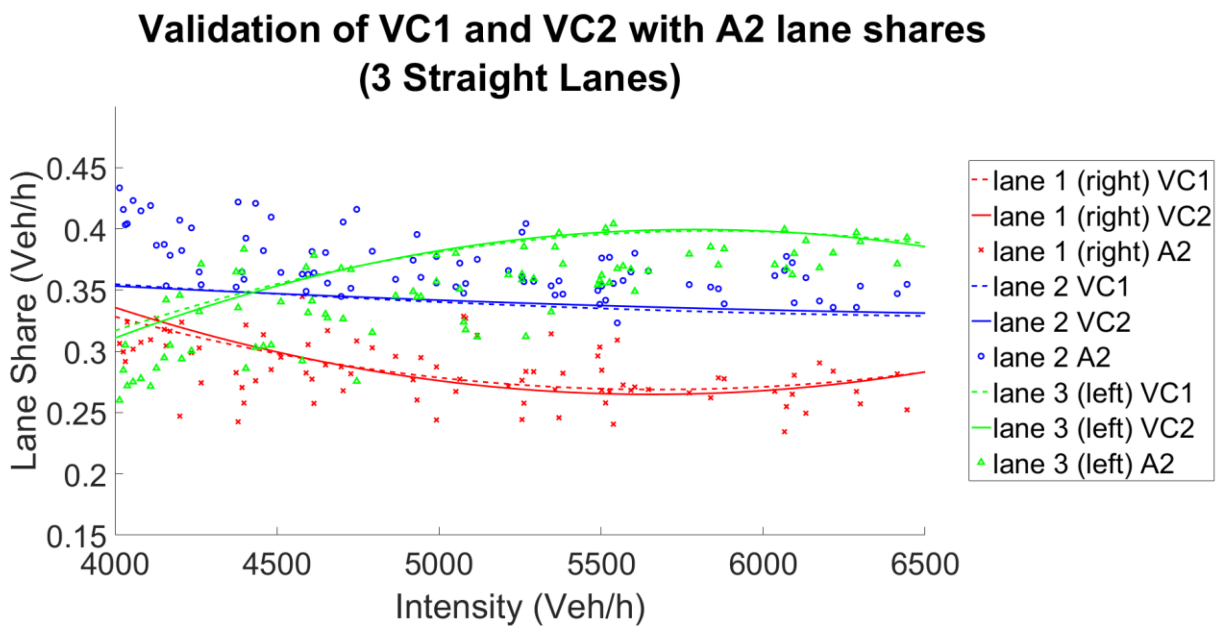

Figure 11: Comparison of modeled (VC1/VC2) and measured (A2) lateral vehicle distribution over 3 straight lanes per intensity for Scenario 0 (VC1) and Scenario 0b (VC2) – Fit of modeled data

While the filtered modeled data shows decent similarities to the A2 reference data, there are more aspects that can validate the model: at congestion lane shares and speeds should become about equal over all lanes. Figure 12 shows that this is the case for both subscenario 0 and 0b (VC1 and VC2 respectively). This confirms that the model is realistic, based on these aspects.

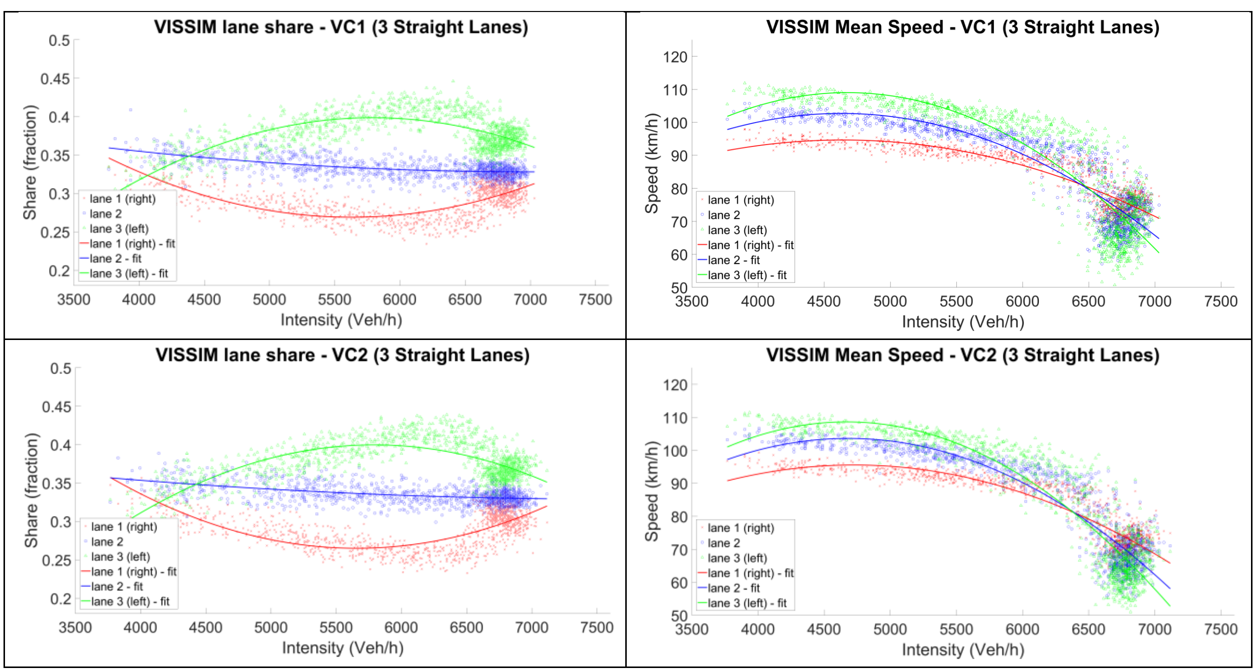

Figure 12: VC1 lane share (top left), Mean Speed (top right), VC2 lane share (bottom left) and Mean Speed (bottom right) for 3 straight lanes – Unfiltered data

3.5.3 Speed distribution (3 straight lanes)

In addition to capacity and vehicle distribution, this validation is also done based on speed. As can be seen in Figure 13, the mean speeds in both scenarios are very similar to each other while there are differences to the A2 reference data set: Both scenarios show higher speeds on the right lane than the A2 and lower speeds on the left lane than the A2, mainly for very high intensities. This corresponds with the findings of the previous subsection, since more vehicles in the model use the left lane and therefore cause lower mean speeds on that lane. In the original data points of both scenarios (Appendix E, Figure 51 and Figure 52) there seem to be data points of (near) congestion left, causing to drop the mean speed fit for high intensities. Another remark must be made for the A2 reference. No fit has been made since there is no clear line between the not congested regime and the congested regime (Figure 13 and Appendix E, Figure 53). Therefore, low mean speeds are also visible for lower intensities.

In general, the speeds in the model show an acceptable calibration. However, since there are differences, the results of vehicle automation (Chapter 4) are compared to the reference scenarios and not only to the theoretical CIA capacities in order to show the relative effects of vehicle automation of remove the systematical effects of the model. The same holds for the Analysis of Lane Distribution and Speeds in chapter 5.

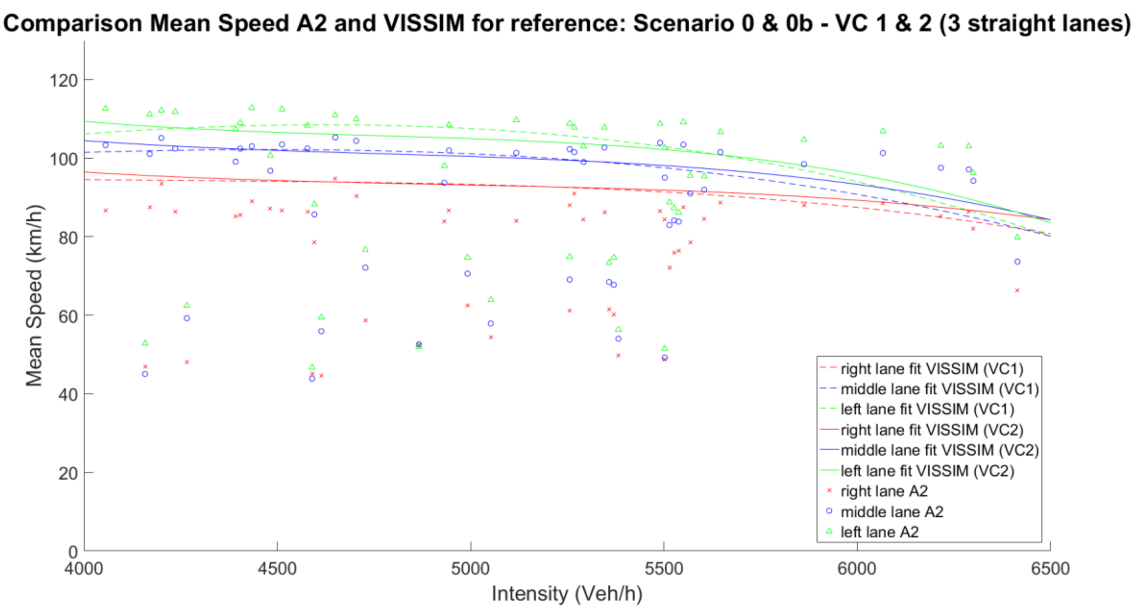

Figure 13: Mean Speed Comparison (Each data point represents 5 minutes)

3.6 AUTONOMOUS AND COOPERATIVE DRIVING

The validation of both reference subscenarios have been completed. Next, the eight road segment types will be run for several levels and (combinations of) penetration rates of automation in order to study the full spectrum from the current situation to a potential final stage of 100% CAV with fixed desired speeds and being able to analyze effects of market penetration on different stages without having to model numerous combinations. This is divided into five scenarios.

3.6.1 Scenarios

Next to the default scenario (scenario 0), there are 5 scenarios consisting of 13 vehicle compositions in total in order to study the effects of vehicle automation on the short term ((C)ACC) as well as on the long term ((C)AV) without (ACC & AV): and with (CACC & CAV) communication. Since the CIA and the reference data of the validation might already include a part of ACC-equipped vehicles and thus also in the default scenario, the ACC scenario has only a 100% subscenario. The other three scenarios all include different levels of market penetration in order to study the effects of partial market penetrations as well. However, studying many (sub)scenarios is very time-consuming, in both simulation as analysis, only three levels of market penetration are studied for each of CACC, AV and CAV. Finally, a CAV+ has been added in order to study the effects of harmonizing traffic flow by fixing desired speed to the speed limit instead of a distribution as in the other scenarios. Thus, there are 2 default subscenarios and the following 5 main scenarios containing 11 more subscenarios:

- ACC (100% ACC)
- CACC (3 combinations of penetration rates for ACC & CACC)
- Autonomous Vehicles (3 combinations of penetration rates for ACC to fully autonomous vehicles)
- Cooperative Autonomous Vehicles (3 combinations of penetration rates for fully autonomous vehicles to fully cooperative autonomous vehicles)
- CAV+ where 100% of the passenger vehicles is modeled as CAV, but with a desired speed fixed at the speed limit instead of a distribution.

This means that there are 13 different combinations of vehicle behavior in total for each of the eight road segment types (Table 16). Each of these combinations, vehicle compositions (VC), have 15% HGV and have 10, 50 or 100% market penetration for passenger vehicles (resulting in 8.5, 42.5 or 85% of total vehicles). If a subscenario has less than 100% market penetration, the remaining passenger vehicles are modeled as a scenario with a lower level of vehicle automation as shown in the table.

Details of the default values in VISSIM as well as the values to model ACC, CACC, AV, CAV and CAV+ are given below and a complete overview is given in the Appendix (Table 37 & Table 39). Based on the literature described chapter 2, the values in this section show how the parameters in VISSIM are set for the different scenarios. Only differences to the default scenario are described in the following subsections.

Table 16: Vehicle Composition Overview

Scenario	Vehicle Composition	Manual Driving [%]	ACC [%]	CACC [%]	AV [%]	CAV [%]	CAV+ [%][19]	HGV (Manual) [%]
Default (0)[20]	VC 1	85	-	-	-	-	-	15
Default Alternative (0b) [21]	VC 2	85[22]	-	-	-	-	-	15
ACC (1)	VC 3	-	85	-	-	-	-	15
CACC (2a)	VC 4	-	76.5	8.5	-	-	-	15
CACC (2b)	VC 5	-	42.5	42.5	-	-	-	15
CACC (2c)	VC 6	-	-	85	-	-	-	15
AV (3a)	VC 7	-	76.5	-	8.5	-	-	15
AV (3b)	VC 8	-	42.5	-	42.5	-	-	15
AV (3c)	VC 9	-	-	-	85	-	-	15
CAV (4a)	VC 10	-	-	-	76.5	8.5	-	15
CAV (4b)	VC 11	-	-	-	42.5	42.5	-	15
CAV (4c)	VC 12	-	-	-	-	85	-	15
CAV+ (5)	VC 13	-	-	-	-	-	85	15

3.6.2 ACC

Scenario 1 is the scenario where current technology becomes standard. In comparison to the default parameters, CF-parameters and the number of observed vehicles is adjusted to represent vehicles equipped with ACC with a 100% market penetration in order to find the potential on highway capacity of ACC. In this subsection, only differences to the default scenario are described. A full overview of all relevant parameter values can be found in Appendix C (Table 37 to Table 39).

Literature gives a relative wide range of values for time headways of ACC. ACC time headways with an average of 1.54 s (±0.41) have been found by Nowakowski et al. (2010), while Bierstedt et al. (2014) use 1.2, 0.8 and 0.6 s for following variation as conservative, intermediate and aggressive ACC settings respectively. Piao and McDonald (2008) state that ACC needs a slightly larger headway time in order to regain control for the driver than when driving manually, indicating that ACC time headways should be larger than the default 0.9 s of VISSIM. Since ACC is assumed to be vehicle-dependent, a distribution around found values is most likely. Therefore, a triangular time headway distribution has been chosen with minimum 1.0, maximum 1.4 and modus 1.2 seconds.

According to Bierstedt et al. (2014), ACC has 4, 3 and 2m for following variation as conservative, intermediate and aggressive ACC settings respectively. Since VISSIM allows only one value and per set of driving behavior parameters, the intermediate value, thus 3 m has been chosen. This means that vehicles in the ACC scenario take a larger headway (about 1.2 in comparison to about 0.9 s) than manual driving in the default scenario, but the headway itself varies less than for manual driving.

[19] Similar to CAV, except Desired Speed (Fixed at speed limit instead of a distribution (see Validation)
[20] Used as reference for straight road segments (2 – 6 lanes)
[21] Used as reference for merging and diverging segments (On-Ramp, Off-Ramp and Weaving Section)
[22] Safety Distance Reduction Factor of 0.4 instead of default 0.6

A few different values have been found for entering following. One study uses -11 as threshold for entering following (Motamedidehkordi, Benz, et al., 2016) while others use -16, -12 and -8 for acceleration at standstill as conservative, intermediate and aggressive ACC settings respectively (Bierstedt et al., 2014). The intermediate value of -12, which is also close to -11, has been chosen for the threshold for entering following in the ACC scenario.

Different values for the negative and positive following thresholds have been found as well: Some use (-)0.1 for the negative and positive following threshold of (C)AV or AV (Bohm & Häger, 2015; Motamedidehkordi, Benz, et al., 2016) while others use (-)0.6, (-)0.35 and (-)0.1 for negative and positive following threshold as conservative, intermediate and aggressive ACC settings respectively (Bierstedt et al., 2014). This means that the VISSIM's default value of (-)0.35 is also useable for ACC and thus kept at equal to the default scenario.

The speed dependency of oscillation has been set to 0 for ACC instead of the default 11.44 since it is assumed that automated systems keep a constant speed in free-flow conditions.

Next to previous CF-parameters, there are several look settings in VISSIM. The minimum look ahead (and back) distance is kept at the default 0 m for ACC, since current systems are comparable as in manual driving for looking distance, but their maximum range can be smaller: according to literature it varies from 150 to 250m (Laquai et al., 2011; Qing & Sengupta, 2003; Wolterink et al., 2010). Therefore, it is assumed that minimum and maximum look ahead/back distances are 0 and 200 m in the ACC scenario.

Different settings for the number of observed vehicles have been found ranging from 6-8 (Aria et al., 2016) observed vehicles and 10 observed vehicles for (C)AV (Bohm & Häger, 2015). However, the latter is better for CAV, thus 8 has been chosen for ACC.

3.6.3 CACC

CACC is scenario 2 in order to study the effects of communication in Cooperative ACC in comparison to standard ACC vehicles. CACC consists of three subscenarios (2a, 2b and 2c, where vehicles equipped with CACC have 10, 50 and 100% market penetration of passenger vehicles respectively, while the rest of the passenger vehicles are modeled as equipped with standard ACC as mentioned in the ACC scenario.
Only differences to ACC are described in this subsection. All values can be found in Appendix C.

Bierstedt et al. use 1.5, 1.25 and 1.0 m for standstill distance as conservative, intermediate and aggressive ACC settings respectively, while Bohm & Häger use 1.0 m for (C)AV. Motamedidehkordi et al. mention the range for standstill distances to be 1 to 4 m. However, the default setting in VISSIM is 1.5 m and automation of driving is expected to cause smaller standstill distances. CACC is assumed in a later and more advanced stage and therefore capable of maintaining a smaller standstill distance than manual driving and ACC (both set at 1.5m): CACC standstill distance is set to 1.25 m.

In addition to the standstill distance, CACC can also maintain smaller time headways. CACC time headways seem to be much smaller than ACC, i.e. 0.71 s (±0.13) (Nowakowski et al., 2010). However, since time headways for ACC have shown a large range of values in literature (Bierstedt et al., 2014; Nowakowski et al., 2010; Piao & McDonald, 2008) and this is only one source, a slightly more conservative distribution than the values of Nowakowski have been chosen for CACC: a triangular distribution with minimum 0.65, maximum 0.85 and modus 0.75 seconds.

Bierstedt et al. (2014) use 4, 3 and 2 m for following variation as conservative, intermediate and aggressive ACC settings respectively, while Bohm and Häger (2015) assume 1 m for (C)AV. CACC is assumed in a later and more advanced stage and therefore capable of having a smaller following variation than manual driving and ACC (4 and 3 m respectively): CACC following variation is set to 2 m.

Bierstedt et al. use 0.4, 0.25 and 0.1 m/s^2 for oscillation during acceleration as conservative, intermediate and aggressive ACC settings respectively. CACC is assumed in a later and more advanced stage and therefore capable of having a smaller oscillation during acceleration than manual driving and ACC (0.4 and 0.25 m/s^2 respectively): CACC oscillation during acceleration is set to 0.1 m/s^2.

The minimum look ahead and back settings will be much larger than the default 0 m due to the communication component. This is confirmed by Laquai et al. (2011) and Qing and Sengupta (2003): The minimum look ahead and back setting for CACC has been set to 150 m. The maximum look ahead and back setting will be similar to ACC and is kept at 200 m.

Finally, there is one of the most important parameters that distinguishes the CACC scenario from ACC: Cooperative lane change. This CACC scenario not only represents a CACC system which acts in the longitudinal dimension of CF-behavior, but also in the lateral dimension a Cooperative Lane Change system (CLC). This means that Cooperative lane change box is checked for the CACC scenario in contradiction to the default and ACC scenario.

3.6.4 Autonomous Vehicles (AV)

AV is scenario 3. This scenario reflects the development of autonomous vehicles reaching significant market penetration rates. Different levels of market penetration are studied. In scenario 3a 10% of the vehicles are modeled as AV in order to study early effects while in scenario 3b 50% are modeled as AV to analyze the effects on capacity of a very mixed situation. In both cases the rest of the vehicles is modeled as the ACC scenario since ACC is expected to be the standard when AV reach significant market penetration rates. To conclude, in scenario 3c, 100% of the vehicles are modeled as AV in order to study the potential of autonomous driving. In this subsection only differences to ACC are explained. A full overview of AV parameters can be found in Appendix C.

Bierstedt et al. use 1.5, 1.25 and 1.0 m for standstill distance as conservative, intermediate and aggressive ACC settings respectively, while Bohm & Häger use 1.0 m for (C)AV. Motamedidehkordi et al. mention the range for standstill distances to be 1 to 4 m. However, the default setting in VISSIM is 1.5 m and automation of driving is expected to cause smaller standstill distances. AV is assumed in a later and more advanced stage and therefore capable of maintaining a smaller standstill distance than manual driving and ACC (both set at 1.5m) as well as than CACC (1.25m): AV standstill distance is set to 1 m.

Time (and distant) headways for autonomous cars (in a simulator) were found to be relatively large for *Fixed follow risk* of 1.8-1.9 s and 1.85-2.00 s for *Free follow risk*, while 1.65-1.71 s for *Fixed follow comfort* and 1.80 -1.98 s for *Free follow comfort* were found (Siebert et al., 2017). However another study uses a time headway of 1.4 s between platoons or 0.3 s within platoons for CAV (Gouy et al., 2014) and Bohm & Häger use 0.5 s for (C)AV (2015). Aria, Olstam & Schwietering (2016) even use 0.3 s for CAV (highly AV). This might be because by the time of AV are common, people will be used more to ACC than they are now. There are many different values found, this might be explained by variation in circumstances. According to Risto & Martens (2014), simulators and instrumented vehicle show similar headway times, while there is an overestimation of headway based on time and an underestimation based on distance (Risto & Martens, 2014; Taieb-Maimon, 2007). Women seem to be overestimating time headway while distance headway and number of vehicles seem to be similar for both genders (Taieb-Maimon & Shinar, 2001). Other research seems to find results which can be linked to these deviations. Hou and colleagues concluded that most human drivers prefer using distance headways over time headways and this will be an important aspect for the acceptance of autonomous vehicle technology (Hou et al., 2014). AV can maintain smaller time headways than ACC, but far less than CAV due to the lack of communication. By the time AV reach significant market penetration rates, they are expected to have very little variation in (minimal) headways and therefore are modeled with a fixed desired speed. Since AV have smaller headways than ACC, but larger than CACC and much larger than CAV, the time headway of AV is set to a fixed value of 0.9 seconds.

The following variation will decrease as vehicle automation develops further. Therefore, a smaller following variation than default and ACC should be taken. This is confirmed by Bierstedt et al. (2014) and Bohm and Häger (2015): Though exact values differ, a value of 2 m has been chosen for following variation in the AV scenario.

Bierstedt et al. (2014) use 0.4, 0.25 and 0.1 m/s^2 for oscillation acceleration as conservative, intermediate and aggressive ACC settings respectively. 0.1 m/s^2 is found suitable for more advanced levels of vehicle automation and is thus also used for AV.

Vehicles are expected to be able to accelerate faster at higher speeds when AV start to become common. However, since humans will still be present in vehicles (at least in most cases), comfort still plays a role. Therefore, the increase in acceleration at high speeds will be limited. This is confirmed by Bierstedt et al. (2014) and Bohm and Häger (2015): Acceleration at 80 km/h is set to 2 m/s^2 for AV.

Look settings are set equal to CACC: 150 m (min.) and 200 m (max.) for both ahead and back since technology is expected to be at least similar. Further improvements might be accomplished, but due to uncertainty these conservative values have been chosen.

3.6.5 Cooperative Autonomous Vehicles (CAV)

The next scenario is scenario 4, where CAV are modeled in order to study the advantages of communication in autonomous vehicles over autonomous vehicles without communication. The same market penetration rates as for ACC and AV are used. This time it is assumed that all other vehicles than CAV are AV. This way, the effect of communication at autonomous vehicles is most clear, because results are most comparable. Below all differences to AV are described. All other parameters are set equal to AV.

Many different values can be found for time headways of automated vehicles, though most values for CAV lie between 0.3 and 0.5 seconds (Aria et al., 2016; Bohm & Häger, 2015; Gouy et al., 2014). The lower end values are mostly for platoon-based CAV; therefore, the more conservative fixed value of 0.5 seconds has been chosen for this study since it concerns non-platoon based CAV.

The following variation will decrease as vehicle automation develops further. Therefore, a smaller following variation than default, ACC, CACC and AV should be taken. This is confirmed by Bohm and Häger (2015): In agreement, a value of 1 m has been chosen for following variation in the CAV scenario.

A few different values have been found for entering following. One study uses -11 as threshold for entering following (Motamedidehkordi, Benz, et al., 2016) while others use -16, -12 and -8 for acceleration at standstill as conservative, intermediate and aggressive ACC settings respectively. Since

CAV scenario is the most advanced scenario and thus most capable of handling deviations, -16 has been chosen for the entering following value of CAV.

Bierstedt et al. (2014) use 3, 3.5 and 4 m/s^2 for acceleration at standstill as conservative, intermediate and aggressive ACC settings respectively, while Bohm and Häger (2015) use 4 m/s^2 for (C)AV. Since CAV scenario is the most advanced scenario, 4 m/s^2 has been chosen.

For CAV look settings, literature is less consequent as other scenarios: Bohm and Häger (2015) use a minimum of 0m and a maximum of 300/500m as look ahead distance and a minimum of 0 m and maximum of 100/300m as look back distance for (C)AV, while it also can be many kilometers due to vehicle-to-vehicle or vehicle-to-infrastructure communication (Laquai et al., 2011). Since this scenario consists of very high vehicle automation in combination with communication to other vehicles and infrastructure, it is assumed that all look settings (min. and max. for both look ahead and look back) are set to 5,000 m for CAV.
The final parameter that is different than AV is the number of observed vehicles. Since beforementioned communication, vehicles in the CAV scenario can (indirectly) observe many (dozens of) vehicles. However, the maximum number allowed in VISSIM is 10, so it this parameter is set to 10 for CAV.

3.6.6 Cooperative Autonomous Vehicles with desired speed fixed at speed limit (CAV+)

The final scenario (5) consists of Cooperative Autonomous Vehicles as well. However, there is one difference, all other parameters are set equal to scenario 4.: The desired speed for passenger vehicles is fixed at the speed limit (120 km/h) instead of the distribution used for all other scenarios. This scenario is used to compare the effects of harmonizing traffic flow on capacity and related traffic characteristics.

3.6.7 Minimal Time Headway (all)

Since most scenarios use distributions for the minimal time headway parameter instead of static values as most other parameters, Figure 14 shows the cumulative probability of the minimal time headway distribution of each vehicle class to visualize the different distributions. The corresponding explanation of these distributions can be found in Appendix D.

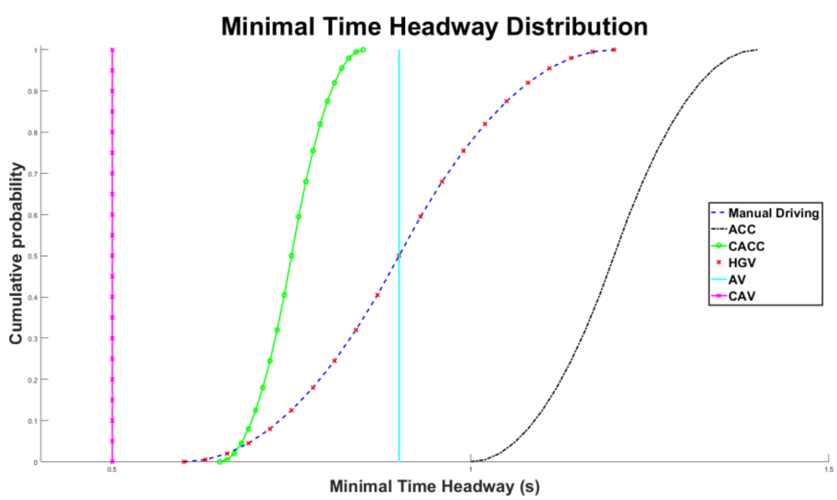

Figure 14: Minimal Time Headway distribution of all vehicles classes

3.7 Summary

To summarize this chapter, the most important findings of this part are listed below:

- A research methodology has been developed to answer the research questions by translating literature input via the model and auxiliary software into information of the results and analysis.
- Standard conditions are assumed and correspond as much as possible to the Dutch Highway Manual (CIA), including: daylight, dry weather, 15% HGV, 120 km/h speed limit.
- CIA definitions of road segments and capacity are maintained as much as possible.
- VISSIM's default parameter values for right-side-rule highway traffic have been used for most parameters in the default scenario. However, two changes have been made: The minimal time headway has been changed from a fixed 0.9 s to a triangular distribution around 0.9 s and the desired speed distribution has been altered to meet the Dutch highway network with a speed limit of 120 km/h.
- VISSIM puts vehicles on the network with random headways at their desired speed. When following vehicles (i.e. a fast passenger vehicle) are put onto the network after slower leading vehicles (i.e. a HGV) at high intensities, this causes unrealistic disturbances near vehicle input locations. This has been resolved by adding a fixed speed section and a transition section upstream of the respective studied road segment where vehicles can accelerate to their desired speed (as far as traffic conditions allow). In future research this can be improved to a greater extent, but current method is sufficient for this study.
- Mandatory lane changes have issues in VISSIM, since vehicles can only anticipate to the lane change to a limited magnitude. Vehicles will not exceed their desired speed and only slow down to find a gap within a limited range when they can actually enter a gap in that range. This is negatively effecting merging and diverging road segments, especially weaving sections. Other studies show that lowering the safety distance reduction factor (SDRF) and thus accepting smaller headways during lane changes, is an effective way of calibration weaving sections. However, this is only partially realistic in comparison to highway traffic in practice. For the other part it must be seen as a workaround to compensate the lack of properly modeling anticipation of drivers at mandatory lane changes in VISSIM.
- A SDRF of 0.6 seems best for straight road segments: Scenario 0 (VC1) is used as a reference for straight road segments. Validation shows fair to very good results.
- A SDRF of 0.4 seems best for road segments with merging and diverging movements (On-Ramp, Off-Ramp and Symmetric Weaving Section): Scenario 0b (VC2) is used as a reference for merging and diverging road segments. Validation shows fair to good results. However, the Symmetric Weaving Section, though major improvements during calibration, still has questionable results.
- Five scenarios for vehicle automation are studied: ACC, CACC, AV, CAV and CAV+, where CACC, AV and CAV each are split into 3 subscenarios with 10%, 50% and 100% market penetration of passenger vehicles each. In case of 10 and 50% market penetration, the remaining vehicles are modeled as a lower level, namely ACC, ACC and AV respectively. HGV are modeled equally in all scenarios: 15% of all vehicles with parameter values equal to the default scenario, except with a special desired speed distribution for HGV.
- A total speed increase of the order of magnitude of 100x to 1000x has been achieved during the study by: changing simulation resolution, encapsulating intensity increase single simulations instead of outside, using RAW output data instead of output via COM-interface and using a faster computer (amongst others with more RAM-memory, an SSD instead of an HDD and a faster CPU). This has resulted in 1300 final simulations (100 random seeds per VC) that produced about xx GB of raw text data and took about 100 simulation hours excluding data (pre-)processing and analyzation.

In additional to the overview on the previous page, research question 2 can also be answered.

Question 2: What is the capacity for those types of road segments in the used traffic model (VISSIM) and how do they compare to the theoretical reference?

- *What is the ratio between CIA values and model values*

The answer to the first part of the questions can be found in Table 17: Vehicle Composition 1 shows capacities of 4218, 5676, 7488, 9648 and 11,940 vehicles per hour for 2 to 6 lanes respectively, which is close to very close to the CIA capacity. The On-Ramp, Off-Ramp and Symmetric Weaving show capacities of 5406, 5886 and 4848 respectively. The Off-ramp has therefore a capacity relatively close to the CIA capacity, but the On-Ramp and especially the Symmetric Weaving Section show much smaller values than the CIA values. VC1 is a good calibration of the reference for straight lanes based on capacity, but is poor for the merging and diverging road segments.

Table 17: Modeled reference capacities and ratio to CIA capacities

Segment	CIA Capacity (veh/h)	VC1 (veh/h)	VC1 Model/CIA-ratio	VC2 (veh/h)	VC2 Model/CIA-ratio	Reference Model/CIA-ratio
Straight 2 lanes	4,300	4,218	**0.981**	4,056	0.943	0.981
Straight 3 lanes	6,200	5,676	**0.915**	5,376	0.867	0.915
Straight 4 lanes	8,200	7,488	**0.913**	7,032	0.858	0.913
Straight 5 lanes	10,250	9,648	**0.941**	9,000	0.878	0.941
Straight 6 lanes	12,000	11,940	**0.995**	11,082	0.924	0.995
On-Ramp 3+1-to-3	6,200	5,406	0.872	5,682	**0.916**	0.916
Off-Ramp 3-to-3+1	6,200	5,886	0.949	6,306	**1.017**	1.017
Symm. Weaving 3+1	6,840	4,848	0.709	5,634	**0.824**	0.824

Vehicle Composition 2 however, shows about the opposite. Straight road segments show values reasonable capacity values, but they are not really close to CIA and worse than VC1, with values of 4056, 5376, 7032, 9000 and 11082 vehicles per hour for 2 to 6 lanes respectively. The merging and diverging segments do show better values than VC1: 5682, 6306 and 5634 for the On-Ramp, Off-Ramp and Symmetric Weaving Section respectively. While the On-ramp value is decent and the Off-Ramp value is very good, the Symmetric Weaving Section still has a much lower capacity in the model than in CIA.

By choosing VC1 as a reference for straight road segments and VC2 as a reference for merging and diverging segments, the Model/CIA-ratios become as shown in the last column of the table. Straight 2 lanes, straight 6 lanes and the Off-Ramp show very good values, with each a ratio between 0.98 and 1.02, while straight 3, 4 and 5 lanes as well as the On-Ramp show decent values with each a ratio between 0.9 and 1.1. However, the Symmetric Weaving Section shows poor calibration with a ratio of just 0.824.

4 RESULTS

4.1 INTRODUCTION

After validation with the intermediate results (section 3.5), the lower bound desired speed distribution has been chosen for all scenarios, except the final CAV+ scenario (scenario 5: Vehicle Composition 13). Scenario 5 has been added to study the effects of harmonizing the traffic flow fixing the desired to the speed limit of 120km/h to see whether this can be beneficial in addition to vehicle automation in car-following and lane change behavior.

As a result of the validation, a new default alternative (with a safety distance reduction factor of 0.4 instead of 0.6) has been included for the final simulations to determine which setting gives a better reference: scenario 2b. In Table 18 a short overview of how all vehicle compositions relate to the scenarios and the respective market penetration of vehicle types. Details of respective vehicle behavior can be found in subsection 3.3.3 and Appendix C.

Table 18: Vehicle Composition Overview

Scenario	Vehicle Composition	Manual Driving [%]	ACC [%]	CACC [%]	AV [%]	CAV [%]	CAV+ [%][23]	HGV (Manual) [%]
Default (0)	VC 1	85	-	-	-	-	-	15
Default Alternative (0b)	VC 2	85[24]	-	-	-	-	-	15
ACC (1)	VC 3	-	85	-	-	-	-	15
CACC (2a)	VC 4	-	76.5	8.5	-	-	-	15
CACC (2b)	VC 5	-	42.5	42.5	-	-	-	15
CACC (2c)	VC 6	-	-	85	-	-	-	15
AV (3a)	VC 7	-	76.5	-	8.5	-	-	15
AV (3b)	VC 8	-	42.5	-	42.5	-	-	15
AV (3c)	VC 9	-	-	-	85	-	-	15
CAV (4a	VC 10	-	-	-	76.5	8.5	-	15
CAV (4b)	VC 11	-	-	-	42.5	42.5	-	15
CAV (4c)	VC 12	-	-	-	-	85	-	15
CAV+ (5)	VC 13	-	-	-	-	-	85	15

[23] Similar to CAV, except Desired Speed (Fixed at speed limit instead of a distribution (see Validation)

[24] Safety Distance Reduction Factor of 0.4 instead of default 0.6

4.2 Straight road segments

As can be seen in the figures for the straight road segments (Figure 15 and Figure 16 in this section, Figure 54 to Figure 56 in the Appendix), the default scenario (VC1) approximates the CIA capacity (horizontal plotted line) better than the new default scenario alternative (VC2). This means that a Safety Distance Reduction Factor of 0.6 over 0.4 and thus larger headways at lane changes, represents the theoretical CIA capacity better and also results in higher capacities. This higher SDRF also seems to be robust than the lower SDRF of 0.4 for straight road segments as well, since the boxplots of VC1 are shorter than those of VC2 showing less deviations of single random seeds to the sample.

Other interesting results can be found in the figures as well. Adaptive Cruise Control with full market penetration for passenger vehicles (VC3) consistently shows the lowest capacities of all vehicle compositions with significantly lower values than the modeled reference (VC1/VC2) and the theoretical CIA capacity. Next, low to average market penetration of both Cooperative Adaptive Cruise Control (VC4 and VC5 respectively) as well as Autonomous Vehicles (VC7 and VC8 respectively) also show lower than to similar to, reference capacities. This can be explained by the other share of these VC, since the rest of the market penetration of these VC are modeled as ACC. Apparently, the CACC needs to have a sufficient market share to significantly effect capacity. For low to average market penetration the magnitude of the effect on capacity is similar for both CACC and AV. However, full market penetration of CACC (VC6), seems to generate larger improvements on capacity than full market penetration of AV (VC9) for especially more than two lanes. Interestingly, full market penetration of CACC also seems to be very robust to the stochastic aspects of driving at a straight road segment of two lanes, shown by the short boxplot in Figure 15. However, this is not the case for more lanes (Figure 16 to Figure 56).

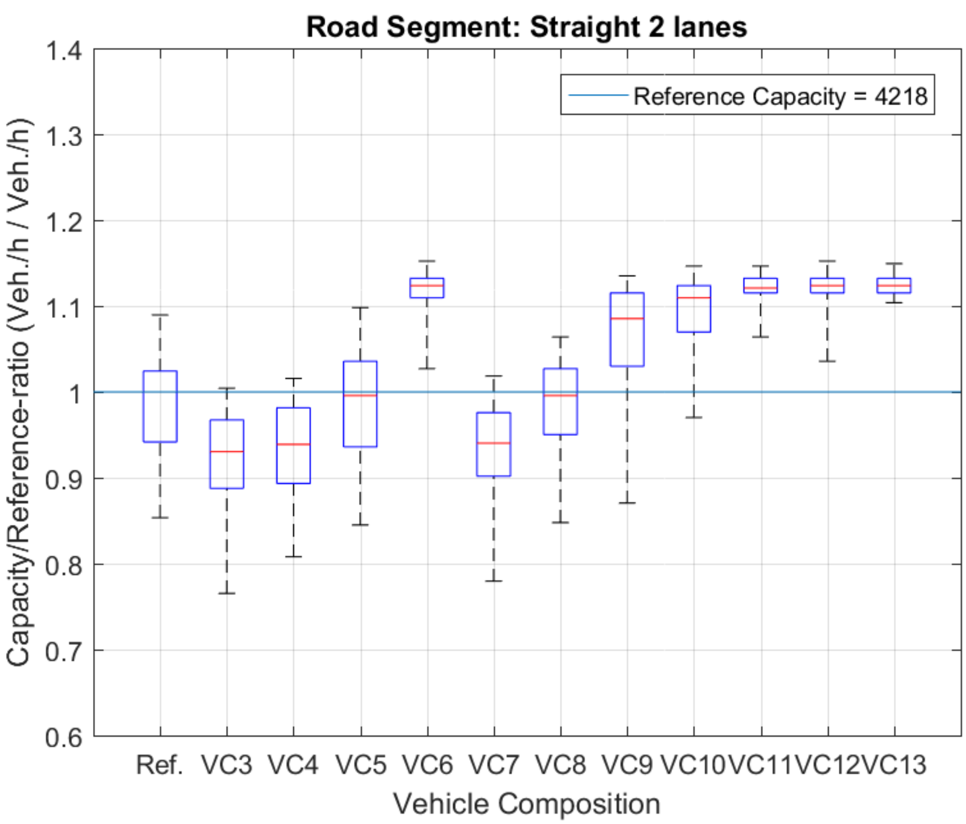

Figure 15: Straight 2 lanes - Capacities (relative to reference) per Vehicle Composition (100 simulations per VC)

The combination of high vehicle automation and the cooperative aspect of driving combined seems to improve capacity even more (VC10, VC11 and VC12). Similar to CACC, though also at lower market share, CAV is very robust to stochastic effects in traffic for a straight road segment of two lanes, but barely more robust than other vehicle compositions at segments with more lanes.

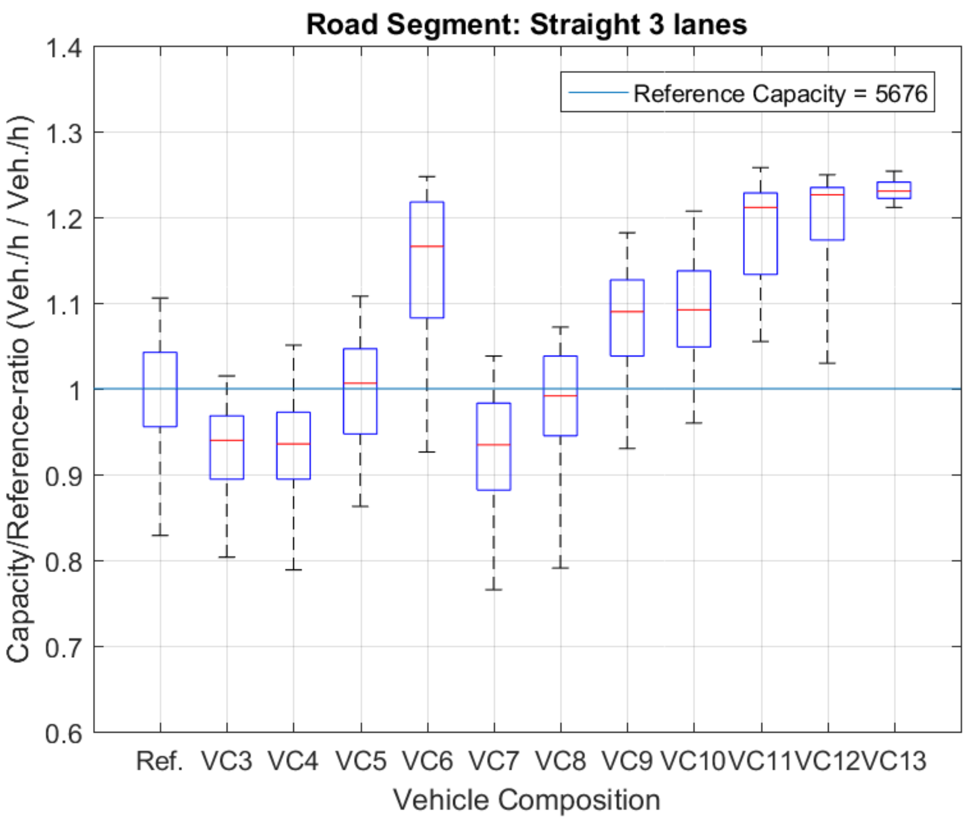

Figure 16: Straight 3 lanes - Capacities (relative to reference) per Vehicle Composition (100 simulations per VC)

4.3 On-Ramp

As can be seen in the figure for an On-Ramp (Figure 17), the default scenario alternative (VC2) approximates the CIA capacity (horizontal plotted line) better than the new default scenario alternative (VC1). This means that a Safety Distance Reduction Factor of 0.4 over 0.6, and thus smaller headways at lane changes, represents the theoretical CIA capacity better, and also results in higher capacities. This lower SDRF seems to be more robust than the lower SDRF of 0.6 for an On-Ramp as well, since the boxplot of VC2 is shorter than the one of VC1 showing less deviation of single random seeds to the sample.

Other interesting results can be found in the figure as well. Adaptive Cruise Control with full market penetration for passenger vehicles (VC3) shows the lowest capacities of all vehicle compositions with a lower value than the modeled reference alternative (VC2) and the theoretical CIA capacity similar to the straight road segments in previous section. However, it has a similar result as the default reference (VC1). Next, low to average market penetration of both Cooperative Adaptive Cruise Control (VC4 and VC5 respectively) as well as Autonomous Vehicles (VC7 and VC8 respectively) also show similar to reference capacities. This can be explained by the other share of these VC, since the rest of the market penetration of these VC are modeled as ACC. Apparently, the CACC needs to have a sufficient market share to significantly effect capacity. For low to average market penetration the magnitude of the effect on capacity is similar for both CACC and AV. However, full market penetration of CACC (VC6), seems to generate larger improvements on capacity than full market penetration of AV (VC9), since the latter one does not show any improvement on capacity in comparison to an average market share of AV (VC8).

The combination of high vehicle automation and the cooperative aspect of driving combined appears to improve capacity at higher market penetration (VC11 and VC12). Similar to straight road segments, CAV is very robust to stochastic effects in traffic for an On-Ramp.

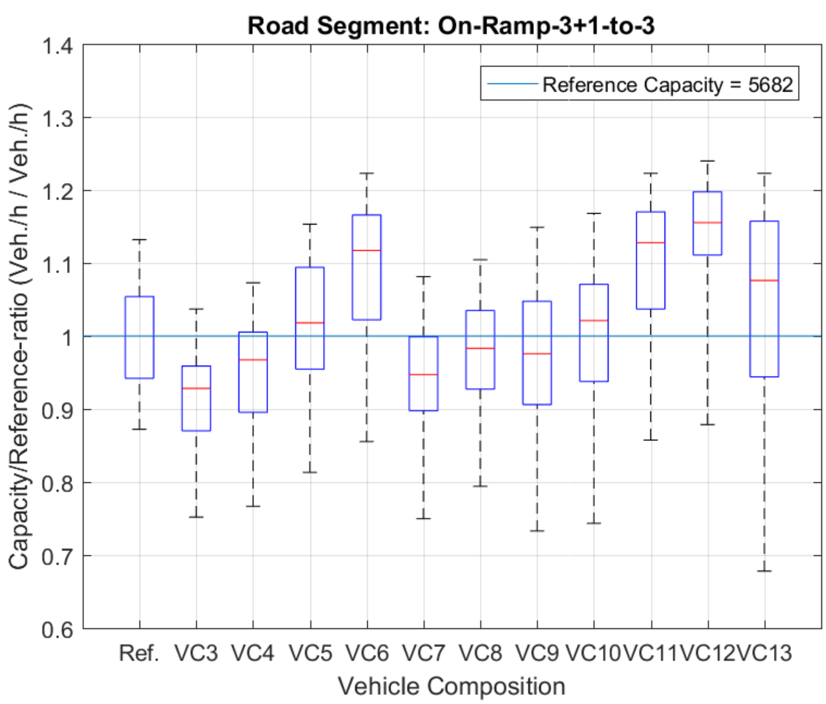

Figure 17: On-Ramp 3+1 to 3 lanes – Capacities (relative to reference) per Vehicle Composition (100 simulations per VC)

4.4 Off-Ramp

As can be seen in the figure for an Off-Ramp (Figure 18), the default scenario alternative (VC2) approximates the CIA capacity (horizontal plotted line) better than the new default scenario alternative (VC1). This means that a Safety Distance Reduction Factor of 0.4 over 0.6, and thus smaller headways at lane changes, represents the theoretical CIA capacity better, and also results in higher capacities.

Contrary to straight road segments and On-Ramps, vehicle automation and communication has little effect on capacity for an Off-Ramp, since most vehicle compositions have a capacity very close to the theoretical CIA capacity. A possible explanation is that this road segment is limited by its three lanes upstream and the Off-Ramp itself causes none to little turbulence. However, the medians of the vehicle compositions for an Off-Ramp with three main lanes and one diverging lane, are even closer to CIA capacity than a straight road segment with three lanes. This might be explained by the higher downstream capacity and thereby fewer downstream incidents causing congestion upstream.

Only CAV with sufficient market penetration (VC11 and VC12) seem to improve capacity.

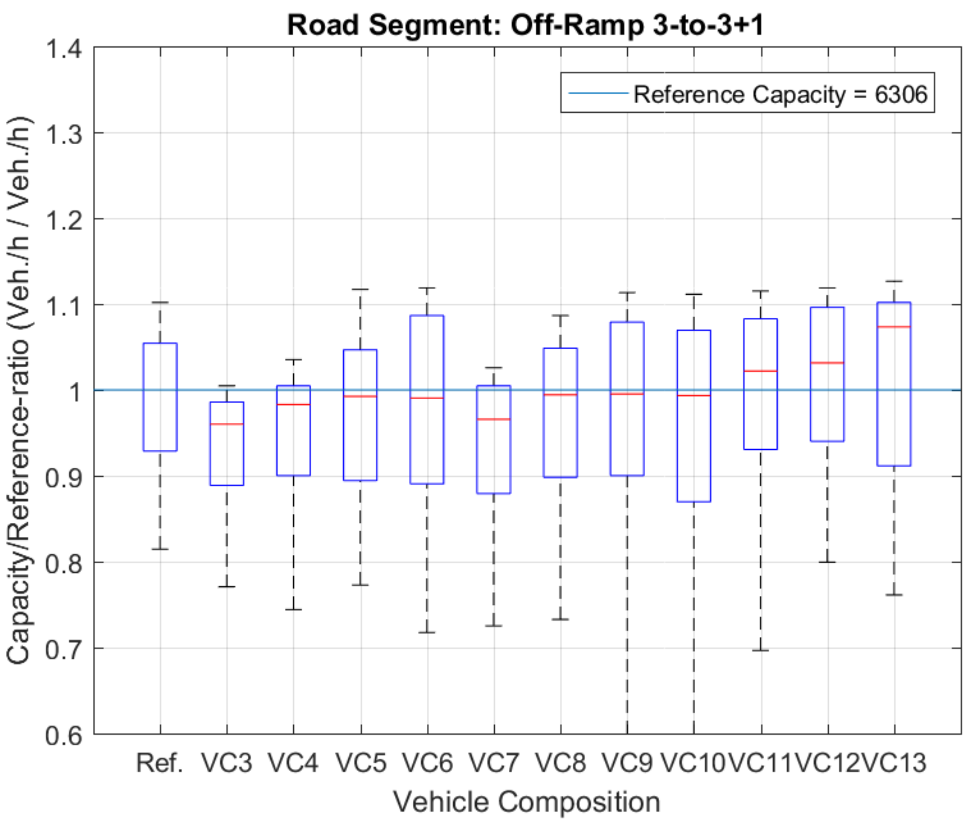

Figure 18: Off-Ramp 3 to 3+1 lanes - Capacities (relative to reference) per Vehicle Composition (100 simulations per VC)

4.5 SYMMETRIC WEAVING

Even after multiple improvements during calibration, modeling and calibrating a Symmetric Weaving Section realistically is very difficult. All simulated vehicle compositions are far below CIA Capacity and results should be interpreted carefully. Two results draw most attention. First, the default alternative with a Safety Distance Reduction Factor of 0.4, and therefore shorter accepted headways for lane changes (VC2), shows a much higher, and closer to CIA, capacity than the default reference with a SDRF of 0.6 (VC1).

Secondly, high market penetration of CAV (VC11 and VC12), show much higher capacities than the other vehicle compositions as well.

However, since the reference is not calibrated well, conclusions are difficult to draw and the causes of these results are analyzed further in section 5.5.

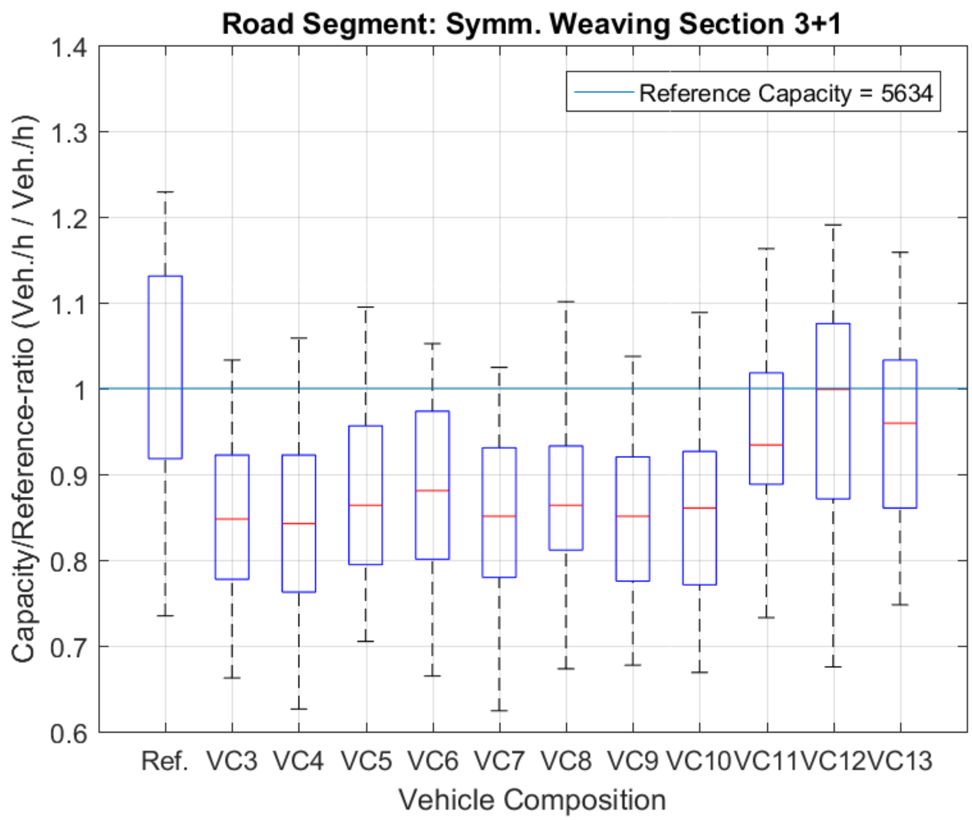

Figure 19: Symmetric Weaving 3+1 lanes - Capacities (relative to reference) per Vehicle Composition (100 simulations per VC)

4.6 SUMMARY

To summarize this chapter, the most important findings of this part are listed below:

- For straight road segments, 100% ACC (VC3) shows worst performance (worse than reference of manual driving), with only a minor improvement of both 10% CACC (VC4) and 10% AV (VC7), while 50% CACC (VC5) and 50% AV (VC8) have similar capacities as manual driving. 100% AV (VC9) and especially 100% CACC (VC6) show significant improvement on highway capacity. The largest improvements are found for the CAV (VC10, 11, 12) and CAV+ (VC13) scenarios.
- Especially CAV+ (VC13) shows a very small spread over random seeds for straight road segments.
- The On-Ramp shows similar results as the straight road segments, except for 100% AV (VC9) and 100% CAV+ (VC13): 100% AV has comparable capacity as manual driving with a slightly larger capacity (mean of measurements), but a larger spread over the random seeds. 100% CAV+ also has a large spread over random seeds and has a much lower capacity than 100% AV. A fixed desired speed instead of a distribution is this not beneficial for the On-Ramp.
- The Off-Ramp shows different results than straight road segments and the On-Ramp: Nearly all VC have similar capacities and relatively large spreads over random seeds. Only 100% ACC and 10% AV have slightly lower capacities than the reference scenario of manual driving and the 50% and 100% CAV and 100% CAV+ scenarios show some improvements on capacity.
- Though the Symmetric Weaving Section has not been calibrated properly, the results give interesting information. Nearly all scenarios show much lower capacities than manual driving; only the 100% CAV(+) scenarios reach similar to reference capacities. This indicates that accepting smaller headways for lane changes at weaving sections or finding other ways to make sure weaving movements can be executed is very important, especially for programming algorithms for automated vehicles.
- In general, the vehicle compositions with partial market penetration (10/90% or 50/50%), show capacities that lie between the two corresponding 100% scenarios. However, this is not linear and strongly differs between vehicle compositions and road segments. In some cases, small market penetration rates already result in a large portion of the capacity increase, while in other cases most of the capacity increase is achieved at (very) high penetration rates.

Research Question 3 can be answered with the findings of this chapter.

Question 3: What is the modeled capacity of these road segments with several levels and penetration rates of autonomous and cooperative vehicles, and how do they compare to the reference?

Table 19: Capacities [vehicles per hour] - Reference and VC3 - VC7

Road Segment	Reference (veh/h)	VC3	VC4	VC5	VC6	VC7
Straight 2 lanes	4,218	3,924	3,960	4,200	4,740	3,966
Straight 3 lanes	5,676	5,334	5,310	5,712	6,618	5,304
Straight 4 lanes	7,488	7,038	7,164	7,656	8,766	7,152
Straight 5 lanes	9,648	8,916	9,072	9,720	11,064	9,036
Straight 6 lanes	11,940	10,962	11,016	11,844	13,788	10,860
On-Ramp 3+1-to-3	5,682	5,274	5,496	5,784	6,348	5,382
Off-Ramp 3-to-3+1	6,306	6,054	6,198	6,258	6,246	6,090
Symm. Weaving 3+1	5,634	4,776	4,746	4,866	4,962	4,794

As can be seen in Table 19 and Table 20, the capacities are, in general, around the CIA capacity. The ratios range from:

- Straight 2 lanes: 3,924 for 100% ACC (VC3) to 4,740 for 100% CACC (VC6), 100% CAV and CAV+ (VC12 and VC13)
- Straight 3 lanes: 5,304 for 10% AV (VC7) to 6,984 for 100% CAV+ (VC13)
- Straight 4 lanes: 7,038 for 100% ACC (VC3) to 9,480 for 100% CAV+ (VC13)
- Straight 5 lanes: 8,916 for 100% ACC (VC3) to 11,868 for 100% CAV+ (VC13)
- Straight 6 lanes: 10,860 for 10% AV (VC7) to 14,118 for 100% CAV (VC12)
- On-Ramp: 5,274 for 100% ACC (VC3) to 6,564 for 100% CAV (VC12)
- Off-Ramp: 6,054 for 100% ACC (VC3) to 6,768 for 100% CAV+ (VC13)
- Symmetric Weaving: 4,746 for 10% CACC (VC4) to 5,628 for 100% CAV (VC12)

Table 20: Capacities [vehicles per hour] - Reference and VC8 - VC13

Road Segment	Reference (veh/h)	VC8	VC9	VC10	VC11	VC12	VC13
Straight 2 lanes	4,218	4,200	4,578	4,680	4,728	4,740	4,740
Straight 3 lanes	5,676	5,628	6,186	6,198	6,876	6,960	6,984
Straight 4 lanes	7,488	7,434	8,040	8,268	8,946	9,414	9,480
Straight 5 lanes	9,648	9,588	10,410	10,662	11,352	11,808	11,868
Straight 6 lanes	11,940	11,574	12,918	13,152	13,782	14,118	14,100
On-Ramp 3+1-to-3	5,682	5,586	5,544	5,802	6,408	6,564	6,114
Off-Ramp 3-to-3+1	6,306	6,270	6,276	6,264	6,444	6,504	6,768
Symm. Weaving 3+1	5,634	4,866	4,794	4,848	5,262	5,628	5,406

This also answer the second part of the question:

- What is the ratio between vehicle automation capacity values and reference capacity values?

Since the capacities of all VC and all road segments are known in addition to the reference capacity values of CIA and the modeled reference scenarios (VC 1 and 2), the Modeled/CIA-ratios can be determined by dividing the capacities of Table 19 and Table 20 by the corresponding CIA capacities. This results in the ratios shown in Table 21 and Table 22. The ratios range from:

- Straight 2 lanes: 0.930 for 100% ACC (VC3) to 1.124 for 100% CACC (VC6), 100% CAV and CAV+ (VC12 and VC13)
- Straight 3 lanes: 0.934 for 10% AV (VC7) to 1.230 for 100% CAV+ (VC13)
- Straight 4 lanes: 0.940 for 100% ACC (VC3) to 1.266 for 100% CAV+ (VC13)
- Straight 5 lanes: 0.924 for 100% ACC (VC3) to 1.230 for 100% CAV+ (VC13)
- Straight 6 lanes: 0.910 for 10% AV (VC7) to 1.182 for 100% CAV (VC12)
- On-Ramp: 0.928 for 100% ACC (VC3) to 1.155 for 100% CAV (VC12)
- Off-Ramp: 0.960 for 100% ACC (VC3) to 1.073 for 100% CAV+ (VC13)
- Symmetric Weaving: 0.842 for 10% CACC (VC4) to 0.999 for 100% CAV (VC12)

Table 21: Capacities (Modeled/Reference ratios) - Reference and VC3 - VC7

Road Segment	Reference	VC3	VC4	VC5	VC6	VC7
Straight 2 lanes	1	0.930	0.939	0.996	1.124	0.940
Straight 3 lanes	1	0.940	0.936	1.006	1.166	0.934
Straight 4 lanes	1	0.940	0.957	1.022	1.171	0.955
Straight 5 lanes	1	0.924	0.940	1.007	1.147	0.937
Straight 6 lanes	1	0.918	0.923	0.992	1.155	0.910
On-Ramp-3+1-to-3	1	0.928	0.967	1.018	1.117	0.947
Off-Ramp 3-to-3+1	1	0.960	0.983	0.992	0.990	0.966
Symm. Weaving Section 3+1	1	0.848	0.842	0.864	0.881	0.851

Table 22Capacities (Modeled/ Reference ratios) - Reference and VC8 – VC13

Road Segment	Reference	VC8	VC9	VC10	VC11	VC12	VC13
Straight 2 lanes	1	0.996	1.085	1.110	1.121	1.124	1.124
Straight 3 lanes	1	0.992	1.090	1.092	1.211	1.226	1.230
Straight 4 lanes	1	0.993	1.074	1.104	1.195	1.257	1.266
Straight 5 lanes	1	0.994	1.079	1.105	1.177	1.224	1.230
Straight 6 lanes	1	0.969	1.082	1.102	1.154	1.182	1.181
On-Ramp-3+1-to-3	1	0.983	0.976	1.021	1.128	1.155	1.076
Off-Ramp 3-to-3+1	1	0.994	0.995	0.993	1.022	1.031	1.073
Symm. Weaving Section 3+1	1	0.864	0.851	0.860	0.934	0.999	0.960

In many cases 100% ACC shows the lowest capacities and 100% CAV (VC12) and CAV+ (VC13) show the highest capacities.

Table 23: Minimum and Maximum ratio to Reference capacities per Vehicle Composition

VC	Ref. (VC1 / VC2)	VC3	VC4	VC5	VC6	VC7	VC8	VC9	VC10	VC11	VC12	VC13
Min.	1	0.848	0.842	0.864	0.881	0.851	0.864	0.851	0.860	0.934	0.999	0.960
Max.	1	0.960	0.983	1.022	1.171	0.966	0.996	1.090	1.110	1.211	1.257	1.266

5 ADDITIONAL ANALYSIS

5.1 INTRODUCTION

The results of the symmetric weaving section presented in last chapter show that the model has not properly been calibrated for this road segment type (section 4.5), a more detailed analysis is necessary to address underlying issues and give insight to traffic conditions. This has been done for all road segment types, but the merging and diverging road segments, especially the symmetric weaving section, are most important.
The main problem seems to be gap finding for mandatory lane changes causing vehicles in the model to stop at the end of a merging, diverging or weaving section. Vehicles can decelerate within a range (SOURCE) depending of VISSIM parameter values. However, this is only the case given the current speed and gap. Vehicles do not decelerate upfront to have more time to find a gap, nor accelerate above desired speed to find a gap further downstream. One could say, the vehicles only passively check whether there is a sufficient gap instead of anticipating on current traffic to actively find a gap. Setting the Safety Distance Reduction Factor to 0.4 instead of 0.6 and thus accepting a smaller gap, resolves most cases for the On-Ramp and Off-Ramp in the model but still many conflicts remain for the symmetric weaving section. Other studies show similar difficulties in calibrating weaving sections (Baat, 2015; Bosdikou, 2017; Oud, 2016). Adjusting the SDRF does improve the model but either the model still shows congestion far below capacity or unrealistically small headways during lane change are used in the model.

Therefore, this chapter addresses a deeper analysis of mandatory lane changes and traffic conditions, since calibration is not properly possible.

Several possible directions for analysis concerning speed, distribution of vehicles over lanes, lane changes and headways have been considered:

- (Mean) Speed (distribution of the total or per time interval relative to intensity)
- Share of vehicles per lane split by congestion lane (total, over time, over time relative to congestion moment or to intensity)
- Lane changes over distance (over distance absolute, over distance in pre-congestion interval, over time absolute, over time relative to congestion or relative to intensity)
- Headway distribution (over time, over time relative to congestion or relative to intensity)

Since the lane change output does not include lane change location (longitudinal position on the link), but only the link, it is not possible to extract lane changes over distance or lane changes over distance relative to congestion, with the available data. These therefore cannot be analyzed.

From all other possible options, the mean speed per time interval (5 minutes) relative to intensity and the share of vehicles per lane per time interval (5 minutes) relative to intensity are chosen to do this analysis for several reasons. First, the reference data of the validation is very suitable for these analyses and this has also been done in the validation for 3 straight lanes. This means that the analysis of several levels of vehicle automation, with and without communication, is very similar and thus also very suitable to compare to the modeled reference and thereby to actual traffic conditions in practice.
To add more depth to the analysis, absolute lane intensities are added to the lane share analysis and the standard deviations within each time interval are added in addition to the mean speeds of each interval which show deviations between different intervals. Finally, for some road segments a brief lane change

analysis is executed as well. However, priority has been given to the earlier mentioned options and a more detailed lane change analysis is recommended for future studies.

As described in the Research Strategy (§3.3.2.4), the focus lies on the scenarios with 100% market penetration ACC (VC3), CACC (VC6), AV (VC9) and CAV (VC12). These are compared to the reference scenario: VC1 for straight road segments and VC2 for the merging and diverging segments. Furthermore, there is elaborated upon other interesting findings separately (i.e. difference between CAV and CAV+, VC12 and VC13 respectively). To refresh the composition of each VC the quick overview of all vehicle compositions is repeated (Table 18). These vehicles compositions are studied for the Straight Road Segments, On-Ramp, Off-Ramp and Symmetric Weaving Section in the next section of this chapter.

Table 24: Vehicle Composition Overview

Scenario	Vehicle Composition	Manual Driving [%]	ACC [%]	CACC [%]	AV [%]	CAV [%]	CAV+ [%][25]	HGV (Manual) [%]
Default (0)[26]	VC 1	85	-	-	-	-	-	15
Default Alternative (0b) [27]	VC 2	85[28]	-	-	-	-	-	15
ACC (1)	VC 3	-	85	-	-	-	-	15
CACC (2a)	VC 4	-	76.5	8.5	-	-	-	15
CACC (2b)	VC 5	-	42.5	42.5	-	-	-	15
CACC (2c)	VC 6	-	-	85	-	-	-	15
AV (3a)	VC 7	-	76.5	-	8.5	-	-	15
AV (3b)	VC 8	-	42.5	-	42.5	-	-	15
AV (3c)	VC 9	-	-	-	85	-	-	15
CAV (4a	VC 10	-	-	-	76.5	8.5	-	15
CAV (4b)	VC 11	-	-	-	42.5	42.5	-	15
CAV (4c)	VC 12	-	-	-	-	85	-	15
CAV+ (5)	VC 13	-	-	-	-	-	85	15

5.2 Straight road segments

The first studied road segments are the straight road segments. Since most of the straight road segments show similar results, 2 and 3 lanes are most common and a road segment with 3 lanes has been used for validation, this section mainly looks into a straight road segment with 3 lanes.

[25] Similar to CAV, except Desired Speed (Fixed at speed limit instead of a distribution (see Validation)
[26] Used as reference for straight road segments (2 – 6 lanes)
[27] Used as reference for merging and diverging segments (On-Ramp, Off-Ramp and Weaving Section)
[28] Safety Distance Reduction Factor of 0.4 instead of default 0.6

5.2.1 Lane Share and Mean Speed

Vehicle Composition 6 and 12 show similar lane shares for each lane as the reference (VC1) as can be seen in the left column of Figure 20, while VC3 clearly shows more vehicles on the left lane at lower intensities (green).

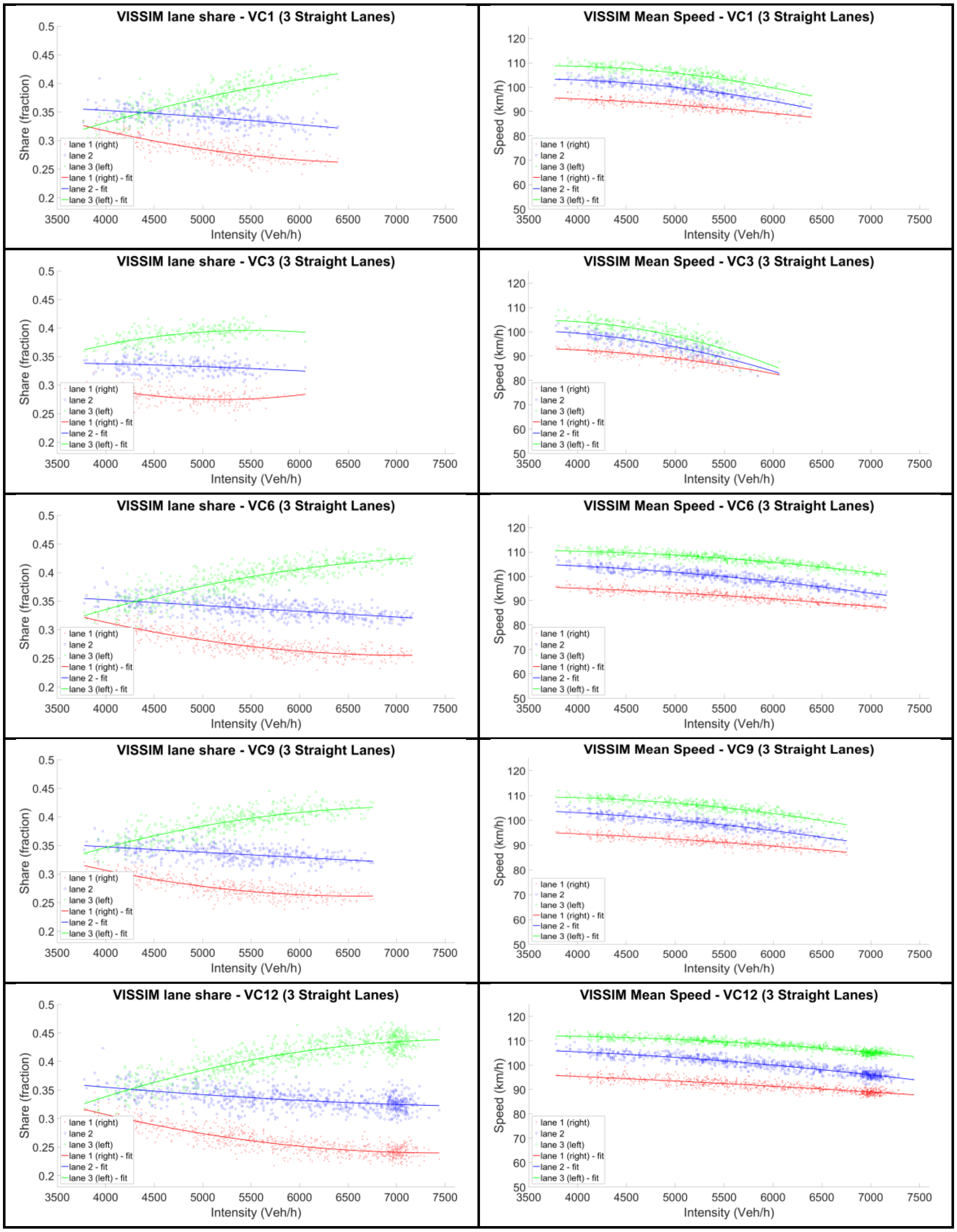

Figure 20: Lane shares and mean speed of 100% scenarios for 3 straight lanes (Each data point represents 5 minutes) – Congestion filtered

This can partially explain the lower capacities seen in the previous chapter, but it does not explain why VC with cooperative vehicles show higher capacities. However, there are differences visible in mean speed on the left lane (green, right column). VC6 and VC12 clearly show higher left lane speeds than VC1, while VC3 has lower speeds on all lanes and declines faster for higher intensities. Since in above figure the congestion datapoints are filtered, it does not show exactly what happens at congestion. Therefore, the unfiltered fata is studied as well.

5.2.2 Unfiltered Lane Share and Mean Speed

In addition to previous findings, more interesting things are visible at the unfiltered lane share figures (Figure 21). As expected and as seen in the validation, for most VC the lane shares head towards ⅓ for each lane. However, in case of the 100% scenarios with cooperative vehicles (VC6, VC12 and VC13) and to lesser extend for CAV with less market penetration (VC10 and VC11), lane shares do not head towards ⅓ per lane. This can be an indication road capacity is still not fully utilized. Therefore, more traffic conditions need to be studied, to start the unfiltered Mean Speed.

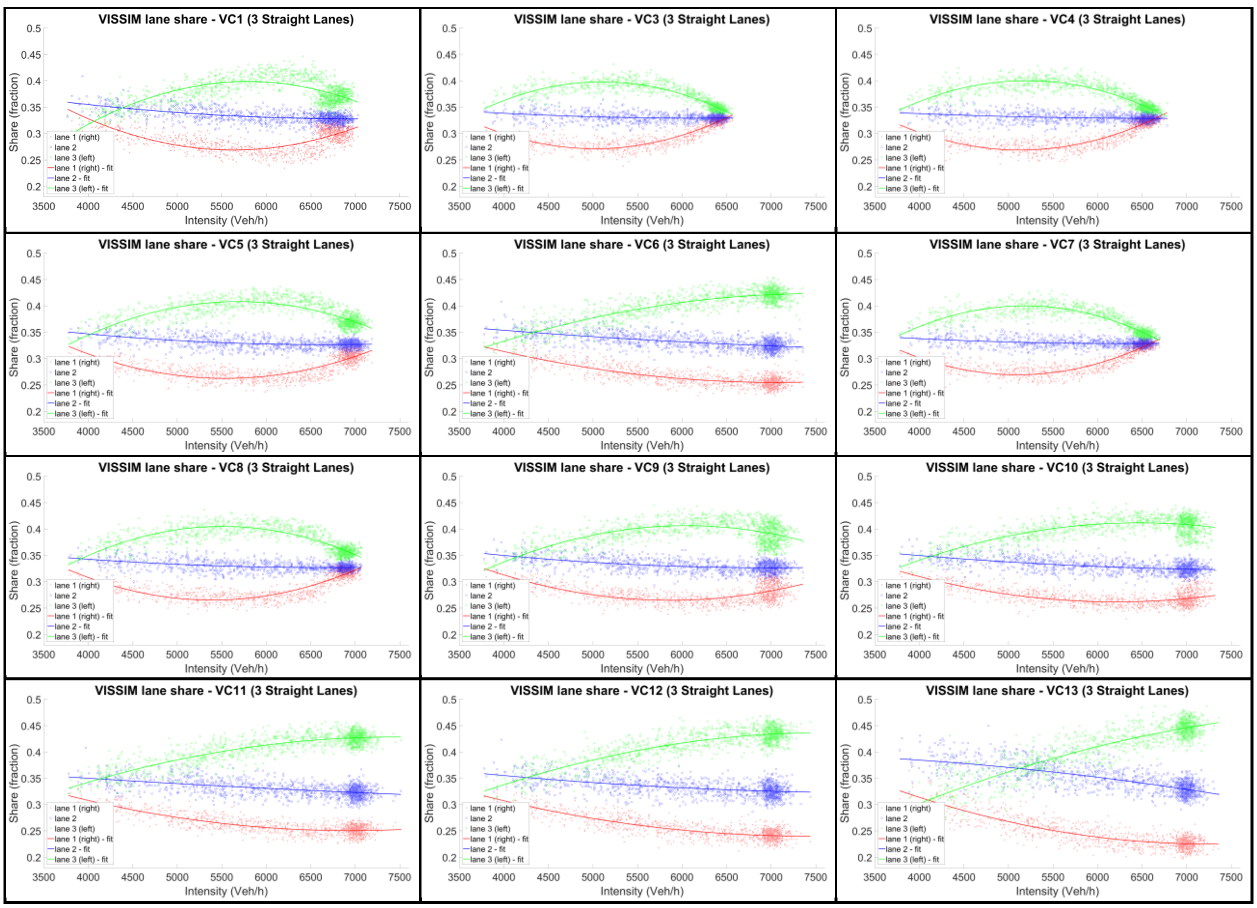

Figure 21: Lane shares of all VC for 3 straight lanes - Unfiltered (Each data point represents 5 minutes)

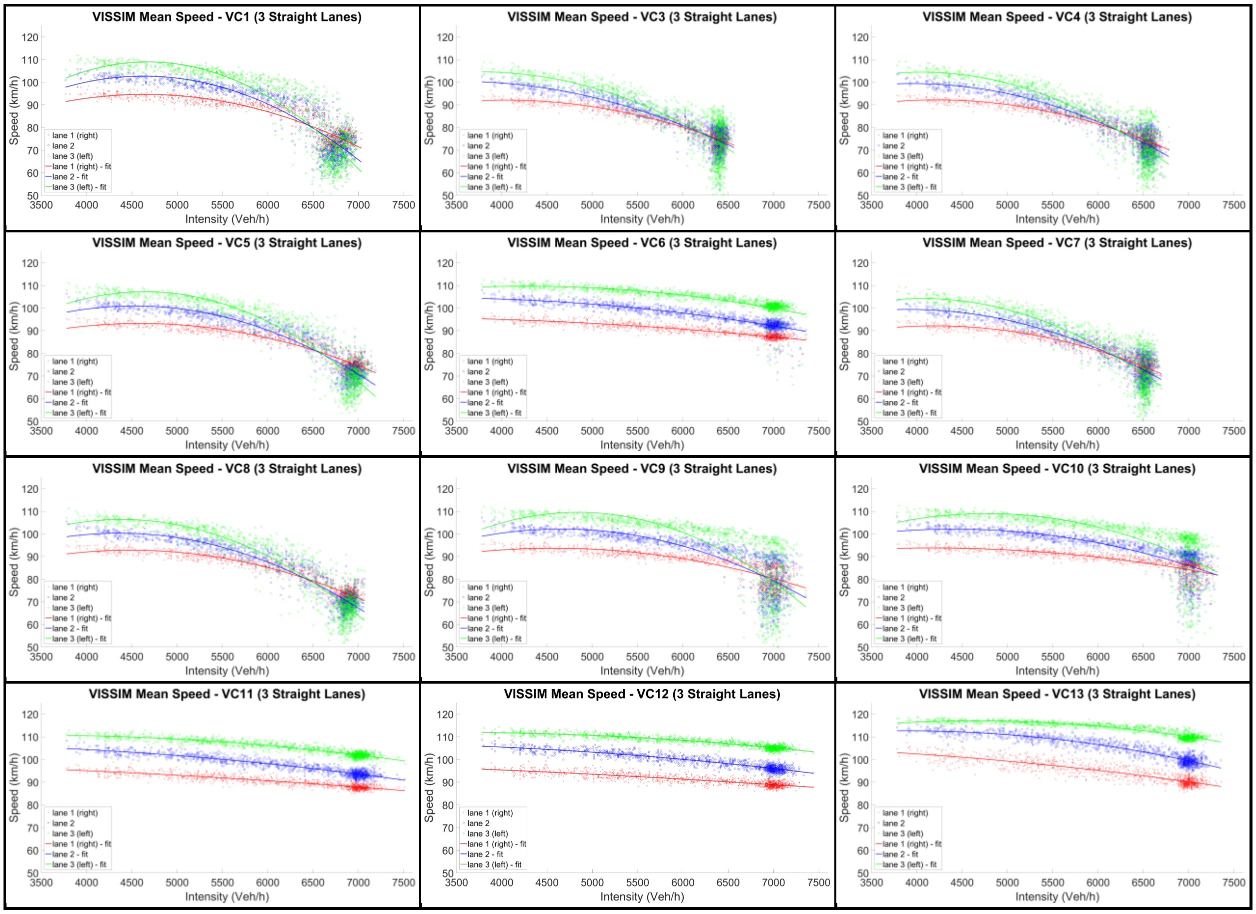

Figure 22: Mean Speeds of all VC for 3 straight lanes - Unfiltered (Each data point represents 5 minutes)

Similar results are visible for the unfiltered Mean Speeds (Figure 22). Again, in case of the 100% scenarios with cooperative vehicles (VC6, VC12 and VC13) and to lesser extend for CAV with less market penetration (VC10 and VC11), mean speeds do not become about equal.

The unfiltered Mean Speed data in Figure 22 barely shows data points in the congested regime as in the fundamental diagram. This is explained by the lack of a physical bottleneck since it concerns a straight road segment and the sharp definition of congestion (1 vehicle below 50km/h on a detector). Traffic is therefore able to recover and keep flowing in most cases. Traffic probably becomes more homogeneous and the road segment can handle more traffic. However, this will be different for road segments with a physical bottleneck (in this study On-Ramp, Off-Ramp and especially Symmetric Weaving Section).

The Mean Speeds also remain high even at high intensities. To investigate this in more detail, Figure 23 on the next page, zooms in at VC1 and VC12 as an example. In this figure, it is visible that the speed deviations between 5-minutes intervals, especially at the left lane (green), are much smaller for VC12 than for VC1. This can be an indication that speed differences are much smaller for cooperative vehicles. In order to verify this, the next step is to look into speed differences within 5-minute intervals. This is done by taking the standard deviation of the speed per lane within each interval.

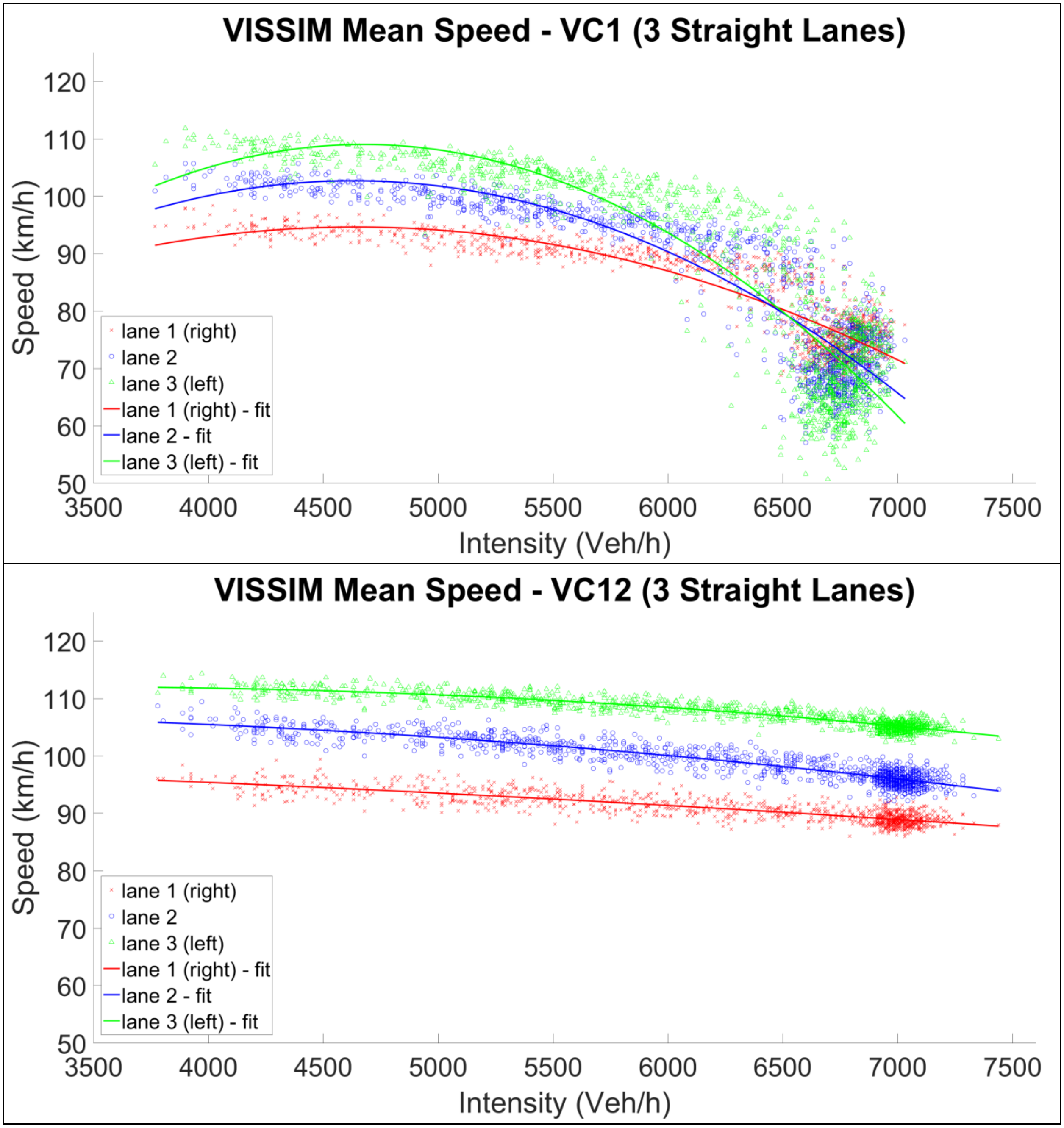

Figure 23: Mean Speeds of VC1 and VC12 (large) - Unfiltered (Each data point represents 5 minutes)

5.2.3 SD Speed

Since the deviation in Mean Speeds of 100% cooperative vehicles (VC6, VC12 and VC13) is much smaller than in the reference (VC1), the Standard Deviations of the 100% scenarios (VC1, VC3, VC6, VC9, VC12 and VC13) are presented in Figure 24. This way the fully cooperative scenarios can be compared to the reference as well as the 100% non-cooperative automated vehicles (VC3 and VC9). Though the right lane (red) and middle lane (blue), show very similar values for the standard deviation within each interval for VC1, 3, 6, 9 and 12, it does not for the left lane. The reference of manual driving (VC1), as well as 100%

ACC (VC3) has large speed deviations at the left lane (SD >10 km/h), while 100% CACC (VC6) and especially 100% CAV (VC12), have smaller deviations at the left lane than the other two (SD < 10 km/h). VC9, with 100% AV, has speed deviations more in between (SD around 10 km/h).

This means that the higher capacities of VC6 and VC12 of the last chapter, as well as the higher left lane speeds and later use of the left lane, can be explained by the smaller left lane speed deviations and the therefore more stable traffic flow.

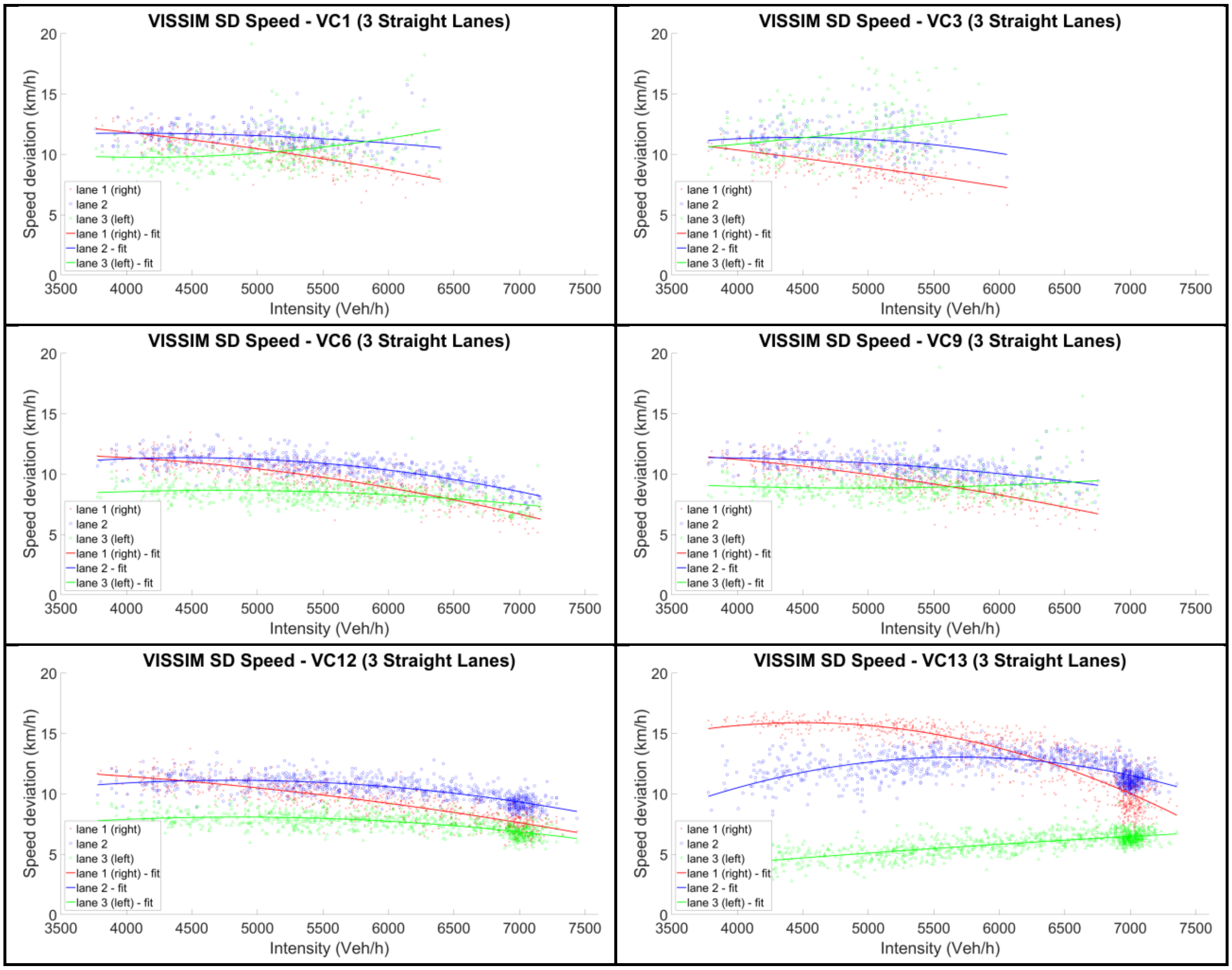

Figure 24: SD Speeds of all 100% scenarios (VC1, 3, 6, 9, 12 and 13) for 3 straight lanes - Unfiltered (Each data point represents 5 minutes)

5.3 ON-RAMP

The straight road segments have been studied. Next, this section looks into the On-Ramp to see whether vehicle automation has a similar effect on the On-Ramp as on straight road segments or that there are major differences. Traffic conditions of the 100% scenarios are studied in order to explain the differences in capacity: a decrease of capacity for -7.2% (100% ACC) to an increase of +15.5% (100% CAV) as described in section 4.3.

5.3.1 Lane Share and Mean Speed

In order to determine effects, the first step is to compare lane shares and speeds of the 100% scenarios to the reference. The 100% cooperative scenarios, CACC (VC6) and CAV (VC12), which have a large increase in capacity (11.7% and 15.5% respectively), show different lane shares for each lane than the reference (VC2) as can be seen in the left column of Figure 25 on the next page: There is much more traffic on lane 4, the most left lane (black), than in the reference situation, while lane 2, the right lane of the main lanes (blue), clearly has a smaller share than in the reference scenario. However, this is also the case for the scenarios that show a decrease in capacity 100% ACC (VC3) and 100% AV (VC9) and the non-100% scenarios (Figure 63 in Appendix L). The corresponding VC show very similar lane distributions except for the reference VC2 as mentioned above and VC13. The effects of the CAV+ with fixed desired speed in VC13 instead of a distribution as for CAV in VC12 are discussed separately in section 5.6, but lane shares alone do not explain the difference in capacity between scenarios.

It is thus necessary to dig deeper to explain the differences in capacity. The cooperative scenarios do show higher speeds than the reference and ACC scenario, but are still barely different than the 100% AV scenario (VC9). The speeds might say something about capacity, but still do not explain everything.

In order to find what does affect capacity at an On-Ramp, the deviation in speed is studied next. Though the deviation in speed between intervals does not give a clear answer (right column in Figure 25), the deviation within intervals might explain more.

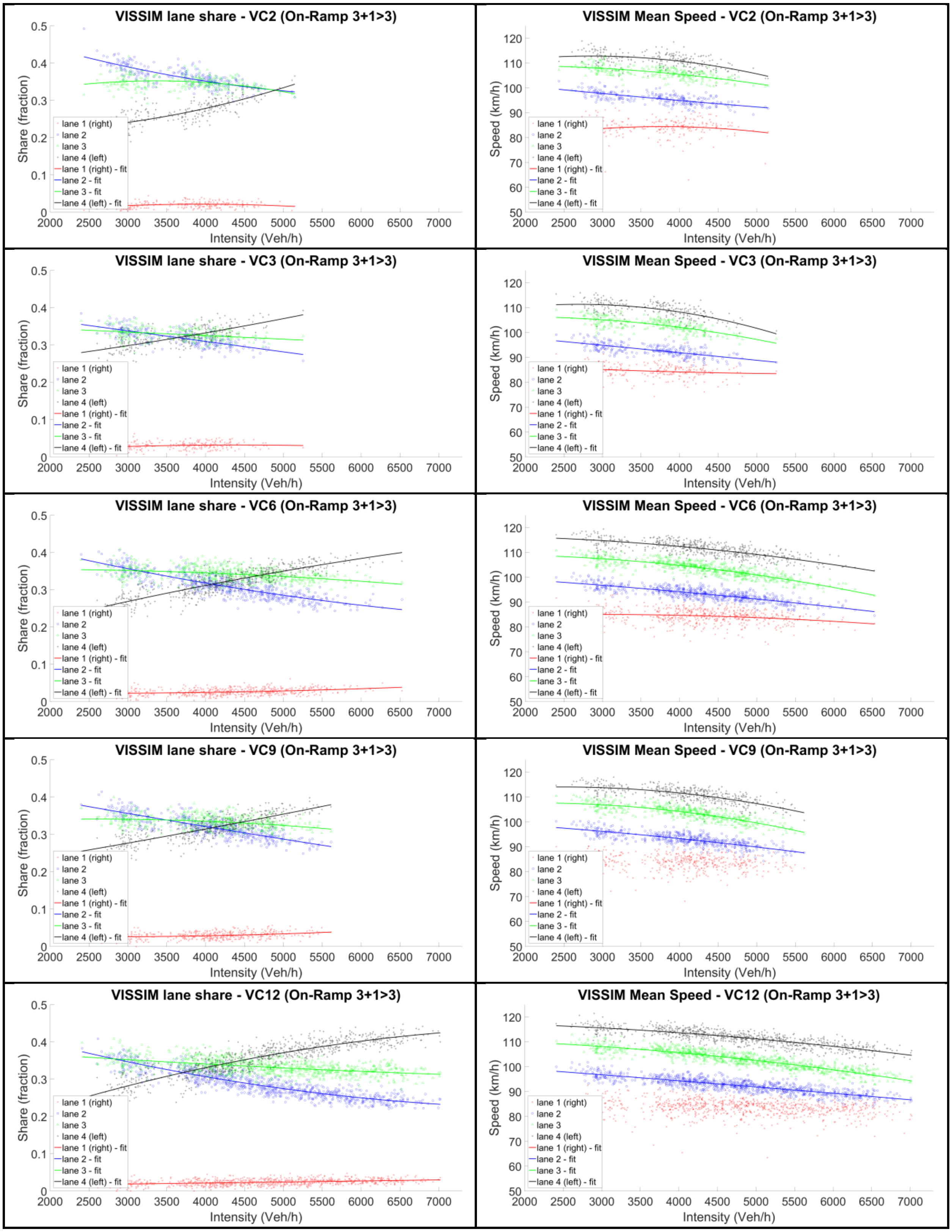

Figure 25: Lane shares and mean speed of 100% scenarios for an On-Ramp (Each data point represents 5 minutes) – Congestion filtered

5.3.2 SD Speed & Lane Changes

The standard deviation within each measurement interval is therefore shown in Figure 26. The cooperative scenarios (VC6, VC12 and VC13) do show smaller left lane standard deviation than the reference (VC2) and the ACC scenario (VC3). However, AV (VC9) still has similar values for the standard deviation at equal intensities as the cooperative scenarios, while AV has a much lower capacity.

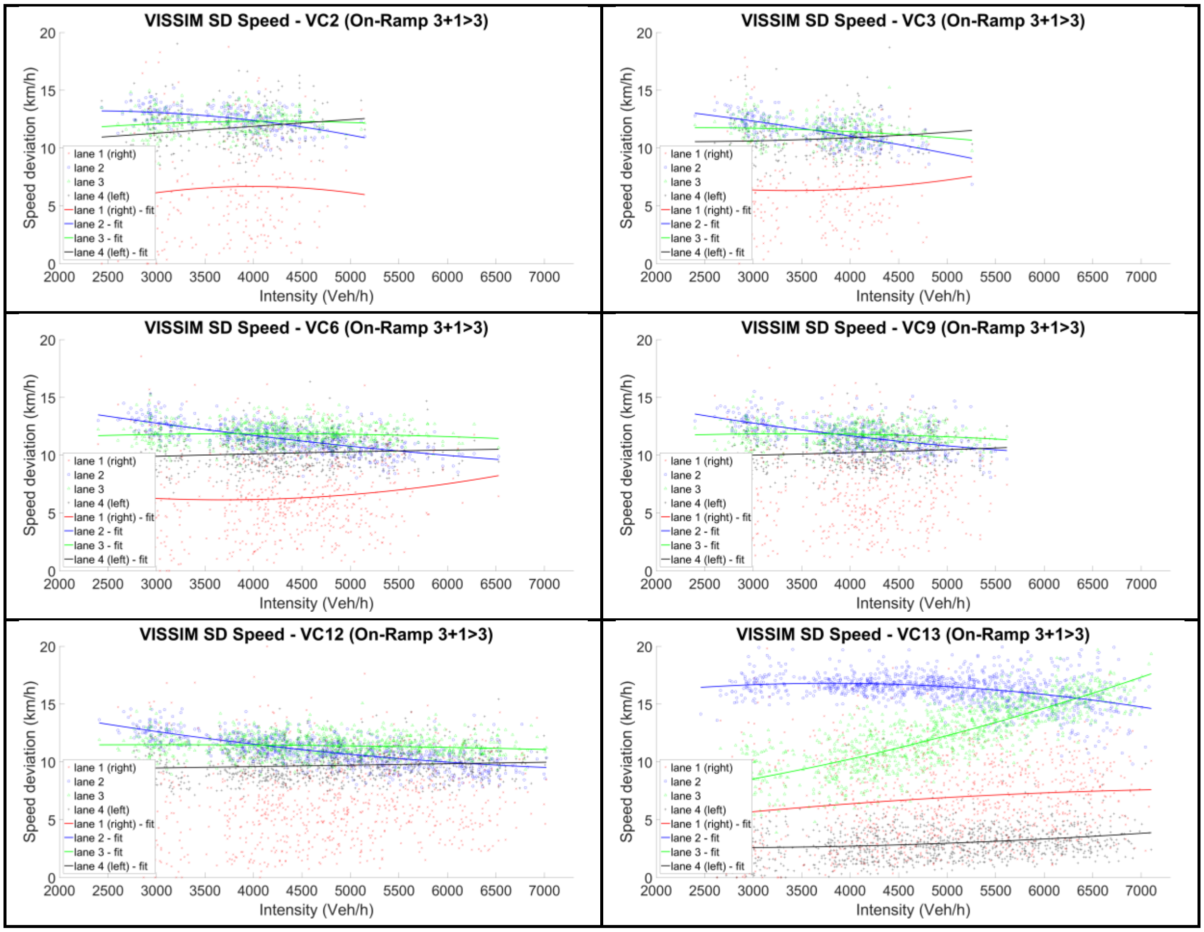

Figure 26: SD Speeds of all 100% scenarios (VC1, 3, 6, 9, 12 and 13) for an On-Ramp - Unfiltered (Each data point represents 5 minutes)

Possibly, the cooperative scenarios show more effective lane changing or more possibilities to change lanes, since VC6, 12 and 13 show the most lane changes of all scenarios (Table 53, Figure 74 and Figure 75 in Appendix O). This is especially the case for lane changes between lane 2 and 3 in both directions for cooperative VC in comparison to the other VC. This should be studied in more detail in future work.

5.4 OFF-RAMP

The effect of the 100% scenarios on the traffic conditions at an Off-Ramp is studied next. A similar analysis as previous road segments is executed.

5.4.1 Lane Share and Mean Speed

In order to determine effects, the first step again is to compare lane shares and speeds of the 100% scenarios to the reference. The 100% cooperative autonomous scenarios, CAV (VC12) and CAV+ (VC13, Appendix M), which have an increase in capacity (3.1% and 7.3% respectively), show different lane shares for each lane than the reference (VC2) as can be seen in the left column of Figure 27 on the next page: There is more traffic on lane 4, the most left lane (black), than in the reference situation, while lane 2, the right lane of the main lanes (blue), clearly has a smaller share than in the reference scenario. The 100% ACC scenario (VC3), which has a capacity drop of about 3%, shows about the opposite: smaller left lane share (black) and larger right lane (blue) share.

However, all other scenarios show results that are similar to the reference (Figure 27, Figure 67 in Appendix M). The corresponding VC show very similar lane distributions except for the reference VC2 as mentioned above and VC13. The effects of the CAV+ with fixed desired speed in VC13 instead of a distribution as for CAV in VC12 are discussed separately in section 5.6, but lane shares alone do not explain the difference in capacity between scenarios.

Again, it is necessary to dig deeper to explain the differences in capacity. The cooperative scenarios do show higher speeds than the reference and ACC scenario, but are still barely different than the 100% AV scenario (VC9). The speeds might say something about capacity, but still do not explain everything.

In order to find what does affect capacity at an Off-Ramp, analog to the On-Ramp, the deviation in speed is studied next. Though the deviation in speed between intervals does not give a clear answer (right column in Figure 27), the deviation within intervals might explain more.

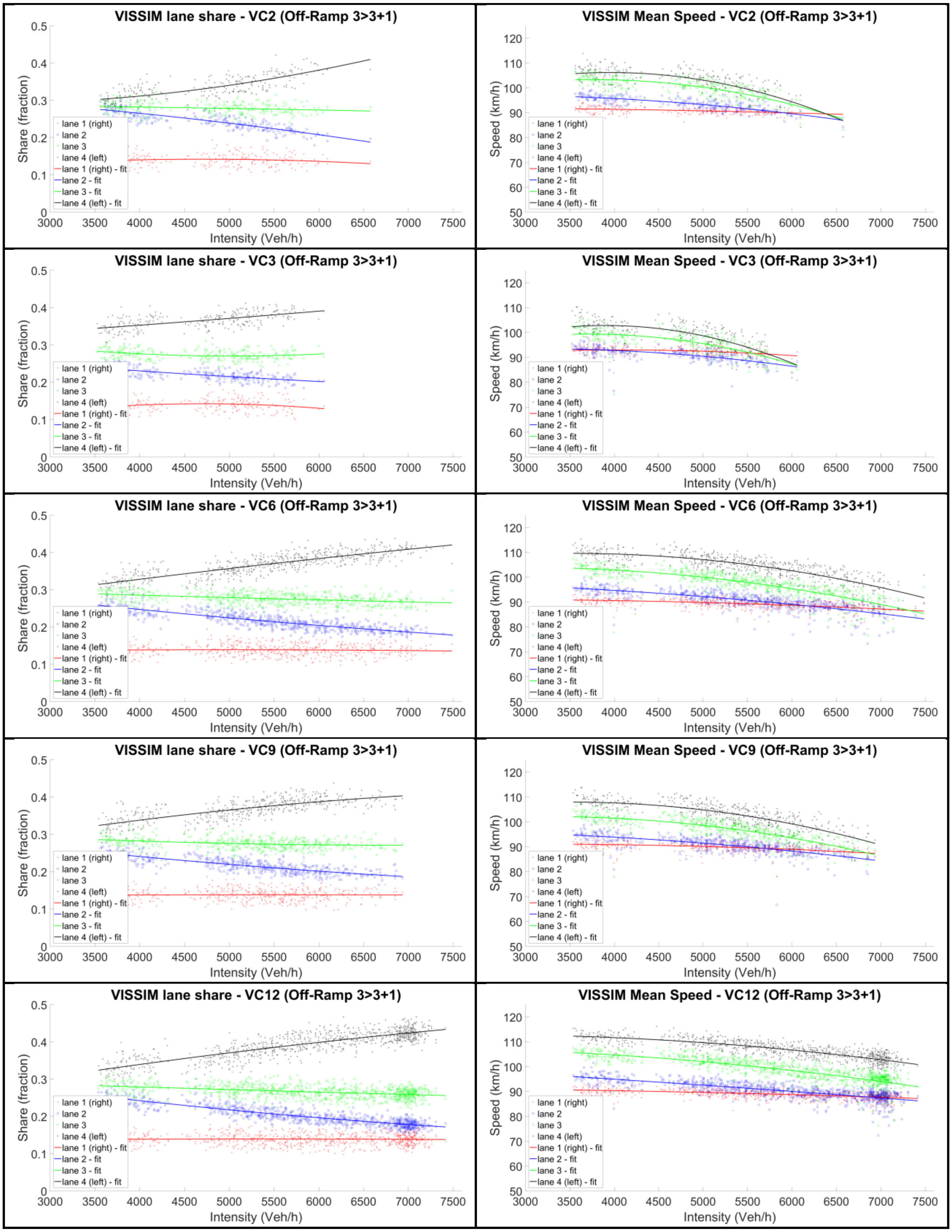

Figure 27: Lane shares and mean speed of all 100% scenarios for an Off-Ramp (3 to 3+1 lanes)

5.4.2 SD Speed & Lane Changes

By looking into the standard deviation in speeds (Figure 28), the same conclusions can be drawn as with straight road segments. Left lane speed (black) deviations mainly explain the change in capacity: Smaller left lane deviations mean higher capacity. However, the effects are smaller than for straight road segments, since the mandatory lane changes to exit the main lanes at an Off-Ramp give more importance to the middle and right lane as well.

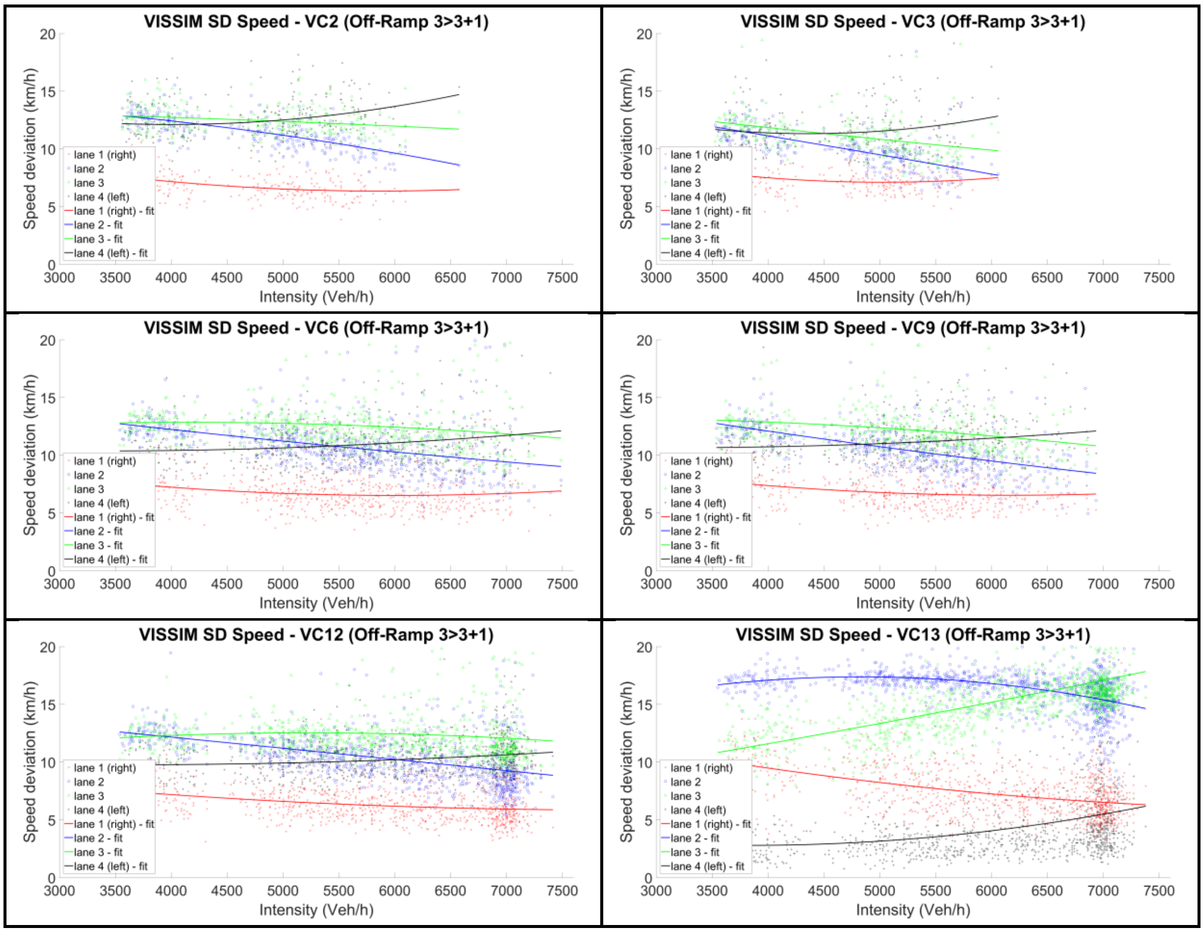

Figure 28: SD Speeds of all 100% scenarios (VC1, 3, 6, 9, 12 and 13) for an Off-Ramp - Unfiltered (Each data point represents 5 minutes)

The scenarios that show changes in capacity also have deviant number of lane changes (Table 54, Figure 74 and Figure 75 in Appendix O). However, in order to draw conclusions to these lane changes, more research is necessary. This is recommended for future studies.

5.5 Symmetric Weaving

Lastly, the traffic conditions at the Symmetric Weaving Section are studied. Since this road segment has not been calibrated properly in the reference, conclusions must be drawn with care. However, the relative effects between scenarios may still give insight in the effects of vehicle automation at a Symmetric Weaving Section.

5.5.1 Lane Share and Mean Speed

The lane shares and mean speeds show very different results in the reference than for other road segments. This can explain why other scenarios have capacities equal to or worse than the reference. This time the left lane of the reference (black, VC2) in Figure 29 on the next page, shows the largest lane share at equal intensities. Also, the speeds lie higher on the left two lanes (black and green) than for the other scenarios.

All other scenarios in comparison to each other do show similar results to the other road segments though. The 100% CAV scenario (VC12) again shows higher left lane share and higher speeds than the other scenarios. Capacity is also about 15% higher than most other scenarios. Thus, the scenarios with the highest capacity still show high left lane shares and high speeds.
Since the deviations in speed (right column of Figure 29) between intervals are not conclusive and the deviation within intervals have been explanatory for the capacity increase or decrease on other road segments, the standard deviation in speed within time intervals is studied next.

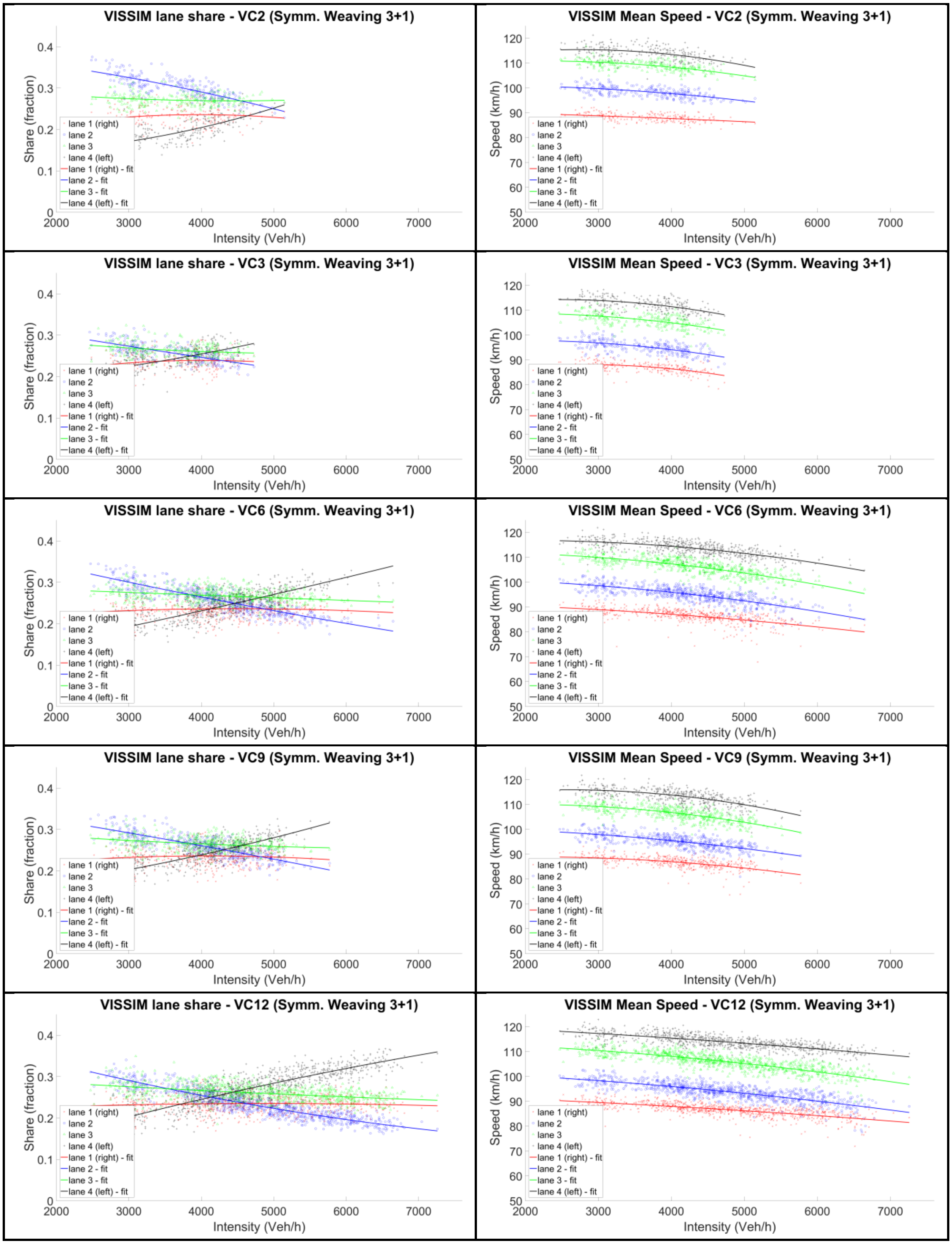

Figure 29: Lane shares and mean speed of all 100% scenarios for a Symmetric Weaving Section (3+1 lanes)

5.5.2 SD Speed & Lane Changes

The deviation within interval is in most cases quite similar (Figure 30). The 100% CAV+ scenario (VC13) again shows very different deviations, but this is discussed separately in the next section.
The 100% CAV scenario (VC12) does have a slightly lower standard deviation in speed on the left lane (black) and this (partially) explains the higher capacity for CAV in comparison to the other vehicle automation scenarios. However, the CAV scenario has a very similar capacity as the reference, but does show relatively different speed deviations. Perhaps, the lane changes can give more insight.

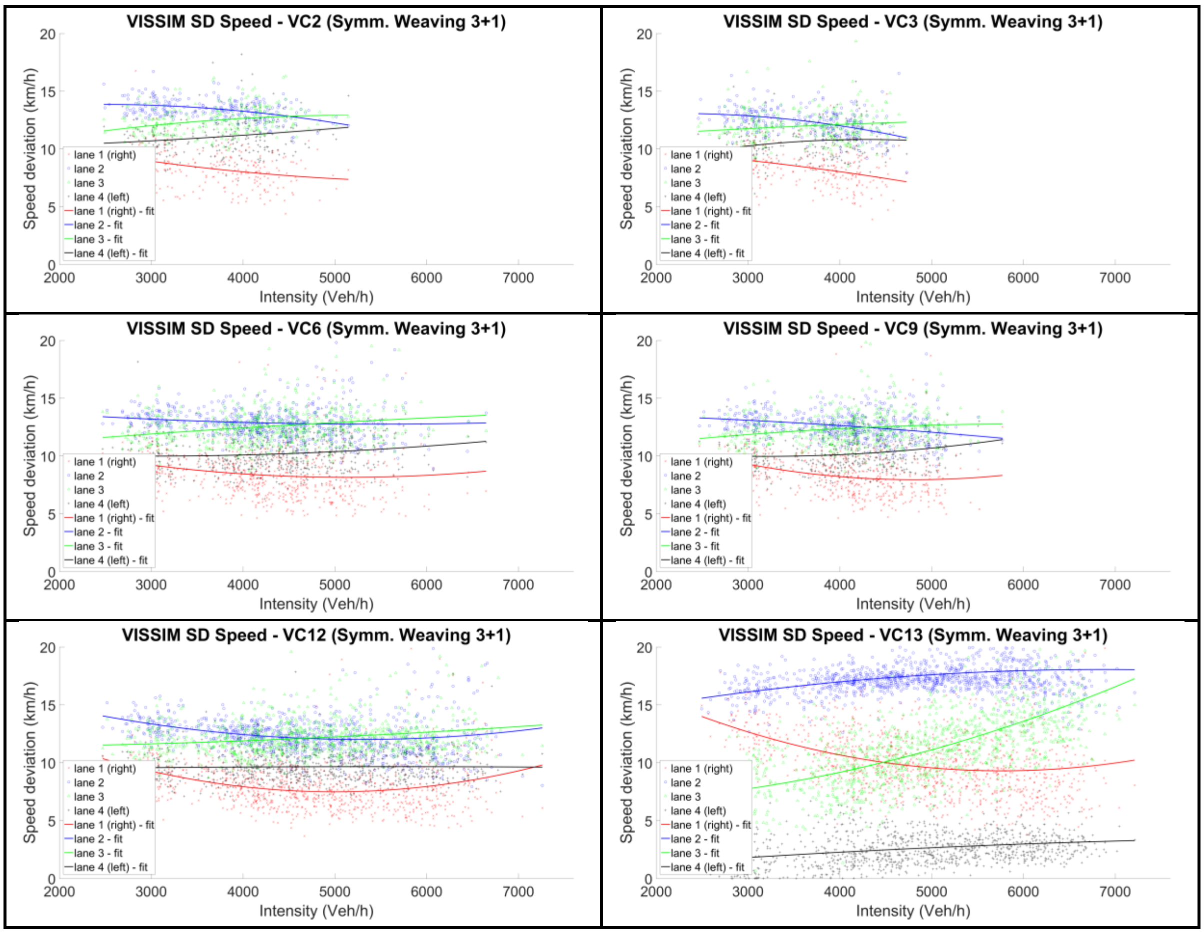

Figure 30: SD Speeds of all 100% scenarios (VC1, 3, 6, 9, 12 and 13) for a Symmetric Weaving Section - Unfiltered (Each data point represents 5 minutes)

The scenarios with relative high capacities (VC2, VC11 and VC12), do show a deviation in the number of total lane changes. However, since this has not been studied in detail, this cannot explain the differences in capacity yet. To do so, more research is necessary.

5.6 FIXED DESIRED SPEED EFFECTS

In chapter 4, capacities have shown to increase as a result of using the speed limit instead of a speed distribution for CAV as well as to decrease the capacity for certain road segments. In addition, there are also differences in the robustness of the network as well. In this section the 100% CAV+ scenario (VC13) is therefore compared to the 100% CAV scenario (VC12) per road segment type.

5.6.1 Straight Road Segments

The results in chapter 4 have shown that homogenizing the traffic flow by the desired speed is beneficial for capacity. Though capacity itself has similar values, the robustness on straight road segments is much better for CAV+. This is studied in more detail by several traffic conditions by using 3 straight lanes.

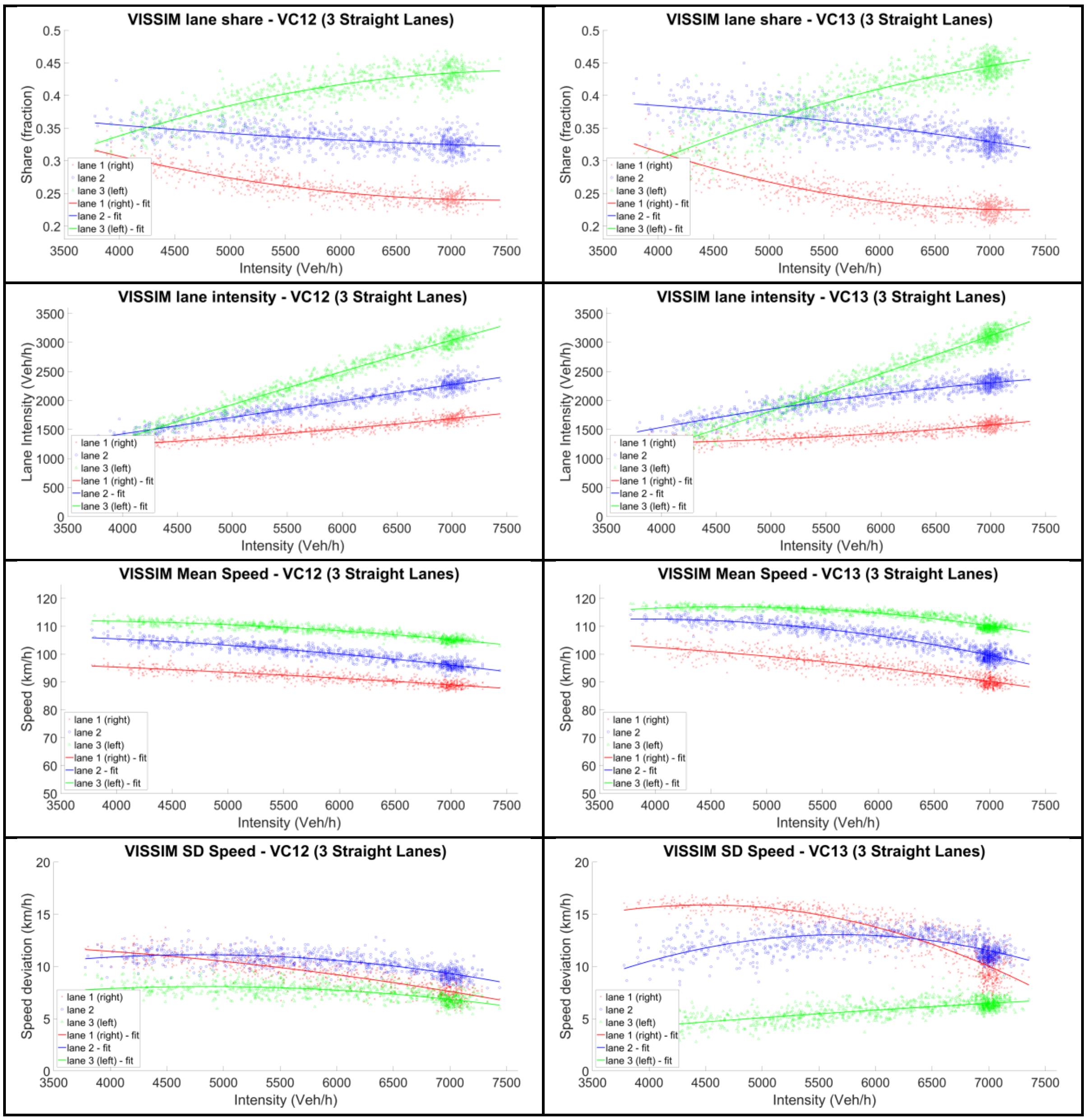

Figure 31: 3 Straight Lanes, 100% CAV - 100% CAV+ traffic conditions comparison (each data point represents 5 minutes) - Congestion filtered

As can be seen in the Figure 31, 100% CAV+ (right) shows much lower left lane shares and left lane intensities than 100% CAV (left) for total intensities up to around 6,000 vehicles per hour. Even though the lane shares and lane intensities are thus higher for CAV+ on the middle and right lane at equal total intensities, CAV+ has higher speeds on all lanes. Homogenizing traffic by the desired speed is thus very effective to increase mean speeds and making the traffic flow more stable. However, this is mainly because of the left lane. As the figure shows, deviations in speed between different intervals appear to be still larger for CAV+ on the middle and right lane. This is supported by looking into the middle and right lane speed deviations within time intervals. The standard deviations of the middle and right lane are significantly higher for CAV+ while only left lane shows smaller a standard deviation within time intervals. This matches the findings of the other scenarios for straight road segments as discussed in section 5.2.
To see whether this is also the case for straight road segments with more lane, an option is to look into the speed deviations for those road segments. For 4, 5 and 6 lanes the capacities are higher, or about equal and more robust for CAV+ than for CAV as discussed in chapter 4 and shown in Appendix E-4. As an example, fig, shows the speed deviations between and within time intervals for 6 straight lanes.

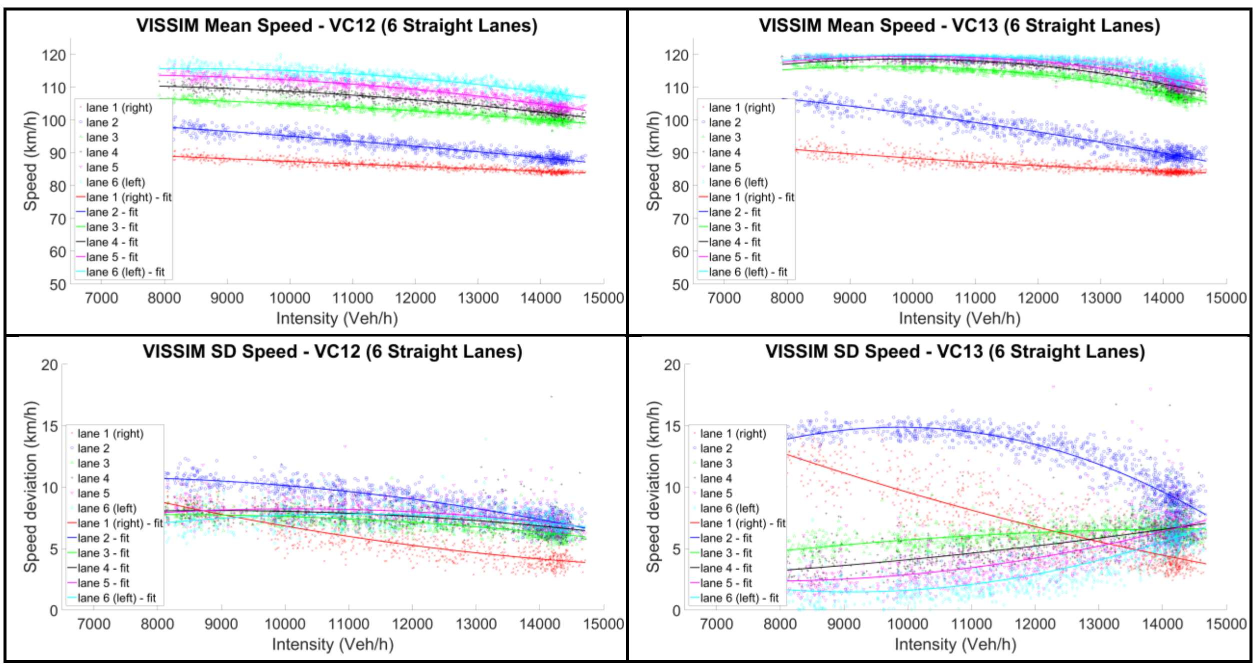

Figure 32: Comparison of speed and speed deviations, between and within intervals for 100% CAV (left) and 100% CAV+ (right) (each data point represents 5 minutes) - Congestion filtered

Again, all lanes show higher speeds for CAV+ (VC13) than for CAV (VC12), but still have higher deviations between intervals as well as within intervals on the 2 most right lanes (red and blue). In conclusion, for straight lanes, the speed deviations on all but the two most right lanes, are very important for capacity:

Smaller deviations on the left lanes of straight road segments mean higher capacity, even when deviations on the two most right lanes are (much) larger.

5.6.2 On-Ramp

In contradiction to the straight lanes, 100% CAV+ has lower capacities and is less robust as well than 100% CAV at the studied On-Ramp as discussed in section 5.3. In order to find a possible explanation, this subsection studies the traffic conditions for mentioned scenarios.

Figure 33 shows that 100% CAV (VC12) has a left lane share around 0.3 for lower intensities and this goes up to over 0.4 for near capacity intensities. However, 100% CAV+ (VC13) has a lane share around 0.15 for lower intensities and goes up to 0.4 for near capacity intensities. Though the CAV scenario has a much higher capacity than CAV+, the lane shares and intensities show similar findings as the straight road segments, while for capacity this is the opposite. Even speeds and the deviation in speeds show similar results as for straight lanes: 100% CAV+ has higher speeds on all lanes than 100% CAV (and about equal on the merging lane in red), and CAV+ has smaller left lane deviations. A possible explanation is that because of the higher speeds, vehicles cannot merge and trigger the congestion criterion.

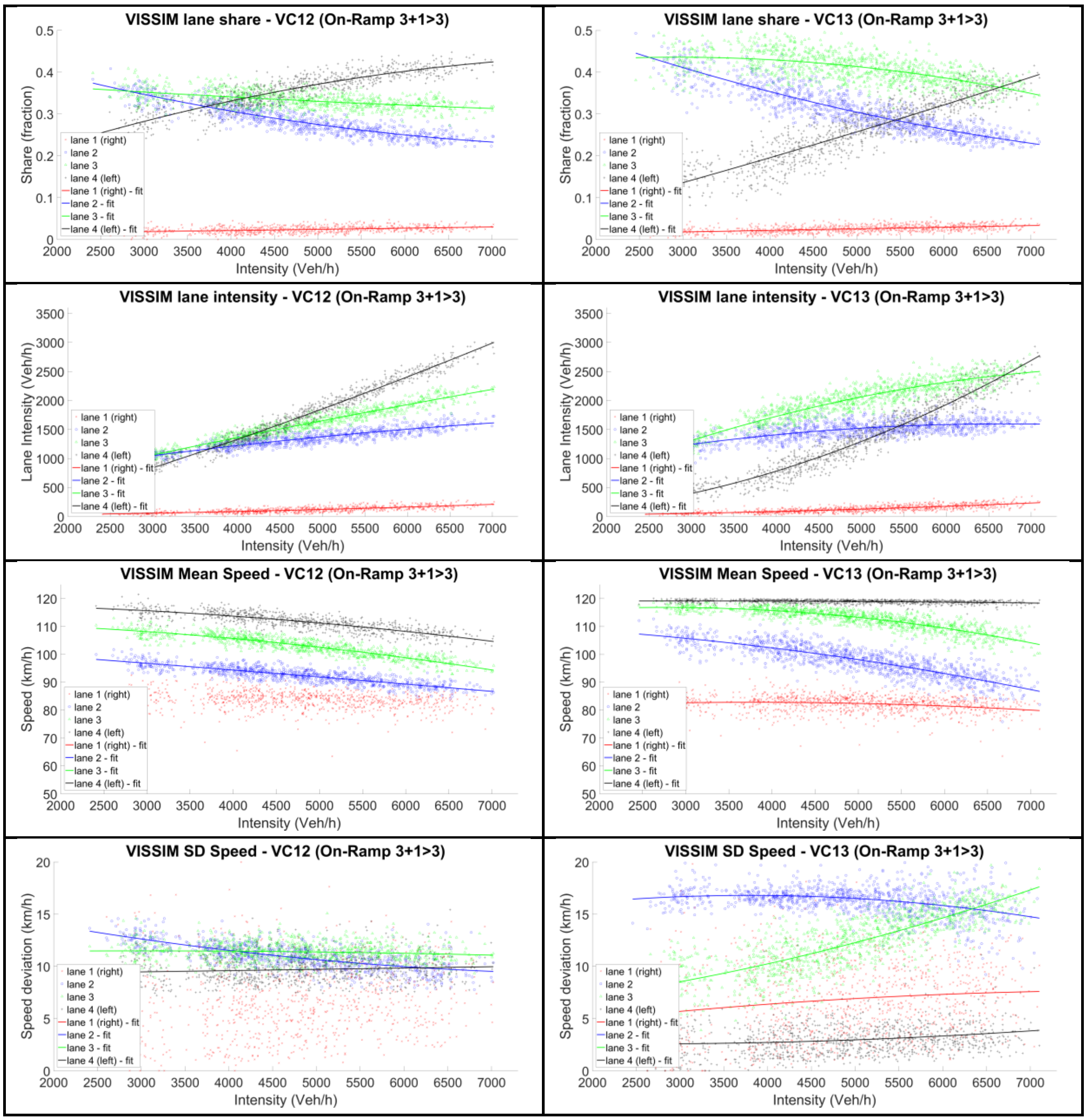

Figure 33: On-Ramp, 100% CAV - 100% CAV+ traffic conditions comparison (each data point represents 5 minutes) - Congestion filtered

5.6.3 Off-Ramp

The effect of the desired speed on an Off-Ramp is studied next. A similar analysis as previous road segments is executed. Though capacities are about 5% higher for 100% CAV+ (VC13) than for 100% CAV (VC12) at the studied Off-Ramp, the robustness is smaller. This subsection tries to find an explanation to this with the help of several traffic conditions (Figure 34).

Again, left lane shares and intensities are smaller, and speeds are higher for CAV+ than for CAV. However, deviations in speed are slightly different than those for straight road segments and the On-Ramp. The left lane (black) still shows the smallest deviations between and within intervals, but the middle main lane (green), shows larger deviations for CAV+ than for CAV. This might explain that CAV+ still has a higher capacity than CAV in general, but the robustness is actually smaller for CAV+.

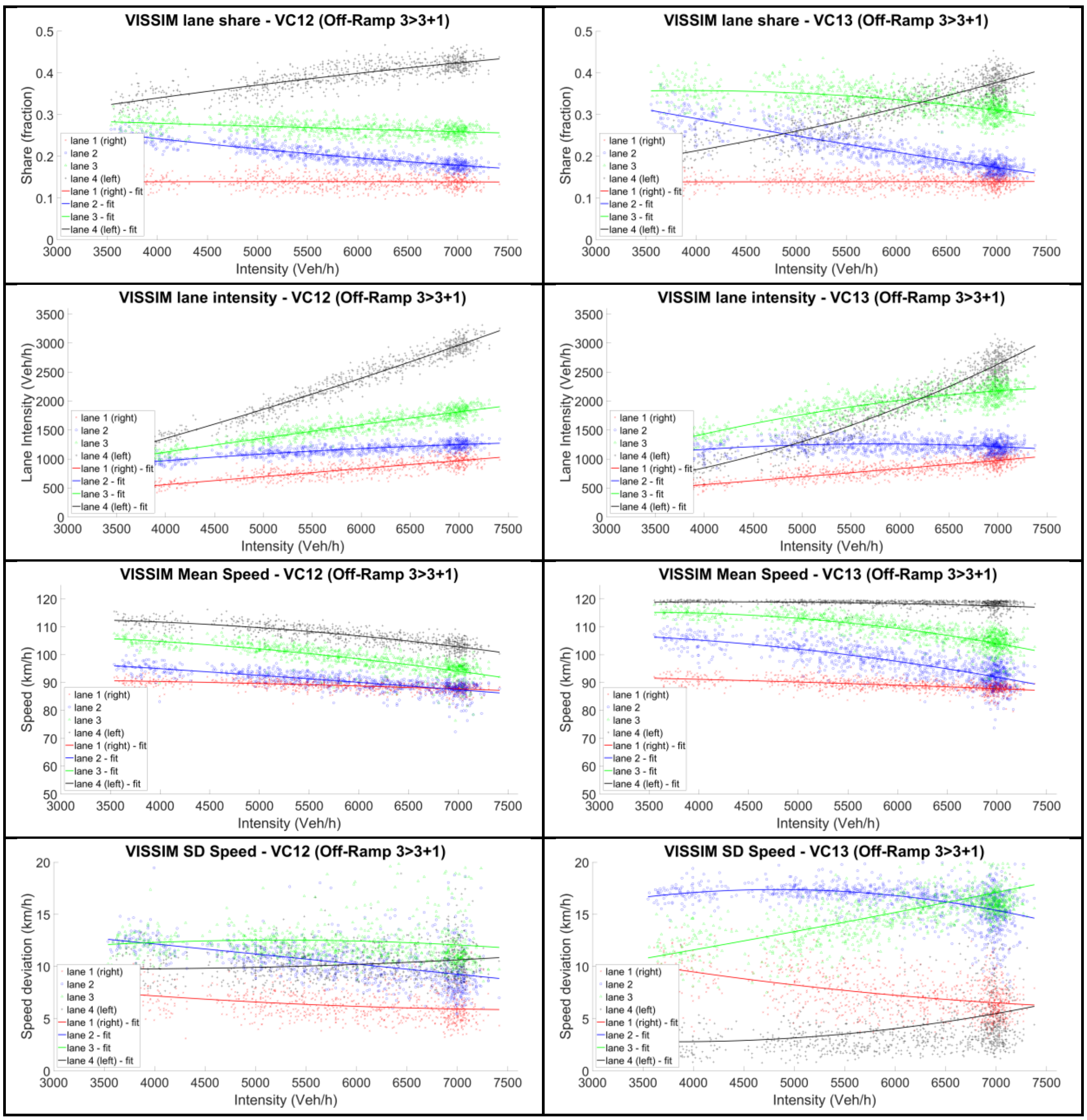

Figure 34: Off-Ramp, 100% CAV - 100% CAV+ traffic conditions comparison (each data point represents 5 minutes) - Congestion filtered

5.6.4 Symmetric Weaving Section

The effect of desired speed on traffic conditions has been studied for all other road segments. This subsection addresses the same traffic conditions for the Symmetric Weaving Section. Again, the left lane (black) shows smaller lane shares and intensities for 100% CAV+ (VC13) than 100% CAV (VC12) and CAV+ has higher average speeds on all lanes. However, capacity is almost 4% lower for CAV+ (Section 4.5), while robustness of CAV+ is better than CAV. Possibly, the merging vehicles have trouble to enter the main lanes, similar to the On-Ramp, which would explain the lower capacity. However, since the robustness is better for CAV+, CAV+ seems to be better to merge in unfavorable conditions. This means that speed and deviations in speed are close to a turning point at the Symmetrical Weaving Section. Large deviations for CAV+ on the right main lane (lane 2, blue) are apparently just critical in high intensity traffic, but are not at slightly lower intensity traffic. However, conclusions must be drawn with care, since the Symmetric Weaving Section has shown to be difficult to calibrate as stated before.

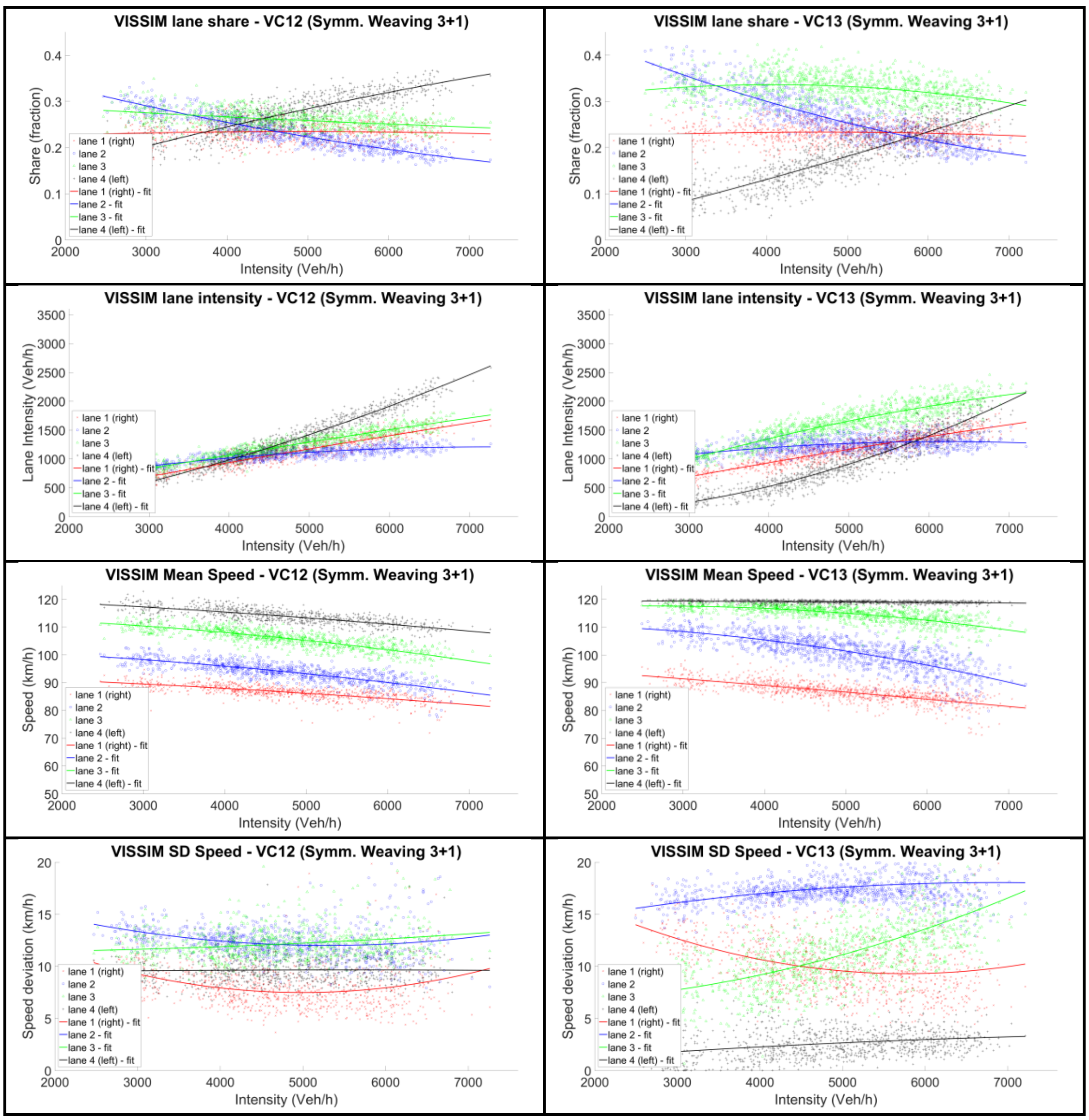

Figure 35: Symmetric Weaving Section, 100% CAV - 100% CAV+ traffic conditions comparison (each data point represents 5 minutes) - Congestion filtered

5.7 SUMMARY

To summarize this chapter, the most important findings of this part are listed below:

- Left lane speed deviations are leading for the effect on capacity of straight road segments: Smaller speed deviations on the left lane mean higher capacity. Cooperative vehicles have the lowest left lane speed deviations.
- Left lane speed deviations seem to have similar effects on the traffic conditions on the main lanes of an On-Ramp as on straight road segments. However, because traffic seems to flow better on the main lanes, vehicles from the merging seem to be blocked to enter the main lanes and are cooperative scenarios are therefore less robust than on straight road segments.
- On an Off-Ramp, the left lane speed deviations are also important. However, the exiting vehicles must use the middle and right main lane as well. The higher speed deviations cancel part of the capacity increase by the improved traffic flow on the left lane.
- The total number of lane changes indicates that lane changes are also important. However, in this study this could not be researched in sufficient detail. Therefore, a lane change analysis is recommended for future studies.
- In general, scenarios that show high capacities, show high left lane shares and higher speeds on all or most lanes. The same scenarios often have smaller speed deviations on the left lane as well, both between as within time intervals.
- By using the unfiltered data, highly cooperative scenarios seem to have unequal lane distributions and different speeds per lane around congestion. The true capacity possibly has not been reached yet. Another explanation is that cooperative vehicles have a higher speed at capacity than HGV have. For mixed traffic conditions, with both private vehicles and HGV, which is the case with 15% HGV in this study, this can lead to different capacities per lane, since HGV mainly use the right lane and to a lesser extend the second right lane.

Above point also give an answer to the last research question:
Question 4: What is the effect of vehicle automation on traffic conditions in comparison to the reference situation?

6 Conclusion, Discussion & Recommendation

This chapter summarizes the study by answering and discussing the research questions of the introduction and by giving recommendations for future use of VISSIM as well as for future studies in general related to autonomous and cooperative driving.

6.1 Conclusion & Discussion

Each of the six research questions is answered and discussed in this section.

Question 1

What is the current capacity for road segments types relevant for the Dutch highway network (i.e. according to CIA)?

In order to study the (relative) effects of vehicle automation on highway capacity, it is necessary to know the current capacity of some of the most important road segments on Dutch highways to compare any results to as well as to help calibrate a reference scenario in the model. Therefore, the current capacity of each of the eight studied road segments needs to be known. The theoretical capacities from CIA for these road segments have been found as shown in Table 25:

Table 25: CIA Capacities of studied Road Segments

Road Segment	Capacity (vehicles per hour)
Straight 2 lanes	4,300
Straight 3 lanes	6,200
Straight 4 lanes	8,200
Straight 5 lanes	10,250
Straight 6 lanes	12,000
On-Ramp 3+1-to-3	≤6,200
Off-Ramp 3-to-3+1	≤6,200
SW 3+1	6,840

Discussion

The CIA has been used as a reference and is the basis for the modeling. Everything is suitable for the Dutch case; road lay-out, a speed limit of 120 km/h and Dutch speed distributions. In addition, the CIA determines capacities under standard conditions and 15% HGV and uses a relative strict threshold to determine capacity: Capacity is the median value of measurements (in practice or modeled) of 5-minute intensities prior to detecting one vehicle below 50 km/h. These points should be considered for comparing to other studies, especially when using absolute values.

Question 2

What is the capacity for those types of road segments in the used traffic model (VISSIM) and how do they compare to the theoretical reference?

- How can parameters in the model be calibrated to fit the CIA values for the reference scenario?
- What is the ratio between CIA values and model values

The second part of question 2 is a direct result of questions 1 and the first part of question 2. The answer to both parts of the question can be found in Table 30:

Vehicle Composition 1 shows capacities close to very close to the CIA capacity. The Off-ramp has a capacity relatively close to the CIA capacity, but the On-Ramp and especially the Symmetric Weaving Section show much smaller values than the CIA values. VC1 is a good calibration of the reference for straight lanes based on capacity, but is poor for the merging and diverging road segments.

Table 26: Modeled reference capacities and ratio to CIA capacities

Segment	**CIA Capacity (veh/h)**	**VC1 (veh/h)**	**VC1 Model/CIA-ratio**	**VC2 (veh/h)**	**VC2 Model/CIA-ratio**	Reference Model/CIA-ratio
Straight 2 lanes	4,300	4,218	**0.981**	4,056	0.943	0.981
Straight 3 lanes	6,200	5,676	**0.915**	5,376	0.867	0.915
Straight 4 lanes	8,200	7,488	**0.913**	7,032	0.858	0.913
Straight 5 lanes	10,250	9,648	**0.941**	9,000	0.878	0.941
Straight 6 lanes	12,000	11,940	**0.995**	11,082	0.924	0.995
On-Ramp 3+1-to-3	6,200	5,406	0.872	5,682	**0.916**	0.916
Off-Ramp 3-to-3+1	6,200	5,886	0.949	6,306	**1.017**	1.017
Symm. Weaving 3+1	6,840	4,848	0.709	5,634	**0.824**	0.824

Discussion

On-Ramps, Off-Ramps and Weaving Sections benefit from smaller accepted gaps for lane changes (0.4 instead of 0.6 times standard headway) while straight road segments benefit from larger accepted gaps for lane changes (0.6 times standard headway). However, though using a smaller accepted gap at lane changes at merging and diverging road segments improves calibration, this is partially a workaround for calibration and only partially based on actual driving behavior. People are more likely to accept smaller gaps nearing an exit or the end of a merging lane, but accepting a smaller gap at mandatory lane changes also compensates for the limited anticipation for mandatory lane changes in the model.

This lack of (C)AV is possibly more realistically modeled than manual driving behavior since automated vehicles might have algorithms similar to models. Any strange behavior, i.e. lack of anticipation for lane changes or accepted headway during lane changes, might have similar issues in practice for automated vehicles as well. This can happen when the system detects another vehicle close in front of the vehicle which is in the origin lane during a lane change, while the target lane is clear and there will be no collision, but the system still breaks or keeps a larger headway.

Question 3

What is the modeled capacity of these road segments with several levels and penetration rates of autonomous and cooperative vehicles, and how do they compare to the reference?

Question 3 is important for the goal of this study. In order to study the (relative) effects of different levels and penetration rates of automated vehicles on Dutch highway capacity, it is necessary to determine the capacity of the different levels of vehicle automation:

- ACC
- CACC
- Autonomous Vehicles
- Cooperative Autonomous Vehicles
- Cooperative Autonomous Vehicles with fixed desired speed

As can be seen below, the capacities are, in general, around the CIA capacity. The ratios range from:

- Straight 2 lanes: 3,924 for 100% ACC (VC3) to 4,740 for 100% CACC (VC6), 100% CAV and CAV+ (VC12 and VC13)
- Straight 3 lanes: 5,304 for 10% AV (VC7) to 6,984 for 100% CAV+ (VC13)
- Straight 4 lanes: 7,038 for 100% ACC (VC3) to 9,480 for 100% CAV+ (VC13)
- Straight 5 lanes: 8,916 for 100% ACC (VC3) to 11,868 for 100% CAV+ (VC13)
- Straight 6 lanes: 10,860 for 10% AV (VC7) to 14,118 for 100% CAV (VC12)
- On-Ramp: 5,274 for 100% ACC (VC3) to 6,564 for 100% CAV (VC12)
- Off-Ramp: 6,054 for 100% ACC (VC3) to 6,768 for 100% CAV+ (VC13)
- Symmetric Weaving: 4,746 for 10% CACC (VC4) to 5,628 for 100% CAV (VC12)

This also gives the answer to the second part of the question:

- What is the ratio between vehicle automation capacity values and reference capacity values?

This results in the following ratios that range from:

- Straight 2 lanes: 0.930 for 100% ACC (VC3) to 1.124 for 100% CACC (VC6), 100% CAV and CAV+ (VC12 and VC13)
- Straight 3 lanes: 0.934 for 10% AV (VC7) to 1.230 for 100% CAV+ (VC13)
- Straight 4 lanes: 0.940 for 100% ACC (VC3) to 1.266 for 100% CAV+ (VC13)
- Straight 5 lanes: 0.924 for 100% ACC (VC3) to 1.230 for 100% CAV+ (VC13)
- Straight 6 lanes: 0.910 for 10% AV (VC7) to 1.182 for 100% CAV (VC12)
- On-Ramp: 0.928 for 100% ACC (VC3) to 1.155 for 100% CAV (VC12)
- Off-Ramp: 0.960 for 100% ACC (VC3) to 1.073 for 100% CAV+ (VC13)
- Symmetric Weaving: 0.842 for 10% CACC (VC4) to 0.999 for 100% CAV (VC12)

In many cases 100% ACC shows the lowest capacities with a ratio around 0.9 in most cases. Scenarios with 100% CAV (VC12) and CAV+ (VC13) show the highest capacities with ratios around 1.15 for straight road segments and smaller values for merging and diverging segments. Symmetric Weaving shows low values in all cases due to the lack of proper calibration. Finally, to compare the overall performance of each vehicle composition, Table 27 shows the minimum and maximum ratio over all road segments of each VC.

Table 27: Minimum and Maximum ratio to CIA capacities per Vehicle Composition

VC	Ref. (VC1 / VC2)	VC3	VC4	VC5	VC6	VC7	VC8	VC9	VC10	VC11	VC12	VC13
Min.	1	0.848	0.842	0.864	0.881	0.851	0.864	0.851	0.860	0.934	0.999	0.960
Max.	1	0.960	0.983	1.022	1.171	0.966	0.996	1.090	1.110	1.211	1.257	1.266

Discussion
The answers to the research question have been given above. However, there are points of discussion. First, the results of the Symmetric Weaving Section must be interpreted carefully since this road segments could not be calibrated properly.

Second, the results show similar findings as in literature. ACC performs worse to about equal as manual driving, while autonomous vehicles show in general an increase in capacity. Their communicative counterparts, CACC and CAV, show larger capacities and the communicative aspect seems to have a greater influence than the vehicle automation itself. However, the capacity changes in this study are overall more moderate (about -15% to +25%) than some changes in literature, where capacity doubles to quadruples or more for cooperative scenarios. In most cases the large improvements are with platooning though, while this study looked into cooperative vehicles without platooning. Still some features of automated vehicles, especially CAV, are not known yet and are not in the used model or are not possible to implement in the model in the used version. The capacity values for vehicle automation, especially on the long turn are thus conservative.

Question 4

What is the effect of vehicle automation on traffic conditions in comparison to the reference situation?

The final question is question 4. Question 4 is the extension of question 3 in order to get more insight in traffic conditions of automated driving in addition to capacities of question 3. In order to do so the following traffic conditions are studied:

- Lane share
- Lane intensity
- Mean Speed
- SD Speed
- (Lane changes)

The distribution over lanes (lane share) and the mean speeds are the focus of this question. Lane intensity and the standard deviation in speed are used to study lane share and mean speed respectively, in more detail. The latter have shown to be the most important to explain differences in capacity, however this is only partially true in some cases:

- Left lane speed deviations are leading for the effect on capacity of straight road segments: Smaller speed deviations on the left lane mean higher capacity. Cooperative vehicles have the lowest left lane speed deviations.
- Left lane speed deviations seem to have similar effects on the traffic conditions on the main lanes of an On-Ramp as on straight road segments. However, because traffic seems to flow better on the main lanes, vehicles from the merging seem to be blocked to enter the main lanes and are cooperative scenarios are therefore less robust than on straight road segments.
- On an Off-Ramp, the left lane speed deviations are also important. However, the exiting vehicles must use the middle and right main lane as well. The higher speed deviations cancel part of the capacity increase by the improved traffic flow on the left lane.
- The total number of lane changes indicates that lane changes are also important. However, in this study this could not be researched in sufficient detail. Therefore, a lane change analysis is recommended for future studies.
- In general, scenarios that show high capacities, show high left lane shares and higher speeds on all or most lanes. The same scenarios often have smaller speed deviations on the left lane as well, both between as within time intervals.
- By using the unfiltered data, highly cooperative scenarios seem to have unequal lane distributions and different speeds per lane around congestion. The true capacity possibly has not been reached yet. Another explanation is that cooperative vehicles have a higher speed at capacity than HGV have. For mixed traffic conditions, with both private vehicles and HGV, which is the case with 15% HGV in this study, this can lead to different capacities per lane, since HGV mainly use the right lane and to a lesser extend the second right lane.

Discussion
The last point of the conclusion is subject to discussion. As stated above there are (at least) two possible explanations for why in cooperative scenarios with high market penetration, show different distributions over the lanes and not equal speeds per lane at congestion:

- Capacity is not reached in those scenarios
- The optimum is different because cooperative vehicles have a higher speed than HGV at capacity

The first explanation can be caused by a bottleneck more upstream. This can be a result of the way the vehicle input has been implemented in the model: There cannot be more vehicles entering the network. The second explanation has to be studied into more detail. This is recommended for future work.

Goal
By answering the research questions above the goal of this study has been fulfilled.

Goal

To determine the effects on capacities of ADAS, autonomous and cooperative vehicles on common road segments of the Dutch highway network, focused on non-platoon based car-following behavior.

6.2 RECOMMENDATION

In previous section all research questions have been answered to achieve the goal of this study. However, there are still recommendations for future studies. In this section the final recommendations for future work, both technical as related to the research subject, are therefore given.

6.2.1 Technical Recommendations

- Improve anticipation for mandatory lane changes since adjusting the Safety Distance Reduction Factor only partially resolves the problem with calibrating lane change behavior for mandatory lane changes and is partially only a work-around in the model. Anticipation, i.e. adjusting speed earlier for a mandatory lane change, should be achieved in future studies.
- Vehicle input is poor since vehicles are put onto the network at their desired speed and large speed differences will cause disturbances near the vehicle input due to poor relaxation in those cases. In future studies this can be addressed to improve the model and thereby the results.

6.2.2 Recommendations for future research

- Aline HGV developments with passenger vehicles. In this study, HGV has been kept fixed for all vehicle compositions. Future work should also look into the combination of passenger vehicles and the automation of HGV in such a way that the study matches both that has meaning in practice.
- At first, this study would also include a driving simulator to test the results of the planned traffic model. However, the driving simulator is not considered developed enough to get sufficiently reliable results at this point. The use of the driving simulator would be interesting for many aspects outside the scope of this study. Three interesting research directions with a driving simulator are: One, studying human responds to automated vehicles in traffic while driving manually themselves; two, studying the human interaction with systems used for vehicle automation; and three, studying how people experience driving in autonomous vehicles.
- Study Lane Changes in more detail, there are large differences between Vehicle Compositions, but this is not yet explained and related to capacity.

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7 APPENDIX

7.1 APPENDIX A: CAPACITIES ACCORDING TO CIA

7.1.1 Weaving capacities

Weaving sections can be divided into two categories: symmetric and asymmetric. Symmetric weaving sections have an equal number for lanes upstream and downstream for both the main lanes as the merging/diverging lane respectively. Asymmetric weaving section do not have this: asymmetric weaving sections have a deviating number of lanes for either or both the main lanes or merging/diverging lanes.

Symmetric weaving

As stated in section 2.2.3, capacity depends on the number of lanes and on the amount of weaving vehicles. In general, the following holds:

- More lanes mean higher capacity (a lot of weaving about 1,000 veh/h, limited weaving about 2,000 veh/h)
- More weaving movements means lower capacity

However, many weaving movements might outweigh the effects of an extra lane, as can be concluded from the minimum capacity of 5 and 6 lanes. A more detailed table is given in Table 28

Asymmetric weaving

Next to symmetric weaving, there are road segments with asymmetric weaving where a lane is added, terminated, or the total number of lanes upstream and downstream are equal but divided differently over the directions. Table 4 shows the corresponding capacities for asymmetric weaving. In general, the following holds:

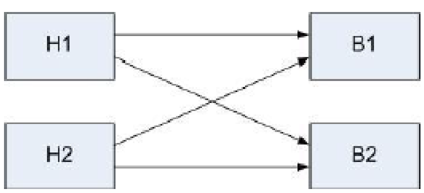
- More lanes mean higher capacity (a lot of weaving about 1,000 veh/h, limited weaving about 2,000 veh/h)
- More weaving means lower capacity
- Lowest capacities are found for n to n+1 with taper (x + 1 > x + 2 with taper)[29]

Asymmetric weaving has similar effects on capacity as symmetric weaving. However, for asymmetric weaving the number of weaving movements and the exact configuration of the road segment have even stronger effects on the capacity. A more detailed table can be seen Table 29 and Table 30).

[29] Where n is the minimum total number of lanes upstream or downstream and x is the number of lanes on the left direction

Table 28: Weaving capacities (symmetric) (Rijkswaterstaat & Grontmij, 2015)

weefvak configuratie	weefvaklengte	H2 -> B1[4]	H1 -> B2[5]	capaciteit
	[m]	[%]	[%]	[mvt/h]
weefvak 1+1[6]	200	100 %	100 %	1.750
weefvak 2+1	600	50 %	25 %	5.590
		75 %	38 %	5.100
		100 %	50 %	4.860
weefvak 1+2	700	25 %	50 %	5.330
		50 %	100 %	4.520
weefvak 3+1	700	50 %	17 %	7.570
		75 %	23 %	6.840
		100 %	33 %	6.440
weefvak 2+2	750	25 %	25 %	7.690
		50 %	50 %	6.640
		75 %	75 %	5.620
weefvak 4+1	700	50 %	13 %	9.310
		75 %	19 %	8.450
		100 %	25 %	7.980
weefvak 3+2	900	25 %	17 %	9.710
		50 %	33 %	8.290
		75 %	50 %	6.790
weefvak 4+2	900	25 %	13 %	11.710
		50 %	25 %	9.880
		75 %	38 %	8.000
weefvak 3+3	1000	25 %	25 %	10.660
		50 %	50 %	7.810
		75 %	75 %	6.250
weefvak 5+1	700	50 %	10 %	11.090
		75 %	15 %	10.150
		100 %	20 %	9.130



[4] Dit geeft het percentage wevend verkeer aan dat weeft van de rechter/onderste inkomende rijbaan naar de linker/bovenste uitgaande rijbaan (van H2 naar B1).

[5] Dit geeft het percentage wevend verkeer aan dat weeft van de linker/bovenste inkomende rijbaan naar de rechter/onderste uitgaande rijbaan (van H1 naar B2).

[6] Het 1+1 weefvak (200m) heeft betrekking op rangeerbanen in klaverbladen.

Table 29: Weaving capacities (asymmetric) (Rijkswaterstaat & Grontmij, 2015)

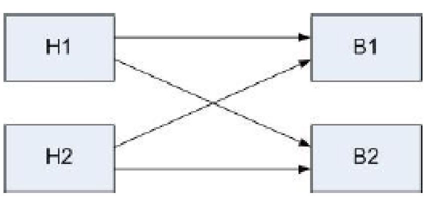
weefvak configuratie	weefvaklengte [m]	H2 -> B1[7] [%]	H1 -> B2[8] [%]	capaciteit [mvt/h]
weefvak 2+1 > 1+2	800	25 %	63 %	5.260
		50 %	75 %	4.850
		75 %	88 %	4.360
weefvak 1+2 > 2+1	800	50 %	0 %	6.020
		75 %	50 %	5.390
		100 %	100 %	4.780
weefvak 2+1 > 2+2	700	25 %	38 %	5.320
		50 %	50 %	5.170
		75 %	63 %	4.870
weefvak 2+1 > 2+2 taper	600	25 %	38 %	4.030
		50 %	50 %	4.010
		75 %	63 %	3.880
weefvak 2+2 taper > 2+1	750	50 %	17 %	5.280
		75 %	42 %	4.760
		100 %	67 %	4.460
weefvak 2+2 > 3+1	850	50 %	0 %	8.280
		75 %	25 %	7.450
		100 %	50 %	6.370
weefvak 3+1 > 2+2	850	25 %	42 %	7.360
		50 %	50 %	6.790
		75 %	58 %	5.900
weefvak 3+2 > 4+1	1.000	50 %	0 %	10.270
		75 %	17 %	9.440
		100 %	33 %	7.790
weefvak 4+1 > 3+2	1.000	25 %	31 %	9.240
		50 %	38 %	8.540
		75 %	44 %	7.580
weefvak 2+3 > 3+2	1.000	50 %	25 %	9.000
		75 %	63 %	6.900
weefvak 2+2 > 3+2	1.000	25 %	5 %	5.400
		50 %	30 %	5.710
		75 %	55 %	6.130
weefvak 2+2 > 3+2 taper	1.000	25 %	5 %	5.160
		50 %	30 %	5.040
		75 %	55 %	5.080
weefvak 3+1 > 3+2	800	25 %	28 %	6.400
		50 %	37 %	6.160
		75 %	45 %	6.170
weefvak 3+1 > 3+2 taper	700	25 %	38 %	5.180
		50 %	37 %	4.910
		75 %	45 %	4.640

[7] Dit geeft het percentage wevend verkeer aan dat weeft van de rechter/onderste inkomende rijbaan naar de linker/bovenste uitgaande rijbaan (van H2 naar B1).

[8] Dit geeft het percentage wevend verkeer aan dat weeft van de linker/bovenste inkomende rijbaan naar de rechter/onderste uitgaande rijbaan (van H1 naar B2)

Table 30: Weaving capacities (asymmetric) cont. (Rijkswaterstaat & Grontmij, 2015)

weefvak configuratie	weefvaklengte	H2 -> B1[9]	H1 -> B2[10]	capaciteit
	[m]	[%]	[%]	[mvt/h]
weefvak 3+2 taper > 3+1	800	50 %	8 %	7.080
		75 %	25 %	6.230
		100 %	42 %	5.650
weefvak 4+1 > 4+2	800	25 %	23 %	7.800
		50 %	29 %	7.460
		75 %	35 %	7.280
weefvak 4+1 > 4+2 taper	700	25 %	23 %	6.140
		50 %	29 %	5.990
		75 %	35 %	5.690
weefvak 4+2 taper > 4+1	850	50 %	5 %	8.760
		750 %	18 %	7.150
		100 %	30 %	6.490
weefvak 5+1 > 5+2	800	25 %	19 %	8.720
		50 %	24 %	8.770
		75 %	29 %	8.260
weefvak 5+1 > 5+2 taper	700	25 %	19 %	7.430
		50 %	24 %	7.020
		750 %	29 %	6.610
		100 %	34 %	6.580
weefvak 5+2 taper > 5+1	850	50 %	3 %	10.520
		75 %	13 %	8.680
		100 %	23 %	6.850
weefvak 4+2 > 3+3	1.100	25 %	38 %	10.370
		50 %	50 %	8.710
		75 %	63 %	7.260
weefvak 3+3 > 4+2	1.100	50 %	17 %	10.970
		75 %	42 %	7.800
weefvak 5+1 > 4+2	1.000	25 %	25 %	11.150
		50 %	30 %	9.840
		75 %	35 %	8.930
weefvak 4+2 > 5+1	1.000	75 %	13 %	10.920
		100 %	25 %	9.140



9 Dit geeft het percentage wevend verkeer aan dat weeft van de rechter/onderste inkomende rijbaan naar de linker/bovenste uitgaande rijbaan (van H2 naar B1).

10 Dit geeft het percentage wevend verkeer aan dat weeft van de linker/bovenste inkomende rijbaan naar de rechter/onderste uitgaande rijbaan (van H1 naar B2).

7.1.2 Other road segment types

Merger

There are two main types of mergers, mergers where the total number of lanes stays equal and mergers with lane termination. These can be approximated as follows:

- *Equal number of lanes*: Downstream capacity is approximately equal to the sum of upstream capacities, some lane changes may occur to reorder vehicles types, but they are spread over a large area
- *Lane termination*: The capacity of the number of lanes downstream of a merger can used for the capacity value of the merger, since the influence of merging vehicles is expected to be small. In case of use of a merge taper, see below.

Merging Taper

A merging taper has small advantages over a merger with lane termination when the right lanes have lower traffic intensity than the left lanes. Traffic on the left lanes can continue on their own lanes and heavy vehicles have fewer lanes to change. Figure 36 shows the capacities of a 750-meter 3+2 merger with lane termination (red) and a 3+2 to 4 merging taper of 250 meters (blue) depending on the ratio of traffic on the left and the right lanes.

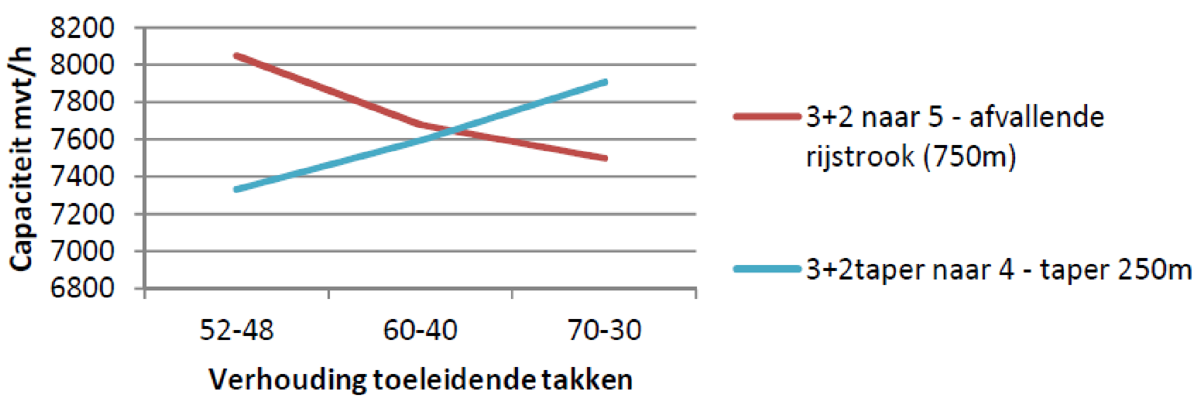


Figure 36: Capacity at 3+2 to 4 lanes with lane termination and taper (Rijkswaterstaat & Grontmij, 2015)

Fork

In general, there is a very limited reduction of capacity at an equal number of lanes before and after split for a fork. There is a possible reduction shortly after the split, depending on traffic flows and number of downstream lanes. However, a large fraction of heavy vehicles on left road does reduce capacity.

Interchanges

The capacity of interchanges is highly dependent on the specific situation. The capacity for ongoing traffic might be reduced by approximately 10%, but that is based on a very limited amount of measurements. The capacity of weaving sections of an interchange is often very low, since in most cases 100% of traffic is weaving.

Main lanes and parallel roads

For the individual road segments one can use the capacities of the respective number of lanes of the road segment. However, in practice not both road segments will be used optimally. Therefore, the total road capacity of main lanes and a parallel road is less than the sum of the two capacities. However, any disturbances caused by exchanges with local roads are strongly reduced.

Extra lane
Downstream capacity with an extra lane is equal to the capacity of the capacity of the number of lanes downstream. However, this capacity will never be reached since upstream capacity would not allow an intensity that reaches this capacity.

Expressways and secondary networks
Capacity for expressways is usually lower than for highways. Intersections are in general leading for the capacity of secondary networks.

7.1.3 Environmental factors

Several environmental factors have influence on road capacity. The CIA uses reduction factors for rain, mist or fog, light conditions and distractions.

Precipitation
Extreme conditions such as snow, extreme precipitation and glazed frost,
are not taken into consideration in the CIA, since they are not leading for design. The CIA uses a 5% reduction for light rain and 10% for heavy rain (Table 31).

Table 31: Reduction factor rain (Rijkswaterstaat & Grontmij, 2015)

Condition	Reduction factor
Dry	1.00
Light to moderate rain	0.95
Heavy rain	0.90

In literature similar values are found. Hoogendoorn and colleagues (R. G. Hoogendoorn, Hoogendoorn, Brookhuis, & Daamen, 2011) refer to two other studies regarding rain: "*In this regard, heavy rain has been reported to reduce freeway capacity by 14 to 19%. (Jones & Goolsby, 1970)*" and "*Furthermore, in research using precise rainfall data with detector data at five highly congested sections at the Tokyo Metropolitan Expressway, it was concluded that rain reduced freeway capacity by 4 to 7% in case of light rain and up to 14% in case of heavy rain (Chung, Ohtani, Warita, Kuwahara, & Morita, 2006)*". In another study, Asamer and Reinthaler found a capacity drop of about 3 (0 – 0.25mm/h rain) to 7% (>1 mm/h rain) for rain and snow (Asamer & Reinthaler, 2010) in urban traffic. Next, Agarwal and colleagues found capacity reductions of 1-3% (trace), 5-10% (light rain) and 10-17% (heavy rain) on freeways (Agarwal, Maze, & Souleyrette, 2006). In addition, Calvert and colleagues found reductions of capacity of about 3-9% (average 5.6% free flow, 5.7% congested) for light rain and about 4-11% (average 8.1% free flow, 6.5% congested) for heavy rain (Calvert, van Stralen, & Molin, 2013).

As shown, comparable results are used in the CIA as in literature. However, for heavy rain capacity is reduced less in the CIA than found in some literature. This might be caused by differences in both the definition of heavy rain as well as the traffic situation (urban or freeways in comparison to highways), but also by differences in the quality of the road surface. In the Netherlands the quality of the asphalt is good and a lot of asphalt with high draining capacity is used (ZOAB). The use of ZOAB might reduce the effects on visibility and grip, caused by heavy rain in comparison to other countries. The CIA mentions that in case of asphalt that can discharge less water (i.e. DAB), one should use stronger reduction factors. The capacity reduction of Calvert et al. is more comparable to the values used in the CIA. Since both have the Dutch highway network as context, this strengthens the possible explanation above.

Mist / Fog
The CIA only refers to the study of Hoogendoorn and colleagues (R. G. Hoogendoorn et al., 2011) and estimates the effects of mist or fog on about 10%. Though Chin and colleagues (Chin, Franzese, Greene, Hwang, & Gibson, 2002) found a significant amount of capacity losses and delay due to fog, most of these relate to urban traffic and very limited information has been found for capacity in fog conditions on highways. Another study does address the effects of fog on highway capacity. Agarwal, Maze and Souleyrette found capacity reductions of 10% - 12% (Agarwal et al., 2006).

Light conditions
In case lighting conditions are different than standard conditions the CIA road segment capacities should be multiplied with the corresponding reduction factor shown in Table 32. These factors are based on values found in literature (Al-Kaisy & Hall, 2003; Goeverden, Botma, & Bovy, 1998; van Toorenburg, 1986).

Table 32: Reduction factors of several light conditions (Rijkswaterstaat & Grontmij, 2015)

Situation	Reduction factor
Daylight	1.00
Street lighting	0.97
Darkness	0.95

Chung and colleagues found a capacity decrease of 12.8% in winter (December 2003) in comparison to summer (June 2003) during the morning period (5 to 7 AM) while using only fine weather conditions (Chung et al., 2006).

Distractions
The CIA mentions that distractions may cause capacity reductions of up to 50%. Though a quantified effect of distractions on capacity seems hard to find, literature does show that drivers are often distracted, i.e. 16.1% of total driving time according to Stutts and colleagues (Stutts et al., 2003) and 14.5% excluding conversing with other passenger in continued work (Stutts et al., 2005). Another study found effects of distraction on speed which strongly indicates an effects on capacity (Horberry, Anderson, Regan, Triggs, & Brown, 2006).

7.1.4 Other factors in CIA
In section 2.2 the variables in the CIA which are considered most useful for this study are discussed. In case other variables will be relevant for another study as well, the CIA also contains information about how to address the following variations:

- Infrastructural factors
    - Cross section
    - Object distance
    - Emergency lanes
    - Slopes
    - Horizontal and vertical road alignment
    - Type of road surface
    - Tunnel
- Traffic factors
- Traffic management factors
- Developments in-car systems and ITS
- Incidental factors
- Road construction

7.2 APPENDIX B: VISSIM MODEL - NETWORK, DETECTOR LOCATIONS & VEHICLE INPUT

7.2.1 Network Characteristics

Table 33: Overview of modeled road segments and their respective lengths[30]

Short name	Description	Length Pre-input	Location fixed speed area	Length transition	Length main section	Length connector down-stream	Length section down-stream
			All vehicles fixed at 85 km/h	*Vehicles accelerate to desired speed[31]*	*Congestion area, main focus area*	*Physically necessary in the model*	*To handle traffic correctly and determine capacity*
S2	"Straight" 2 lanes	200 m	0 – 150 m (Pre-input)	≈200 m	1,000 m	-	-
S3	"Straight" 3 lanes	200 m	0 – 150 m (Pre-input)	≈200 m	1,000 m	-	-
S4	"Straight" 4 lanes	200 m	0 – 150 m (Pre-input)	≈200 m	1,000 m	-	-
S5	"Straight" 5 lanes	200 m	0 – 150 m (Pre-input)	≈200 m	1,000 m	-	-
S6	"Straight" 6 lanes	200 m	0 – 150 m (Pre-input)	≈200 m	1,000 m	-	-
SW 3+1	Symmetric Weaving, 3 lanes (left) + 1 lane (right)	≈396 m (main) 200 m (on)	0 – 150 m (Pre-input, both main and on)	≈271 m (main) ≈367 m (on)	≈700 m	< 1 m (main) < 1 m (off)	≈300 m (main) ≈300 m (off)
On Ramp 3+1>3	On Ramp, 3 main lanes, 1 merging lane	≈396 m (main) ≈408 m (on)	0 – 150 m (Pre-input, both main and on)	672 m (main) 562 m (on)	≈300 m	< 1 m	≈300 m
Off Ramp 3>3+1	Off Ramp 3 main lanes, 1 exit lane	≈396 m	0 – 150 m (Pre-input)	718 m	≈250 m	< 1 m (main) < 1 m (off)	≈300 m (main) ≈300 m (off)

[30] VISSIM only allows to drag road sections to move or resize which makes round numbers difficult to attain for connectors, merging, diverging and weaving sections. Therefore, all numbers with an '≈' are close to the following number with a maximum deviation of 1m.
[31] As far as traffic allows

7.2.2 Network Detector Locations

Table 34: Modeled detector locations

Short name	Description	Location Detectors[32]
S2	“Straight” 2 lanes	100 m, 200 m, 300 m, 400 m, 500 m, 600 m (main section)
S3	“Straight” 3 lanes	100 m, 200 m, 300 m, 400 m, 500 m, 600 m (main section)
S4	“Straight” 4 lanes	100 m, 200 m, 300 m, 400 m, 500 m, 600 m (main section)
S5	“Straight” 5 lanes	100 m, 200 m, 300 m, 400 m, 500 m, 600 m (main section)
S6	“Straight” 6 lanes	100 m, 200 m, 300 m, 400 m, 500 m, 600 m (main section)
On Ramp 3+1>3	On Ramp, 3 main lanes, 1 merging lane	≈200 m (main section, 100 m before end of merging lane), 100 m (downstream section)
Off Ramp 3>3+1	Off Ramp 3 main lanes, 1 exit lane	≈150 m (main section, 100 m before diversion point), 100 m (downstream section, main lanes and exit lane)
SW 3+1	Symmetric Weaving, 3 lanes (left) + 1 lane (right)	600 m (main section, 100 m before diversion point), 100 m (downstream section, main lanes and exit lane)

7.2.3 Vehicle Input

Table 35: Vehicle Input Values per road segment type

Road segment Type	CIA Capacity (veh/h)	Start Vehicle Input (veh/h)	Step duration (s)	Step size (+veh/h)	Final Vehicle Input (veh/h)
“Straight” 2	4,300	3,000	60	50	5,950
“Straight” 3	6,200	4,500	60	75	8,925
“Straight“ 4	8,200	6,000	60	100	11,900
“Straight“ 5	10,250	7,500	60	125	14,875
“Straight“ 6	12,000	9,000	60	150	17,850
On-Ramp 3+1>3	≤6,200	3,000 + 500	60	50 + 8.33	5,950 + 991.67
Off-Ramp 3>3+1	≤6,200	4,500	60	75	8,925
Symmetric Weaving 3+1	6,840	3,000 + 500	60	50 + 8.33	5,950 + 991.67

[32] Beginning of section (upstream) is 0.

7.2.4 Lateral parameters in VISSIM

Table 36: VISSIM Driving behavior - Lane change parameters

Parameter	Short description	Default value[33]	Remark
Maximum deceleration	Enter the maximum deceleration for changing lanes based on the specified routes for **own vehicle overtaking** (**MaxDecelOwn**) and the **trailing vehicle** (**MaxDecelTrail**)	-4.00 m/s^2 (own) -3.00 m/s^2 (trailing)	No improvement on realism by changing this parameter found during validation
-1m/s² per distance	In addition, the change of the deceleration is specified (in meters per -1 m/s2). This reduces the **Maximum deceleration** with increasing distance from the emergency stop distance linearly by this value down to the **Accepted deceleration**.	200 m (own) 200 m (trailing)	No improvement on realism by changing this parameter found during validation
Accepted deceleration	Lower bound of deceleration for own vehicle and trailing vehicle for a lane change	-1.00 m/s^2 (own) -0.50 m/s^2 (trailing)	No improvement on realism by changing this parameter found during validation
Waiting time before diffusion	Made to remove vehicles blocking the network	60 s	Not relevant, since congestion takes places before this occurs
Minimum headway (front/rear dist.)	The minimum distance between two vehicles that must be available after a lane change, so that the change can take place (default value 0.5 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.	0.50 m	No improvement on realism by changing this parameter found during validation
To slower lane if collision is above	Only for **Slow lane rule** or **Fast lane rule**: defines the minimum distance to a vehicle in front, in seconds, which must be present on the slower lane, so that an overtaking vehicle switches to the slower lane.	11.00 s	Not used

[33] For Right-side rule (motorized) Driving Behavior in VISSIM

<table>
<tr>
<td>Safety distance reduction factor</td>
<td>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 outThe safety distance of the lane changer itselfThe distance to the preceding, slower lane changerDuring the lane change Vissim reduces the safety distance to the value that results from the following multiplication:Original safety distance • safety distance reduction factorThe default value of 0.6 reduces the safety distance by 40%. Once a lane change is completed, the original safety distance is taken into account again.</td>
<td>0.60</td>
<td>Initially kept at default, but studied at validation (§3.5), default used for straight road segments, 0.4 used for reference of merging and diverging segments</td>
</tr>
<tr>
<td>Maximum deceleration for cooperative braking</td>
<td rowspan="2">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.Vehicle A behaves during this lane change as if it would have to change lanes due to a connector at a long distance. It accepts its own Maximum deceleration and the deceleration of the trailing vehicle C on the new lane, in accordance with the parameters for the necessary lane change.Vehicle A does not make a cooperative lane change, when the following conditions are true:the new lane is less appropriate for continuing its routeif vehicle B is faster than the maximum speed difference (in the example 10.80 km/h (=3 m/s)if the collision time exceeded the maximum collision time (in the example 10 seconds), and the speed of vehicle A increased by the maximum speed difference (in the example 10.80 km/h). When you select Cooperative lane change, the user-defined cooperative lane change rule is activated for the respective driving behavior parameter set. For Maximum speed difference and Maximum collision time the user-defined settings are used. If this option is not selected, the user-defined cooperative lane changing behavior is not active for the particular driving behavior parameter set.</td>
<td>-3.00 m/s^2</td>
<td>No improvement on realism by changing this parameter found during validation</td>
</tr>
<tr>
<td>Cooperative lane change</td>
<td>Unchecked</td>
<td>Useable to model cooperative systems</td>
</tr>
</table>

Lateral correction of rear end position	If a lane change takes place at a lower speed than specified in the **Maximum speed** box, the vehicle's rear end moves laterally. This is corrected through rear correction. This causes the vehicle to be aligned to the middle of the lane at the end of the lane change, instead of at angle in the original lane. **Lateral correction of rear end position** affects the capacity.**Lateral correction of rear end position** is only performed if the **Keep lateral distance to vehicles on next lane(s)** option is selected for the driving behavior parameter Lateral behavior (see “Editing the driving behavior parameter Lateral behavior” on page 260).**Maximum speed**: Speed up to which the correction of the rear end position should take place. Default value 3km/h. Lateral correction of the rear end position is not performed for faster vehicles.**Active during time period from**: Time after the start of the lane change at which the lateral movement of the rear end position should start, default value 1.0 s.**until**: Time after the start of the lane change at which the lateral movement of the rear end position should end. The value includes 3 s for the lane change of the front end, default value 10.0.	Unchecked	Not used

7.3 APPENDIX C: VISSIM PARAMETER SETTINGS

Table 37: Overview of longitudinal parameters in VISSIM

Longi-tudinal Para-meters	Scenario	Default (0, 0b), all HGV	ACC (1)	CACC (2a, 2b, 2c)		AV (3a, 3b, 3c)		CAV (4a, 4b, 4c)		CAV + (5)
				Most adv. System	Most basic system	Most adv. System	Most basic system	Most adv. System	Most basic system	
	System	Def.	ACC	CACC	ACC	AV	ACC	CAV	AV	CAV +
	Market penetration of passenger vehicles	[1]*85%	[1]*85%	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[1]*85%
	Market penetration HGV	15%	15%	15%	15%	15%	15%	15%	15%	15%
CC0	Standst. dist. (m)	1.5	1.5	1.25	1.5	1	1.5	1	1	1
CC1	Headway t. (s)[34]	~T(0.6, 1.2, 0.9)	~T(1.0, 1.4, 1.2)	~T(0.65, 0.85, 0.75)	~T(1.0, 1.4, 1.2)	0.9	~T(1.0, 1.4, 1.2)	0.5	1	0.5
CC2	Following Var.	4	3	2	3	2	3	1	2	1
CC3	TH for entering following	-8	-12	-12	-12	-12	-12	-16	-12	-16
CC4	Neg. following TH	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35
CC5	Pos. following TH	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
CC6	Speed dep. Osc.	11.44	0	0	0	0	0	0	0	0
CC7	Osc. Acc. (m/s^2)	0.25	0.25	0.1	0.25	0.1	0.25	0.1	0.1	0.1
CC8	Standst. acc. (m/s^2)	3.5	3.5	3.5	3.5	3.5	3.5	4	3.5	4
CC9	Acc. At 80km/h (m/s^2)	1.5	1.5	1.5	1.5	2	1.5	2	2	2

[34] ~T(a,b,c) is an approximated triangular distribution with minimum a, maximum b and modus c. HGV always uses the default distribution. See Appendix D for details.

Desired Speed Distribution

Figure 37 and Table 38 show the desired speed distributions used during the study. Final simulations all an approximately Gaussian distribution around 85 km/h for HGV. All passenger vehicles all use an approximately Gaussian distribution around 114 km/h in final simulations, except scenario 5 where the desired speed is fixed at the speed limit (120 km/h). Appendix D explains how these distributions are determined.

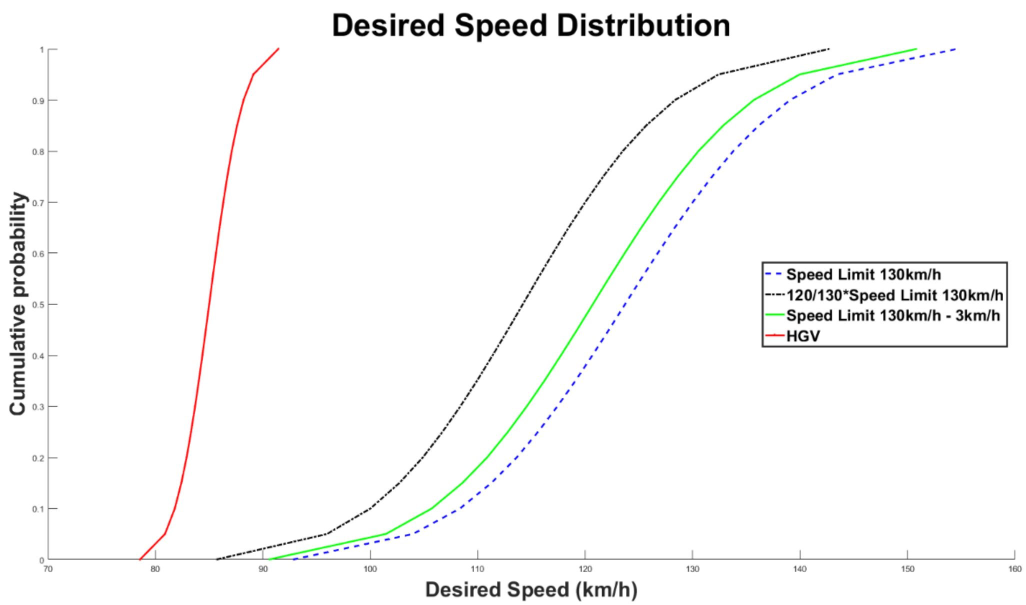


Figure 37: Cumulative Probability of Desired Speed Distributions

Table 38: Desired Speed Distributions details

Distribution	Vehicle type	Scenario	Speed limit (km/h)	μ (km/h)	σ (km/h)	Color in figure	Used in final simulations
HGV	HGV	Literature & All	[120]	85	2.5	Red	Yes
Speed limit 130km/h (Original)	Passenger	Literature	130	123.7	12.0	Blue dotted	-
120/130 *Original	Passenger	0 – 4	120	114.18	11.08	Black	Yes
Fixed at 120 km/h	Passenger	5	120	120	0	-	Yes
3 km/h slower than Original	Passenger	0’	120	120.7	11.71	Green	No

Table 39: Overview of look settings, lane change parameters and lateral parameters in VISSIM

Look settings, lane change parameters and lateral parameters		Scenario	Default (0 & 0b)	ACC (1)	CACC (2a, 2b, 2c)		AV (3a, 3b, 3c)		CAV (4a, 4b, 4c)		CAV+ (5)
					Most adv. System	Most basic system	Most adv. System	Most basic system	Most adv. System	Most basic system	
		System	Def.	ACC	CACC	ACC	AV	ACC	CAV	AV	CAV+
		Market penetration of passenger vehicles	[1]*85 %	[1]*85 %	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[0.1, 0.5, 1]*85%	[0.9, 0.5, 0]*85%	[1]*85 %
		Market penetration HGV	15%	15%	15%	15%	15%	15%	15%	15%	15%
Look settings	Look ahead distance	Min (m)	0	0	150	0	150	0	5000	150	5000
		Max (m)	250	200	200	200	200	200	5000	200	5000
	Look back distance	Min (m)	0	0	150	0	150	0	5000	150	5000
		Max (m)	150	200	200	200	200	200	5000	200	5000
	Observed vehicles	#	2	8	8	8	8	8	10	8	10
Lane change parameters	Cooperative lane change	Checked / Unchecked (C / UC)	UC	UC	C	UC	UC	UC	C	UC	C
	Safety Distance Reduction Factor	Factor to CC1 headway	0.6 (0) 0.4 (0b)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Other		Def.	Def.	Def.	Def.	Def.	Def.	Def.	Def.	Def.
Lateral parameters	All		Def.	Def.	Def.	Def.	Def.	Def.	Def.	Def.	Def.

7.4 Appendix D: Explanation Desired speed distribution & Headway distribution

Desired speed distribution

Car (Maximum speed 130 km/h)

μ = 123.7 km/h, σ = 12.0 km/h (Wouter Jochem Schakel, 2015)

Heavy Vehicles

μ = 85 km/h, σ= 2.5 km/h (Wouter Jochem Schakel, 2015)

Since the speed limit is 120 km/h instead of 130 km/h rescaling the desired speed distribution is necessary. It is assumed that the desired speed distribution lies somewhere between 120/130 * the desired speed distribution of 130 km/h and the desired speed distribution of 130 km/h minus 3 km/h:

- Slow distribution - 120/130 * Distribution of 130 km/h, all passenger vehicles rescaled according to speed limit
- Fast distribution - Distribution rescaled by lowering the mean by 3 km/h:

According to research (Rijkswaterstaat, 2011), the increase of the maximum speed from 120 to 130 km/h, increased the average speed of passenger cars only by about 3 km/h (see also Figure 38). Reversing that would mean lowering the 130 km/h distribution by 3 km/h (at the average speed) in order to get the distribution of a 120 km/h highway. Both limits are tested during calibration

Traject		gemiddelde snelheid (*)			V85 (**)		
		voor	na	verschil	voor	na	verschil
A2 Everdingen - Deil		118,1	121,1	3,0	132,8	136,2	3,4
A6 Almere-Joure	*dag*	116,2	115,9	-0,3	129,5	129,2	-0,3
	nacht	119,9	122,9	3,0	134,4	137,3	2,9
A7 Wognum-Lorentzsluizen		118,1	120,7	2,6	132,4	137,3	4,9
A16 Klaverpolder - Galder	100-130	110,8	119	8,2	124,5	133,1	8,6
	120-130	117,9	121,1	3,2	132,2	135,7	3,5
A17/58 Klaverpolder- Begen op Zoom		117,8	119,9	2,1	131,7	134,1	2,4
A32 Steenwijk - Heerenveen		116,2	118,4	2,3	132,6	135,3	2,7
A37 Hoogeveen - Klazinaveen		116,2	118,5	2,3	130,9	133,8	2,9
A58 Rithem - Vlissingen		114,5	117,3	2,8	131,2	134,6	3,4

Figure 38: Average speed before and after speed limit increase at several Dutch highways (Rijkswaterstaat, 2011)

- Average speeds at 114.5 – 119.9 km/h at a speed limit of 120km/h
- Average speeds at 115.9 – 122.9 km/h at a speed limit of 130km/h
- Average speed increase of about 3 km/h
- No influence on heavy vehicles

Table 40: Speed distributions 130 km/h, approximated 120 km/h and heavy vehicles

Cumulative Fraction of Vehicles	Speed distribution (130km/h) **$\mu \approx 123.7$** **σ ≈ 12.0**	120/130 * Speed Distr. (130km/h) [slow distribution] **$\mu \approx 114.18$** **σ ≈ 11.08**	Speed Distribution (130km/h) – 3 km/h [fast distribution] **$\mu \approx 120.7$** **σ ≈ 11.71**	Distribution Heavy Vehicles **$\mu \approx 85$** **σ ≈ 2.5**
0[35]	92.79	85.65	90.54	78.56
0.05	103.96	95.96	101.44	80.89
0.1	108.34	100.01	105.71	81.80
0.15	111.26	102.70	108.56	82.41
0.2	113.62	104.88	110.86	82.90
0.25	115.60	106.71	112.80	83.31
0.3	117.40	108.37	114.55	83.69
0.35	119.08	109.92	116.19	84.04
0.4	120.66	111.38	117.73	84.37
0.45	122.20	112.80	119.24	84.69
0.5	***123.70***	***114.18***	***120.70***	***85.00***
0.55	125.20	115.57	122.16	85.31
0.6	126.74	116.99	123.67	85.63
0.65	128.32	118.45	125.21	85.96
0.7	130.00	120.00	126.85	86.31
0.75	131.80	121.66	128.60	86.69
0.8	133.78	123.49	130.54	87.10
0.85	136.14	125.67	132.84	87.59
0.9	139.06	128.36	135.69	88.20
0.95	143.44	132.41	139.96	89.11
1[36]	154.61	142.72	150.86	91.44

Since VISSIM cannot use a Gaussian distribution, a linear approximation of the CDF values of 20 intervals has been used.
The slow (mean 114.185 km/h) and fast (mean 120.7 km/h) distributions in table 1 are very similar to the values found by Rijkswaterstaat (average speeds of 114.5 – 119.9 km/h at a speed limit of 120km/h). This verifies that the mean of the distribution is in this range and the distribution is likely to be similar.

[35] VISSIM lower limit (0) is set at 0.005% of the distribution since the distribution has no actual limit
[36] VISSIM upper limit (1) is set at 0.995% of the distribution since the distribution has no actual limit

Headway distribution

For most distributions a median or mean value (equal for symmetric distributions) and the boundaries can be estimated though the actual shape of the distribution is likely to be close to a normal distribution. Therefore, a symmetric triangular distribution has been chosen since it is a reasonable approximation of a close to normal distribution with boundaries. Since VISSIM cannot directly use a triangular distribution a linear approximation of the CDF values of 20 intervals (Table 40) is used.

- Manual (130 km/h) 0.56 – 1.2s (Wouter Jochem Schakel, 2015), speed (limit) marginal influence on time headways. Original Preparation Master Thesis 0.9s (fixed), minimum values of 0.66s found → Triangular(0.6,1.2,0,9)
- ACC, mean of 1.2s as in Preparation, slightly smaller deviation in comparison to manual driving → Triangular(1.0,1.4,1,2)
- CACC: mean of 0.75s as in Preparation, smaller deviation in comparison to ACC, because of lower mean (relative values similar) and larger influence of system instead of human driver (relative value smaller as well) → Triangular(0.65,0.85,0.75)
- AV: Assumed that there is no variation when vehicles have high automation (also without communication) , original value of 0.9s from Preparation used. → Fixed(0.9)
- CAV: Assumed that there is no variation when vehicles have high automation, original value of 0.5s from Preparation used → Fixed(0.5)
- HGV: Assumed the same as for manual driving of passenger cars → Triangular(0.6,1.2,0,9)

Table 41: Triangular distribution approximation for VISSIM: Manual Driving, ACC & CACC

		Manual Driving & HGV			ACC			CACC	
		FX	X		FX	X		FX	X
0		**0.6**	**0**		**1**	**0**		**0.65**	**0**
0.05		**0.63**	**0.005**		**1.02**	**0.005**		**0.66**	**0.005**
0.1		**0.66**	**0.02**		**1.04**	**0.02**		**0.67**	**0.02**
0.15		**0.69**	**0.045**		**1.06**	**0.045**		**0.68**	**0.045**
0.2		**0.72**	**0.08**		**1.08**	**0.08**		**0.69**	**0.08**
0.25		**0.75**	**0.125**		**1.1**	**0.125**		**0.7**	**0.125**
0.3		**0.78**	**0.18**		**1.12**	**0.18**		**0.71**	**0.18**
0.35		**0.81**	**0.245**		**1.14**	**0.245**		**0.72**	**0.245**
0.4		**0.84**	**0.32**		**1.16**	**0.32**		**0.73**	**0.32**
0.45		**0.87**	**0.405**		**1.18**	**0.405**		**0.74**	**0.405**
0.5		**0.9**	**0.5**		**1.2**	**0.5**		**0.75**	**0.5**
0.55		**0.93**	**0.595**		**1.22**	**0.595**		**0.76**	**0.595**
0.6		**0.96**	**0.68**		**1.24**	**0.68**		**0.77**	**0.68**
0.65		**0.99**	**0.755**		**1.26**	**0.755**		**0.78**	**0.755**
0.7		**1.02**	**0.82**		**1.28**	**0.82**		**0.79**	**0.82**
0.75		**1.05**	**0.875**		**1.3**	**0.875**		**0.8**	**0.875**
0.8		**1.08**	**0.92**		**1.32**	**0.92**		**0.81**	**0.92**
0.85		**1.11**	**0.955**		**1.34**	**0.955**		**0.82**	**0.955**
0.9		**1.14**	**0.98**		**1.36**	**0.98**		**0.83**	**0.98**
0.95		**1.17**	**0.995**		**1.38**	**0.995**		**0.84**	**0.995**
1		**1.2**	**1**		**1.4**	**1**		**0.85**	**1**

7.5 APPENDIX E: DETAILS CALIBRATION, VALIDATION AND RESULTS

Since initial calibration has been done based on input values found in literature as described in section 3.3, further calibration is necessary. This has therefore been done in multiple steps as described in this Appendix.

7.5.1 Calibration: Large sim - Intermediate results

The first large simulation for straight road segments with 2-6 lanes and a symmetric weaving section (Table 42 S2-S6 and SW3+1 and their corresponding boxplots in Figure 39 to Figure 44), show very low capacities and unrealistic driving behavior. It has been found that the model puts vehicles with random headways on the network at their desired speed: regularly passenger vehicles at i.e. 120 km/h are put at random intervals based on vehicle input volumes after its preceding vehicle. However, when this happens in case a passenger vehicle enters the network after a HGV, this causes the following vehicle to break immediately and generating disturbances at the beginning of the network which results in unrealistic traffic conditions and thereby unrealistic capacities.

Table 42: Large sim - Intermediate results Capacities S2-S6 and SW 3+1 (Manual Driving)

Segment_Name	CIA_Capacity	Manual_Driving_SLOW	Manual_Driving_FAST
S2	4,300	**3,906**	**4,128**
S3	6,200	**5,772**	**5,634**
S4	8,200	**7,212**	**7,074**
S5	10,250	**9,732**	**9,378**
S6	12,000	**11,820**	**11,994**
SW 3+1	*6,840*	***1,794***	***1,932***

Table 43: Large sim - Intermediate results Capacities S2-S6 and SW 3+1 (ACC & CACC):

Segment_Name	CIA_Capacity	ACC_100	ACC_90_CACC_10	ACC_50_CACC_50	CACC_100
S2	4,300	3,774	3,954	4,338	4,698
S3	6,200	5,532	5,382	5,754	6,390
S4	8,200	7,146	7,026	7,854	9,030
S5	10,250	8,844	8,844	9,978	11,118
S6	12,000	10,752	11,376	11,952	13,428
SW 3+1	*6,840*	*5,256*	*5,376*	*4,200*	*4,146*

Table 44: Large sim - Intermediate results Capacities S2-S6 and SW 3+1 (AV & CAV)

Segment_Name	CIA_Capacity	ACC_90_AV_10	ACC_50_AV_50	AV_100	ACC_90_CAV_10	ACC_50_CAV_50	CAV_100
S2	4,300	3,870	4,170	4,020	4,512	4,698	4,716
S3	6,200	5,670	5,748	6,048	6,012	6,834	6,846
S4	8,200	7,098	7,734	8,076	8,172	9,090	8,442
S5	10,250	9,102	9,654	10,224	10,698	11,664	11,640
S6	12,000	11,178	11,736	12,720	13,392	14,046	13,422
SW 3+1	*6,840*	*4,152*	*2,862*	*3,024*	*3,072*	*4,206*	*5,424*

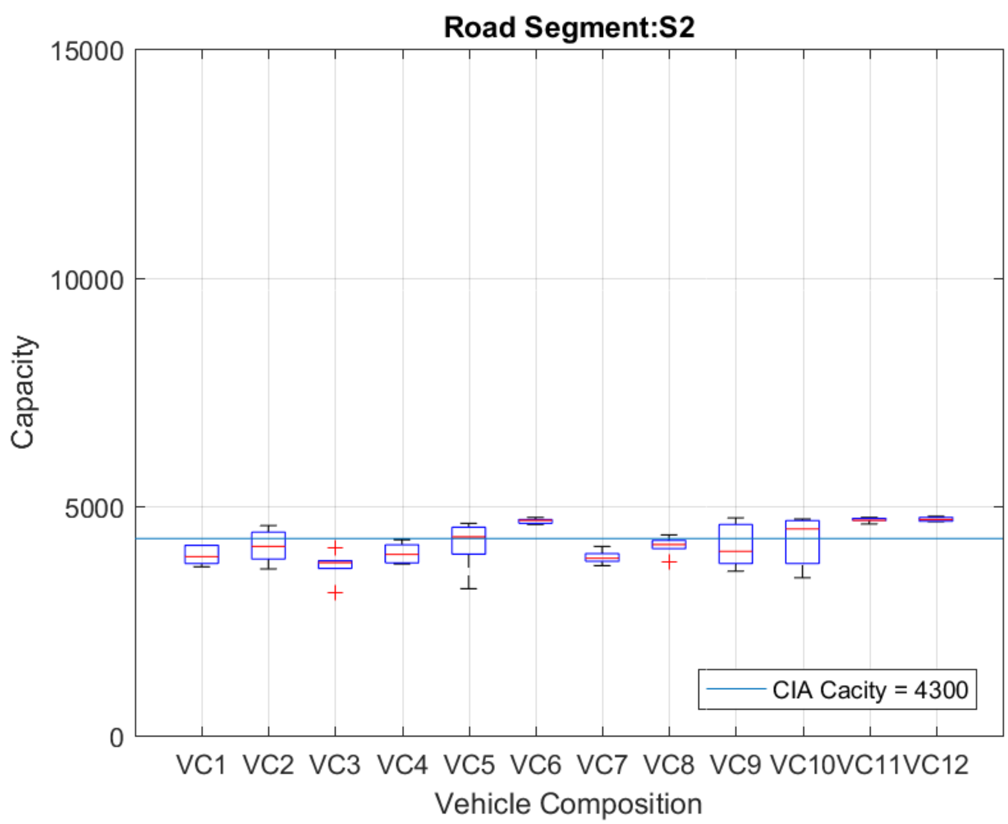


Figure 39: Capacity "Straight 2 lanes" Large test - intermediate results of Monte Carlo Simulation (

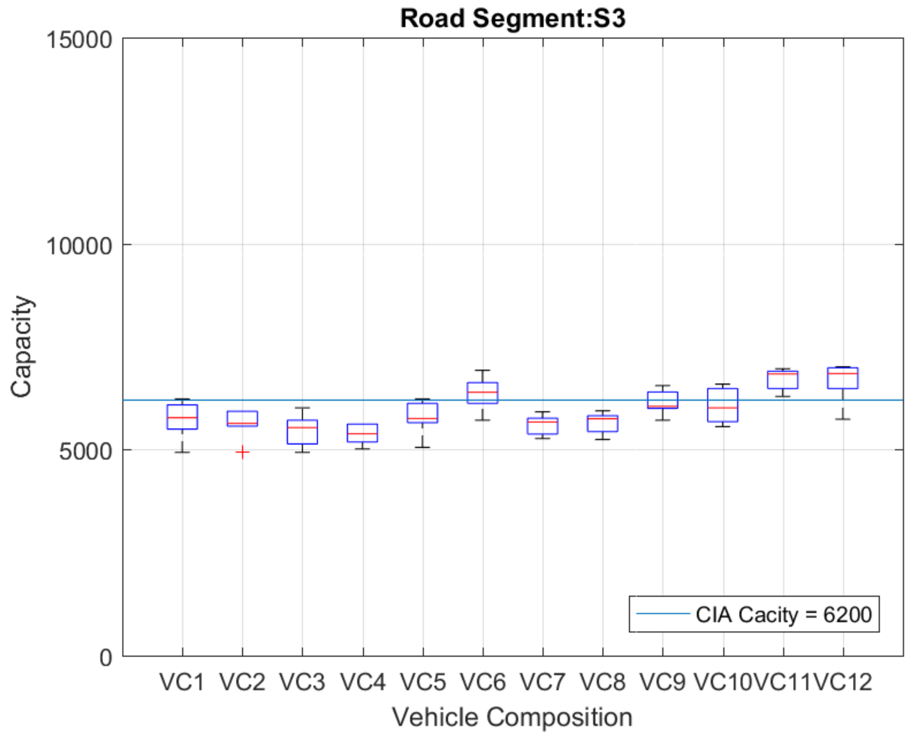


Figure 40: Capacity "Straight 3 lanes" Large test - intermediate results of Monte Carlo Simulation

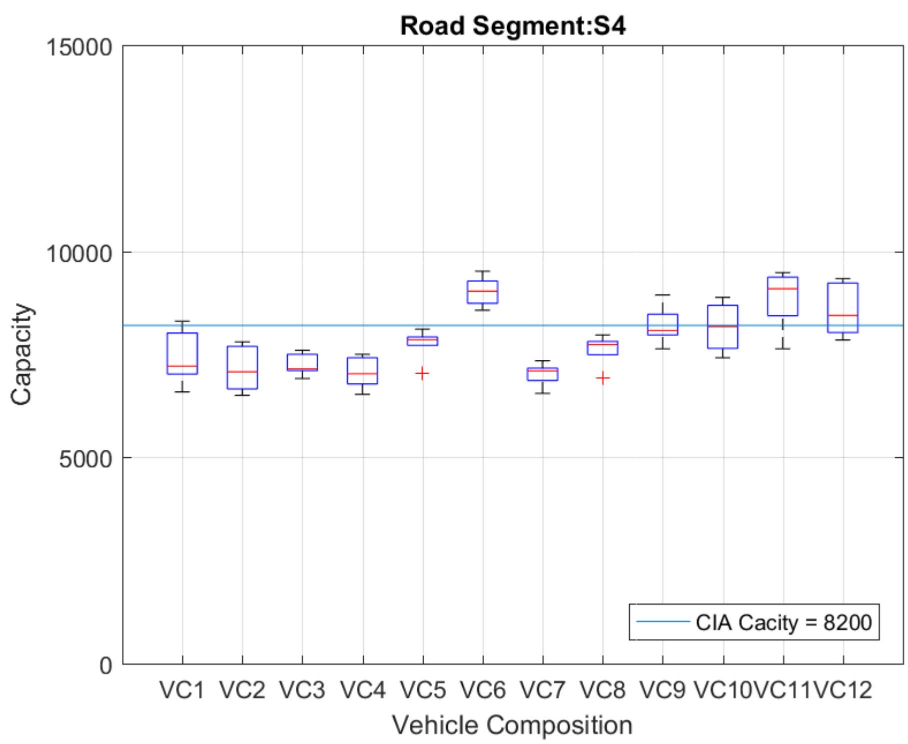


Figure 41: Capacity "Straight 4 lanes" Large test - intermediate results of Monte Carlo Simulation

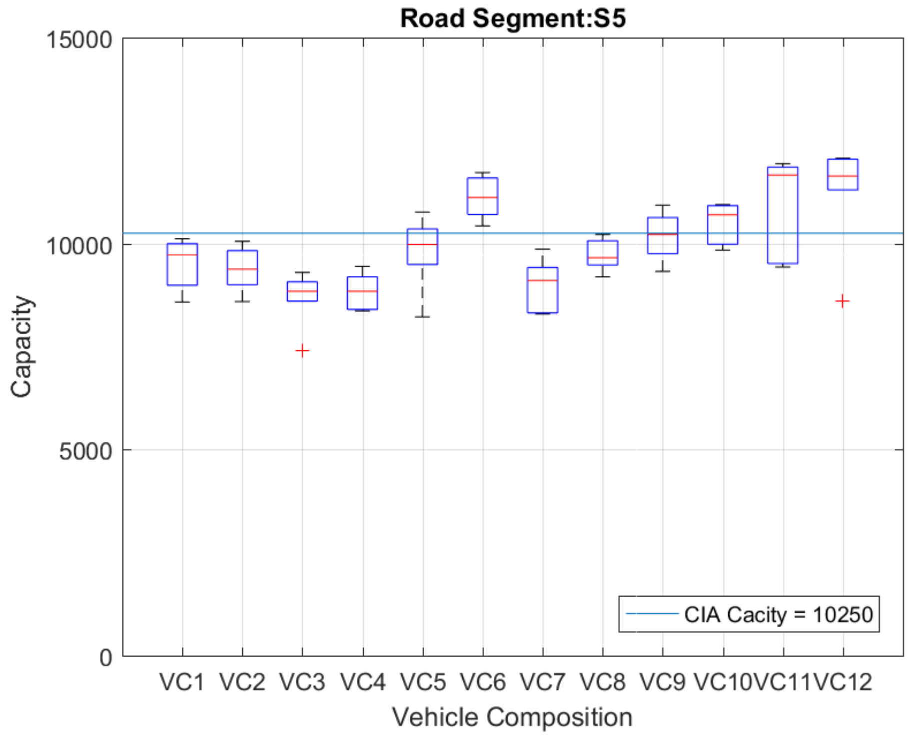


Figure 42: Capacity "Straight 5 lanes" Large test - intermediate results of Monte Carlo Simulation

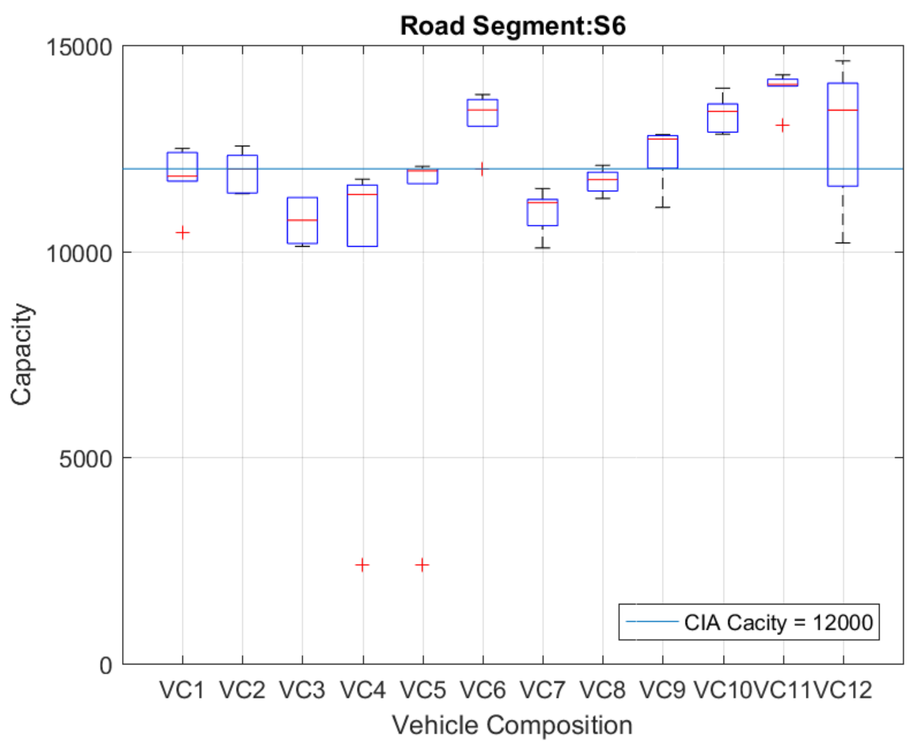


Figure 43: Capacity "Straight 6 lanes" Large test - intermediate results of Monte Carlo Simulation

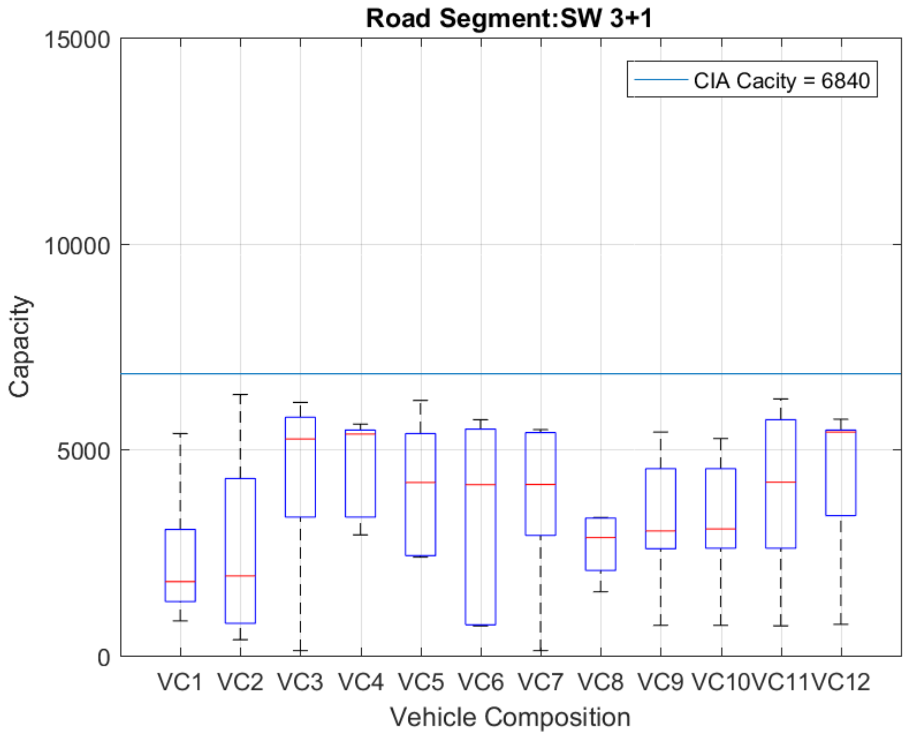


Figure 44: Capacity "Symmetric Weaving 3+1 lanes" Large test - intermediate results of Monte Carlo Simulation

[relaxation]

This unrealistic turbulence at the beginning of the modeled network has been addressed by adding road with fixed driving behavior (all vehicles exactly 85 km/h for the first 150 meters), then a transition (200 meters for straight road segments, see subsection 3.3.2) to go to their desired speed, as far as traffic conditions allow, to generate a more realistic traffic flow and next the part with detectors where traffic usually breaks down. This has been done in a similar fashion for a Symmetric Weaving section 3+1 (SW3+1), on-ramp, 3+1 to 3 lanes (OnR 3+1 > 3) and off-ramp, 3 to 3+1 lanes (OffR 3>3+1) as well. In order to test whether this recalibration results in more realistic results an extra simulation has been executed.

7.5.2 Calibration: Extra sim - Weaving and merging

Based on both visual observations of the model as well as the determined capacities (Table 45 new 0.6 and their corresponding boxplots in Figure 45 to Figure 47), Manual Slow, and therefore a desired speed distribution on the lower end of the expected spectrum, seems better in general than Manual Fast and is therefore chosen for final simulations.

However, a new problem arises for the latter three, in particular the weaving section. Vehicles tend to wait for a gap even for a necessary lane change and do no adjust their speed to find a gap further up- or downstream, so in the model vehicles mainly react instead of anticipate on surrounding traffic. This occasionally results in vehicles driving side-by-side blocking a necessary lane change and causing one or both vehicles to stop at the split (or and of the merging lane in case of the on-ramp). This gives both unrealistic driving behavior as well as significantly lower capacities. After studying this into detail, adjusting the value for the safety distance redactor factor, meaning adjusting the temporary (shorter) accepted headway for lane changes, has potential to improve calibration. Other studies (Baat, 2015; Bosdikou, 2017) suggest that a SDRF of 0.40 – 0.50 to as low as 0.05 – 0.20 are best to calibrate weaving sections.

Since, the latter values would mean time headways of less than 0.1 up to 0.3 seconds and this is considered very low, but lower values for the SDRF are promising, an extra simulation for the three segments with merging and diverging movements, with 12 random seeds each, is executed with a SDRF of 0.4, 0.2 and 0.1 to study whether adjusting lowering the SDRF improves the model (Table 45).

A Safety Distance Reduction Factor of 0.4 seems most promising. Though de Baat, amongst others, calibrate for the Dutch case for even a SDRF of 0.05 – 0.2, this seems highly unrealistic and does not necessary contribute to a better calibration in combination of other parameter values of this study. Therefore, a SDRF value of 0.4 in combination with the Slow desired speed distribution, is chosen as a second reference for the final simulations next to the 0.6 (default) with the Slow desired speed distribution to study whether this generates more realistic results for manual driving.

To see a first effect off automated and cooperative driving as well, the corresponding vehicle compositions are simulated as well (Table 46 and Table 47). First conclusions are that they show realistic effects on capacity. However, the sample size is still very limited and therefore many more random seeds are used during final simulations.

Table 45: Extra sim Capacities - SW 3+1, On-ramp and Off-ramp (Manual Driving, Slow and Fast)

		Manual Driving SLOW					Manual Driving FAST				
Segment Name	CIA Capacity	old 0.6	new 0.6	new 0.4	new 0.2	new 0.1	old 0.6	new 0.6	new 0.4	new 0.2	new 0.1
	Seeds per VC	*6*	*8*	*12*	*12*	*12*	*6*	*8*	*12*	*12*	*12*
SW 3+1	6840	1794	4602	6108	6240	6354	1932	4320	6006	5748	5754
On-Ramp-3+1-to-3	≤6200	-	5664	5436	6042	5226	-	5448	5436	5118	4950
Off-Ramp 3-to-3+1	≤6200	-	5880	6510	5556	6318	-	5694	6366	6438	6060

Table 46: Extra sim Capacities - SW 3+1, On-ramp and Off-ramp (ACC & CACC)

		ACC_100	ACC_90_CACC_10	ACC_50_CACC_50	CACC_100
Segment Name	CIA Capacity	new 0.6	new 0.6	new 0.6	new 0.6
	Seeds per VC	*8*	*8*	*8*	*8*
SW 3+1	6,840	5,250	4,950	4,704	5,016
On-Ramp-3+1-to-3	≤6,200	5,412	5,448	6,108	6,384
Off-Ramp 3-to-3+1	≤6,200	6,120	6,246	6,312	6,156

Table 47: Extra sim Capacities - SW 3+1, On-ramp and Off-ramp (AV and CAV)

		ACC_90 AV_10	ACC_50 AV_50	AV_100	ACC_90 CAV_10	ACC_50 CAV_50	CAV_100
Segment Name	CIA Capacity	new 0.6	new 0.6	new 0.6	new 0.6	new 0.6	new 0.6
	Seeds per VC	*8*	*8*	*8*	*8*	*8*	*8*
SW 3+1	6,840	4,938	5,226	4,674	4,812	5,022	5,034
On-Ramp-3+1-to-3	≤6,200	5,478	5,958	5,340	5,634	6,402	6,540
Off-Ramp 3-to-3+1	≤6,200	6,132	6,306	5,682	5,628	6,492	6,720

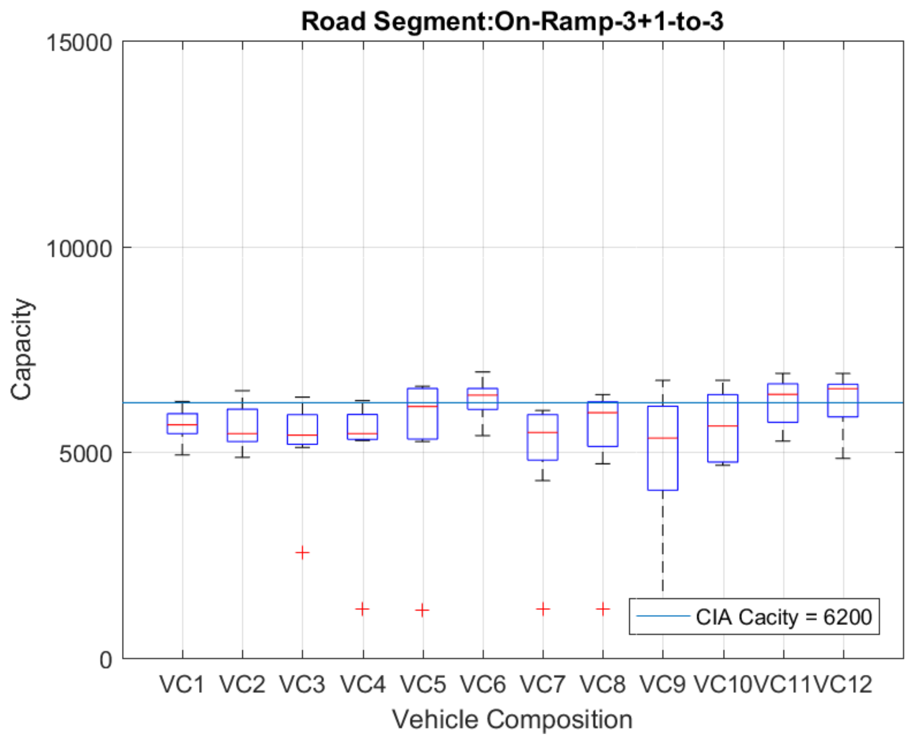


Figure 45: Capacity "On-Ramp 3+1 to 3 lanes" Extra sim - intermediate results of Monte Carlo Simulation

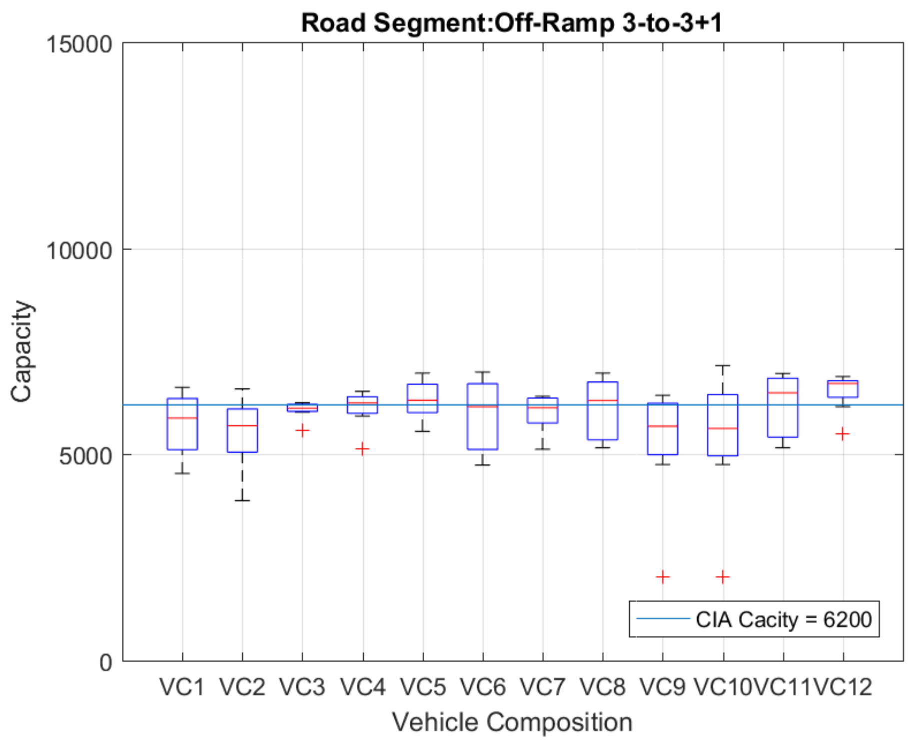


Figure 46: Capacity "Off-Ramp 3 to 3+1 lanes" Extra sim - intermediate results of Monte Carlo Simulation

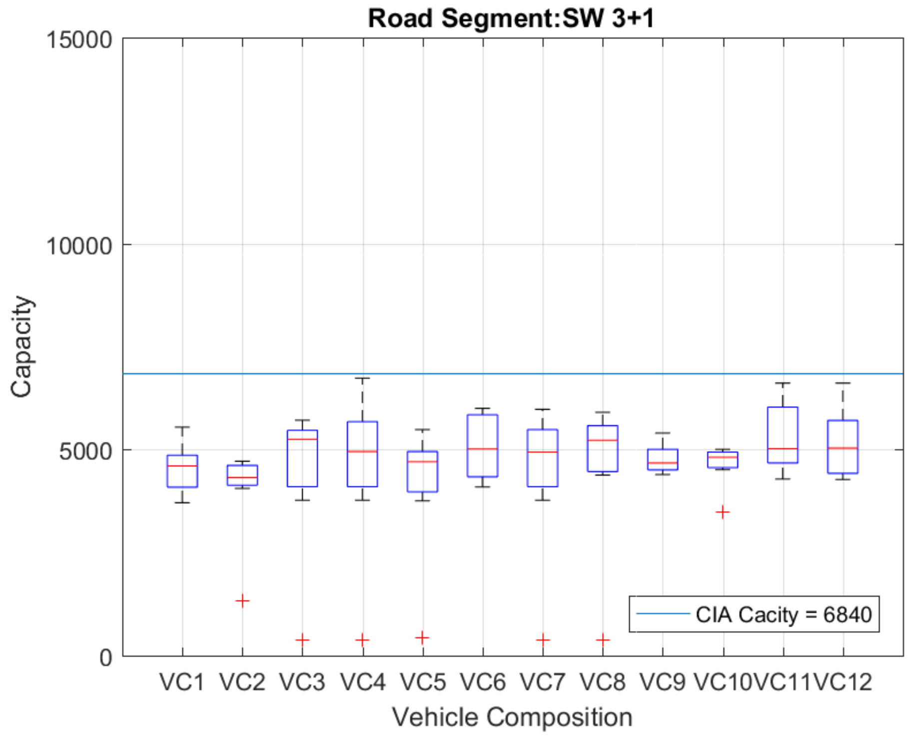


Figure 47: Capacity "Symmetric Weaving 3+1 lanes" Extra sim - intermediate results of Monte Carlo Simulation

7.5.3 Validation: Final Simulations

Vehicle lane distribution

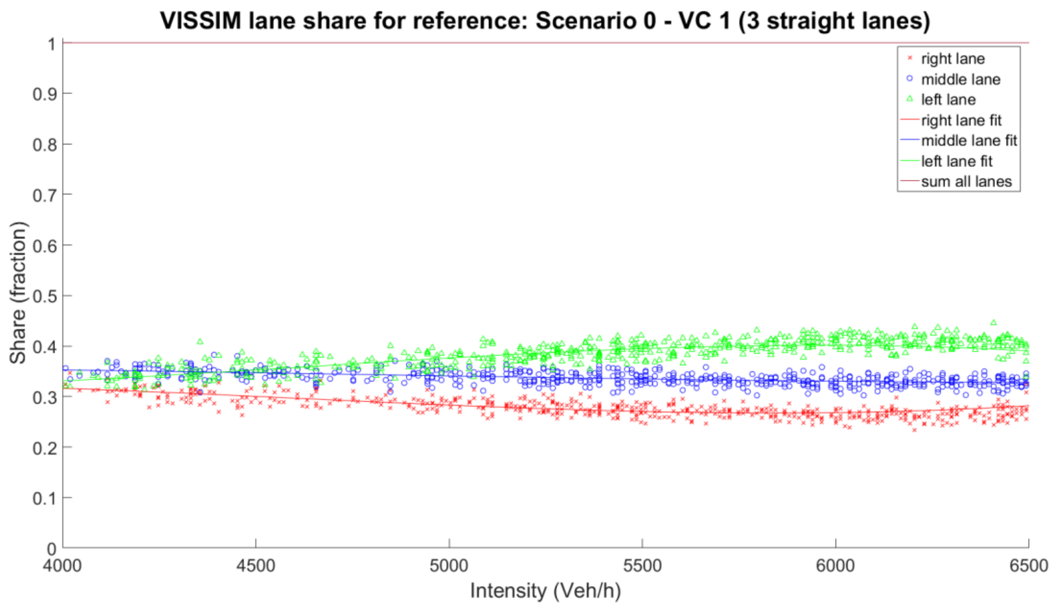


Figure 48: Modeled (VISSIM) vehicle lane distribution over 3 straight lanes per intensity for Scenario 0 (VC1) – Data points (1 per 5 minute interval) and fit

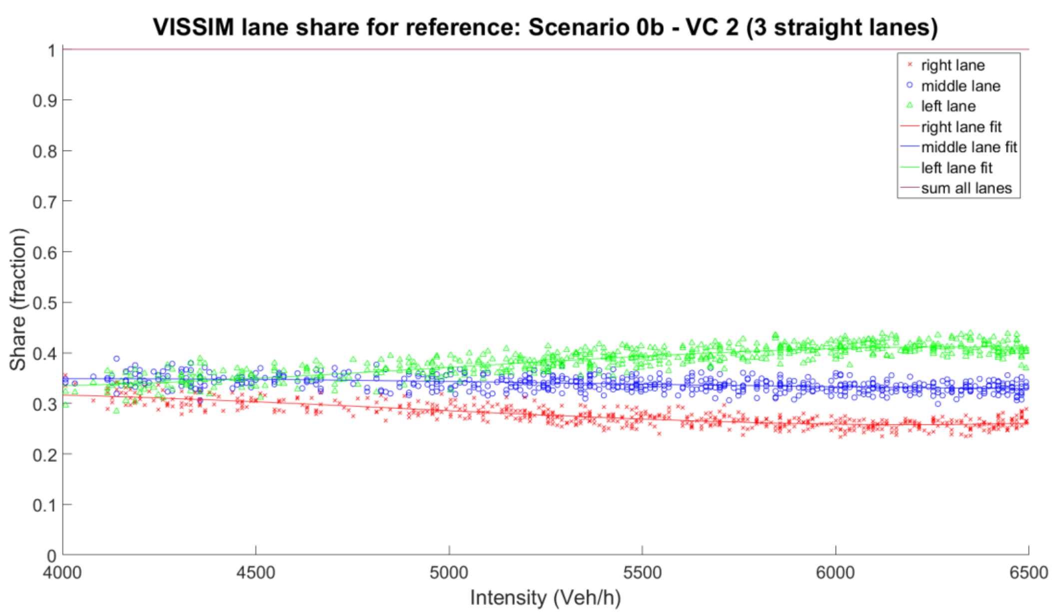


Figure 49: Modeled (VISSIM) vehicle lane distribution over 3 straight lanes per intensity for Scenario 0b (VC2) – Data points (1 per 5 minute interval) and fit

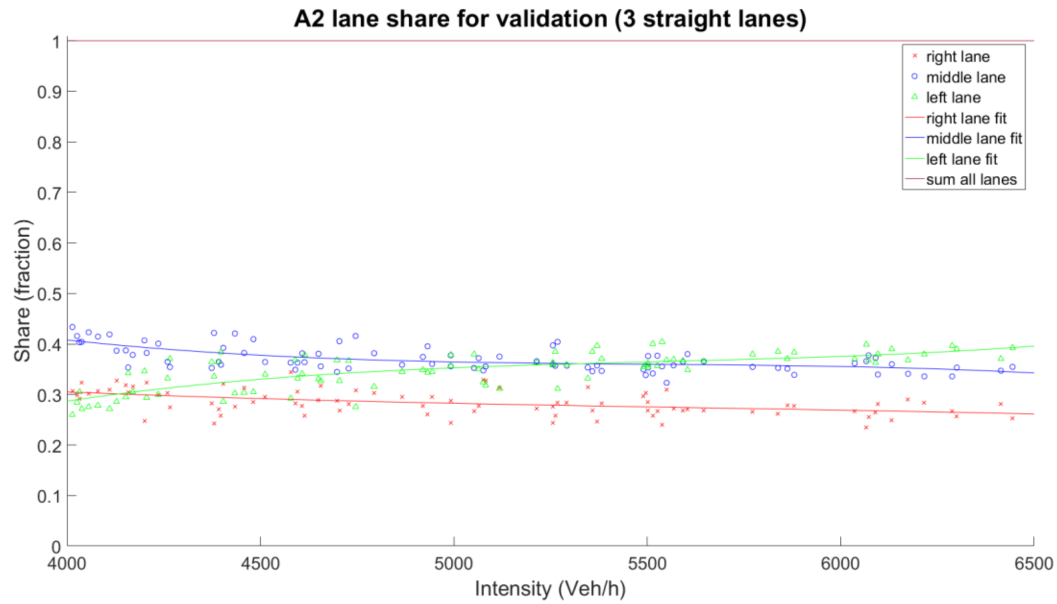


Figure 50: Measured vehicle lane distribution over 3 straight lanes per intensity for A2 – Data points (1 per 5 minute interval) and fit

Mean Speed

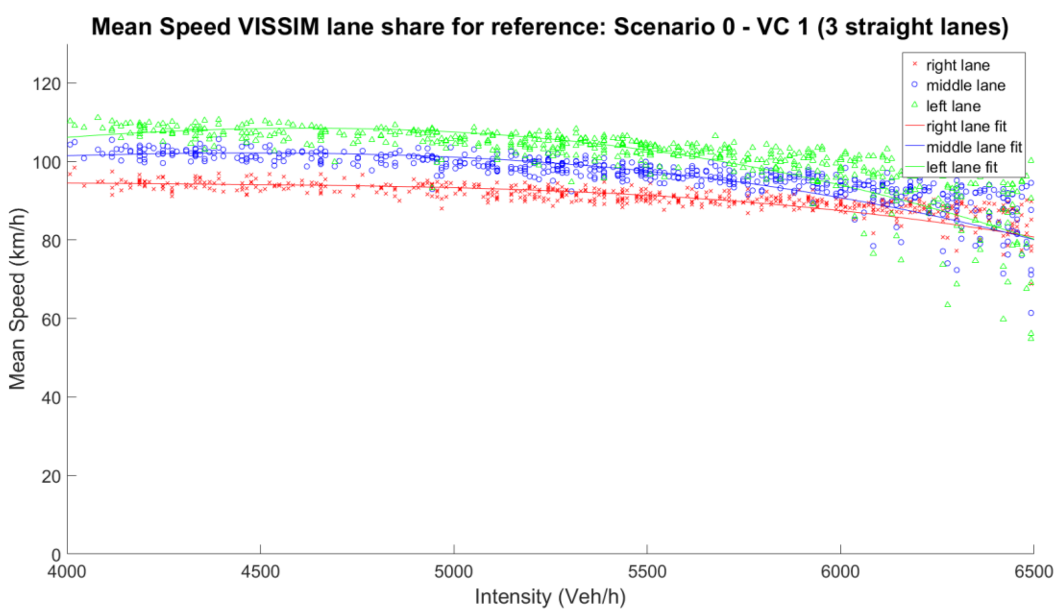


Figure 51: Modeled Mean Speed (VISSIM) Scenario 0 (VC1) for 3 straight lanes – Data points (1 per 5 minute interval) and fit

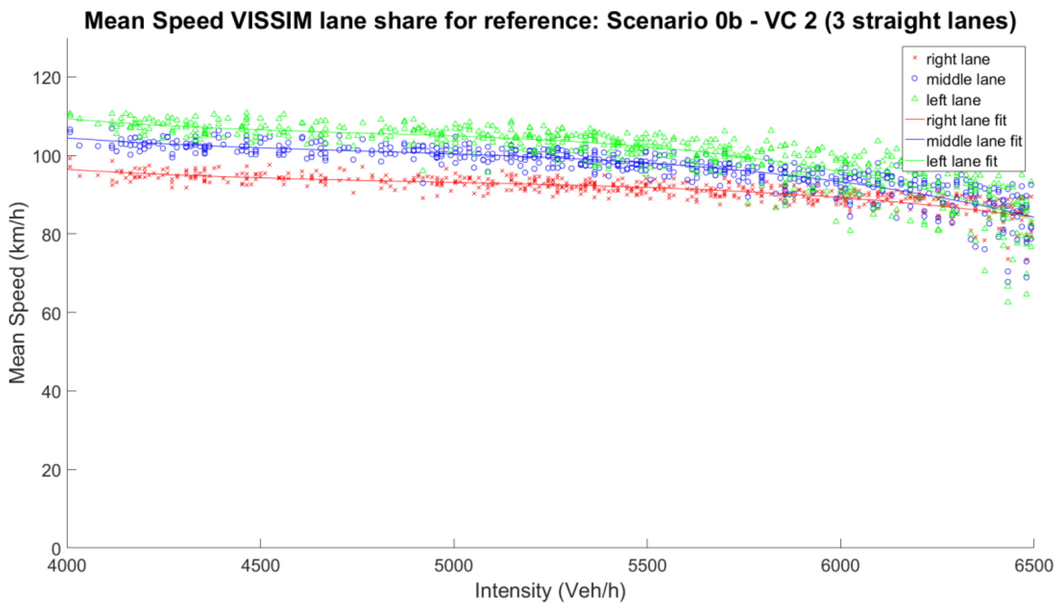


Figure 52: Modeled Mean Speed (VISSIM) Scenario 0b (VC2) for 3 straight lanes– Data points (1 per 5 minute interval) and fit

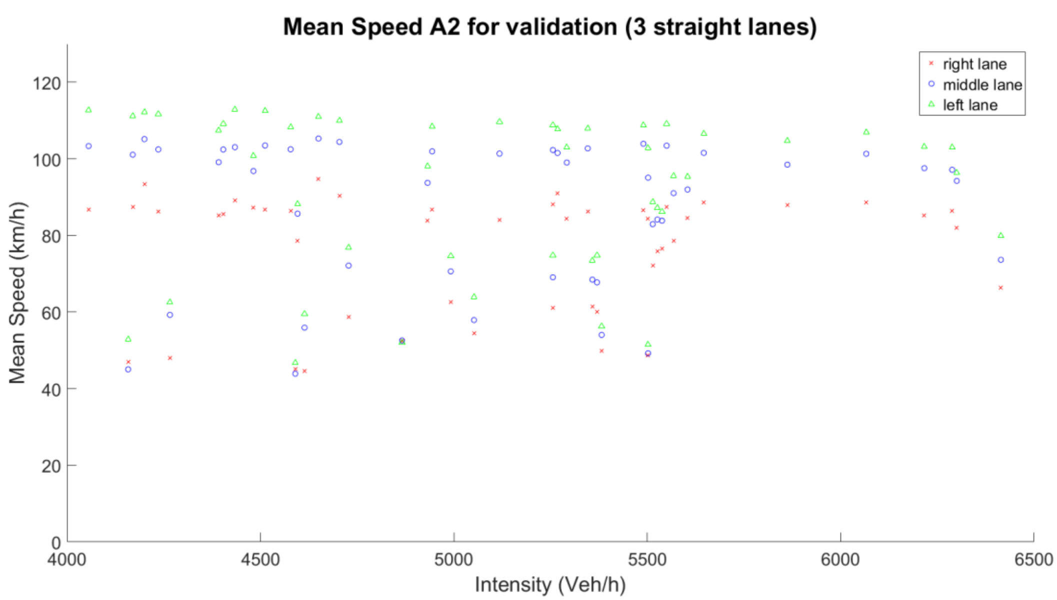


Figure 53: Measured Mean Speed (A2) – Data points (1 per 5 minute interval)

7.5.4 Results – Figures (4, 5 and 6 straight lanes) Final Simulations

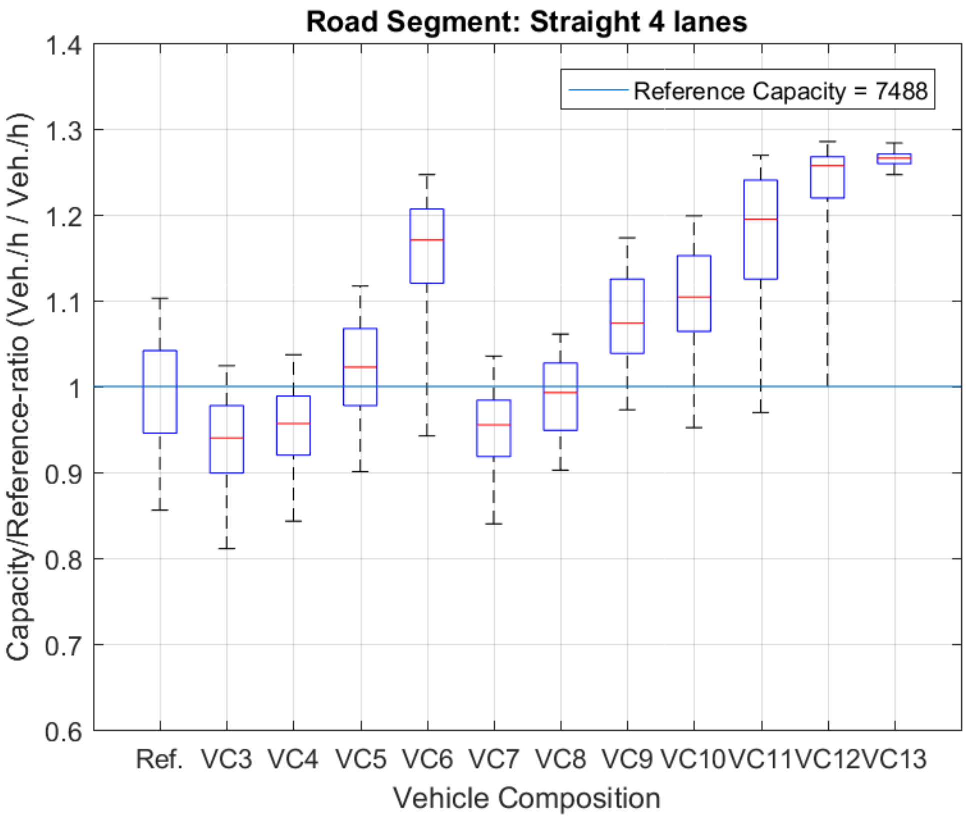


Figure 54: Straight 4 lanes - Capacities (relative to CIA) per Vehicle Composition (100 simulations per VC)

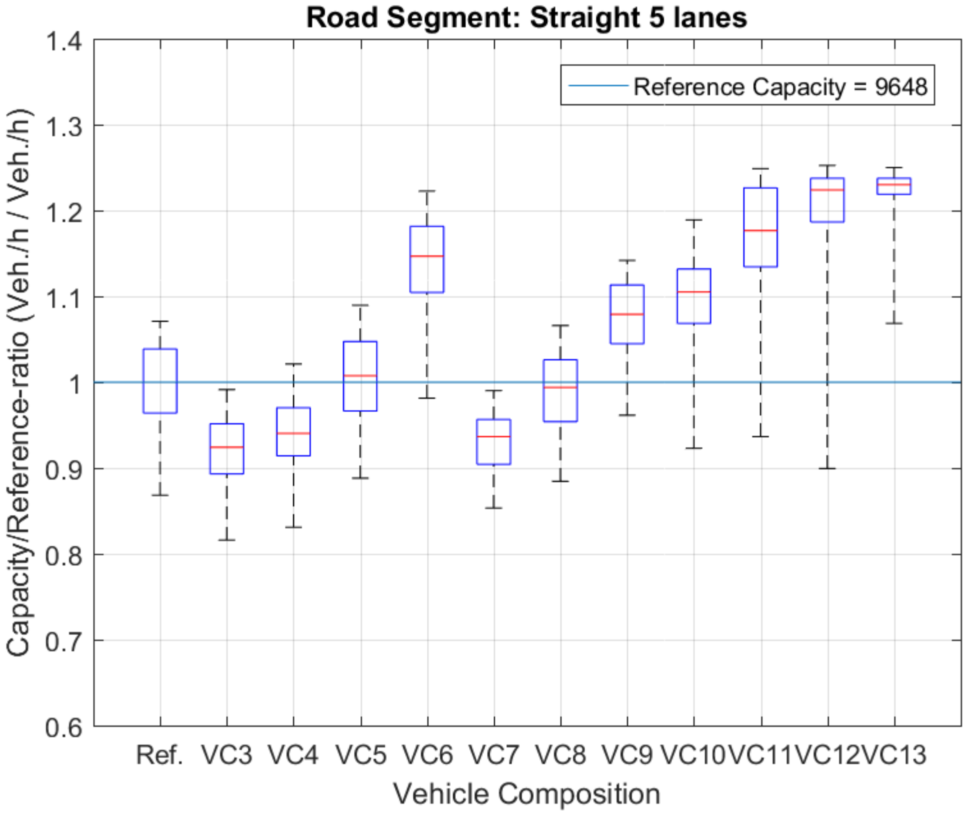


Figure 55: Straight 5 lanes - Capacities (relative to CIA) per Vehicle Composition (100 simulations per VC)

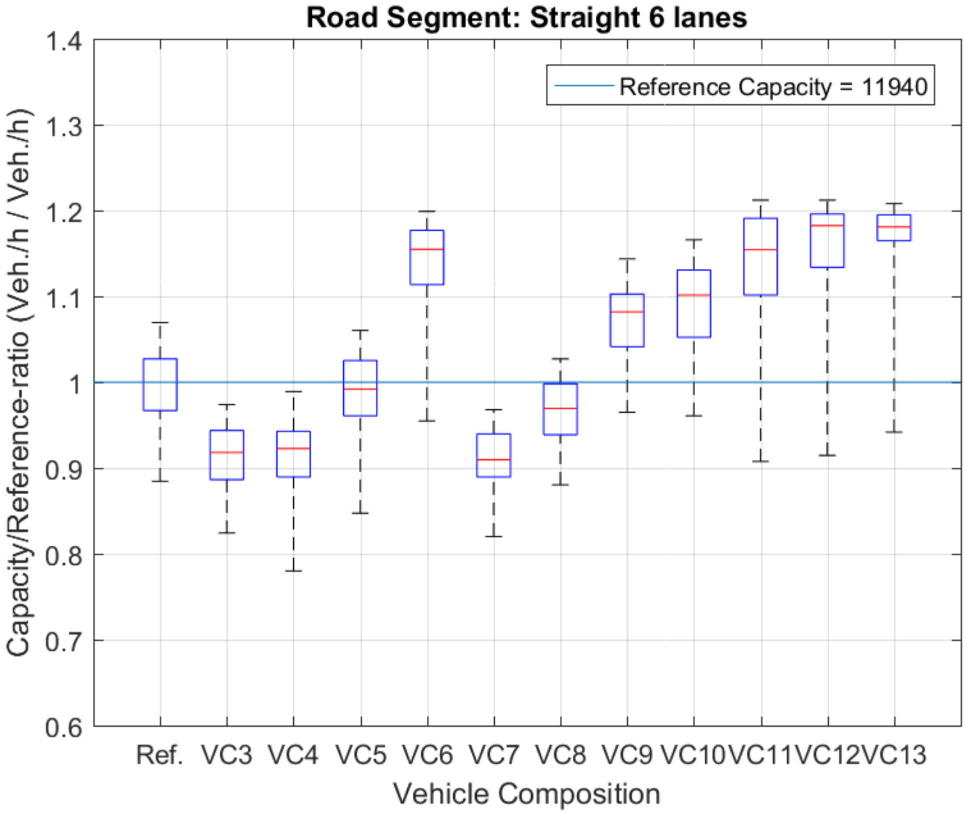


Figure 56: Straight 6 lanes - Capacities (relative to CIA) per Vehicle Composition (100 simulations per VC)

7.6 APPENDIX F: MATLAB SCRIPT - "RUN VISSIM"

The script to control VISSIM via the COM-interface has run 13 times for the final results to do a total of 1300 simulations of 100 random seeds for each of the 13 vehicle compositions resulting in a total of over 3.5 days net run time and produced about 100 GB of VISSIM output data in text format (;-separated) for the data collection points and lane changes combined (Table 48). The full code of this script can be found in de script attachment, script I.

Table 48: Run time of final VISSIM simulations

Vehicle Composition	Run Time	Random Seeds	Total File Size (.mer &.spw: txt)
VC 1	6h 27m	100	7.58 GB
VC 2	5h 30m	100	7.94 GB
VC 3	6h 26m	100	7.03 GB
VC 4	7h 1m	100	7.15 GB
VC 5	5h 52m	100	7.54 GB
VC 6	6h 57m	100	7.89 GB
VC 7	5h 38m	100	7.12 GB
VC 8	7h 16m	100	7.42 GB
VC 9	6h 0m	100	7.69 GB
VC 10	6h 51m	100	7.75 GB
VC 11	6h 27m	100	7.98 GB
VC 12	8h 40m	100	8.22 GB
VC 13	6h 46m	100	8.16 GB
Total	3d 13h 51m	1300	99.47 GB

7.7 Appendix G: Alteryx Data preparation

7.7.1 Data Preparation - Data Collection Points (to determine capacities)

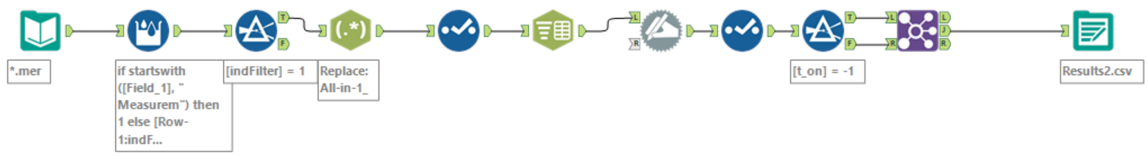


Figure 57: Alteryx data preparation of data collection points data workflow

Steps:

- Load .mer files (text output of VISSIM)
- Add column with “1” for data rows, “0” for other rows.
- Remove non-data rows
- Delete All-in-1_from file name (number of random seed stays)
- Remove “1” column
- Split ; separated column into multiple columns
- Transform row 1 into column headers
- Select desired data columns (all other data columns are removed)
- Split lines with entry on detector from lines with exit data in 2 data sets
- Merge entry and exit data on same line
- Save to csv file

Memory usage 13-13.5 / 16 GB

Final Net Run time: 2h 49m 38s
In total the net run time to prepare the data collection point data to determine capacities is 2 hours, 49 minutes and 38 seconds to convert 1200 (100 random seeds for each of 12 vehicle compositions) .mer VISSIM output files totaling 15.56 GB of text to 1 csv-file of 3.55 GB.

Table 49: Final Run time of Alteryx Data Preparation of detectors

Vehicle Composition	**Random Seed numbers**	**Amount of Random Seeds**	**Run Time**	**Total File Size (before, .mer text-file)**	**Total File Size (after, csv-file)**
VC 1	1-50	50	7m 00s	3.14 GB	729 MB
	51-100	50	7m 01s	3.15 GB	732 MB
VC 2	1-50	50	7m 15s	3.14 GB	728 MB
	51-100	50	7m 20s	3.14 GB	731 MB
VC 3	1-50	50	6m 32s	3.04 GB	707 MB
	51-100	50	7m 03s	3.04 GB	709 MB
VC 4	1-50	50	6m 50s	3.07 GB	715 MB
	51-100	50	6m 58s	3.07 GB	718 MB
VC 5	1-50	50	7m 17s	3.17 GB	736 MB
	51-100	50	7m 29s	3.17 GB	739 MB
VC 6	1-50	50	7m 44s	3.20 GB	737 MB
	51-100	50	6m 55s	3.20 GB	740 MB
VC 7	1-50	50	6m 39s	3.06 GB	713 MB
	51-100	50	6m 46s	3.06 GB	716 MB
VC 8	1-50	50	7m 36s	3.15 GB	732 MB
	51-100	50	7m 17s	3.16 GB	735 MB
VC 9	1-50	50	7m 24s	3.19 GB	737 MB
	51-100	50	7m 19s	3.19 GB	741 MB
VC 10	1-50	50	7m 08s	3.19 GB	738 MB
	51-100	50	7m 06s	3.19 GB	741 MB
VC 11	1-50	50	7m 14s	3.20 GB	738 MB
	51-100	50	7m 01s	3.20 GB	741 MB
VC 12	1-50	50	6m 12s	3.20 GB	735 MB
	51-100	50	6m 32s	3.20 GB	738 MB
VC 13	1-50	50	6m 20s	3.20 GB	699 MB
	51-100	50	6m 53s	3.20 GB	702 MB
Total	**13* 1-100**	**1300**	**3h 02m 51s**	**81.92 GB**	**18.66 GB**

7.7.2 Data preparation - Lane Changes

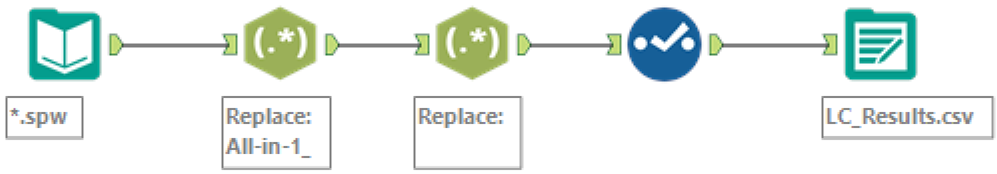


Figure 58: Alteryx data preparation of lane change data workflow

Steps:

- Load .spw files text output of VISSIM) and exclude first 10 rows with simulation info (non-data rows)
- Delete All-in-1_from file name (number of random seed stays)
- Remove spaces
- Select desired data columns (all other data columns are removed)
- Save to csv file

Memory usage 9.5-11.2 / 16 GB

In total the net run time to prepare the lane change data is 9 minutes and 34 seconds to convert 1200 (100 random seeds for each of 12 vehicle compositions) .spw VISSIM output files containing nearly 113 million lane changes, totaling 15.56 GB of text to 1 csv-file of 3.55 GB.

Table 50: Final Run time of Alteryx Data Preparations of lane changes

Vehicle Composition	Random Seeds	Run Time	Total number of lane changes	Total File Size Before (spw text-file)	Total File Size Afterwards (csv-file)
VC 1	100	51s	9,323,437	1.29 GB	293 MB
VC 2	100	53s	10,882,039	1.51 GB	341 MB
VC 3	100	34s	6,937,290	956 MB	218 MB
VC 4	100	35s	7,265,655	1.00 GB	228 MB
VC 5	100	41s	8,671,271	1.12 GB	272 MB
VC 6	100	51s	10,812,055	1.50 GB	340 MB
VC 7	100	36s	7,164,005	988 MB	225 MB
VC 8	100	42s	8,060,350	1.11 GB	253 MB
VC 9	100	57s	9,461,926	1.31 GB	297 MB
VC 10	100	52s	9,858,307	1.37 GB	310 MB
VC 11	100	57s	11,365,234	1.58 GB	357 MB
VC 12	100	01m 05s	13,090,494	1.82 GB	411 MB
VC 13	100	1m 44s	12,692,462	1.77 GB	399 MB
Total	**1300 (13*100)**	11m 18s	125,584,525	17.32 GB	3.944 GB

7.8 APPENDIX H: MATLAB SCRIPTS - DETERMINE CAPACITY

Originally the script used to determine capacity addressed all vehicle compositions together. However this was at the edge of the computational power and available memory of the used computer[37]. This script (subsection 7.8.1) is used for the first large test (12 VC, 6 RS per VC for 2-6 lanes + SW3+1) as well as the following tests with adjusted Vehicle input (12 VC, 8 RS per VC for SW3+1, On-Ramp 3+1 to 3 lanes and Off-Ramp 3 to 3+1 lanes) and optimizations weaving and merging optimizations (2 VC * 3 adjusted safety distance reduction factor , 12 RS per VC for SW3+1, On-Ramp 3+1 to 3 lanes and Off-Ramp 3 to 3+1 lanes). Since the total of 72, 96 and 72 runs respectively produced a large amount of data and required all available memory (16GB) the script had to be rewritten in order to process the data of the final 1300 runs (13 VC, 100 RS per VC).

7.8.1 Determine capacity - Intermediate results script

This script has been used to determine the capacity of intermediate results during calibration. Run time has not been logged during calibration, but many hours of net calculation time have been used by this script. The full code of this script can be found in de script attachment, script III.1.

[37] HP Pavilion 15-bc035nd with an Intel Core i7-6700HQ and 16 GB memory, running on Windows 10, 64 bit.

7.8.2 Determine capacity – Final results script

The script to determine capacity has run 26 times for the final results to process 1300 simulations of 100 random seeds for each of the 13 vehicle compositions resulting in a total of about 12 hours net run time (Table 51). The full code of this script can be found in de script attachment, script III.2.

Table 51: Run time of the Determine capacity MATLAB script

Vehicle Composition	Random Seed numbers	Amount of Random Seeds	Run Time
VC 1	1-50	50	29m 38s
	51-100	50	30m 07s
VC 2	1-50	50	29m 29s
	51-100	50	29m 59s
VC 3	1-50	50	27m 49s
	51-100	50	28m 30s
VC 4	1-50	50	28m 18s
	51-100	50	26m 01s
VC 5	1-50	50	29m 35s
	51-100	50	26m37s
VC 6	1-50	50	27m 39s
	51-100	50	26m 51s
VC 7	1-50	50	25m 40s
	51-100	50	25m 45s
VC 8	1-50	50	25m 10s
	51-100	50	26m 15s
VC 9	1-50	50	26m 29s
	51-100	50	25m 45s
VC 10	1-50	50	26m 04s
	51-100	50	25m 56s
VC 11	1-50	50	28m 32s
	51-100	50	26m 11s
VC 12	1-50	50	29m 05s
	51-100	50	27m 00s
VC 13	1-50	50	30m 26s
	51-100	50	26m 25s
Total		**1300 (13*100)**	**11h 55m 16s**

7.8.3 Determine capacity – Combine VC Results script

This script combines the results when multiple vehicle combinations have been processed separately in the detcap_many_per_VC.m script. Run time is neglectable. The full code of this script can be found in de script attachment, script III.3.

7.8.4 Determine capacity – Present results script

This script reorders, summarizes and presents the results determined by the determine capacity script of the final results, outcomes are shown in chapter 5. Run time is neglectable. The full code of this script can be found in de script attachment, script III.4.

7.9 Appendix I: MATLAB script - lane change analyzation

This script is used to determine total lane changes main section of each road segment. It loads the csv-files produced by Alteryx (Appendix G) and saves bar charts to .png-files and tables to .xlsx-files.
The final run time of this script is approximately 5 minutes to process lane change data of 1300 simulations (13 Vehicle Compositions * 100 Random Seeds) of 3600 simulated seconds per simulation from any to any adjacent lane. The script processes all 8 road segments but only lane changes of the On-Ramp, Off-Ramp and Symmetric Weaving Section are analyzed. MATLAB used a maximum of about 3.2 GB of memory during running this script.

The full code of this script can be found in de script attachment, script IV.

7.10 Appendix J: MATLAB scripts – Validation and Analysis

For Validation as well as the Analysis the same two scripts have been used: one for calculation and one to present the outcomes in figures.

7.10.1 Validation and Analysis - Calculation

This script loads the same .csv-files produced by Alteryx as the scripts to determine capacity (containing detector data). Per VC it loads the csv-file holding data of 50 simulations and then determines four aspects which describe elements of how traffic is flowing:

- Lane shares
- Lane intensities
- Mean Speeds of interval
- Standard Deviation of Speeds within interval

Each of these four are:

- Per lane
- Per 5-minute interval
- Relative to total intensity

This results in a .mat-file holding data of 50 simulations. In each .mat-file 3 matrices (Mean Speeds, SD Speeds and Intensities[38]) and a variable for processing time are saved. This means 26 .mat-files for 13 VC in total. Table 52 shows that creating mentioned .mat-files took a net run time of over an hour.

[38] Lane shares (as a fraction of total intensity) and Lane Intensities can be derived from the same matrix.

Table 52: Final Run time of MATLAB Validation and Analysis Calculation

Vehicle Composition	Random Seed numbers	Amount of Random Seeds	Run Time
VC 1	1-50	50	2m 54s
	51-100	50	2m 49s
VC 2	1-50	50	2m 48s
	51-100	50	2m 47s
VC 3	1-50	50	3m 08s
	51-100	50	3m 10s
VC 4	1-50	50	2m 46s
	51-100	50	2m 43s
VC 5	1-50	50	2m 51s
	51-100	50	3m 02s
VC 6	1-50	50	3m 13s
	51-100	50	3m 16s
VC 7	1-50	50	2m 47s
	51-100	50	2m 43s
VC 8	1-50	50	2m 52s
	51-100	50	2m 50s
VC 9	1-50	50	3m 18s
	51-100	50	2m 58s
VC 10	1-50	50	2m 41s
	51-100	50	2m 42s
VC 11	1-50	50	2m 43s
	51-100	50	2m 44s
VC 12	1-50	50	3m 04s
	51-100	50	3m 05s
VC 13	1-50	50	3m 06s
	51-100	50	3m 02s
Total		**1300 (13*100)**	**1h 16m 02s**

The full code of this script can be found in the script attachment, script V.1.

7.10.2 Validation and Analysis – Present script

This script makes figures of the data stored in the .mat-files created by the calculation script and saves them to .png-files. For the final simulations, there are 832 figures created and saved (8*13*4*2):

- 8 Road Segments
- 13 Vehicle Compositions
- 4 traffic aspects (Lane shares, Lane Intensities, Means Speed, SD Speeds)
- 2 (With and without congestion filtered)

Creating and saving all figures takes approximately half an hour. The full code of this script can be found in de script attachment, script V.2.

7.11 APPENDIX K: OVERVIEW TRAFFIC CONDITIONS OF 100% VEHICLE COMPOSITIONS (STRAIGHT ROAD SEGMENTS)

7.11.1 Lane share and Mean Speed of 100% scenarios (2 straight lanes)

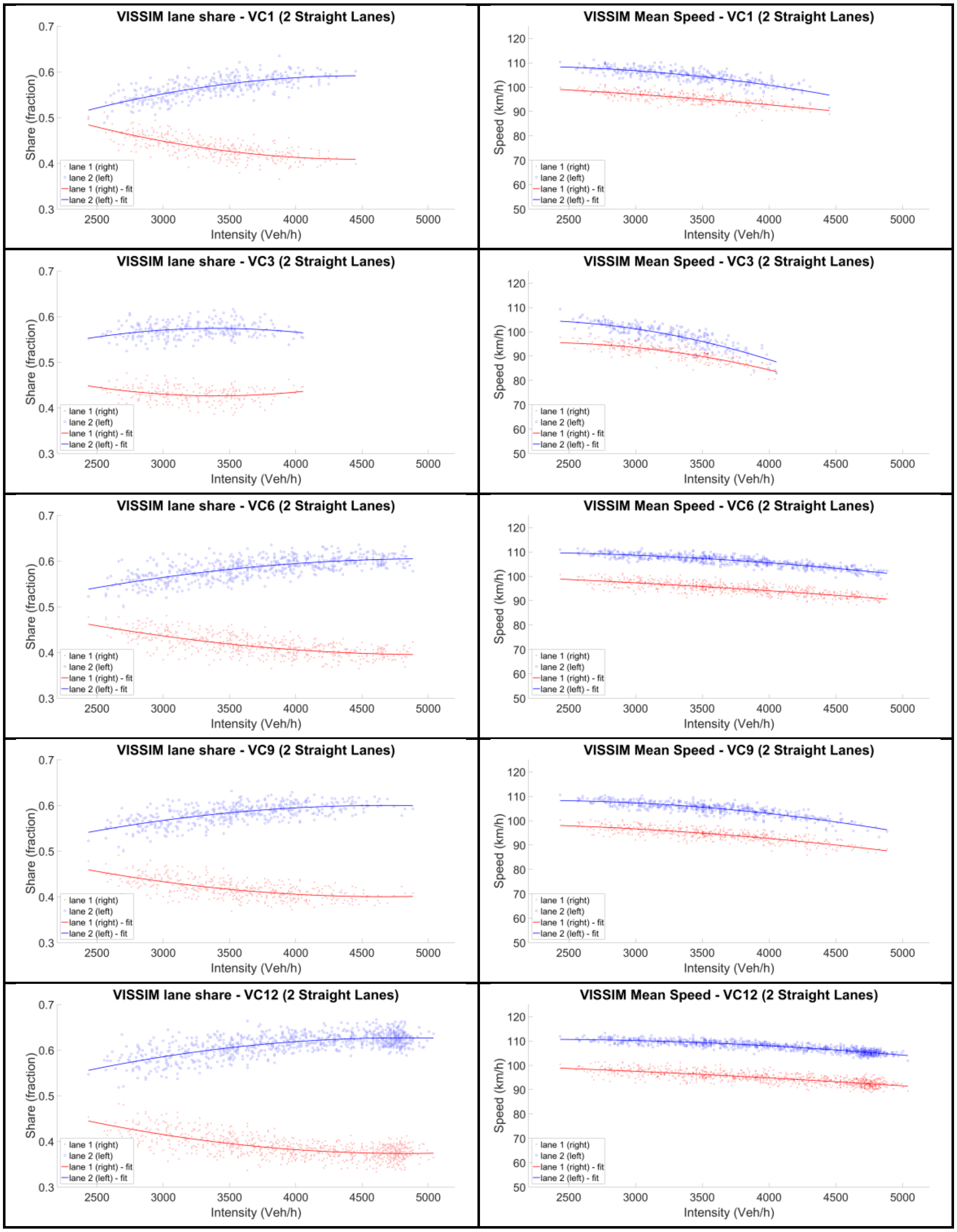


Figure 59: Lane shares and mean speed of 100% scenarios for 2 straight lanes (Each data point represents 5 minutes) – Congestion filtered

7.11.2 Lane share and Mean Speed of 100% scenarios (4 straight lanes)

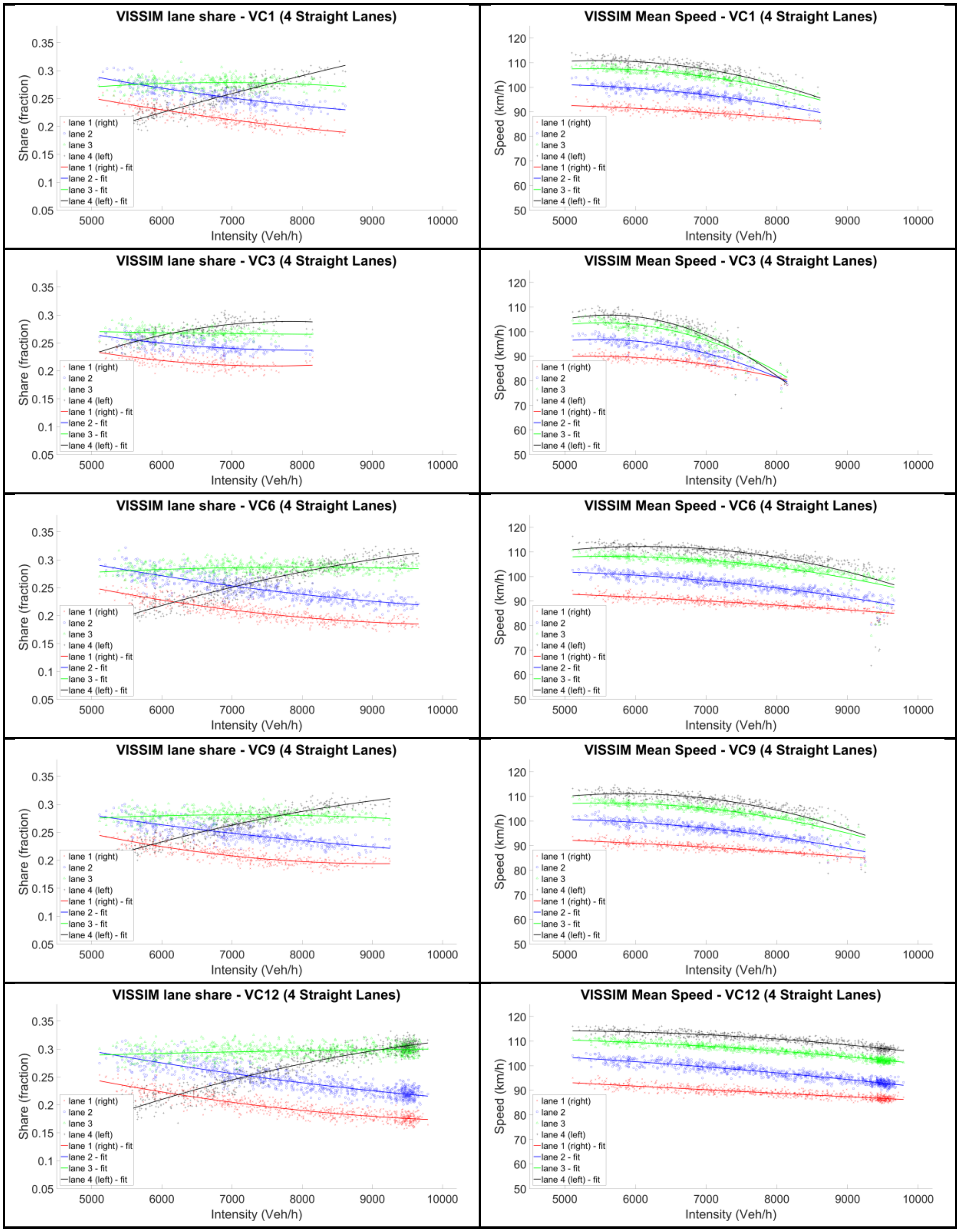


Figure 60: Lane shares and mean speed of 100% scenarios for 4 straight lanes (Each data point represents 5 minutes) – Congestion filtered

7.11.3 Lane share and Mean Speed of 100% scenarios (5 straight lanes)

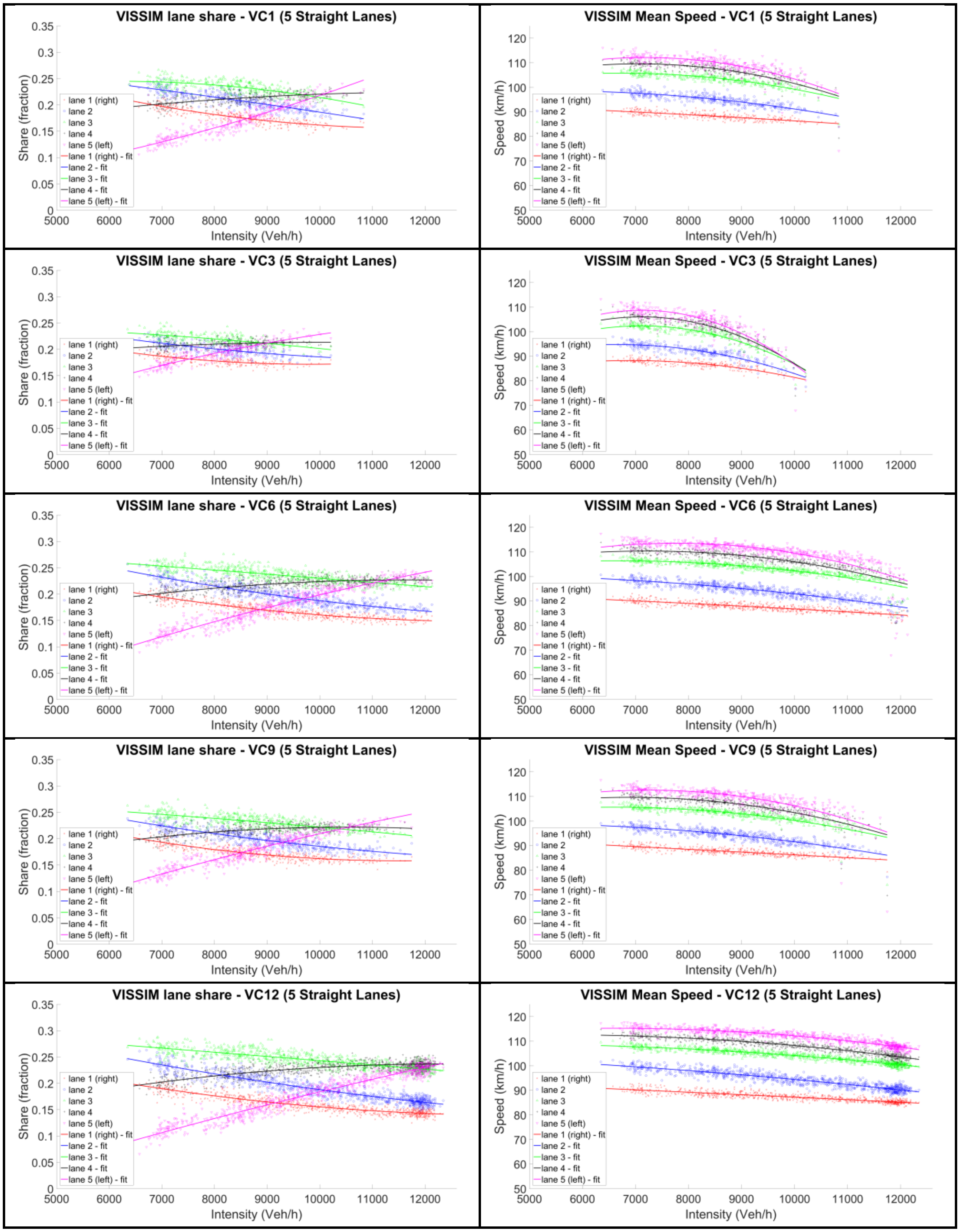


Figure 61: Lane shares and mean speed of 100% scenarios for 5 straight lanes (Each data point represents 5 minutes) – Congestion filtered

7.11.4 Lane share and Mean Speed of 100% scenarios (6 straight lanes)

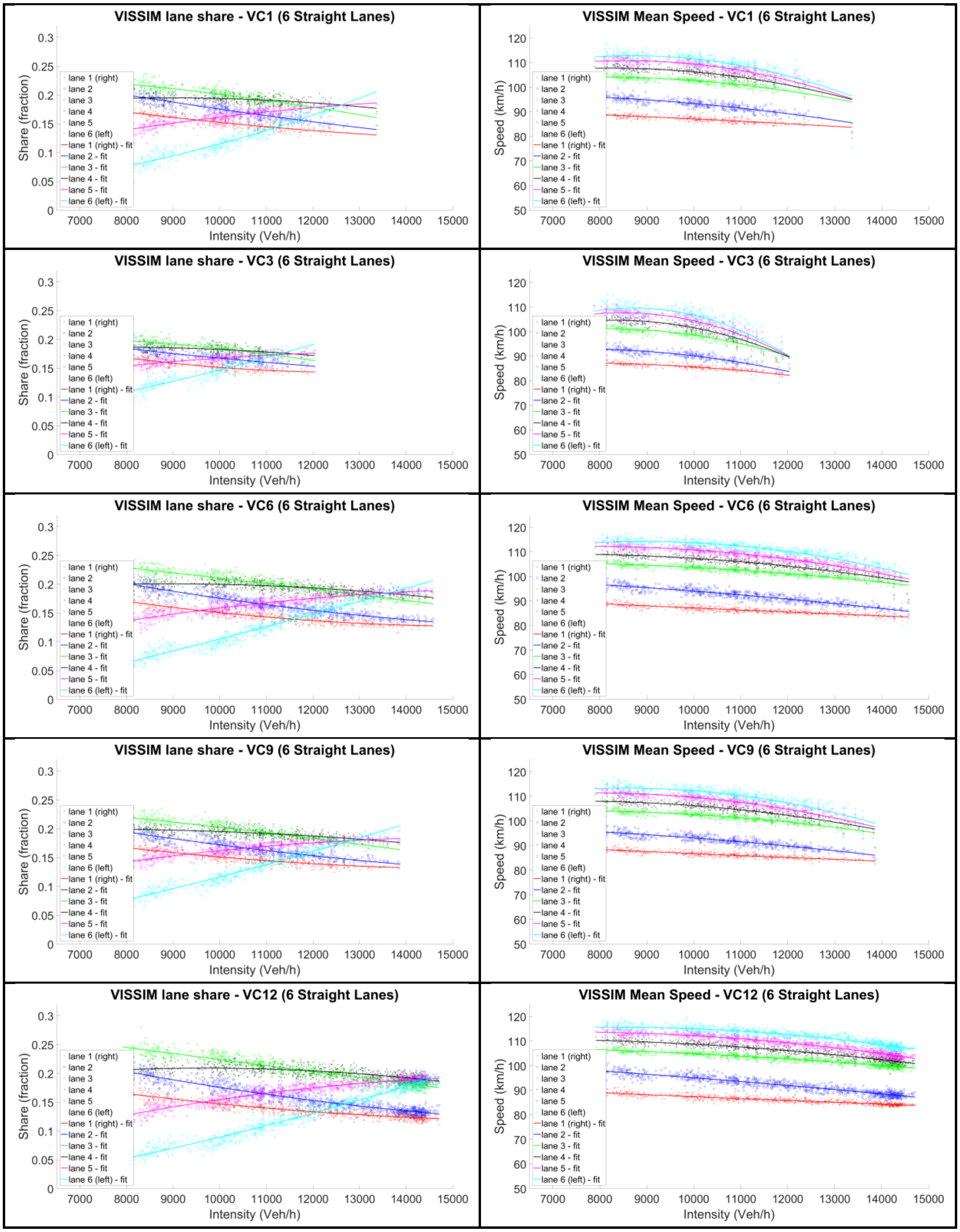


Figure 62: Lane shares and mean speed of 100% scenarios for 6 straight lanes (Each data point represents 5 minutes) – Congestion filtered

7.12 Appendix L: Overview traffic conditions of 100% Vehicle Compositions (On-Ramp)

7.12.1 Lane share On-Ramp

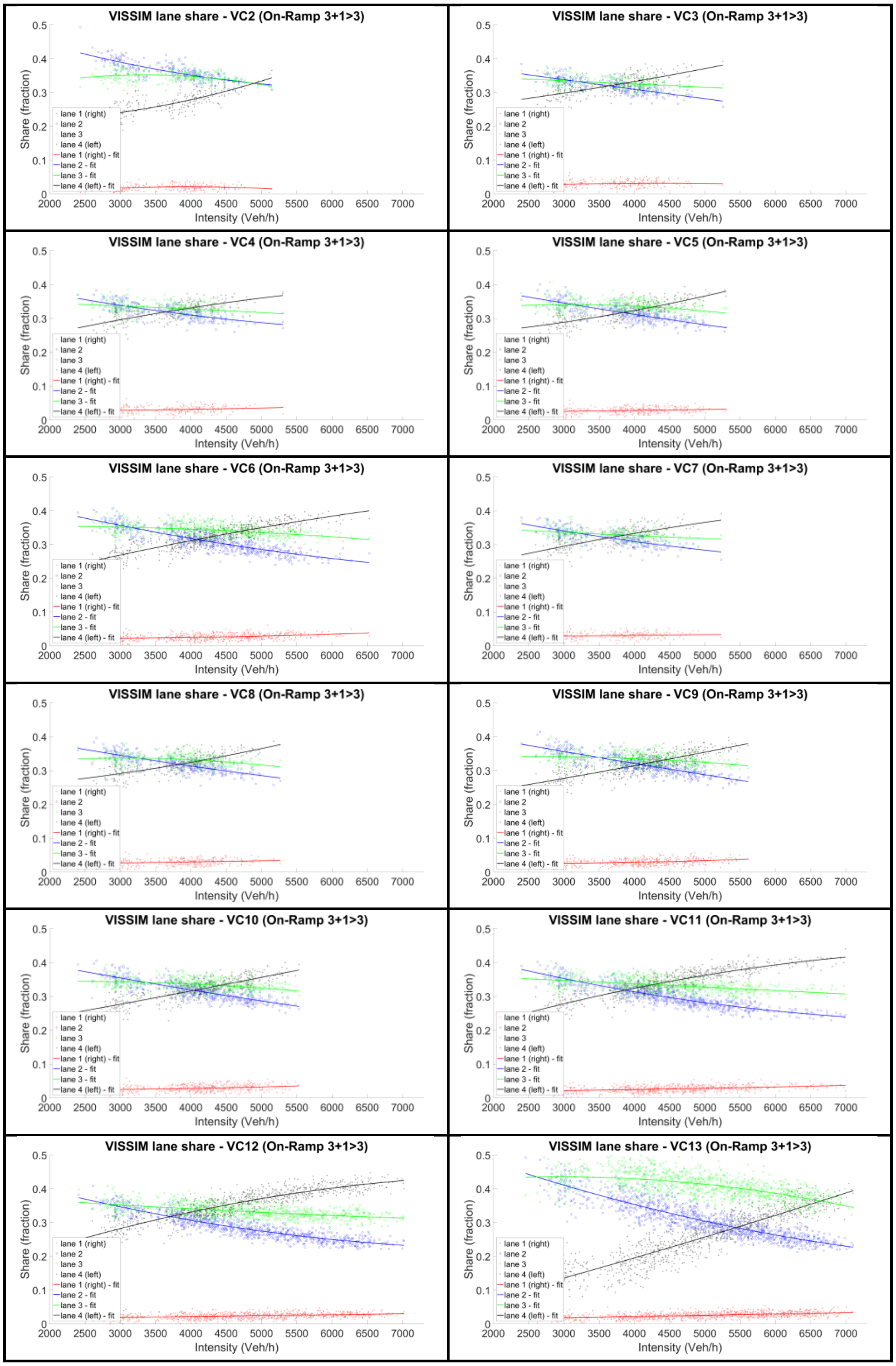


Figure 63: All On-Ramp lane shares (Each data point represents 5 minutes) – Congestion filtered

7.12.2 Lane intensity On-Ramp

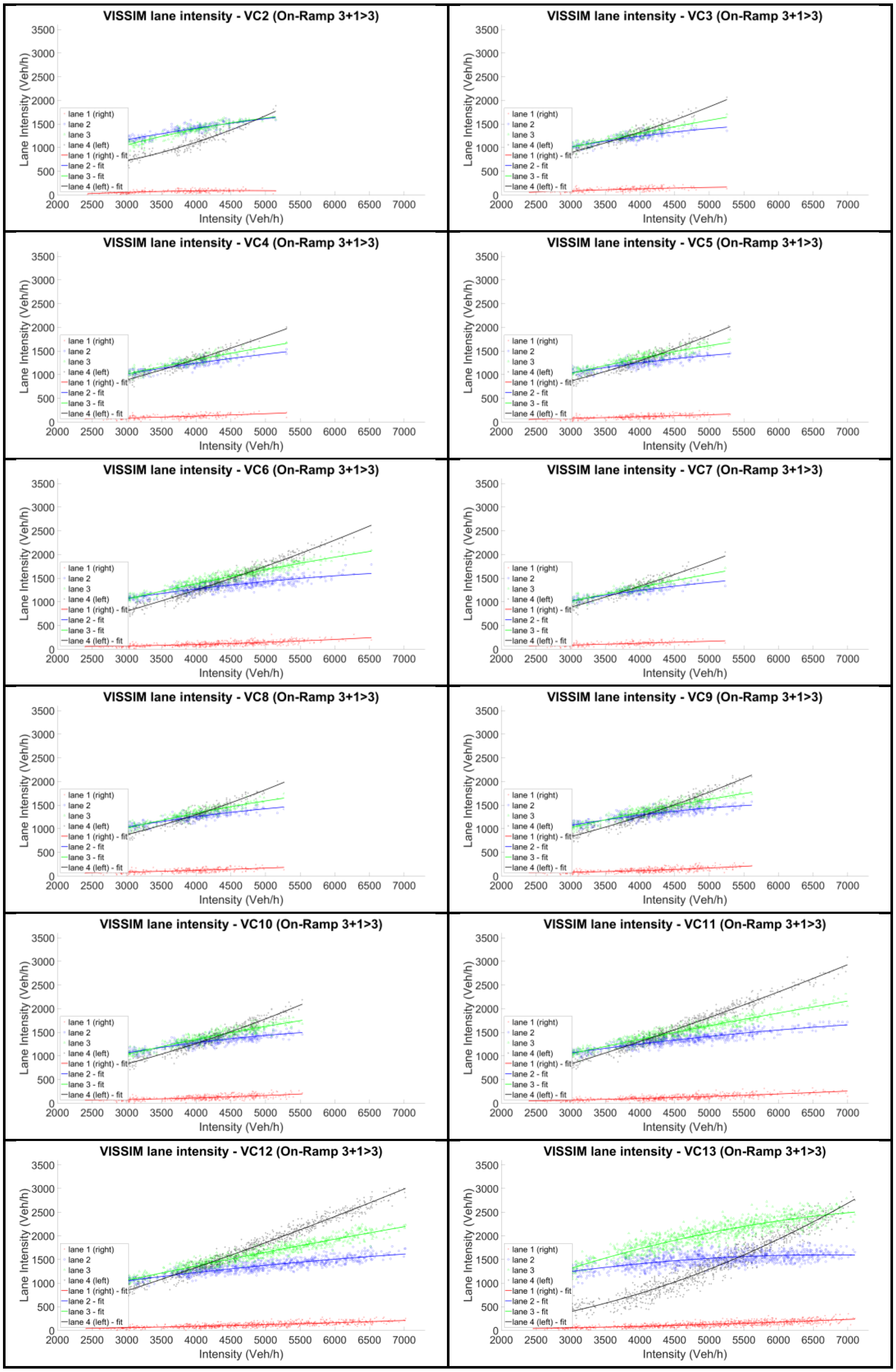


Figure 64: All On-Ramp lane intensities (Each data point represents 5 minutes) – Congestion filtered

7.12.3 Mean Speed On-Ramp

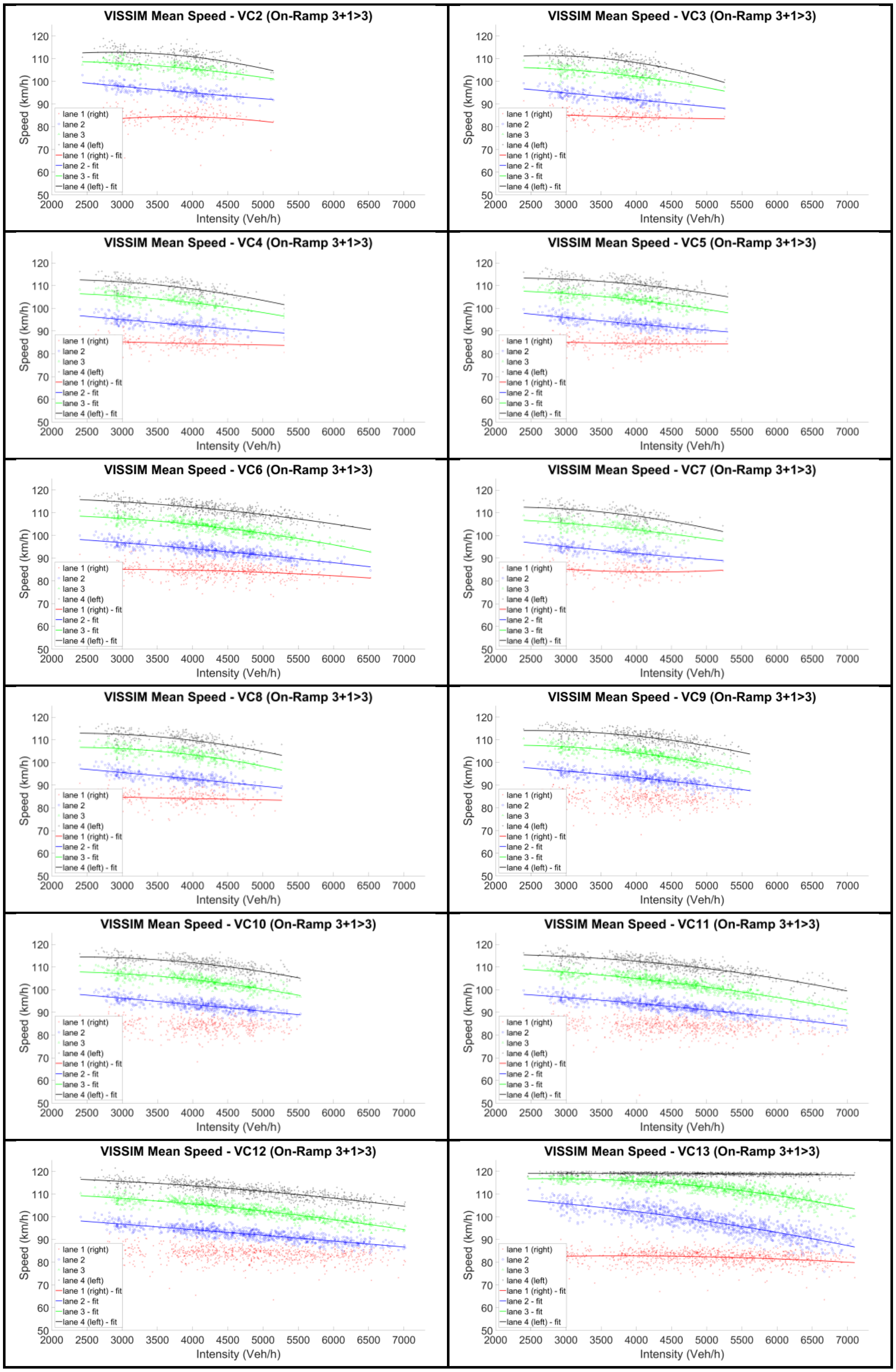


Figure 65: All On-Ramp Mean Speeds (Each data point represents 5 minutes) – Congestion filtered

7.12.4 SD Speed On-Ramp

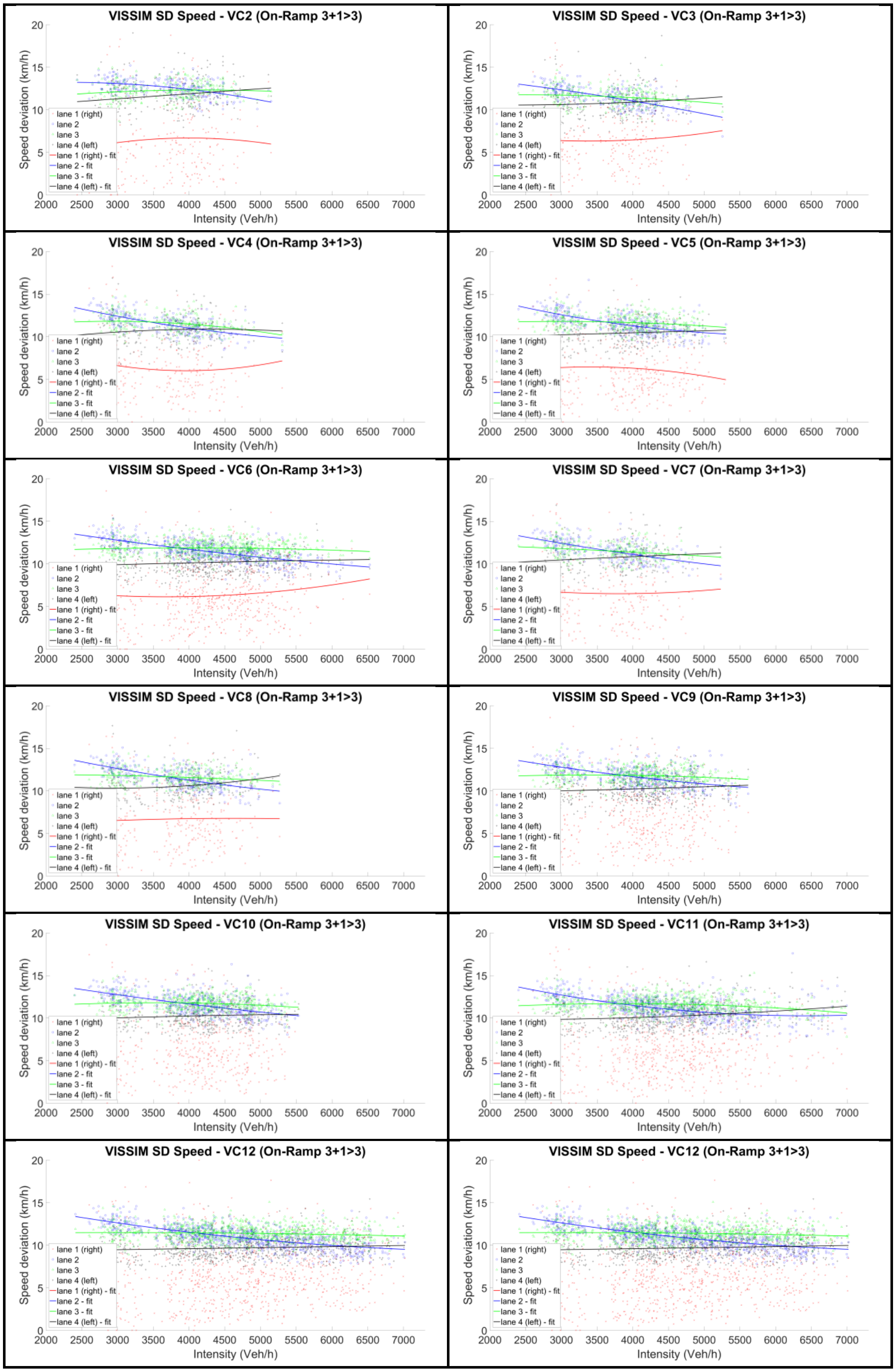


Figure 66: All On-Ramp SD Speeds (Each data point represents 5 minutes) – Congestion filtered

7.13 APPENDIX M: OVERVIEW TRAFFIC CONDITIONS OF 100% VEHICLE COMPOSITIONS (OFF-RAMP)

7.13.1 Lane share Off-Ramp

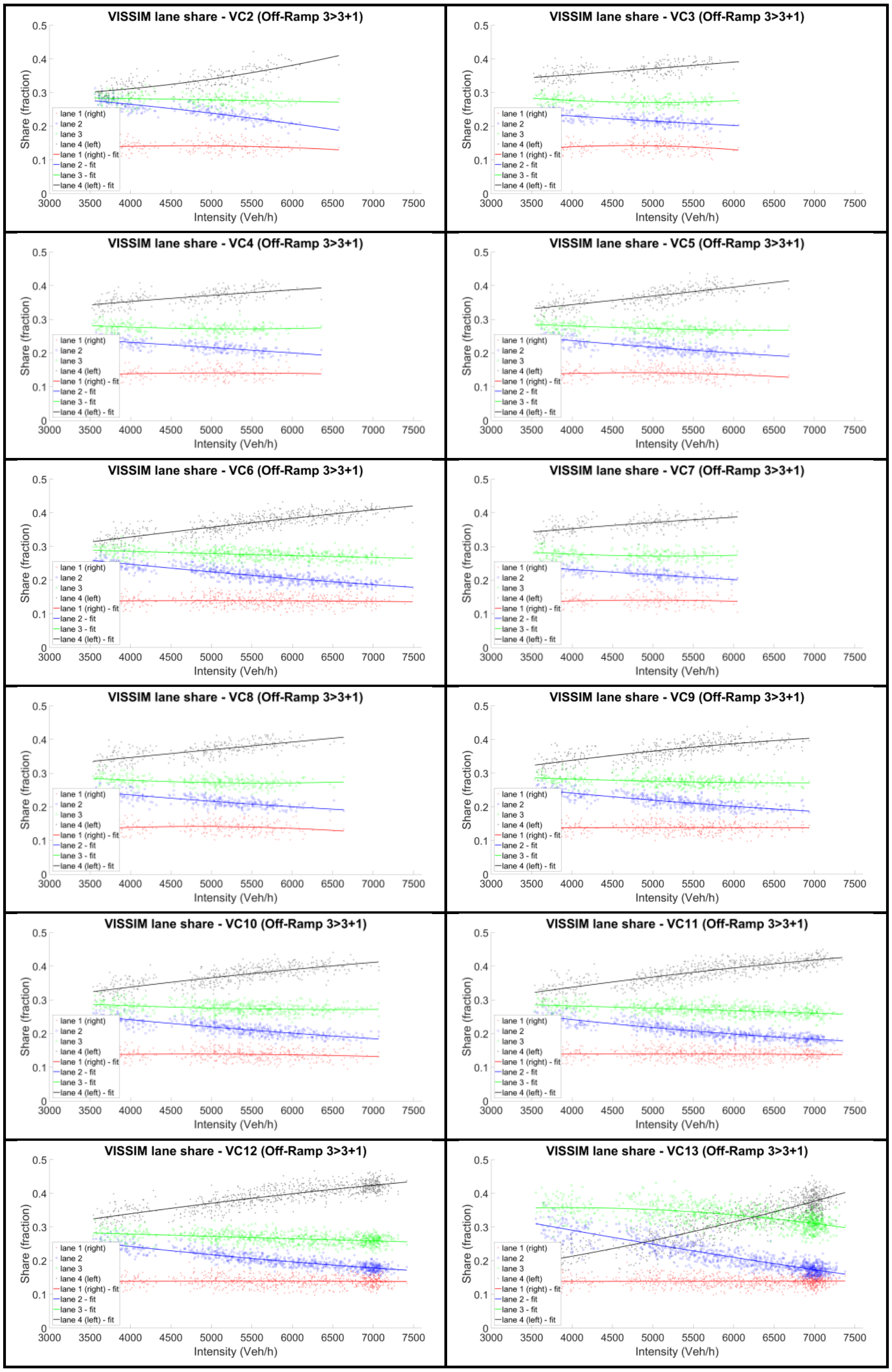


Figure 67: All Off-Ramp lane shares (Each data point represents 5 minutes) – Congestion filtered

7.13.2 Lane intensity Off-Ramp

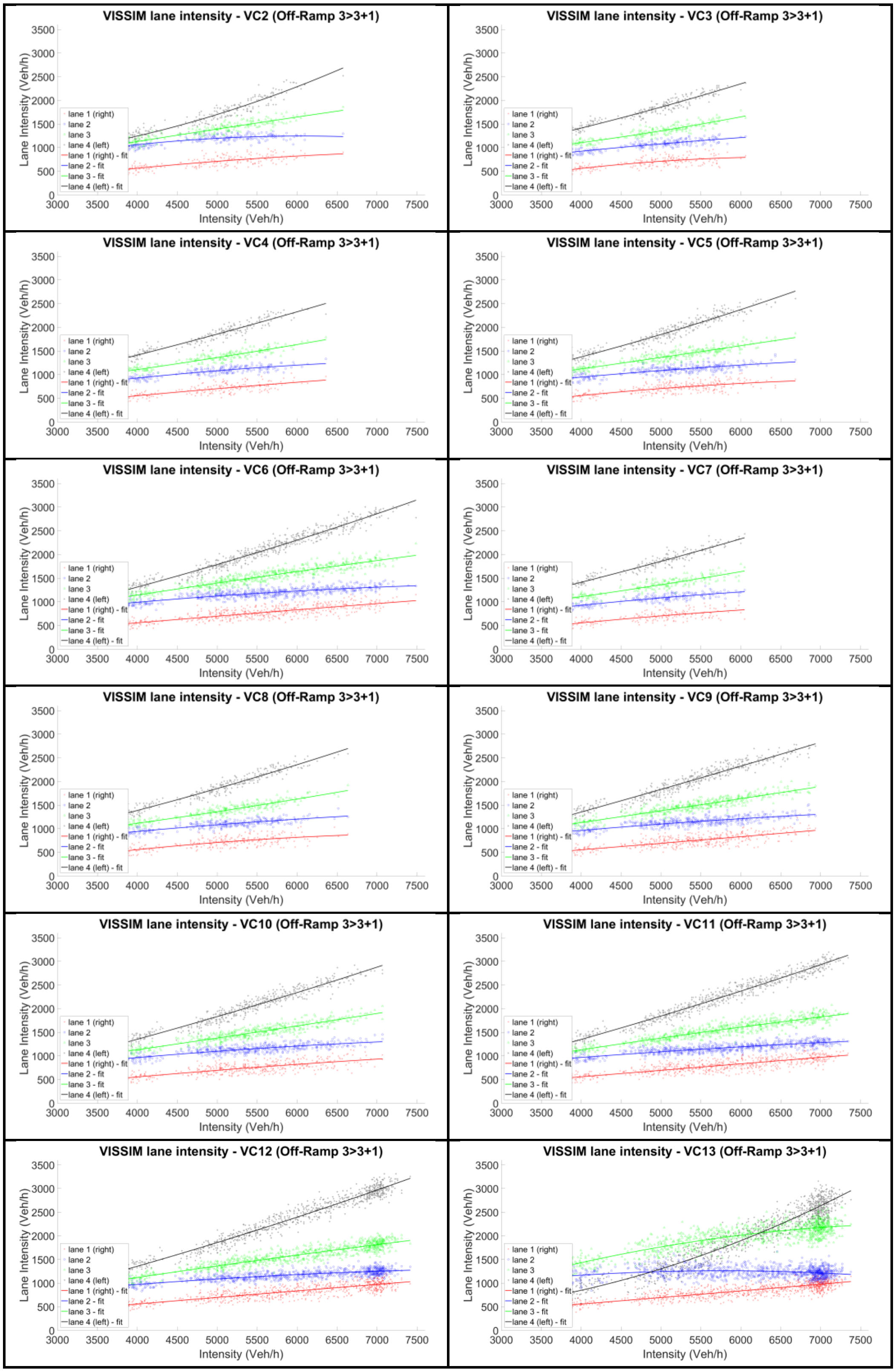


Figure 68: All Off-Ramp lane intensities (Each data point represents 5 minutes) – Congestion filtered

7.13.3 Mean Speed Off-Ramp

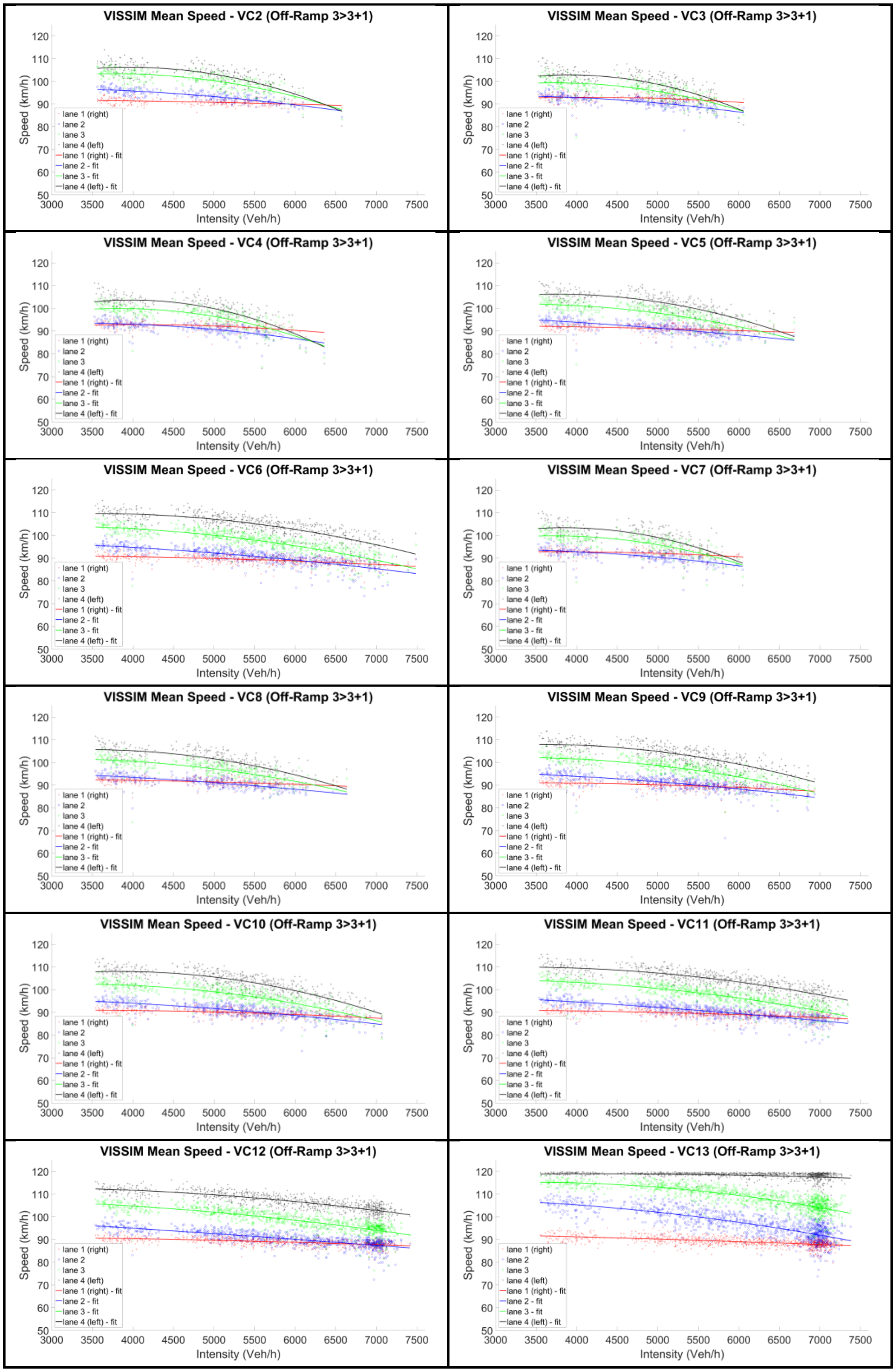


Figure 69: All Off-Ramp Mean Speeds (Each data point represents 5 minutes) – Congestion filtered

7.13.4 SD Speed Off-Ramp

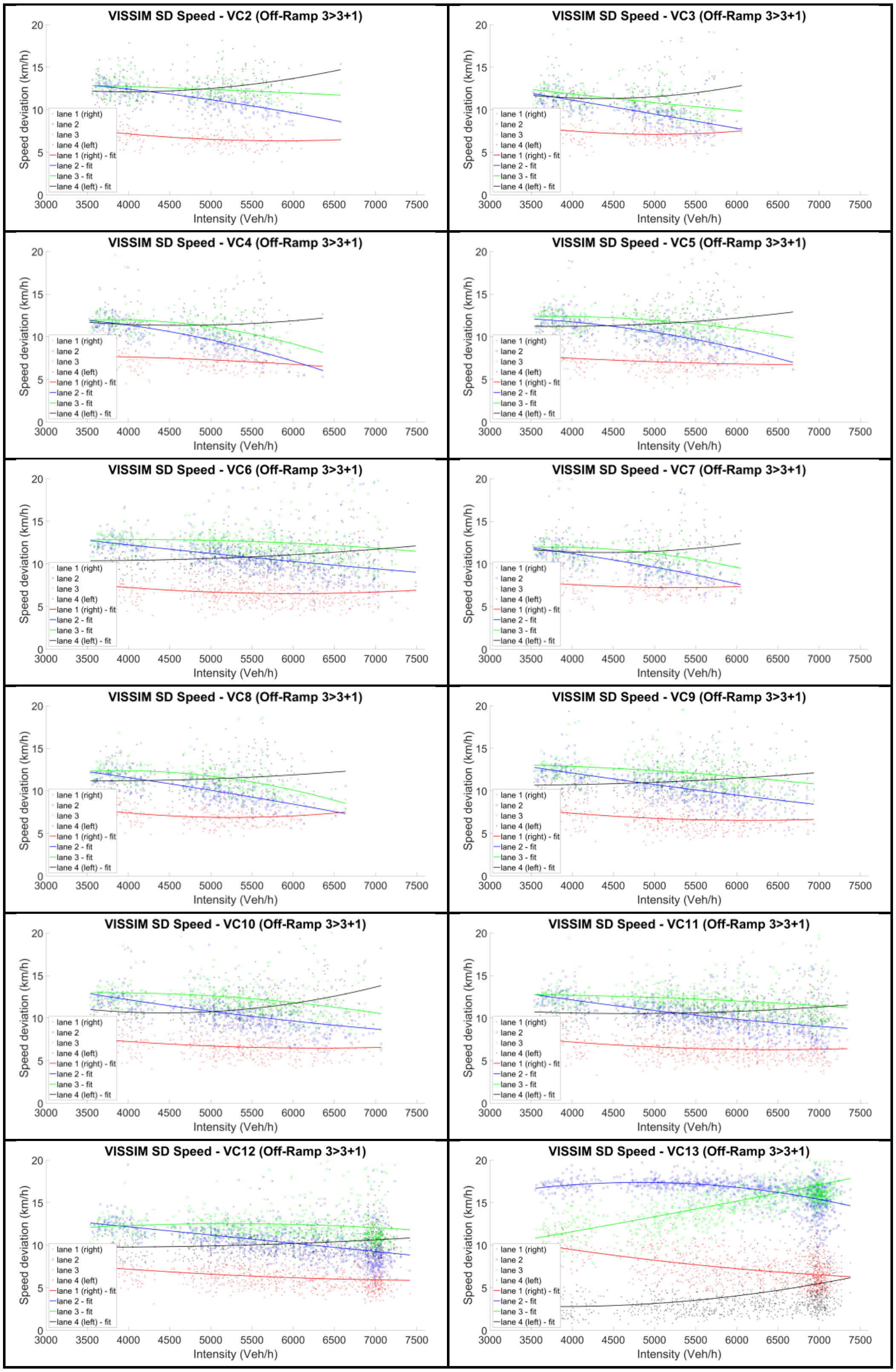


Figure 70: All Off-Ramp SD Speeds (Each data point represents 5 minutes) – Congestion filtered

7.14 Appendix N: Overview traffic conditions of 100% Vehicle Compositions (Symmetrical Weaving Section)

7.14.1 Lane share Symmetrical Weaving Section

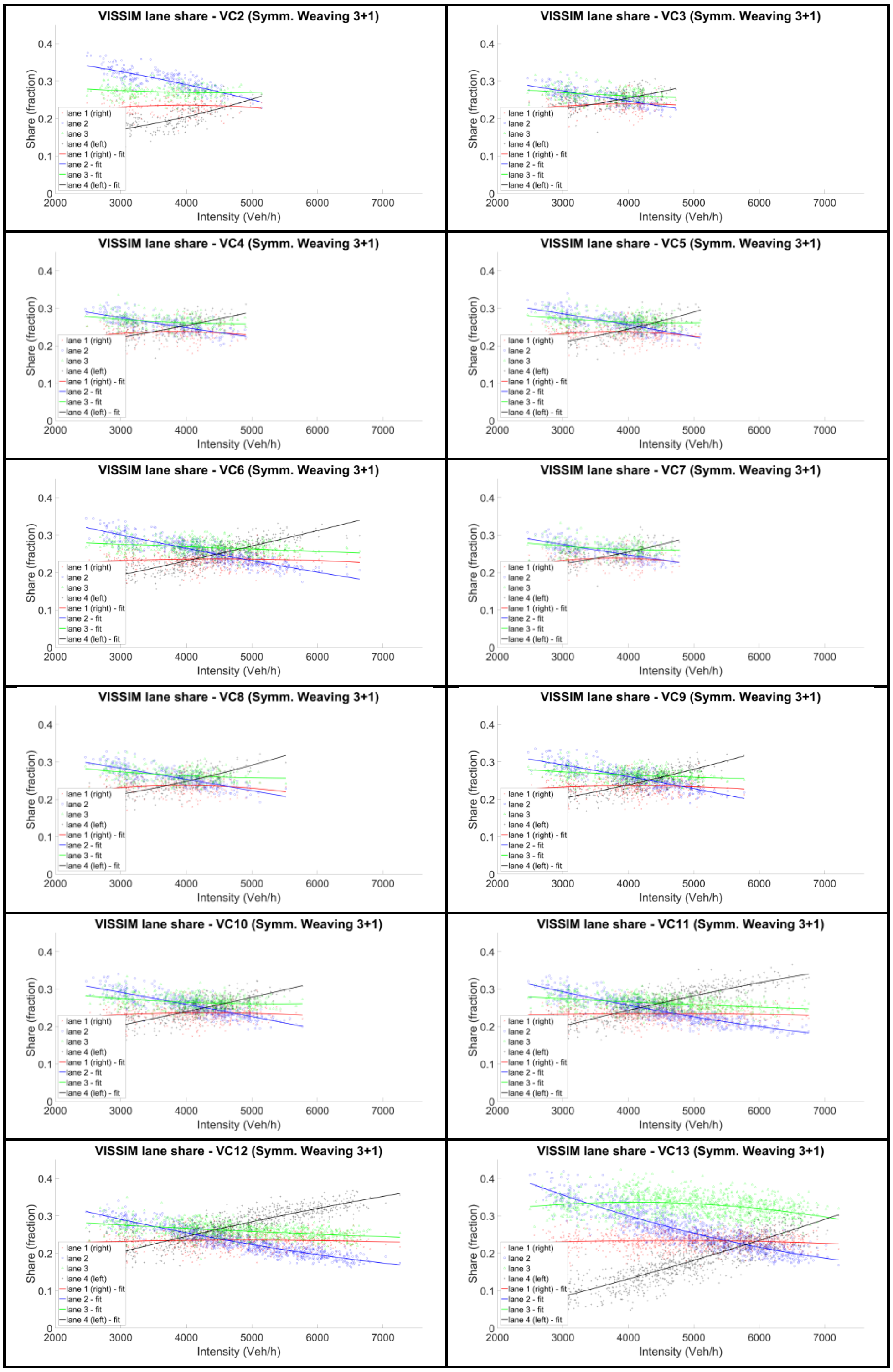


Figure 71: : All Symmetric Weaving Section lane shares (Each data point represents 5 minutes) – Congestion filtered

7.14.2 Lane intensity Symmetrical Weaving Section

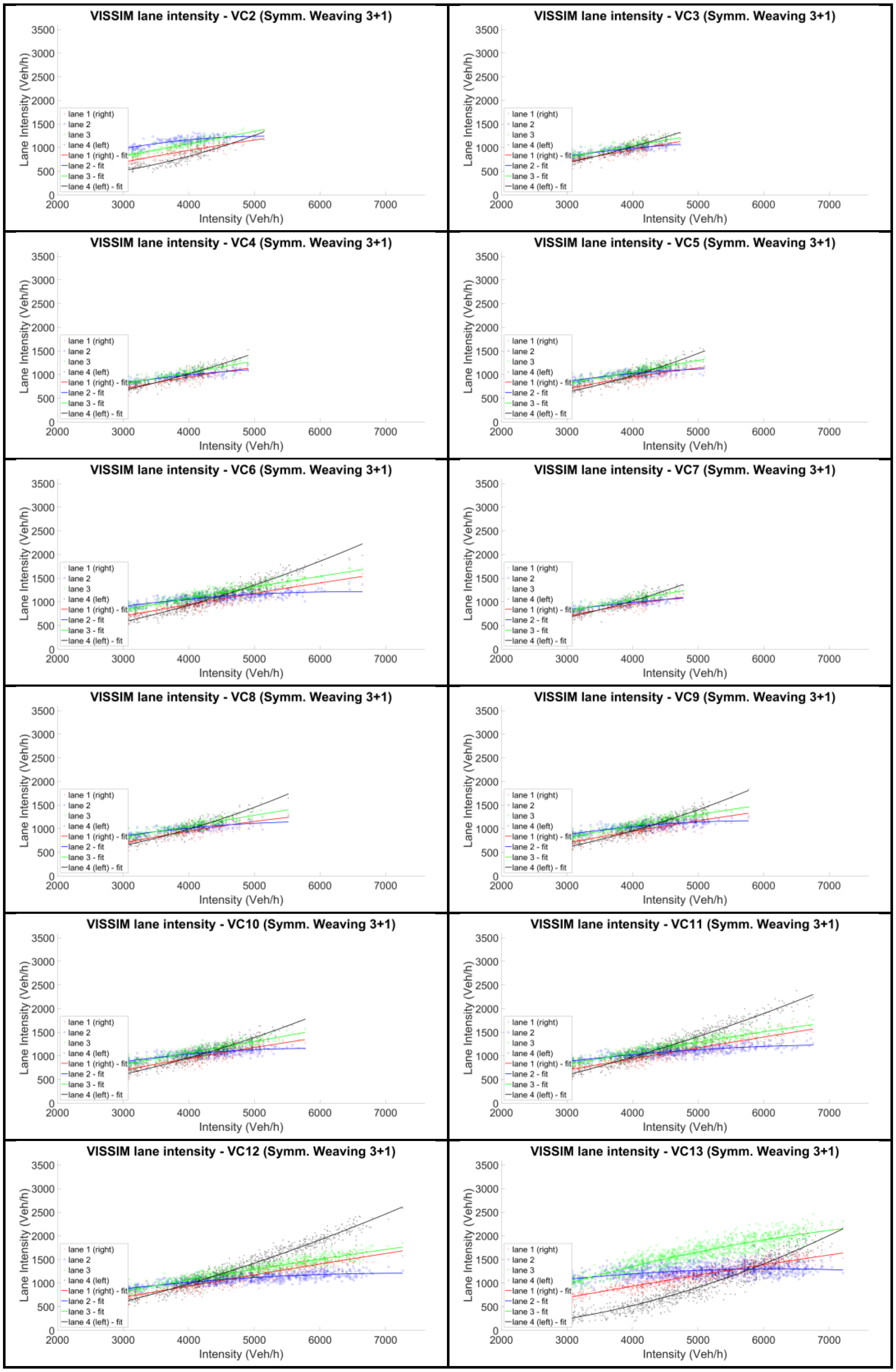
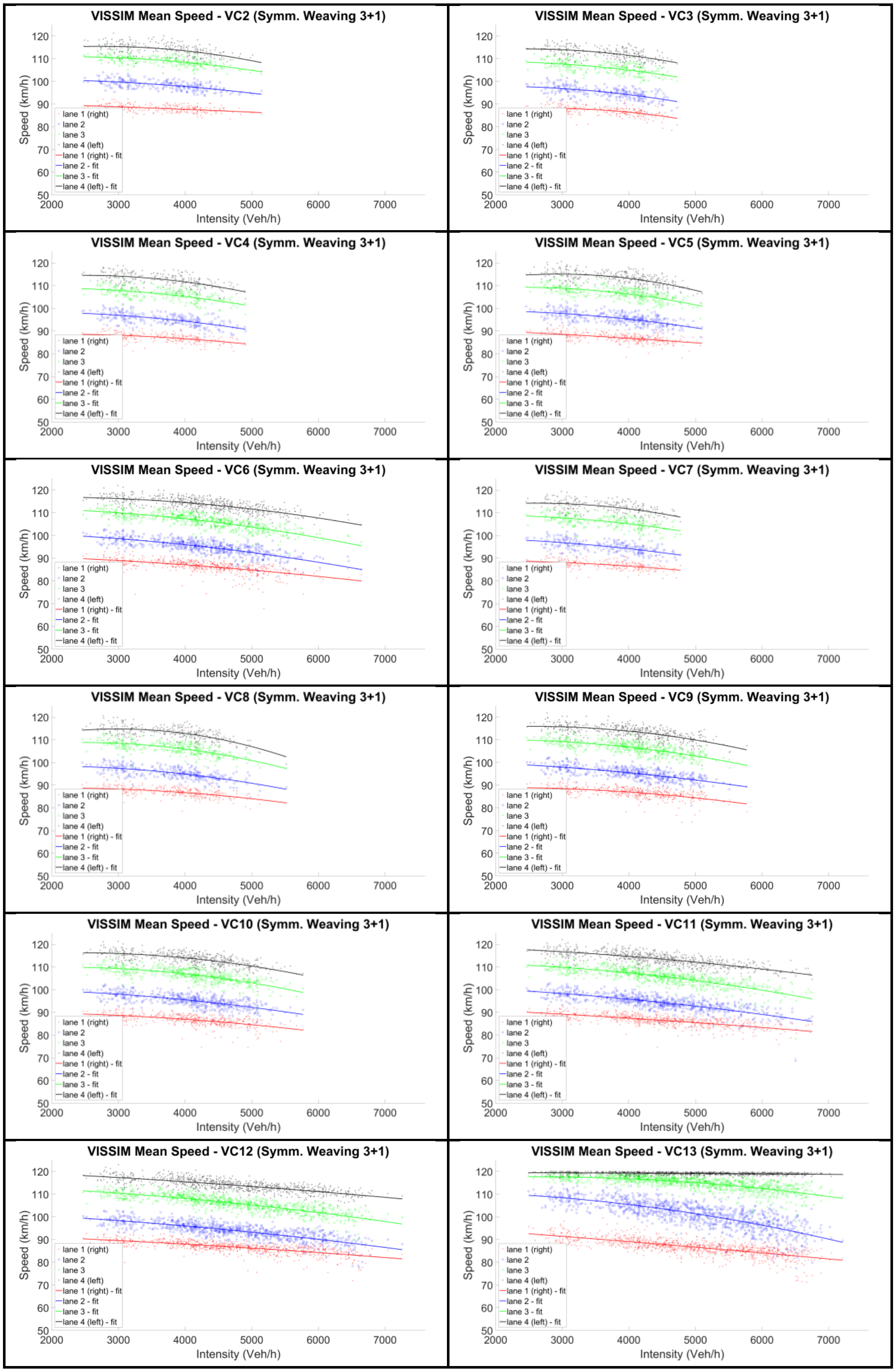


Figure 72: : All Symmetric Weaving Section intensities (Each data point represents 5 minutes) – Congestion filtered

7.14.3 Mean Speed Symmetrical Weaving Section



7.14.4 SD Speed Symmetrical Weaving Section

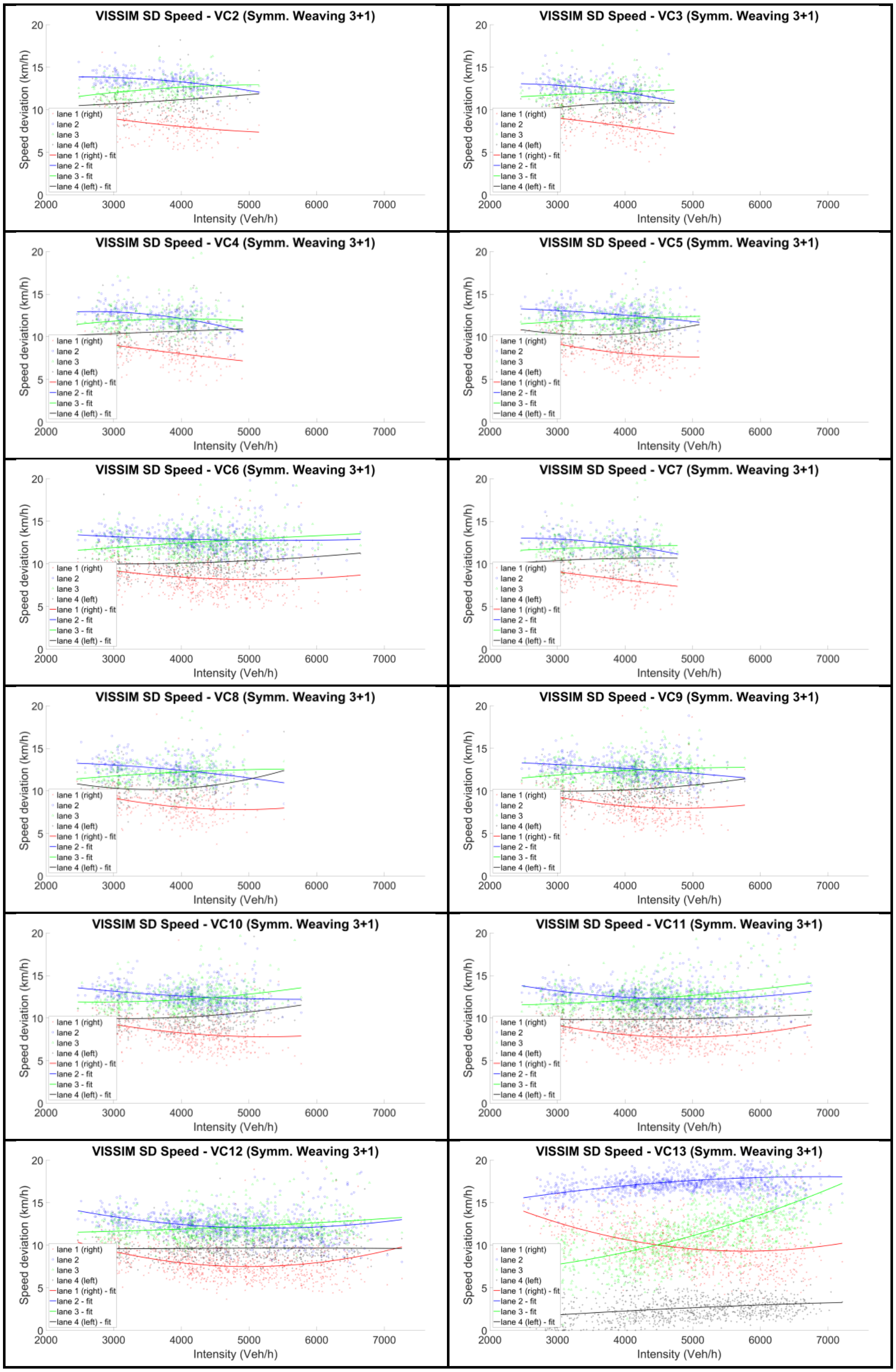


Figure 73: SD

7.15 Appendix O: Overview of Total Lane Changes

7.15.1 Lane Changes On-Ramp

*Table 53: Total Lane Changes on the Main Section per VC – On-Ramp 3+1 to 3 lanes (in 100 * 3600 simulated seconds)*

VC	Lane_1_to_2 [39]	Lane_2_to_1	Lane_2_to_3	Lane_3_to_2	Lane_3_to_4	Lane_4_to_3
1	72,102	-	64,651	19,759	46,929	25,712
2	73,082	-	74,158	25,957	55,240	31,602
3	70,843	-	43,664	10,623	29,494	15,008
4	71,093	-	47,026	11,661	31,720	16,103
5	72,780	-	60,036	15,745	40,806	20,838
6	73,409	-	70,870	20,448	51,993	26,881
7	70,868	-	45,812	11,223	31,008	15,746
8	72,016	-	52,757	13,404	36,767	18,870
9	73,078	-	60,004	15,975	44,179	22,687
10	73,213	-	62,071	16,729	45,991	23,641
11	73,398	-	68,605	19,128	52,582	27,497
12	73,440	-	73,960	21,775	59,472	31,852
13	73,435	-	83,187	34,271	65,851	41,053

7.15.2 Lane Changes Off-Ramp

*Table 54: Total Lane Changes on the Main Section per VC - Off-Ramp 3 to 3+1 lanes (in 100 * 3600 simulated seconds)*

VC	Lane_1_to_2 [40]	Lane_2_to_1	Lane_2_to_3	Lane_3_to_2	Lane_3_to_4	Lane_4_to_3
1	-	87,263	20,388	49,813	21,349	38,251
2	-	87,555	25,518	56,658	26,641	45,664
3	-	82,495	13,836	41,527	12,268	25,414
4	-	83,664	14,807	42,150	13,311	27,029
5	-	87,797	17,383	43,957	17,777	31,489
6	-	88,080	18,229	43,589	22,843	40,703
7	-	83,400	14,528	42,200	12,987	26,348
8	-	86,721	16,425	43,013	16,110	29,176
9	-	88,049	17,675	44,346	19,296	35,972
10	-	88,063	17,355	43,047	19,763	36,828
11	-	88,090	17,659	41,212	24,222	41,564
12	-	88,097	18,993	39,058	29,351	46,520
13	-	88,084	24,974	47,128	38,229	66,057

[39] Lane 1 is the merging lane, lane 2 is the right main lane (thus there are no lane changes from lane 2 to lane 1)
[40] Lane 1 is the diverging lane, lane 2 is the right main lane (thus there are no lane changes from lane 1 to lane 2)

7.15.3 Lane Changes Symmetrical Weaving Section

*Table 55: Total Lane Changes on the Main Section per VC - Symmetrical Weaving Section 3+1 lanes (in 100 * 3600 simulated seconds)*

VC	Lane_1_to_2 [41]	Lane_2_to_1	Lane_2_to_3	Lane_3_to_2	Lane_3_to_4	Lane_4_to_3
1	54,721	101,555	96,112	87,997	89,150	82,704
2	54,762	101,651	107,386	99,556	100,563	95,232
3	54,717	101,520	74,566	67,328	68,710	62,436
4	54,713	101,556	76,520	68,570	71,171	64,323
5	54,743	101,596	84,571	73,709	80,842	72,616
6	54,739	101,602	95,030	80,560	91,453	80,896
7	54,705	101,544	75,781	68,135	70,318	63,903
8	54,736	101,590	80,584	71,295	76,382	69,076
9	54,722	101,573	86,950	74,940	83,877	74,595
10	54,731	101,581	88,459	75,279	85,670	75,711
11	54,747	101,624	93,724	76,740	93,646	80,847
12	54,742	101,641	99,658	78,109	103,074	86,544
13	54,756	101,650	118,294	106,544	94,258	105,243

[41] Lane 1 is the merging and diverging lane, lane 2 is the right main lane

7.15.4 Lane Changes - Bar charts

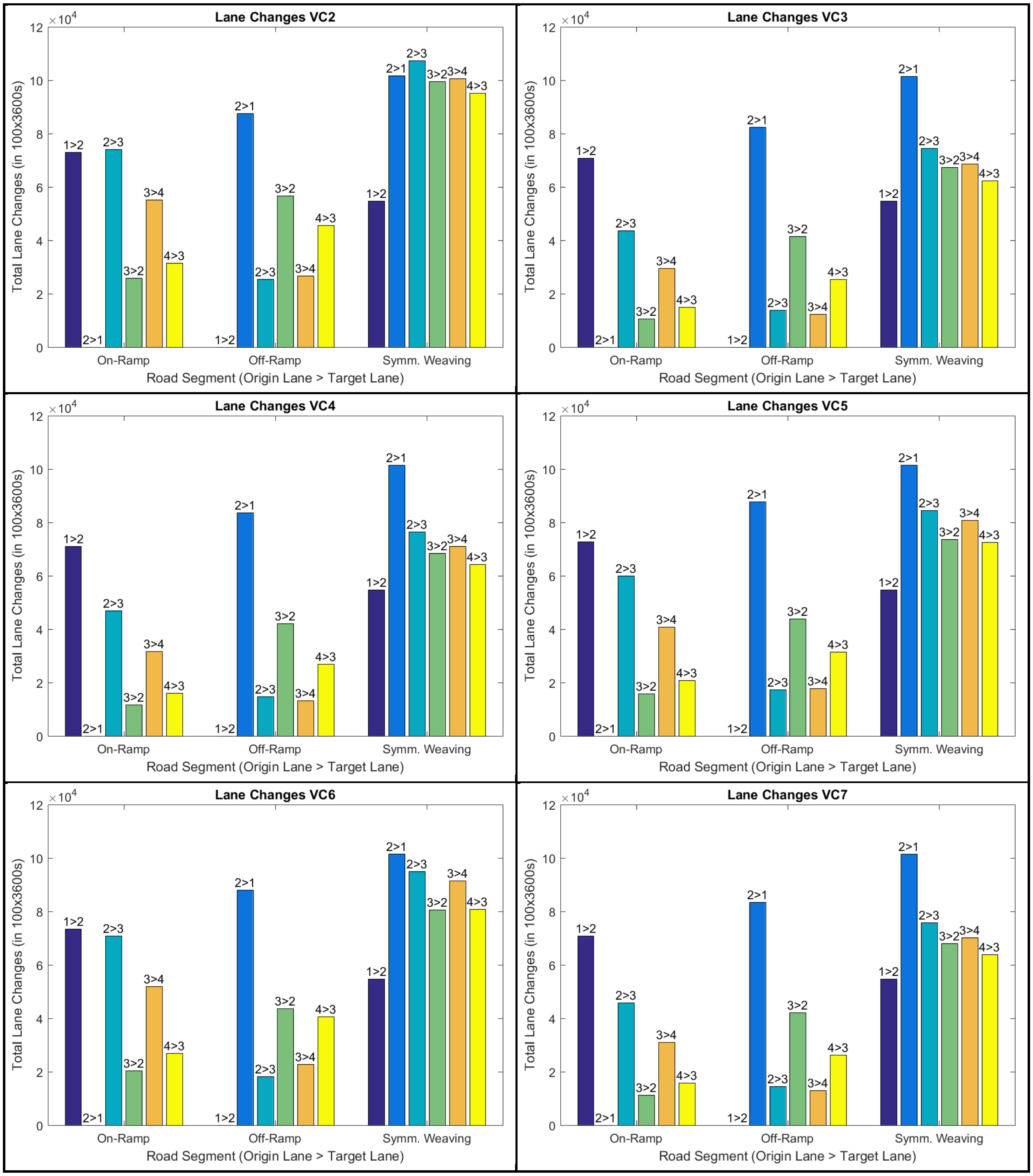


Figure 74:Bar charts of Total Number of Lane Changes during 100x3600 simulated seconds (VC2 - VC7)

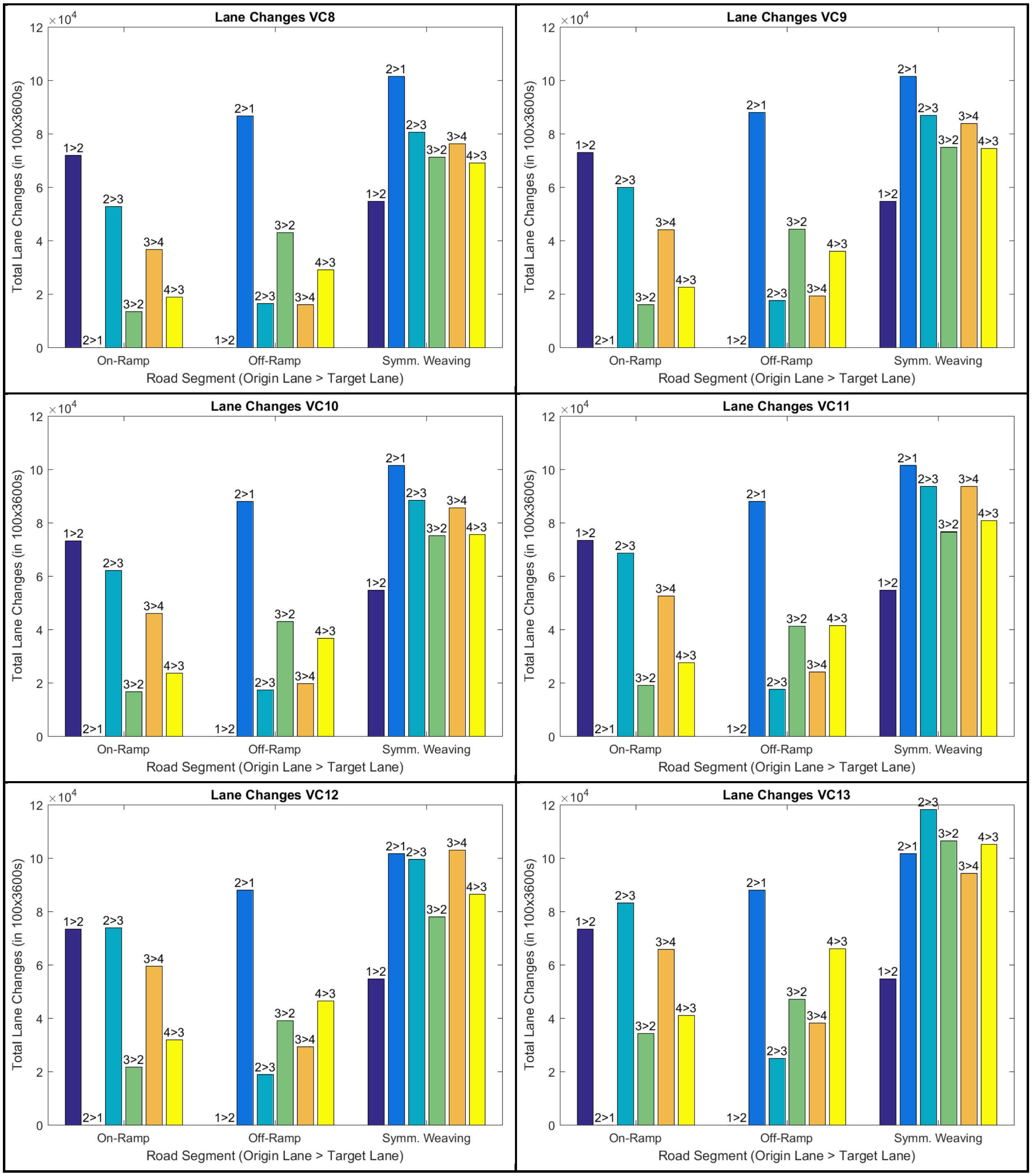


Figure 75:Bar charts of Total Number of Lane Changes during 100x3600 simulated seconds (VC8 - VC13)