# THE IMPACT OF THE SELF-DRIVING CAR ON URBAN TRAFFIC CAPACITY

Research into the changes in loss times and queue lengths at different types of intersections concerning the implementation of self-driving cars


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# Abstract

Self-driving cars (SDCs) are seen as vehicles that can have very promising effects on the efficient use of the road network. Automotive and tech companies are developing vehicles which are able to (partly) drive on their own. These vehicles are arranged certain level of automation: the higher the level, the more automated the vehicle is. Currently, quite some research has been done into the effects of these SDCs on highways, however the effects of SDCs in urban environments is still underexposed.

This research investigates the impact that SDCs have on loss times, queue lengths and capacities in urban environments. Since urban traffic is often dominated by the interaction of vehicles with intersections, this research focusses on the effects of SDCs around a regular intersection, a roundabout and a signalised intersection. First, a literature study has been carried out to understand how SDCs can be simulated in the modelling software VISSIM. The outcomes of this study are used to analyse the impact of five parameters, which describe SDC driving behaviour in VISSIM, on the loss times and queue lengths at three penetration rates. With these individually assessed parameters, various combinations of parameters are set up to actually describe certain types of SDCs which differ in level of automation and level of trust in technology (i.e. high or low safety margins applied). The impact of these types of SDCs are analysed depending on penetration rates (i.e. 5 levels) on the loss times and queue lengths. Finally, the results regarding loss times are converted to changes in capacity.

The literature analysis showed that SDCs are mainly becoming more deterministic in their behaviour compared to human drivers. Besides, SDCs might have the ability to have shorter headways, but on the other hand, this is also debated when the aspect of safety is concerned. When translating the expected SDC-effects to VISSIM, there are multiple parameters to use. The five most relevant parameters are identified to be: CC0, standstill distance; CC1, headway time; CC2, following variation; CC8, standstill acceleration and CC9, acceleration at 80 km/h. It was found that the CC1 parameter is most influential for the loss times at all intersections. CC2 and CC8 have noticeable, but smaller impact. CC0 and CC9 seem to have few impacts on the loss times. Nevertheless, the CC0 has a very clear impact on the queue lengths at all intersections. Here, the CC1, CC2 and CC8 have some influence as well. CC9 has few impacts on the queue lengths. Besides, it was noticed that non-ranged parameters like acceleration oscillation desired speed and acceleration function, which are set to default values for SDCs but are not ranged or analysed in detail, have clear, yet currently unexplained impacts as well.

With these results, six different combinations are established describing various degrees of aggressiveness of SDCs. The various combinations have been linked to the aforementioned levels of automation. The results of the simulation of these combinations showed that the penetration rate creates a progressive trend of either a positive or negative influence. Noticeable is the result that only the most extreme cautious combination has a substantial (more than 20%) negative effect on the loss times. In most other cases, the other 5 scenarios had relatively few (less than 5%) negative or a positive impact on the loss times. Queue lengths show the same trend, however to lesser extent than the loss times. With the translation from loss times to capacity, it became clear that the roundabout has relatively few possible negative impacts (maximum -3.1%) and quite some possible positive impacts (max. +27%). Noteworthy is the fact that the signalised intersection has the fewest impact loss time-wise, but has the largest capacity changes, ranging from max. 19% negatively to max. 32% positively.

In the end, a direction for a range of impacts of SDCs can be given, altering from great positive to great negative effects on loss times, queue lengths and capacities. What needs to be kept in mind, is the fact that this research focussed on individual intersections rather than entire networks and slow traffic is ignored. How the results will be applicable to real life, is dependent on this interplay with the complete network and slow traffic and the degree to which automotive companies allow for aggressive vehicles.

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# PREFACE

In front of you, you can find the report that I have written as the final part of my Bachelor's programme Civil Engineering at the University of Twente. This thesis is the result of a ten-week research which I carried out at the Goudappel Coffeng mobility consulting firm in the period May to July 2019. In this period, it was interesting to get familiar with working at a company on a full-time basis, which gave new insights in both theoretical and practical aspects of a traffic engineering profession.

As part of this preface of the report, I want to thank the supervisors of my research. Special thanks go out to my external supervisor Leon Suijs for being a sparring partner throughout the research. It was inspiring to get new insights based on the topics brought up during our conversations about the research. Discovering a bug in VISSIM is one of the interesting highlights that occurred during our brainstorms about the analysis of the data. I also want to thank my second external supervisor Luc Wismans for his critical review of the various versions of my report and my internal supervisor Eric van Berkum for providing feedback on the set-up and various versions of the research and the possibility to make use of his network during my (initial and unfortunately unsuccessful) search for an international thesis.

Besides my supervisors, I want to thank my colleagues on the 'flexplein' on the third floor of the office of Goudappel Coffeng in Deventer. Alex, Bernike, Frans, Jurre, Martijn, Rajco, Reinder, Rogier, Rogier and others, thank you for the walks in the break, for the games of table football, for the Friday trips to the market to get some fish and for providing me with freshly filled bottles of water when mine was empty.

Finally, I want to thank my parents for supporting me in my ambitions and supporting me with the various decisions I made throughout the past four years. More specifically concerning this research, I want to thank them for brainstorming about, providing information for and giving feedback on this research.

If any questions arise concerning this research, it is possible to contact me via i.m.bruijl@student.utwente.nl.

Ivo Bruijl

Deventer, 16 July 2019

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Figure 96. Median 90th percentile queue lengths of the north entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied. LIII

Figure 97. Median 90th percentile queue lengths of the east entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIII

Figure 98. Median 90th percentile queue lengths of the south entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIII

Figure 99. Median 90th percentile queue lengths of the west entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIII

Figure 100. Median 90th percentile queue lengths of the north entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied. LIV

Figure 101. Median 90th percentile queue lengths of the east entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIV

Figure 102. Median 90th percentile queue lengths of the south entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIV

Figure 103. Median 90th percentile queue lengths of the west entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied LIV

# Nomenclature

Here, the used abbreviations, symbols and terms which are present in the main report are explained.

## List of Abbreviations

Shown in Table 1 are the abbreviations used in this report in alphabetical order.

*Table 1. Abbreviations used in this report in alphabetical order.*

| Abbreviation | Meaning |
|---|---|
| ACC | Adaptive Cruise Control |
| CACC | Cooperative Adaptive Cruise Control |
| DDT | Dynamic Driving Task |
| MaaS | Mobility as a Service |
| OD-matrix | Origin/Destination-matrix |
| ODD | Operational Domain Design |
| PCE | Passenger Car Equivalent |
| SAE | Society of Automotive Engineers |
| SDC | Self-Driving Car |

## List of Symbols & Units

Shown in Table 2 are the symbols and units used in this report in alphabetical order.

*Table 2. Symbols used in this report in alphabetical order.*

| Symbol | Symbol or Unit | Meaning |
|---|---|---|
| % | Unit | Percent |
| h | Unit | Hour |
| km/h | Unit | Kilometre per hour |
| L | Symbol | Vehicle length |
| $L_{queue,max,i}$ | Symbol | Maximum queue length of entry direction i. |
| m | Unit | Metre |
| $m/s^2$ | Unit | Metre per second squared |
| s | Unit | Second |
| v | Symbol | Speed |
| Δv | Symbol | Difference in speed |
| Δx | Symbol | Headway distance |
| δ | Symbol | Dummy variable used in Wiedemann 1999 model. Explained on page 9. |

## Used Terms

Within this report, some terms are used which are defined differently in some literature but can be used interchangeably.

In this report, the definition of a Self-Driving Car (SDC) is used for a personal vehicle that can (partly) drive without interference of the driver. Literature sometimes uses Automated Vehicle (abbreviated: AV) for the same object.

In this report, the definition of headway time is the same as the definition of time headway, which is sometimes used in literature.

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# 1. INTRODUCTION

A driverless future is often considered science-fiction, since it is often thought that computers cannot be better at analysing and assessing traffic situations than humans. However, the future of Self-Driving Cars (SDCs) may be closer than expected. Tesla has already implemented Autopilot in their cars, which has the ability to control the car in certain circumstances; Waymo, the successor of the Google Driverless Car project, is implementing autonomous taxis in Phoenix, United States and in Singapore a self-driving bus will launched to drive on the public road (Nu.nl, 2019).

There are different definitions of self-driving cars. The Society of Automotive Engineers (SAE) has established a framework to define various degrees of automation. A description of the different degrees of automation is given in Figure 1.

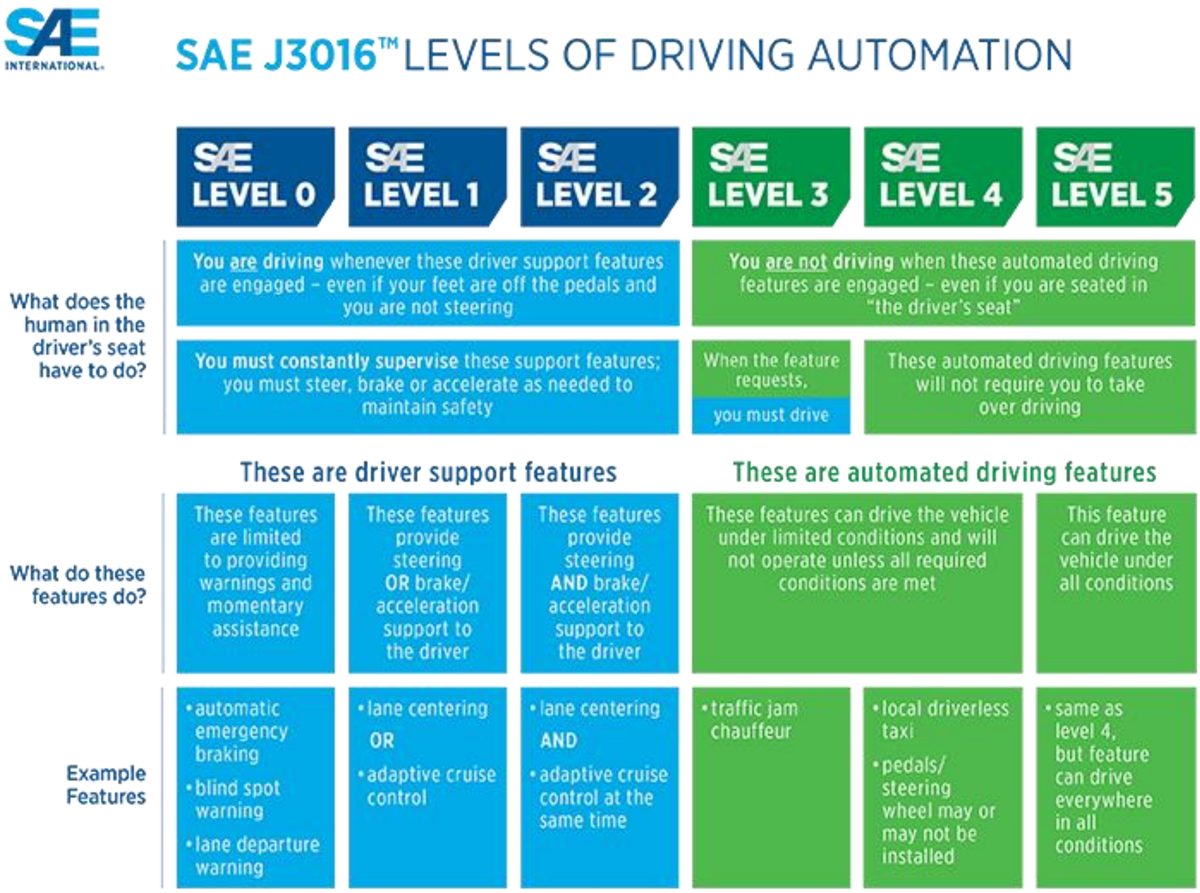



*Figure 1. Levels of automation as described by (SAE International, 2018).*

Currently, most of the vehicles do not have any degree of automation, however, more and more vehicles with some degree of automation are implemented in the total fleet every year. The automotive industry is currently experimenting with level 3 SDCs with some level 4 aspects, like the Waymo and Uber automated taxi services in the Phoenix Metropolitan Area, United States (Maughan, 2019). Since the Dynamic Driving Task (DDT) and Operational Design Domain (ODD) are fundamentally different in these levels of SDCs compared to level 3 and lower, these experiments encounter quite some difficulties on a technical and an ethical scale. Therefore, relatively little is known about the exact impacts which these SDCs will have.

Whereas some people, like Daimler's Director of Autonomous Driving, expect that fully automated cars will be present within inner cities within a few years (VPRO, 2019), researchers have made predictions that level 2 SDCs will have a market share of 50% in 2040 and in the same year the first level 4 and even 5 SDCs might become available for public purchase (Nieuwenhuijsen, 2015). Even though it is speculation on how fast the implementation of SDCs will be, there have been some researches describing the future penetration rates of SDCs, which have the ability to describe the traffic situations at different moments in the coming decades.

An aspect which might play an important role in this speed of implementation, is the development of Mobility as a Service (MaaS). The MaaS concept means, amongst others, that people will move away from privately owned vehicles to shared vehicles. A vehicle is only accessed when there is a need for mobility and is available for other users after travel. SDCs can play an important role in this concept, since the SDCs are able to travel from one user to another independently. This means that when MaaS is implemented in the coming years and/or decades, it might speed up the demand and therefore the development of SDCs. It might also work the other way around: the implementation of SDCs to the fleet might lead to more interest and development in MaaS-related aspects.

Quite some research has been done on the impact of SDCs on an entire traffic system including aspects like the modal split, in other words on a macro-scale. A study on the Dutch National Model System that incorporated self-driving cars and self-driving trucks showed that the implementation of SDCs might lead to more vehicle mileage instead of cycling or walking mileage (Smit, et al., 2017). Besides, the same study showed that there can be both an increase as a decrease on average capacity of the road network, influenced by aspects like communication between vehicles and the penetration rate of SDCs.

Most of the modelling research on the individual car level, or in other words on micro-scale, is carried out on highway levels (Puylaert, 2016; Meyer, Becker, Bösch, & Axhausen, 2017; Rossen, 2018). The researches that are carried out on a more urban-oriented level often only concern small aspects of an urban traffic network, like a traffic light on a single lane, rather than a complete intersection (Wang & Wang, 2018). Research on micro-scale show various outcomes concerning the effects which SDCs will have on traffic operations. There might be a theoretical quadrupling of capacity on highways assuming the capability of these vehicles to drive with high speeds and small following distance as well as optimised merging behaviour (Van den Berg & Verhoef, 2016). However, due to safety and safety perception issues as well as comfort issues such as motion sickness, the use of the aforementioned capabilities made to SDCs may be limited (Smit, et al., 2017; Snelder, Van Arem, Hoogendoorn, & Van Nes, 2015), which causes there to be no difference at all (Puylaert, 2016) to capacity reductions (Snelder, et al., 2018; Smit, et al., 2017).

The mentioned researches almost all focus on the micro-scale impact that SDCs will have on highways and some focus on the macro-scale impact resulting from the implementation of SDCs. There is a knowledge gap concerning the influence of SDCs on the micro-scale urban traffic environment. It is unclear whether SDCs will positively or negatively influence traffic operations in the urban environment, which is caused by uncertainty on how SDCs will behave around intersections. Therefore, the Goudappel Coffeng mobility consultancy firm is very interested to see what impact SDCs will have on the mobility structures which are present now. Since the urban traffic performance is mainly determined by the interaction of vehicles at intersections, this aspect is the topic of research in this thesis.

# 2. Subject of Research

This chapter concerns the goal of the research. To reach this goal, multiple research questions have been established in a hierarchical structure and the methodology describes how these questions are answered. Besides the research questions, the boundaries of the scope are defined in order to counter proliferation of the research. Finally, the models used in the research and the assessment framework are described.

## 2.1. Goal of the Research

The main idea of the research was to analyse the possible degrees to which SDCs will have an influence on the traffic operations in the current urban road system. Within the urban road system, intersections play key roles in the traffic operations of the network. Therefore, one of the specific aims of this research was to investigate the traffic operations of intersections when SDCs are implemented to the road system. Therefore, the predefined goal of the research is:

*Investigate the range of impacts on traffic operations as well as capacities depending on penetration levels of SDCs and on current intersection design alternatives.*

## 2.2. Research Questions & Methodology

The main research question is:

*What is the impact of SDCs on the capacity of the urban road network?*

Capacity is formulated as the broadest context of traffic operations. Besides actual vehicle capacity, totalled loss times and maximum queue lengths are analysed in order to see the changes which SDCs will have on the traffic system operation. In order to answer this question, a set of sub-questions and an accompanying methodology are established, which are shown in Figure 2 and below.

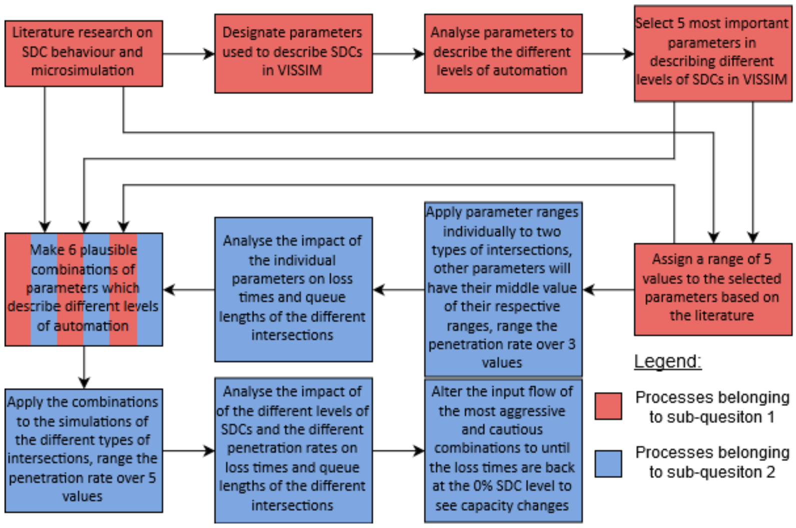



*Figure 2. The flowchart describing the methodological processes of the research. An enlarged version is visible in Appendix A: Methodological Process Scheme*

The sub-questions to this main question are:

1. *How can SDCs be modelled within VISSIM?*
    a. *What behavioural models of vehicles are altered in SDCs compared to regular vehicles?*
    b. *How can different levels of automation be modelled in VISSIM?*
        i. *What parameters of VISSIM are important in modelling different levels of SDCs?*

1. *Can different values of parameters in VISSIM be used to describe specific levels of automation?*
2. *What are proper ranges of parameters in VISSIM in modelling SDCs?*

The first sub-question specifically mentions VISSIM as software to model SDCs. VISSIM is chosen as simulation software because of two main reasons. First of all, the Goudappel Coffeng has most experience concerning micro-simulations with VISSIM and therefore it is most relevant for the company to use VISSIM as simulation software. Secondly, VISSIM has the possibility to describe SDCs by changing various parameters of driving behaviour. It uses Wiedemann parameters to describe a large part of the vehicle behaviour, which have been analysed by other studies in order to describe SDCs (Stanek, Huang, Milam, & Wang, 2017). Besides, PTV Group, the developer of VISSIM, proposes specific changes of Wiedemann parameters and other parameters in order to describe SDCs, which gives an interesting starting point for the research (PTV Group, 2017).

The methodology used to answer the sub-questions related to the first sub-questions of the research will mainly be executed through a literature analysis concerning the behavioural differences between regular vehicles and SDCs and the modelling of SDCs in VISSIM. The outcome of the literature research will be used to see what parameters are relevant in describing the different levels of automation. After this analysis, the five most relevant VISSIM parameters which describe the behaviour of SDCs will be selected to be analysed in detail by ranging. The literature research will also be used to assign ranges of five values per range to these most influential parameters in order to get relevant and appropriate ranges for the parameters.

2. *How do SDCs influence the capacity of urban road networks, concerning different types of intersections?*
    a. *How do SDCs influence the capacity of different types of intersections when relevant parameters of the SDCs are ranged and various penetration rates are applied?*
        i. *How are the loss times at different intersections effected by ranging the relevant parameters describing SDCs and various penetration rates are applied?*
        ii. *How are the queue lengths at different intersections effected by ranging the relevant parameters describing SDCs and various penetration rates are applied?*
        iii. *Is there an optimum type of intersection to optimize the capacity of SDCs in urban environments?*
    b. *How do SDCs influence the capacity of different types of intersections concerning different penetration rates of SDCs?*
        i. *Is there a minimum penetration rate which is needed to see a substantial impact (5% change in loss times) on the capacity of road systems when the SDC is introduced?*

The ranges as defined in the first sub-question will be used for the second sub-question. The identified parameters will be analysed individually in order to see the actual impact of individual parameters on the loss times and the queue lengths. During a simulation where a parameter is not individually analysed, it will get the value which is most proposed by literature. Besides the ranged parameters, other relevant parameters will be set on a fixed value to describe SDCs. In order to see the effects concerning of a parameter at different degrees of implementation, penetration rates of 40%, 70% and 100% will be analysed. In this way, the effect of a single parameter can be assessed and checked whether it has a significant influence on a different penetration rate.

Three types of intersections will be analysed: a regular priority intersection with directional lanes for the left turn on the priority road, a regular roundabout and a signalised intersection with directional lanes for each direction. The exact intersections are discussed in section 2.4.

The assessed criterions are stated in the research questions: the average loss time of all vehicles and the queue lengths. During the first series of simulations, the absolute and relative impact of the applied ranges of parameters are analysed at three penetration rates. With the output of this analysis, six ways of describing SDCs of level 3 and 4/5 are put forward. These six types are then analysed for their impact at various penetration rates. With the changes in loss times, the final step is made to translate the loss times into changes in capacity, by ranging the input flow of SDCs until the loss times are at the level they were at when there were no SDCs. The exact assessment framework is discussed in section 2.5.

## 2.3. Boundaries of scope

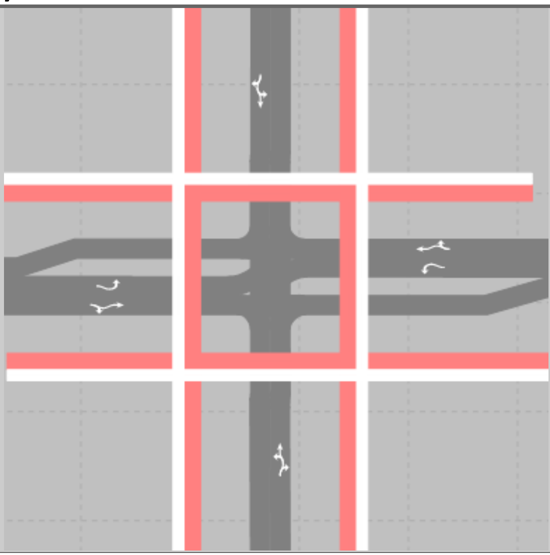
Since this research has a limited amount of resources concerning time, it is important to define the boundaries of the research scope. The goal of the research had to be reachable within ten weeks. In order to do this, the following boundary conditions were established:

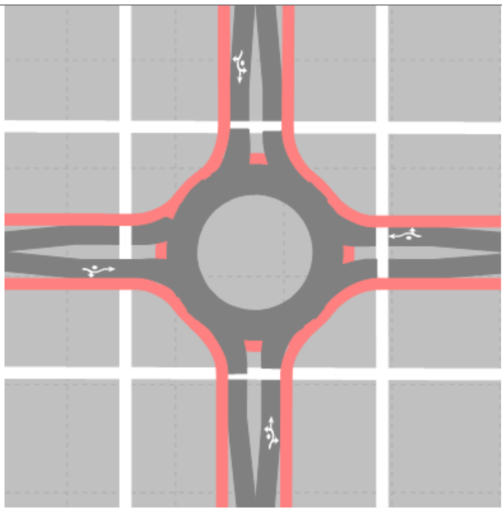
- The research only focussed on passenger cars. For simplicity, other types of mobility will not be incorporated. It might be possible to translate 'regular' passenger cars to possible other vehicles using the Passenger Car Equivalent (PCE). Pedestrians and cyclists have been ignored for time resource related reasons. Nevertheless, pedestrians and cyclist might have impacts on the traffic operations of the urban road network, since these road users cross and mix with SDCs around intersections. This is elaborated on more in chapter 5. Discussion.
- Connectivity might have interesting influences on the traffic operations of the urban road network, e.g. due to the fact that platoons might cross intersections quicker. However, during the transition period there will be quite some regular vehicles mixing with the SDCs, in which case connectivity cannot play a large role. Since modelling connectivity is a time-consuming activity, it has been left out of scope.

## 2.4. Analysed Intersections

Three types of intersections are analysed in this research: a signalised intersection, a roundabout and a regular intersection. The lay-outs and remarks of the intersections are shown in Table 3.

*Table 3. Lay-out and remarks concerning the analysed intersections.*

| Type | Lay-out | Remarks |
|---|---|---|
| **Regular** |  | • Regular priority intersection lay-out as used by Goudappel Coffeng for testing.<br>• Small alterations made to make robust for Wiedemann 99.<br>• Static traffic assignment based on the Aalsmeerderweg – Machineweg roundabout analysis in Aalsmeer.<br>• Used OD-matrix visible in Appendix F.1: OD-matrix of the regular intersection. |

| | | |
|---|---|---|
| **Roundabout** |  | • Regular roundabout lay-out as used by Goudappel Coffeng for testing.<br>• Small alterations made to make robust for Wiedemann 99.<br>• Static traffic assignment based on the Aalsmeerderweg – Machineweg roundabout analysis in Aalsmeer.<br>• Used OD-matrix visible in Appendix F.2: OD-matrix of the roundabout. |
| **Signalised** |  | • Intersection of the N214 and N216 roads in the South-Holland province of the Netherlands.<br>• No possible influences from other (access) roads.<br>• Dynamic traffic assignment based on rush-hour intensity.<br>• Used OD-matrices visible in Appendix F.3: OD-matrices of the signalised intersection. |

In order to see the general impact on the road network, only passenger vehicles are analysed. Other vehicle or mobility types like freight traffic, public transport, bicycles and pedestrians are left out of scope. This, for example, leads to the fact that there are no delaying pedestrians and cyclists at the regular intersection and roundabout. At the signalised intersections, there will be no green times for pedestrians and cyclists and the bus stops are removed.

### 2.4.1. Regular Intersection & Roundabout

The simulations of the regular intersection and roundabout are executed with a simulated time of 1 hour or 3600 seconds, excluding the warm-up time of 900 seconds. This warm-up time has been decided upon by Goudappel Coffeng as a suitable warm-up time for their VISSIM projects. The simulation time of 3600 seconds has been decided upon similarly.

As stated in Table 3, the traffic demand of the regular intersection and roundabout are based upon the traffic assignment as Goudappel Coffeng has done for the analysis of the Aalsmeerderweg – Machineweg roundabout in Aalsmeer. This traffic demand includes freight traffic, bicycles and pedestrians, which left out of scope here. The sole personal vehicular traffic demand does not create a saturated situation. Nevertheless, a saturated traffic situation is desired, since that will show the increased impact of the various behavioural changes of SDCs when they are implemented. Therefore, the traffic input is increased by 25% for the regular intersection and 30% for the roundabout.

### 2.4.2. Signalised Intersection

The simulations of the signalised intersection are executed with a simulated time of 2 hours and 15 minutes or 8100 seconds, in order to incorporate the dynamic traffic assignment of the rush hour. This simulation also has the warm-up time of 900 seconds, excluded in the 8100 second simulation time.

The lay-out of the signalised intersections is presented in Table 3. It is an intersection at which the east-west connection, the N214, has a two-lane entry and two-lane exit. Both sides have a separate left- and right turning lane respectively. The north-south connection, the N216, has a different design. The lane originating north has three different directional lanes: one lane for turning right, one lane for going straight and one lane for turning left. The lane originating south has one lane for turning right, one lane for going straight and two lanes for turning left.

In the original model presented by Goudappel Coffeng, the traffic was not saturated in such a way that the maximum green times were reached throughout the cycle time. This has to do with the fact that pedestrians and bicycles are removed from the model, which have a large share in the originally designed signalling plan.

Since a saturated intersection will give an enhanced insight into how the vehicles will behave around intersections, the dynamic traffic assignment has been scaled proportionally. In order to have a suitable saturation, a visual analysis was made of a simulation where only regular vehicles were present. Three aspects were assessed in order to have a suitable saturation of the model:

- No second red times for waiting vehicles;
- Maximum green time is reached for most of the traveling directions.
- No blocking of the entrance to other directional lanes;

In the end, this led to an increase in traffic input of 85%.

Another aspect of an undesired modelling problem arose with the implementation of this enhanced traffic demand. VISSIM has issues with traffic behaviour at merging sections and two merging section were located shortly after the east-west exits of the intersection. This caused unintended problems in the traffic handling at these locations, which eventually lead to congestion at the intersection itself. Since this research focusses on the intersections rather than the merging sections, the merging sections were removed and exists of the east-west connection are remodelled two-lane roads entirely.

Important to incorporate in the analysis of the signalised intersection, is the fact that a direction will never have an unlimited green time. It is therefore imminent that delays will occur, no matter how efficient SDCs will be able to drive, and these delays should be removed from the loss time data in order to have a fair view on the loss times caused by behaviour of vehicles around the intersection. This fixed loss time is determined by the clearance times which need to occur because of the conflicting signal group. The conflicting signalling group has been determined using the COCON traffic signalling programme. The resulting conflicting clearance times, which turned out to be only 2 seconds, are subtracted from the measured loss times.

## 2.5. Assessment Framework

In order to analyse the intersections for the impact of SDCs on traffic operations, it is important to have a clear assessment framework for the research. Since the research exists of two parts of simulation, two different assessment frameworks are set up. These assessment frameworks have clear similarities since they both show the impact of SDCs on urban traffic performance. However, the input of the different parts of simulation differs.

The data which is exported from the simulations are the raw data on individual vehicles, which include loss times of individual vehicles, and the queue counter data collection, which includes the queue lengths during intervals of 60 seconds during the runs. Queue counters are located at all directional lanes of the intersection. The exact equations explaining the data gathering and processing are visible in Appendix B: Formulas Applied for Data Gathering and Processing.

The first series of simulations concerns ranging five different parameters over five different values and with penetration rates of 40%, 70% and 100%. The output data can be shown in graphs where the absolute impact of changing the individual parameters are shown, by putting normalised parameter settings on the horizontal, and the assessment criterion (loss time or queue length) at the different penetration rates of SDCs is shown on the vertical axis. The input parameters which are altered between an upper and lower level using 4 interval steps are normalised based on a default SDC value for the parameter. In this way, the relative change of these parameters and their individual impact on the loss times and queue lengths can be compared.

Besides the absolute impact, it is relevant to analyse the relative impact of ranging the parameters concerning the penetration rates to see if the parameters have different degrees of influence when the penetration rates are altered. This is done by normalising the outcomes of the assessment criterions based on the output at the default SDC value for the ranged input parameter. The data can be analysed for relevant trends describing the influence of individual behaviour aspects of SDCs on the capacity of urban traffic networks and assessing the relative influence of the parameters on the assessment criteria.

Using the absolute and normalised impacts of ranging the parameters, it can be stated which combinations of parameters are relevant in describing the 3 and 4/5 levels of vehicle automation. Since it will follow that the levels of automation can be described in multiple ways, a limit is set to six different combinations of parameter values. The different combinations will be based on the first simulations as well as the outcome of the literature research, since the literature will have more detailed descriptions on how the different levels will act. In order to analyse possible future traffic situations, the range of penetration rates for the second series of simulations is expanded to 10%, 20%, 40%, 70% and 100%. The results will be analysed for trends between the different penetration rates and the assessment criteria in order to see the impact of a certain type of SDC.

Finally, the loss times are used to determine the impact on the capacities. This is done by analysing the loss time of a certain type of SDC at 100% penetration and ranging the input flow of vehicles with decreasing steps starting at 10% difference compared to the original value, until the loss time is within 2% of the loss time without SDCs. The relative change in input flow can be seen as change in capacity. This process of determining capacity is based on determining how many more or less vehicles the network in a 100% SDC penetration rate scenario can handle in order to have a similar performance of the network as compared to the 0% SDC penetration rate scenario.

*Table 4. Description of the various assessments.*

| Serie of simulations | Assessment | Relevance |
|---|---|---|
| **1** | Absolute impact as result of normalised input. | Analysis of absolute impact of altering parameters and comparison between penetration rates. |
| | Normalised impact as result of normalised input. | Analysis of relative impact of altering parameters and penetration rate. |
| **2** | Absolute impact as result of penetration rate. | Analysis of absolute impact of certain types of SDCs at different penetration rates |
| | Normalised impact al result of penetration rate. | Analysis of relative impact of certain types of SDCs at different penetration rates |
| | Capacity change as result of change in loss times. | Analysis of actual capacity changes as a result of the implementation of SDCs. |

# 3. Modelling Self-Driving Cars in VISSIM

Two different types of vehicle movement can be distinguished: longitudinal and lateral movements. Longitudinal vehicle moment concerns car following, lateral vehicle moment concerns lateral position on a lane and lane changes. Lateral vehicle movement can be important to take into account when analysing SDCs, especially concerning aspects like overtaking and (increased) rutting due to platooning. When looking at intersections, lateral movements also occur when choosing lanes or merging traffic flows. However, since intersections are selected where merging is not the leading aspect in the capacity, lateral movement is left out of the scope of this research.

Within VISSIM the longitudinal driver behaviour is mainly modelled after the Wiedemann car-following models of 1974 and 1999, which explain the different phases of car-following behaviour. The 1974 model is stated to be more suitable for urban arterial roads and the 1999 model is stated to be more suitable for free- and highways (Aghabayk, Sarvi, Young, & Kautzsch, 2013). With this conclusion, it seems logical to focus on the Wiedemann 1974 model, however, this model provides few parameters to range in order to describe the different levels of automation of SDCs. The Wiedemann 1999 model provides ten parameters which can be altered to describe SDCs. A visualisation of the general principle of the general principle of the Wiedemann 1999 model is visible in Figure 3.

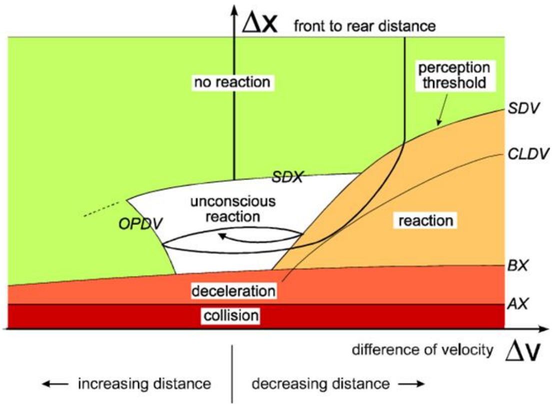



*Figure 3. The schematisation of the car-following model of Wiedemann 1999 with one vehicle trajectory visualised (Fellendorf & Vortisch, 2001).*

The ten parameters describing the various thresholds in Figure 3 are visible in Table 5. The CC0 to CC6 parameters are implemented in the model by equations, which are visible in the last column of Table 5. The CC7, CC8 and CC9 parameters are implemented by actually describing the possible acceleration at their respective moments. In the equations in Table 5, L is the length of the lead vehicle, v is the speed of the vehicle, Δx is the space headway between two successive vehicles and δ is a dummy variable which is equal to 1 when the vehicle speed is greater than CC5 and 0 else (Aghabayk, Sarvi, Young, & Kautzsch, 2013).

*Table 5. The parameters of the Wiedemann 1999 model with its accompanying descriptions in VISSIM and the equations through which they are implemented in the model.*

| Parameter | Description | Unit | Implementation equation (Aghabayk, Sarvi, Young, & Kautzsch, 2013) |
|---|---|---|---|
| CC0 | Standstill distance | m | $AX = L + CC0$ |
| CC1 | Headway time | s | $BX = AX + CC1 * v$ |
| CC2 | Following variation | m | $SDX = BX + CC2$ |
| CC3 | Threshold for entering 'following' | | $(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4$ |

| | | | |
|---|---|---|---|
| CC4 | Negative 'following' threshold | | $$(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4$$ $$CLDV = \frac{CC6}{17000} * (\Delta x - L)^2 - CC4$$ |
| CC5 | Positive 'following' threshold | | $$OPDV = -\frac{CC6}{17000} * (\Delta x - L)^2 - \delta * CC5$$ |
| CC6 | Speed dependency of oscillation | | $$CLDV = \frac{CC6}{17000} * (\Delta x - L)^2 - CC4$$ $$OPDV = -\frac{CC6}{17000} * (\Delta x - L)^2 - \delta * CC5$$ |
| CC7 | Oscillation acceleration | $m/s^2$ | |
| CC8 | Standstill acceleration | $m/s^2$ | |
| CC9 | Acceleration at 80 km/h | $m/s^2$ | |

With the equations in Table 5, it is possible to visualise what the effects of the various changes in the parameter values on the car-following model will be when these parameters are altered. These effects of the parameter alterations are visible in Table 31 in Appendix C: The Wiedemann 1999 Model. Besides the Wiedemann parameters, VISSIM also uses other parameters, functions and distributions to describe driving behaviour relevant for urban road networks (Sukennik & Fléchon, 2018). These are summarized in Table 6.

*Table 6. Summary of parameters, functions & distributions in VISSIM as stated by (Sukennik & Fléchon, 2018) describing driving behaviour which might be relevant for SDCs but are not directly described within the Wiedemann 1999 model.*

| **Parameter/function/distribution description** | **Unit** |
|---|---|
| Minimum look ahead distance | m |
| Maximum look ahead distance | m |
| Number of observed vehicles | |
| Minimum look back distance | m |
| Maximum look back distance | m |
| Duration of lack of attention | s |
| Probability of lack of attention | % |
| Behaviour at amber signal at end of green | |
| Factor of reduced safety distance at stop line | |
| Meso standstill distance | m |
| Maximum & desired acceleration function | |
| Maximum & desired deceleration function | |
| Desired speed distribution | |
| Headway time distribution | |

## 3.1. Comparing Behaviour of SDCs to Regular Vehicles

SDCs are expected to be far less stochastic and might be even up to 100% deterministic in their driving behaviour due to the fact that they are controlled by sensor and computers. This will lead to different traffic behaviour when comparing to regular vehicles. It is important to identify these changes in order to be able to model SDCs correctly in VISSIM.

As mentioned in the Introduction, there is not one single type of SDC: there can be multiple definitions of a vehicle which drives autonomously. In order to create a standardized view on automated vehicles, the SAE developed the aforementioned framework which defines these different aspects of the various levels of SDCs, which is already presented in the Introduction in Figure 1.

In order to get insight into what way SDCs behave differently, literature is analysed which describes the behavioural differences between SDCs and regular vehicles. (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017) give an overview of the expected behavioural changes, which are presented in the first column of Table 7. Besides, mobility behaviour expert Matthijs Dicke-Ogenia has been consulted to see if any other main influences are to be expected.

When combining the levels of automation visible in Figure 1 and the behavioural descriptions available in the first column of Table 7, it is possible to determine what changes will occur at the different levels of automation. It is assumed that at level 4/5, all of the mentioned behavioural changes in Table 7 will be present. However, when describing level 3 automation, not all aspects of automation might be present since the DDT and ODD of level 3 SDCs have significant differences when compared to level 4/5. Table 7 therefore also gives an expectation of the degree of presence of the autonomous behaviour in a level 3 SDC.

*Table 7. Behavioural changes of SDCs compared to regular vehicles as stated by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017) and the expected degree of presence of these aspects in level 3 and level 4/5 SDCs.*

| Autonomous vehicle behaviour | Expected degree of presence in automation level 3 | Difference in presence in level 4/5 compared to level 3 |
|---|---|---|
| Keep smaller standstill distances | Level 3 SDCs will have the ability to be efficient in driving in traffic jams and other queues, so standstill distances are affected. However, since the DDT is still with the driver in cases that are not incorporated in the ODD, the standstill distances will be longer than at level 4/5 SDCs. | Lower value compared to level 3, since level 4/5 will be able to drive more aggressively concerning standstill distances. |
| Keep smaller distances at non-zero speed | Level 3 SDCs will have the ability to be efficient in driving in traffic jams, platoons and other queues, so following distances are affected. However, since the DDT is still with the driver in cases that are not incorporated in the ODD, the standstill distances will be longer than at level 4/5 SDCs. | Significantly lower compared to level 3, since level 4/5 will be able to drive significantly more aggressive concerning distances at non-zero speeds. |
| Accelerate faster and smoothly from standstill | Present. Level 3 SDCs will have the ability to be efficient in driving in traffic jams and other queues, which means smooth acceleration will be affected. | Similar compared to level 3. |
| Keep constant speed with no or smaller oscillation at free flow | Present. It is incorporated in the ODD of Level 3 SDCs to have the ability to drive efficiently in free flow or, when connected, in platoons. | Similar compared to level 3, since it is incorporated in the ODD of level 4/5 in a similar way. |
| Follow other vehicles with smaller distance oscillation | Present. Level 3 SDCs will have the ability to have less speed fluctuations due to sensory control of the vehicle. | Similar compare to level 3. |
| Form platoons of vehicles | Possibly present. When communication between vehicles is available, level 3 SDCs will presumably have this feature to the same degree as level 4/5 SDCs when in automated driving mode. | It is reasonable that level 4/5 will have the ability to communicate with each other, since it is key for non-human controlled vehicles to exchange information to drive safely. |

| | | |
|---|---|---|
| Following vehicles react on green signal at the same time as the first vehicle in the queue | Possibly present. Level 3 SDCs will have the ability to accelerate based on other vehicles. | Possibly more aggressive than level 3, since the DDT is incorporated with the vehicle in all the situations incorporated in the ODD. |
| Communicate with other SDCs, i.e. broken-down vehicle and other avoid it | Possibly present. When communication between vehicles is available, level 3 SDCs will presumably have this feature to the same degree as level 4/5 SDCs when in automated driving mode. | It is reasonable that level 4/5 will have the ability to communicate, since it is key for non-human controlled vehicles to exchange information to drive safely. |
| Communicate with the infrastructure, i.e. vehicles adjusting speed profile to reach a green light at signals | Possibly present. When communication between vehicles is available, level 3 SDCs will presumably have this feature to the same degree as level 4/5 SDCs when in automated driving mode. | It is reasonable that level 4/5 will have the ability to communicate, since it is key for non-human controlled vehicles to exchange information to drive safely. |
| Perform more co-operative lane change as lane changes could occur at higher speed co-operatively | Possibly not present. Since the driver should have the ability to interfere, it is undesired for level 3 SDCs to create situations where a regular driver is not used to, like lane changes at higher speeds than regularly, which is a clear distinction in the ODD of level 3 SDCs. | Contrary to level 3, co-operative driving might be present in level 4/5, since the vehicle should drive all by its own and can anticipate to possible dangerous situations. |
| Smaller lateral distances to vehicles or objects in the same lane or on adjacent lanes | Level 3 SDCs will have the ability to drive closely to other vehicles, so lateral distances are affected. However, since the driver should have the ability to interfere if needed, the lateral distances will be longer than at level 4/5 SDCs. | Lower value compared to level 3, since level 4/5 will be able to drive more aggressively concerning lateral distances. |
| Exclusive SDC lanes, with and without platoons | Not present, since a level 3 SDCs has the ability to be controlled by a human driver, which conflicts with the principle of an independent SDC lane. | Possibly present, since level 4/5 should be able to drive on their own completely. |
| Drive as Communicative SDC on the selected routes (or areas) and as conventional human controlled vehicles on the other routes, i.e. Volvo DriveMe project | Possibly present. When communication between vehicles is available, level 3 SDCs will presumably have this feature to the same degree as level 4/5 SDCs when in automated driving mode. | Presence is more likely in level 4/5, since communication in level 4/5 is highly likely. However, since level 4/5 SDCs might not have a steering wheel, these SDCs might not be able to drive as human controlled vehicles at all. |
| Divert vehicles already in the network onto new routes and destinations; i.e. come from a parking place or position in the network to pick up a rideshare app passenger on demand | Possibly present. When communication between vehicles is available, level 3 SDCs will presumably have this feature to the same degree as level 4/5 SDCs when in automated driving mode. | Presence is more likely in level 4/5, since communication in level 4/5 is highly likely. However, since level 4/5 SDCs might not have a steering wheel, these SDCs might not be able to drive as human controlled vehicles at all. |

Noteworthy about keeping smaller standstill distances and distances at non-zero speeds is that whereas it is theoretically possible, it is debated whether smaller distances will be kept in practice. This mainly has to do with the party who will be responsible concerning accidents resulting from smaller headway distances. As a result, it might be that the headways will be increased as a safety factor so that less accidents will occur in the first place.

Concerning the contact with Matthijs Dicke-Ogenia (personal communication, 23 May 2019), he mentioned the differences in behaviour stated in Table 7 as important aspects as well. Therefore, it can be seen that Table 7 included the most influential behavioural changes. The only aspect which was not mentioned, is the desired speed distribution. This aspect will therefore be discussed in Table 9. Besides changes in driving behaviour, Dicke-Ogenia stressed that slow traffic (pedestrians and cyclists) will be relevant for the changes on the Dutch road system as well, since they are often present in the mixed urban traffic environment. Nevertheless, they are out of scope of this research.

## 3.2. Literature review into relevant parameters

Table 5 and Table 6 already provide an overview of parameters, functions and distributions which might be altered for SDCs when compared to regular human controlled vehicles. Section 3.1 describes to what extend the altered behaviour might influence these parameters. In this section, the relevance of the various parameters concerning this research is discussed and analysed to see what the most relevant parameters are in the description of the different levels of vehicle automation.

Some of the behavioural changes mentioned in Table 7 are specifically relevant for this research. Others are less relevant, because they handle aspects like lateral movement and communication, which are either simply not relevant or left out of scope. The relevant aspects with its proposed adjustments as stated in Table 8. The entire analysis of relevance is visible in Appendix D: Relevance Analysis of Behavioural Changes of SDCs.

*Table 8. The relevant behavioural changes of SDCs based on the expected behavioural changes by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017) and the proposed adjustments done by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017) to describe the changes in VISSIM.*

| **Autonomous vehicle behaviour** | **Relevance** | **Adjustments to make to Wiedemann 1999** |
|---|---|---|
| Keep smaller standstill distances | Relevant, since this will happen when SDCs wait at intersections | Change CC0 |
| Keep smaller distances at non-zero speed | Relevant, since this plays an important role in SDCs following other vehicles | Change CC0, CC1 and CC2 |
| Accelerate faster and smoothly from standstill | Relevant, since acceleration from standstill will occur at intersections | Change acceleration functions and CC8 and CC9 |
| Keep constant speed with no or smaller oscillation at free flow | Relevant, since SDCs might not have to stop at certain intersections at certain moments | Use COM interface |
| Follow other vehicles with smaller distance oscillation | Relevant, since speed oscillations are important factors in traffic approaching intersections and crossing intersections | Change CC2 |
| Following vehicles react on green signal at the same time as the first vehicle in the queue | Indirectly relevant, since SDCs might accelerate simultaneously with the car directly in front of it, regardless of a green signal | Use COM interface |

In order to limit the scope of the research, the 5 most relevant Wiedemann 1999 parameters are selected to range over five values. From Table 8, it becomes visible that parameters CC0 and CC2 are featured in multiple behavioural aspects and can therefore be considered key parameters within this research. The other Wiedemann 1999 parameters which are present in Table 8 are CC1, CC8 and CC9 which completes the limited number of five parameters to range.

Nevertheless, these parameters are not the only aspects important in modelling SDCs. As can be seen in Table 6, there are various other parameters, functions and distributions which can or need to be altered in order to correctly describe an SDC. Moreover, the other Wiedemann 1999 parameters play an important role as well. All the other parameters, functions and distributions which are altered besides the ranged Wiedemann 1999 parameters are shown in Table 9. All together, these fixed values serve as a slightly aggressive default for the driving behaviour of SDCs and can be seen as a sixth analysed parameter all together.

*Table 9. The non-ranged Wiedemann parameters and parameters, functions and distributions as mentioned in Table 6 which are set to a fixed value in order to specifically describe SDCs.*

| **Parameter/function/ distribution** | **Value/changes** | **Value for regular cars** | **Unit** | **Explanation/Source (apart from (Sukennik & Fléchon, 2018))** |
|---|---|---|---|---|
| CC3: Threshold for entering 'following' | -12 | -8 | | (Rossen, 2018) |
| CC4: Negative 'following' threshold | -0.35 | -0.35 | | (Rossen, 2018) |
| CC5: Positive 'following' threshold | 0.35 | 0.35 | | (Rossen, 2018) |
| CC6: Speed dependency of oscillation | 0 | 11.44 | | (Rossen, 2018) |
| CC7: Oscillation acceleration | 0.1 | 0.25 | $m/s^2$ | (Rossen, 2018) |
| Maximum look ahead distance | 160 | 250 | m | (Swief & El-Habrouk, 2018; Horlings, 2019) |
| Number of observed vehicles | 3 | 5 | | Since communication is out of scope, it is assumed that an SDC has limited capabilities concerning observing other vehicles. A built-in radar has the capability to analyse vehicle driving around 160 metres in front of the SDC. This range is reduced by the number of vehicles which the radar has to go through, so the number of observed vehicles is lowered compared to the value for regular vehicles of 5 (Swief & El-Habrouk, 2018; Horlings, 2019). |
| Behaviour at amber signal at end of green | Continuous check | Continuous check | | (Wang & Wang, 2018; PTV Group, 2018) |
| Factor of reduced safety distance at stop line | Kept the same as for regular vehicles | - | | It is not expected that automated vehicles will reduce the safety distances in mixed traffic circumstances (SDCs and regular vehicle present) when close to |

| | | | | |
|---|---|---|---|---|
| | | | | signalised intersections, which is why the same value is selected as for regular vehicles. |
| Maximum acceleration function | No minimum curves | - | | A free flowing SDC will have a programmed acceleration curve and not fluctuate from that curve |
| Desired acceleration function | No minimum curves | - | | A free flowing SDC will have a programmed acceleration curve and not fluctuate from that curve |
| Maximum deceleration function | No minimum and maximum curves | - | | A free flowing SDC will have a programmed deceleration curve and not fluctuate from that curve |
| Desired deceleration function | No minimum and maximum curves | - | | Free flowing SDCs will have a programmed deceleration curve and not fluctuate from that curve |
| Desired speed distributions | Linear distribution around desired speed with a maximum deviation of 5% | - | | Free flowing SDCs will operate with a much lower spread of desired speeds because they are more likely to strictly obey speed limits |

Some notable aspects can be seen in the proposed changes of Table 9. First of all, the value for CC6 is set to 0, since it is expected that SDCs will not be sensible for oscillations in their own speed due to the fact that they maintain their speed accurately because they are computer driven.

Secondly, the acceleration curves are set to be without minimum curves, since SDCs can be regulated to accelerate smoothly and according to a pre-set acceleration curve. The maximum curve is left in in order to be able to model the changes in acceleration resulting from alterations of CC8 can CC9. There might be a debate, however, on what exact acceleration curve is desirable. When a uniform acceleration curve is set for all SDCs, the SDCs are likely to accelerate more uniformly since they behave in a similar way. If acceleration curves are set by the user of an SDC, results may turn out completely different. Since one user may prefer a smoother curve because of aspects like a possibility to sleep in a car, another may prefer a more aggressive curve for time-related reasons or even a reason like driving experience. If this user-directed scenario is the case, it is more relevant to go for an acceleration function with a minimum and maximum curve set as boundaries for the function. However, since there is the reasonable possibility that acceleration curves are set by the automotive industry, the minimum and maximum curves are removed and the acceleration curves of regular vehicles is selected

Finally, the desired speed distribution is decreased in range. This is done because it is realistic to say that SDCs will strive for the exact desired/maximum speed more precisely than human drivers. Whereas some human drivers might strive for driving faster than the obligated maximum speed and other drivers are too afraid to drive close to the desired speed, SDCs can be set to a drive in the most optimal way and safe way, which will be close to the desired speed.

## 3.3. Establishing relevant ranges for parameters

The five Wiedemann parameters which are ranged are: CC0, CC1, CC2, CC8 and CC9, or in words, the standstill distance, the headway time, the following variation, the standstill acceleration and the acceleration at 80 km/h. These parameters are ranged analysed individually over five values, in order to get an independent insight into the possible ranges and effects of the parameters. As a starting point, the Wiedemann 1999 parameter values used for regular vehicles are visible in Table 10.

*Table 10. Wiedemann 1999 values for regular vehicles in VISSIM models of Goudappel Coffeng.*

| Parameter | CC0 | CC1 | CC2 | CC3 | CC4 | CC5 | CC6 | CC7 | CC8 | CC9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Unit** | m | s | m | - | - | - | - | $m/s^2$ | $m/s^2$ | $m/s^2$ |
| **Value** | 1.00 | 0.9 | 4.0 | -8.0 | -0.35 | 0.35 | 11.44 | 0.25 | 4.0 | 1.5 |

The ranged values are based on previously used or advised values in literature. The default value of the parameter which describes regular vehicles in the VISSIM models of Goudappel Coffeng is used as a starting point, which are visible in Table 10. (Sukennik & Fléchon, 2018) provide a guide on how to model SDCs in VISSIM, however they give a qualitative rather than a quantitative proposal for the parameters. (Stanek, Huang, Milam, & Wang, 2017) provide the parameter values which they used in their research on monitoring the impact of SDCs on congested networks. (Rossen, 2018) gives an overview of various sources of parameter values for his research into highway capacity of SDCs. The ranges which are defined are established based on values found for cautious SDCs on one hand and aggressive SDCs on the other. In this way, both possibilities of the development of SDC behaviour can be investigated.

The **CC0** parameter describes the standstill distance between two vehicles. The default value for this parameter within the VISSIM models of Goudappel Coffeng is 1.00 m. (Sukennik & Fléchon, 2018) advice to keep the default value for CC0. (Stanek, Huang, Milam, & Wang, 2017) assign a value of 1.25 m to this parameter. (Rossen, 2018) assigns a value of 1.5 m for ACC settings, 1.25 for CACC settings and 1.0 for (C)SDC settings. (Sukennik & Fléchon, 2018) argue that the CC0 parameter only gets smaller when the SDC is made an 'all-knowing' vehicle, or in other words a vehicle connected to vehicles and the infrastructure. Taking these considerations into account, it is feasible to assign a range with values 0.75 m, 1.0 m, 1.25 m, 1.5 m and 1.75 m. These values are visible in Table 11.

The **CC1** parameter describes the headway time. This is done by the time distribution. The default value for this parameter within the VISSIM models of Goudappel Coffeng is 0.9 s. (Sukennik & Fléchon, 2018) state that the CC1 parameter will be higher than default at cautiously driving SDC and will be slightly smaller than default with a more aggressive SDC. (Stanek, Huang, Milam, & Wang, 2017) assign a value of 0.25 s to this parameter. (Rossen, 2018) found various values for the headway time, ranging from 0.5 s for aggressive SDCs to 2.0 s for cautious ACC with the possibility that a human driver needs to take over the driving activity. In order to combine the mentioned aspects, a range is set up with the values 0.3 s, 0.6 s, 0.9 s, 1.3 s and 1.8 s. A standard deviation of 0 is applied to the time distributions describing CC1.

The **CC2** parameter describes the following variation. The default value for this parameter within the VISSIM models of Goudappel Coffeng is 4.0 m. (Sukennik & Fléchon, 2018) state that the CC2 parameter will be smaller than default in most of the cases. Only in a very cautious scenario it is expected that the default value will remain. (Stanek, Huang, Milam, & Wang, 2017) put a value of 3.0 m forward for describing an SDC. (Rossen, 2018) assigns a range of 1 m, 2 m, 3 m and 4 m for CSDC, CACC/SDC, ACC and default respectively. The range set up for the CC2 parameter is 1.0 m, 2.0 m, 3.0 m, 4.0 m, and 5.0 m.

The **CC8** parameter describes the standstill acceleration of the vehicle. The default value for this parameter within the VISSIM models of Goudappel Coffeng is 3.5 $m/s^2$. (Sukennik & Fléchon, 2018) argue that the value for CC8 will be reduced in the case of a cautious SDC but will remain default with a more aggressive SDC. (Stanek, Huang, Milam, & Wang, 2017) propose to keep the value for CC8 the same as the default value: 3.5 $m/s^2$. (Rossen, 2018) gives two possible values for this parameter: 3.5 $m/s^s$ and 4 $m/s^2$. In order to create a suitable range, a range is established from 2.5 $m/s^2$ to 4.5 $m/s^2$ with steps of 0.5 $m/s^2$.

The **CC9** parameter describes the acceleration at 80 km/h. The default value for the parameter within the VISSIM models of Goudappel Coffeng is 1.5 $m/s^2$. Similar to CC8, (Sukennik & Fléchon, 2018) argue that the value for CC9 will be reduced in the case of a cautious SDC, but will remain default with a more aggressive SDC. Again, similar to CC8, (Stanek, Huang, Milam, & Wang, 2017) propose to keep the default value for CC9: 1.5 $m/s^2$. (Rossen, 2018) gives two possible values for the CC9 parameter: 1.5 $m/s^2$ for describing the default, ACC and CACC and 2.0 $m/s^s$ for SDC and CSDC. To establish a range and to take the notice of (Sukennik & Fléchon, 2018) into account, a range is set up with the values 1.0 $m/s^2$, 1.25 $m/s^2$, 1.5 $m/s^2$, 2.0 $m/s^2$ and 2.25 $m/s^2$.

*Table 11. The final range values for the ranged parameters. The value which is set as fixed default SDC value when another parameter is fixed, in other words the default value, is highlighted in orange cells.*

| Parameter | Unit | Value 1 | Value 2 | Value 3 | Value 4 | Value 5 | Regular cars |
|---|---|---|---|---|---|---|---|
| **CC0** | m | 0.75 | 1.0 | 1.25 | 1.5 | 1.75 | 1.0 |
| **CC1** | s | 0.3 | 0.6 | 0.9 | 1.3 | 1.8 | 0.9 |
| **CC2** | m | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 4.0 |
| **CC8** | $m/s^2$ | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 4.0 |
| **CC9** | $m/s^2$ | 1.0 | 1.25 | 1.5 | 2.0 | 2.25 | 1.5 |

Since the parameters are adjusted individually, fixed values are needed for the parameters which are not analysed. The values for these fixed parameters are determined by selecting the value which is closest to the description of an SDC as stated by (Rossen, 2018). These values are visualised in Table 11 with the orange cells. The outcome of the simulations is elaborated on in chapter 4. The actions needed to implement the SDCs in VISSIM is explained in Appendix E: Explanation of the implementation of SDCs in VISSIM.

An important part in section 4.2, is the fact that combinations of parameters are established in order to describe a complete functional SDC. This is done by analysing the influence of the individual ranged parameters and combining these outcomes with the description of the vehicle automation level 3 as presented in Table 7. When limiting Table 8 to the changes which influence the Wiedemann 1999 parameters, and subsequently combining Table 7 and the altered version of Table 8, Table 12 emerges, which can be used to establish the combinations of parameter values to describe the level 3 and level 4/5 parameters.

*Table 12. The relevant behavioural changes which influence Wiedemann 1999 parameters and its degree of presence in vehicle automation level 3.*

| Autonomous vehicle behaviour | Degree of presence in automation level 3 | Adjustments to make to Wiedemann 1999 (PTV Group, 2017; Stanek, Huang, Milam, & Wang, 2017) |
|---|---|---|
| Keep smaller standstill distances | Present, but with a higher value than at level 4/5. Level 3 SDCs will have the ability to be efficient in driving in traffic jams and other queues, so standstill distances are affected. However, since the DDT is still with the driver in cases that are not incorporated in the ODD, the standstill distances will be longer than at level 4/5 SDCs. | Change CC0 |
| Keep smaller distances at non-zero speed | Present, but with a significant higher value than at level 4/5. Level 3 SDCs will have the ability to be efficient in driving in traffic jams, platoons and other queues, so following distances are affected. | Change CC0, CC1 and CC2 |

| | | |
|---|---|---|
| | However, since the DDT is still with the driver in cases that are not incorporated in the ODD, the standstill distances will be longer than at level 4/5 SDCs. | |
| Accelerate faster and smoothly from standstill | Present. Level 3 SDCs will have the ability to be efficient in driving in traffic jams and other queues, which means smooth acceleration will be affected. | Change acceleration functions and CC8 and CC9 |
| Follow other vehicles with smaller distance oscillation | Present. Level 3 SDCs will have the ability to have less speed fluctuations due to sensory control of the vehicle. | Change CC2 |

As can be seen in Table 12, the main differences between level 3 and level 4/5 SDCs will follow from the 'keep smaller standstill distances' and 'keep smaller distances at non-zero speed' behavioural changes. The exact determination of the parameter values to describe the different automation levels is done in section 4.2, however based on Table 12 it can already be stated that in order to describe a level 3 SDC, the values for CC0, CC1 and CC2 are likely higher when compared to a level 4/5 SDC.

## 3.4. Conclusion

There are various aspects of vehicle modelling to keep in mind when modelling SDCs. As Table 5 and Table 6 show, there is a wide range of parameters which can be used to describe the behaviour of vehicles and therefore of SDCs. Through literature it has been identified what the most important expected changes are in the behaviour of SDCs as compared to regular vehicles. These behavioural changes are related to the facts that SDCs will probably have more adequate reactions and have less fluctuations in their style of driving. The relevance of these behavioural changes has been assessed, which is visible in Table 8 and in Appendix D: Relevance Analysis of Behavioural Changes of SDCs. As a result of this assessment, the seven most relevant behavioural changes were identified.

The identified behavioural changes can, amongst others, be described by five different Wiedemann parameters. For the explorative research on the impact of SDCs on the urban traffic operations and the fact that there are various degrees of automation, a range is established for each of these five Wiedemann parameters. These ranges are based upon advices for and values of these parameters found in various literature. In the end, the ranges were established as described in Table 11. Besides the ranged parameters, there are other parameters relevant for describing SDCs, which are put forward in Table 5 and Table 6. These fixed/default values are visible in Table 9.

Now that it is known how SDCs behave differently from regular vehicles and what parameter values are relevant for the description of SDCs, it is possible to move on to the next step in the research. This will be the actual modelling of SDCs on various intersections. For this modelling, the described parameter values of Table 9 and the parameter ranges of Table 11 will be used for implementation of SDCs in the model.

# 4. Modelling Self-Driving Cars at Intersections

In order to be able to see the effects of SDCs, they are modelled using VISSIM. As described in chapter 0, VISSIM uses Wiedemann parameters to describe the various aspects of driving behaviour. These behavioural parameters are altered based on the conclusions of section 3.4 and are applied to the intersection designs discussed in section 2.4.

## 4.1. Ranging individual parameters

The ranges of the individual parameters have been established in 3.3. These ranges are used for the simulations in this section. Besides the ranges, the parameters, distributions and functions as described in Table 9 are applied in order to describe the behaviour of SDCs concerning other behavioural aspects which are not covered by the ranges.

Each intersection is analysed with various penetration rates of SDCs. As a base scenario, a simulation is carried out where there are no SDCs present. Three different penetration rates are analysed to see the different effects of this variable. The applied penetration rates are 40%, 70% and 100%.

### 4.1.1. The regular intersection

The regular intersection consists of one priority road in the east-west direction, visible in Table 3 in section 2.4. Vehicles from the north-south road need to yield for this road. The Origin/Destination(OD)-matrix of this intersections is visible in Table 34 in Appendix F: OD-matrices of the intersections.

#### *4.1.1.1. Loss times*

The results of the loss times when altering individual parameters and the penetration rates are visible in Table 13, Figure 4 and Figure 5. Graphs of the results of individual penetration rates are available in Appendix G.1: Loss Times at the Regular Intersection.

*Table 13. Average loss times at the regular intersection when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for the ranged parameters and the non-ranged parameters of Table 9 are applied.*

| Penetration rate of SDCs | Average loss time (s) | Percentual decrease relative to 0% scenario |
|---|---|---|
| 0% | 26.0 | - |
| 40% | 23.2 | 11% |
| 70% | 22.1 | 15% |
| 100% | 20.7 | 20% |

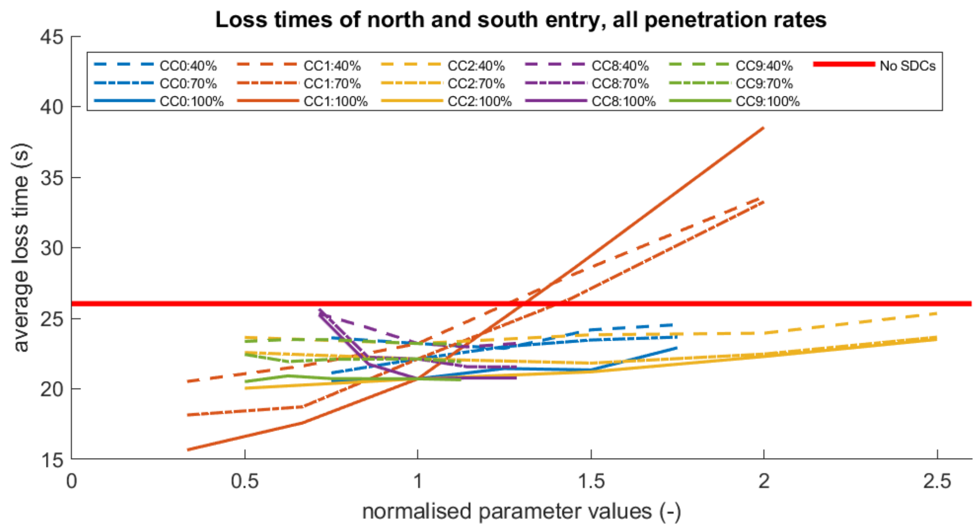



*Figure 4. Absolute loss times plotted against normalised parameters for the regular intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

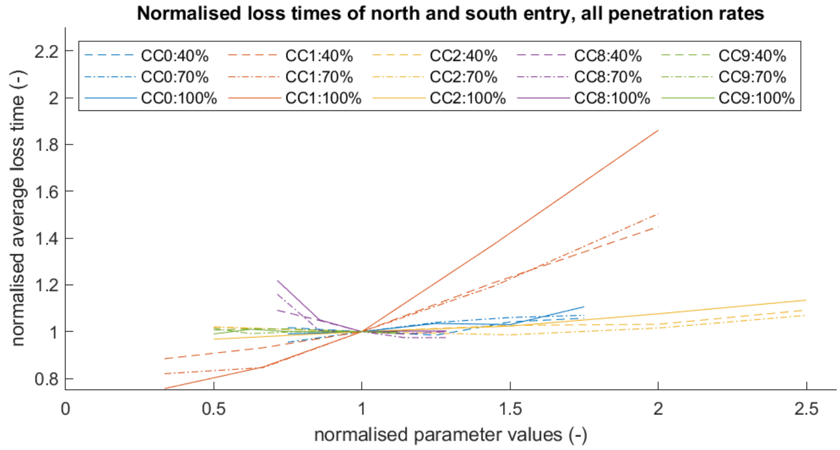



*Figure 5. Normalised differences in loss times plotted against normalised parameters for the regular intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

As can be concluded from Table 13 and Figure 4, the implementation of SDC to the fleet of vehicles can lead to a clear reduction of loss times, if implemented with the assumed characteristics stated in Table 9 and the default values of Table 11. The impact of the default values of Table 9 even seems bigger than the impact of some of the ranged parameters, since the loss time decrease when the penetration rate is increased and the ranged parameters of Table 11 are set to their default values.. When looking at Figure 5 it is possible to see the CC1 parameter, which describes the headway time, to have the clearest largest relative influence in the effects when compared to the other specifically analysed Wiedemann parameters. Moreover, when the headway time is increased, increased loss times also occur. This is an interesting observation, since it is expected that the headway time is one of the most important aspects in describing the aggressiveness of an SDC. This high degree of impact is explainable through the fact that the headway time has influence on two major aspects: 1. the distance groups of vehicles take up on the priority road, and 2. the distance vehicles hold on the side roads when approaching the intersection. When CC1 is lower than the reference value, vehicles on the priority road take up less space, there is more room on the road for vehicles on the side roads to cross the intersection, and vice versa. Moreover, the vehicles on the side road drive closer to each other which causes vehicles to enter the intersection from the side roads in shorter succession, and vice versa.

The other parameters seem to have fewer impact on the loss times. The CC8 concerning the acceleration at 0 km/h, does have a negative influence when adjusted negatively, but does not have a clear positive impact when adjusted positively. The CC2, describing the following variation, seems to have a negative influence when altered conservatively, as does CC0. CC9 has few impacts. Interestingly, the combined effect of the parameter values in Table 9 seem to have a large influence, since the loss times are decreased anyhow when the penetration rate is increased and the default values of Table 11 are selected, which is visible by the drops of the lines in Figure 4.

#### *4.1.1.2. Queue lengths*

The queue lengths are collected for every seed, every directional lane, every minute of the simulation. These are sorted per originating direction: directional lanes originating from the northern entry are grouped, as are the eastern, southern and western respectively. Subsequently, the data is filtered per minute: only the 90$^{th}$ percentile queue length ($L_{queue,max,i}$) for a certain originating direction, for a certain minute remains, all other values are ignored. The 90$^{th}$ percentile instead of the maximum is selected to erase possible outliers. Afterwards, the maximum queue length of the various directional lanes per minute is selected to be the value of the queue length of that originating direction for the minute of the simulation. Finally, in order take an average of the queue lengths, the median of the queue lengths is analysed. The mathematical procedure of this filtering is visible in Appendix B: Formulas Applied for Data Gathering and Processing. A schematisation of the filtering process is visible in Figure 6.

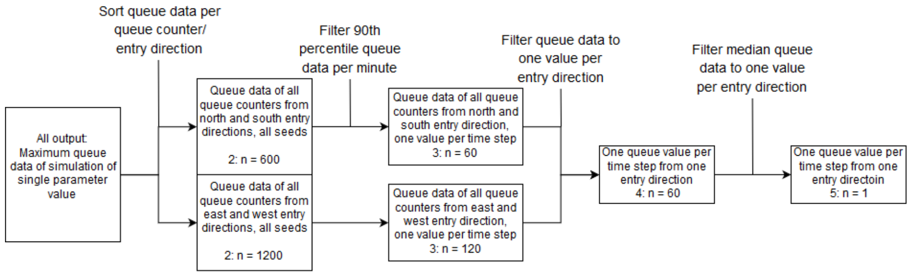



*Figure 6. Schematisation of the data filtering process with number of used data points for the regular intersection*

As already stated in section 2.4, the analysed intersection concerns a priority road. It is therefore not useful to look at the queues at the priority road, since queues will likely not occur there. It is therefore more relevant to look at the north and south side entries, rather than the priority road.

The results of the queue lengths when altering individual parameters and the penetration rates are visible in Table 14 and Figure 7. Graphs of the results of individual penetration rates are available in Appendix H.1: Queue Lengths at the Regular Intersection.

*Table 14. Median 90$^{th}$ percentile queue lengths at the north and south entries of the regular intersection when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for all ranged parameters.*

| Penetration rate of SDCs | $L_{queue,max,north}$ (m) | Percentual decrease north relative to 0% scenario | $L_{queue,max,south}$ (m) | Percentual decrease south relative to 0% scenario |
|---|---|---|---|---|
| 0% | 55.3 | - | 36.8 | - |
| 40% | 48.4 | 12.5% | 33.7 | 8.4% |
| 70% | 46.7 | 15.5% | 29.8 | 19% |
| 100% | 45.8 | 17.1% | 30.1 | 18% |

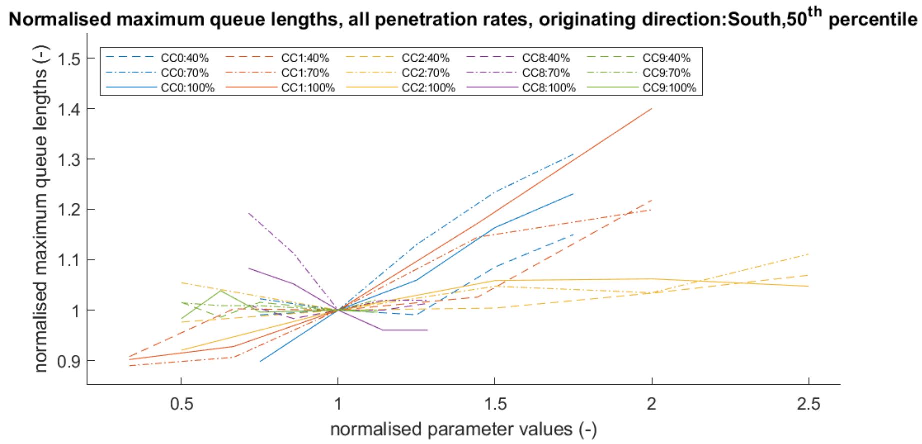



*Figure 7. Normalised median 90$^{th}$ percentile queue lengths of the south entry of the regular intersection plotted against normalised parameters for the signalised intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

Figure 7 shows a typical effect that ranging the parameters has on the queue lengths of the regular intersection: it is possible to indicate trends for the CC0, standstill distance, and CC1, headway time, parameters. The CC0 has an increased effect when a higher penetration rate is applied, especially on the negative side. The CC1 has the same trend as with the loss times: clearly it is the most influential parameter with both positive and negative influences when ranged. The CC8 parameter, describing acceleration at 0 km/h, interestingly has most effect at a 70% penetration rate when altered negatively. The same is true for CC0: the largest effect is visible at 70% penetration. This phenomenon might be explainable through the fact that the interaction with regular vehicles causes less uniformity in the vehicle behaviour and therefore causes longer queues.

### 4.1.2. THE ROUNDABOUT

The roundabout consists of a regular roundabout where all entry directions have the same directional lanes and there is no priority for certain directions, as visible in Table 3 in section 2.4. The OD-matrix of this intersection is shown in Table 35 in Appendix F: OD-matrices of the intersections.

#### *4.1.2.1. Loss times*

The results of the loss times when altering individual parameters and the penetration rates are visible in Table 15, Figure 8 and Figure 9. Graphs of the results of individual penetration rates are available in Appendix G.2: Loss Times at the Roundabout.

*Table 15. Average loss times at the roundabout when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for the ranged parameters and the non-ranged parameters of Table 9 are applied.*

| Penetration rate of SDCs | Average loss time (s) | Percentual decrease relative to 0% scenario |
|---|---|---|
| 0% | 15.3 | - |
| 40% | 12.1 | 21% |
| 70% | 8.5 | 44% |
| 100% | 8.4 | 45% |

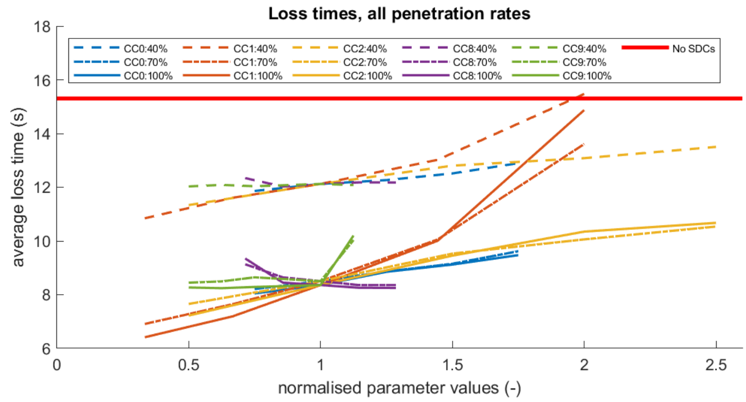



*Figure 8. Absolute loss times plotted against normalised parameters for the roundabout, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

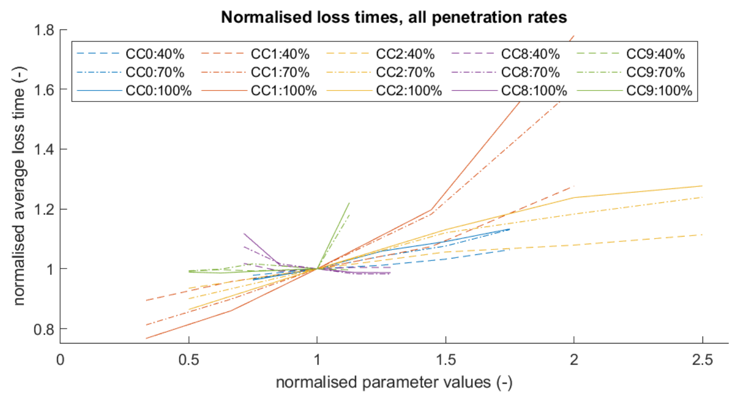



*Figure 9. Normalised differences in loss times plotted against normalised parameters for the regular intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

The first striking detail in Table 15 and Figure 8, is the very small differences between the 70% and 100% penetration rate of SDCs. This causes the idea that there seems to be a limit to the decrease in loss times concerning the penetration rate or the applied traffic inputs cause a saturation of the intersection. Nevertheless, the default SDC configuration concerning the parameters of Table 9 seem to have a clear impact on the loss times, since the loss times only increase above the loss times at the 40% penetration rate with the highest value for the headway time.

Concerning the parameters which are influential, the CC1, which describes the headway time, has the clearest and largest influence on the loss times, followed by the CC2 describing the following variation. This is similar to the regular intersection discussed in section 4.1.1. As also mentioned in section 4.1.1, the CC8 parameter describing acceleration at 0 km/h, only seems to have a (negative) influence when the value is lowered. When the value is increased, it does not seem to have an effect on the loss times. The CC9 parameter has a negative impact when increased, which is weird since a faster acceleration would imply less loss times.  It is therefore unclear how this result is caused. The CC0 parameter seems to have relatively few impacts on the loss times. Again, the parameters of Table 9 seem to have a relatively large impact concerning the 40% and 70% penetration rates.

##### *4.1.2.2. Queue lengths*

The filtering process of queue lengths is already described in section 4.1.1.2. The way this filtering process works out number-of-measurement-wise for the roundabout is visible in Figure 10.

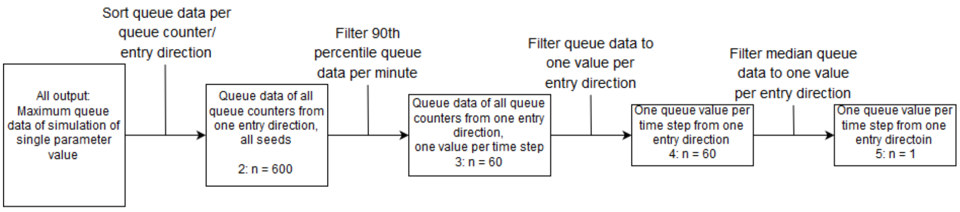



*Figure 10. Schematisation of the data filtering process with number of used data points for the roundabout.*

The results of the queue lengths when altering individual parameters and the penetration rates are visible in Table 16, Table 17 and Figure 11. Graphs of the results of individual penetration rates are available in Appendix H.2: Queue Lengths at the Roundabout.

*Table 16. Median 90th percentile queue lengths at the north and east entries of the roundabout when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for all ranged parameters.*

| Penetration rate of SDCs | $L_{queue,max,north}$ (m) | Percentual increase north relative to 0% scenario | $L_{queue,max,east}$ (m) | Percentual decrease east relative to 0% scenario |
|---|---|---|---|---|
| 0% | 52.0 | - | 52.1 | - |
| 40% | 48.0 | -7.7% | 44.6 | 14% |
| 70% | 55.4 | 6.5% | 39.8 | 24% |
| 100% | 52.4 | 0.75% | 41.0 | 21% |

*Table 17. Median 90th percentile queue lengths at the south and west entries of the roundabout when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for all ranged parameters.*

| Penetration rate of SDCs | $L_{queue,max,south}$ (m) | Percentual decrease south relative to 0% scenario | $L_{queue,max,west}$ (m) | Percentual decrease west relative to 0% scenario |
|---|---|---|---|---|
| 0% | 27.2 | - | 33.5 | - |
| 40% | 25.6 | 5.8% | 27.8 | 17% |
| 70% | 24.0 | 12% | 28.8 | 14% |
| 100% | 24.9 | 8.7% | 28.9 | 14% |

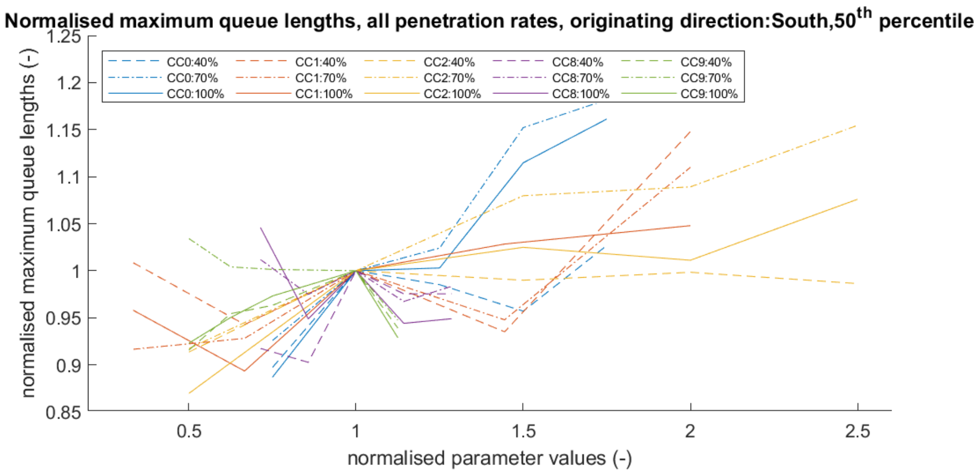



*Figure 11. Normalised median 90th percentile queue lengths of the south entry of the roundabout plotted against normalised parameters for the roundabout, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

Interesting about the data visible in Table 16 and Table 17 is the fact that there is no clear progression of decreasing queue lengths when the penetration rate keeps increasing. The north queue even increases in length. This seems to be partially in line with the observation made in section 4.1.2.1: there is a limit to the decrease of loss times/queue lengths. Also noteworthy, is the fact that at the west and south entries of the roundabout, the maximum queue lengths increase when at 100% penetration compared to 70% penetration.

Figure 11 shows a typical effect that ranging the parameters has on the queue lengths of the roundabout: there are some general trends visible in the figure, however, there are some unexpected and unexplainable effects as well, e.g. the drops in queue lengths after the default value. First of all, the CC0 parameter, describing the standstill distance between vehicles, has an influence. This is logical, since the standstill distance is a key aspect in queue lengths. Also the CC1, headway time, and CC2, following variation, parameters have an impact, mainly when the value is increased. CC8 and CC9 seem to fluctuate a lot, which can be caused by the fact that acceleration around roundabouts is dependent on the degree to which vehicles can simply continue their flow or have to come to a standstill, which makes it impossible to describe a trend for the acceleration parameters.

### 4.1.3. The signalised intersection

The signalised intersection has an irregular lay-out since it is based on a real-life case. The model of the signalised intersection has a dynamic traffic assignment. Therefore, there are multiple OD-matrices of this intersection, which are in Appendix F: OD-matrices of the intersections.

#### *4.1.3.1. Loss times*

The results of the loss times when altering individual parameters and the penetration rates are visible in Table 18, Figure 12 and Figure 13. Graphs of the results of individual penetration rates are available in Appendix G.3: Loss Times at the Signalised Intersection.

*Table 18. Average loss times at the signalised intersection when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for the ranged parameters and the non-ranged parameters of Table 9 are applied.*

| Penetration rate of SDCs | Average loss time (s) | Percentual decrease relative to 0% scenario |
|---|---|---|
| 0% | 26.0 | - |
| 40% | 25.2 | 3.0% |
| 70% | 24.8 | 4.6% |
| 100% | 24.0 | 7.7% |

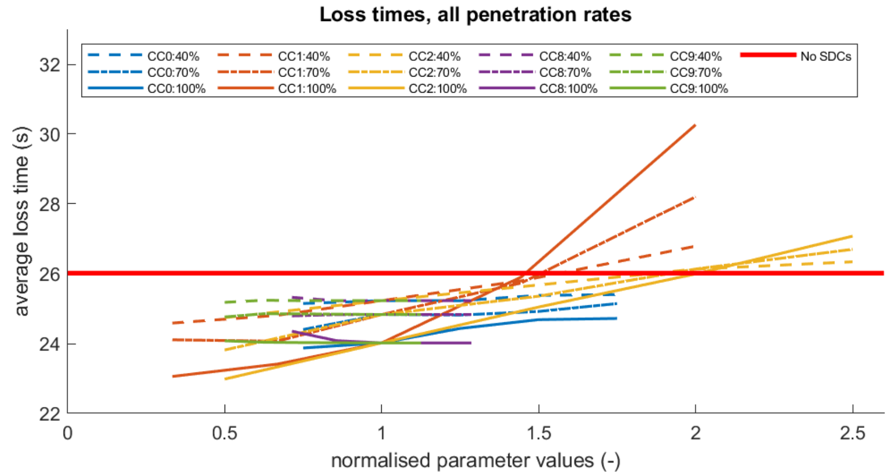



*Figure 12. Absolute loss times plotted against normalised parameters for the signalised intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

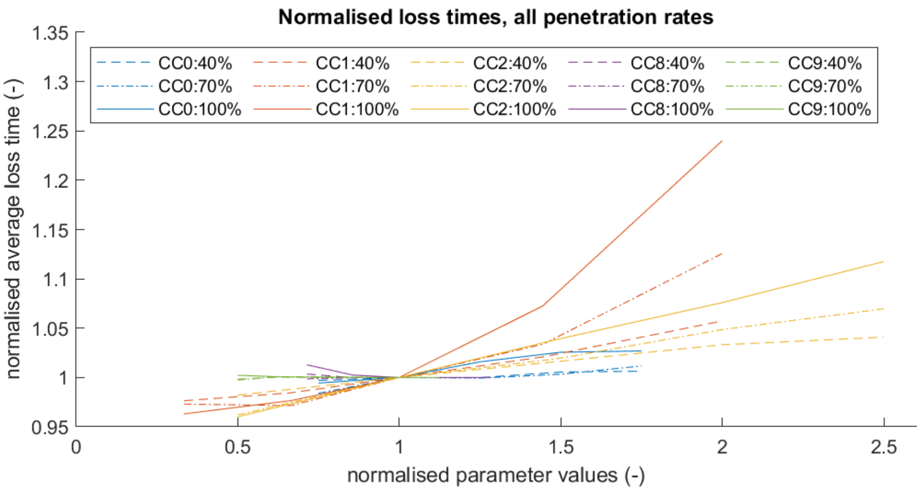



*Figure 13. Normalised differences in loss times plotted against normalised parameters for the signalised intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

Figure 13 has a similar shape when compared to the other normalised loss time graphs in Figure 5 and Figure 9. However, an interesting difference between the signalised intersection and the roundabout is that the overall normalised impact is smaller at the signalised intersection, especially concerning the CC8 parameters. This is unexpected, since more vehicles will be coming to a complete standstill at a signalised intersection compared to a roundabout. It might, however, be caused by the fixed loss time, which was already mentioned in section 2.4.2. The smaller influence, to the CC8 parameter specifically but also all the parameters in general, might be caused by the fact that not all vehicles will come to a standstill and some might be able to continue driving anyway, whereas at a roundabout vehicles slow down anyway. The clear influences of the parameters values of Table 9 are visible here, since a similar effect on the different penetration rates as seen in section 4.1.1 is noticed here as well.

#### *4.1.3.2. Queue lengths*

The filtering process of queue lengths is already described in section 4.1.1.2. The way this filtering process works out number-of-measurement-wise for the signalised intersection is visible in Figure 14.

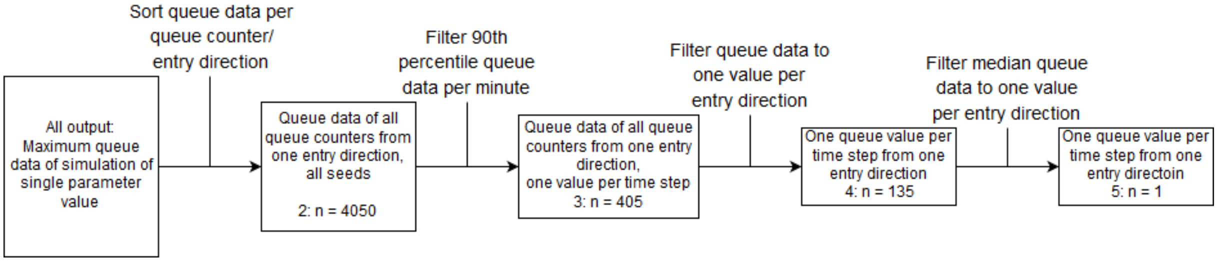



*Figure 14. Schematisation of the data filtering process with number of used data points for the signalised intersection.*

The results of the queue lengths when altering individual parameters and the penetration rates are visible in Table 19, Table 20 and Figure 15. Graphs of the results of individual penetration rates are available in Appendix H.3: Queue Lengths at the Signalised Intersection.

*Table 19. Median 90$^{th}$ percentile queue lengths at the north and east entries of the signalised intersection when normalised parameter value 1 (i.e. the default SDC value of Table 11) is selected for all ranged parameters.*

| Penetration rate of SDCs | $L_{queue,max,north}$ (m) | Percentual decrease north relative to 0% scenario | $L_{queue,max,east}$ (m) | Percentual increase east relative to 0% scenario |
|---|---|---|---|---|
| 0% | 73.0 | - | 71.2 | - |
| 40% | 68.9 | 5.5% | 71.1 | 0.15% |
| 70% | 68.9 | 5.5% | 69.1 | 2.9% |
| 100% | 65.6 | 10% | 68.0 | 4.5% |

*Table 20. Median 90$^{th}$ percentile queue lengths at the south and west entries of the signalised intersection when normalised parameter value 1(i.e. the default SDC value of Table 11) is selected for all ranged parameters.*

| Penetration rate of SDCs | $L_{queue,max,south}$ (m) | Percentual decrease south relative to 0% scenario | $L_{queue,max,west}$ (m) | Percentual decrease west relative to 0% scenario |
|---|---|---|---|---|
| 0% | 56.1 | - | 50.6 | - |
| 40% | 54.6 | 2.6% | 49.3 | 2.7% |
| 70% | 52.9 | 5.6% | 49.9 | 1.3% |
| 100% | 53.7 | 4.2% | 49.5 | 2.2% |

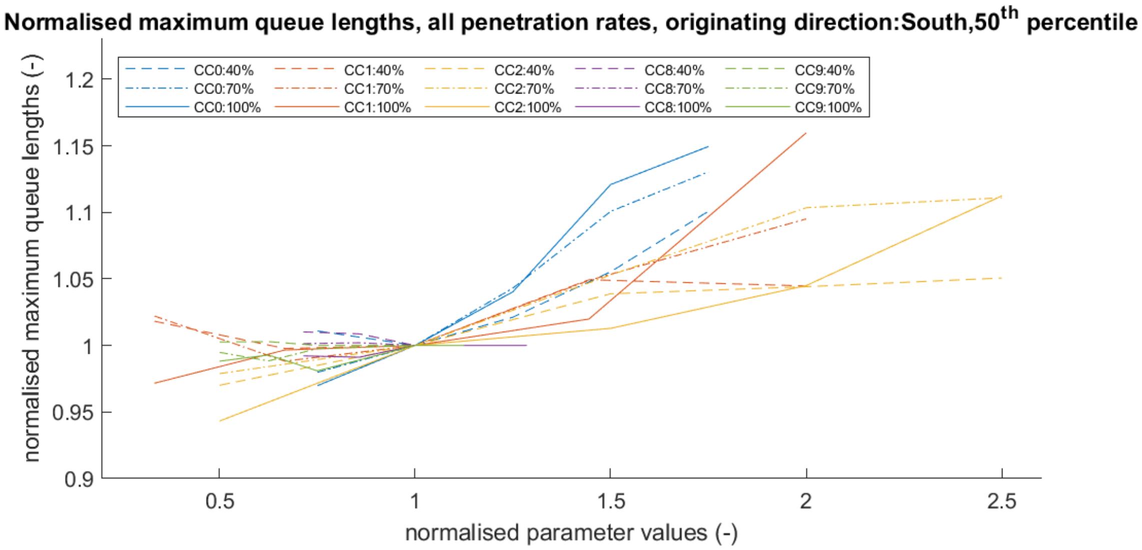



*Figure 15. Normalised median 90$^{th}$ percentile queue lengths of the south entry of the signalised intersection plotted against normalised parameters for the signalised intersection, combination of penetration rates. The lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value.*

Figure 15 shows a typical effect that ranging the parameters has on the queue lengths of the signalised intersection. It seems mostly influenced by the CC0, standstill distance, parameter, which is logical, since vehicles come to a complete standstill at a red light. Furthermore, the CC2, or following variation, parameter has equal influence than the CC1, headway time, parameter in most of the cases. This is explainable due to the fact that the headway and following variation both have influences on vehicles slowing down for queues. Nevertheless, the CC1 parameter has a clearer influence than the CC2 parameter on a 100% penetration rate at the highest parameter value. The CC8, acceleration at 0 km/h, and the CC9, acceleration at 80 km/h, seem to have few influences.

#### 4.1.4. Conclusion

Based on the results of sections 4.1.1, 4.1.2 and 4.1.3, it is possible to conclude that SDCs can contribute to decreasing loss times, since in almost all cases the loss times are decreased, visible in Figure 4, Figure 8, Figure 12, Table 13, Table 15 and Table 18. This drop in loss times is also observed when only the default SDC values of Table 9 are applied. It is therefore possible that one of the parameters described in Table 9 has an unexpected substantial and progressive influence in this decrease of loss times. This has been analysed briefly in Appendix I: Analysis of the Progressive Decrease in Loss Times, but the three most suspected possible caused (CC3, CC6 and desired speed), did not seem to have the expected individual influence. Since no individual cause can be indicated, it is currently unclear what the exact cause of progressive decrease in loss times is, however it is possible that this is caused by the combination of the various parameter values, rather than the individual adjustments.

Concerning the result of ranging the parameters, the CC1, or headway time, is by far the most influential in both the aggressive and cautious ways for the loss times and has a clear influence on the queue lengths as well. After that, the CC2, describing the following variation, seems to have a substantial influence for the loss times at all types of intersections. The effect is seen to a somewhat lesser extend at the queue lengths. When altering the standstill acceleration CC8, it is also visible that it mainly has impact on the loss times and queues when altered cautiously, especially concerning the regular intersection and the roundabout. The standstill distance between vehicles, CC0, is mainly influential for the queue lengths around all the intersections in both aggressive and cautious ways. In the six various combinations of parameters, it is therefore most interesting to focus on ranging the CC0, CC1, CC2 and CC8 parameters. CC9, used for describing acceleration at 80 km/h, seems to have very few influence, which can be attributed to the facts that vehicles in the urban environments will not drive at speeds of 80 km/h and the influence which this parameter has on other acceleration rates seems negligible. Since most effects occur when more cautious values are selected compared to the default SDC values, it is relevant to investigate combinations with more cautious values than the default values.

### 4.2. Combining parameters

Six combinations of parameters will be established to describe the various levels of autonomy and various degrees of aggressiveness. In order to differentiate between level 3 and level 4/5 SDCs, Table 12 has been taken into account. The resulting combinations, visible in Table 21, are established based on section 4.1.4 to give insights in various possible scenarios of SDC behaviour. The values of other driving behaviour parameters as described in Table 9 are applied to the SDCs as well. Since the CC9 parameter, describing acceleration at 80 km/h, does not seem to have clear influence, this parameter is ranged together with the value of CC8, since both are involved in acceleration. Since most of the effects occur when a more cautious parameter value is selected compared to the default SDC value, more of the combinations are guided towards more cautious SDCs.

*Table 21. Parameter values as selected to describe various degrees of aggressiveness of SDCs. Orange cells indicate the default SDC value, green cells indicate a more aggressive value than default, red cells indicate a more cautious value than default.*

| Combination | Description | CC0 (m) | CC1 (s) | CC2 (m) | CC8 (m/s²) | CC9 (m/s²) |
|---|---|---|---|---|---|---|
| **1.** | L3 cautious | 1.5 | 1.8 | 5.0 | 2.5 | 1.0 |
| **2.** | L3 intermediate | 1.25 | 1.3 | 2.0 | 3.0 | 1.25 |
| **3.** | L3 aggressive | 1.0 | 0.9 | 3.0 | 3.5 | 1.5 |
| **4.** | L4/5 cautious | 1.25 | 1.3 | 3.0 | 3.5 | 1.5 |
| **5.** | L4/5 intermediate | 0.75 | 0.6 | 2.0 | 3.5 | 1.5 |
| **6.** | L4/5 aggressive | 0.75 | 0.3 | 1.0 | 4.5 | 2.25 |
| **Regular cars** | - | 1.0 | 0.9 | 4.0 | 4.0 | 1.5 |

The combinations will lead to changes to the visualisation of the Wiedemann 1999 model. How these changes work out per combination is visible in Appendix J: Changed Wiedemann 1999 Models for various Combinations.

Since it has been seen in section 4.1 that there is a decrease of loss times independently of the ranged parameters, a 'Reference SDC' value is used in this section in which the ranged parameters are set to values of regular vehicles and only the values of Table 9 are applied. In this way, it is possible to see what the impact is of the analysed parameters apart from the default SDC values.

The combination will be analysed at more penetration rates that done with the individually ranged parameters, so the impact of gradual implementation of SDCs can be analysed. The penetration rates which will be analysed are: 10%, 20%, 40%, 70% and 100%.

### 4.2.1. The Regular Intersection

The same regular intersection is analysed which is used in section 4.1 with the same OD-matrix which is visible in Appendix F: OD-matrices of the intersections

#### *4.2.1.1. Loss times*

From Table 22 and Figure 16 it can be concluded that aggressive SDCs and intermediate level 4/5 SDCs might have positive impact on the average loss times of vehicles of up to 46% compared to the situation without SDCs. On the other side, cautious level 3 SDCs might have a far greater negative impact of 189% compared to no SDCs applied. The relative impact of the Wiedemann parameters described in Table 21 ranges from 249% negative to 35% positive, when compared to the parameters described in Table 9 at a penetration rate of 100%.

*Table 22. Loss times of the various combinations of parameters at the regular intersection and the relative differences with reference scenarios*

| Combination | Description | Loss times (at 100% penetration) (s) | Relative change compared to 0% penetration | Relative change comparted to 100% penetration of Table 9 |
|---|---|---|---|---|
| - | 0% penetration | 26.0 | - | - |
| - | 100% penetration of vehicles with only Table 9 applied. | 21.6 | 17% | - |
| **1.** | L3 cautious | 75.3 | -189% | -249% |
| **2.** | L3 intermediate | 28.8 | -11% | -33% |
| **3.** | L3 aggressive | 21.3 | 18% | 1.4% |
| **4.** | L4/5 cautious | 30.2 | -16% | -40% |
| **5.** | L4/5 intermediate | 17.8 | 32% | 18% |
| **6.** | L4/5 aggressive | 14.0 | 46% | 35% |

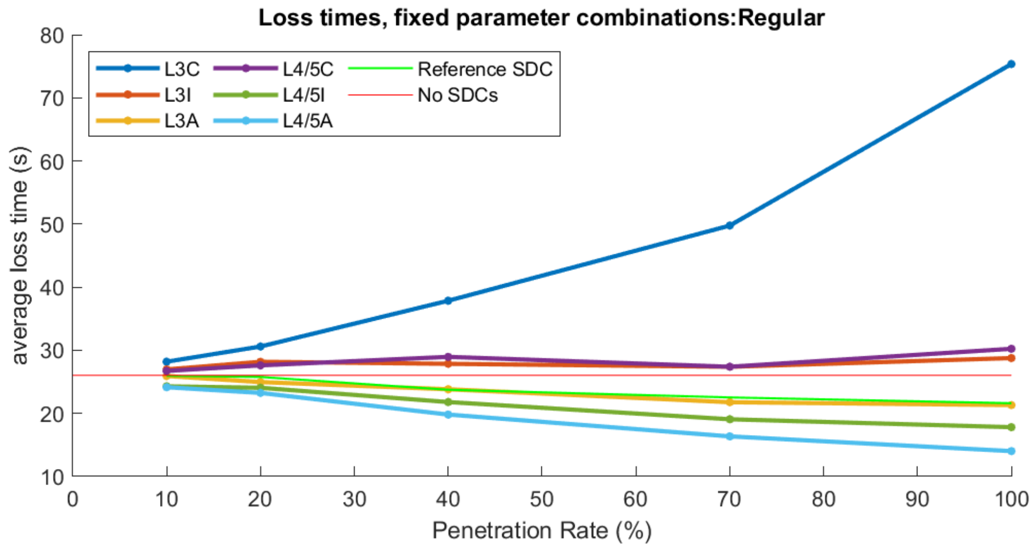



*Figure 16. Loss times of the various combinations of the parameters at the regular intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

#### 4.2.1.2. Queue lengths

For the combination of parameters, the same filtering process is used for the queues as is used in section 4.1.

Figure 17 shows the general trend of the queue length changes at the regular intersection, which has a great similarity to the shape of the loss times in Figure 16. The most cautious modelled SDC has an outstanding negative influence on the queue lengths, more than tripling at 100% penetration compared to 0% penetration and the reference SDC scenario. In the most aggressive SDC scenario, the queue lengths are about halved, which is similar to the loss times.

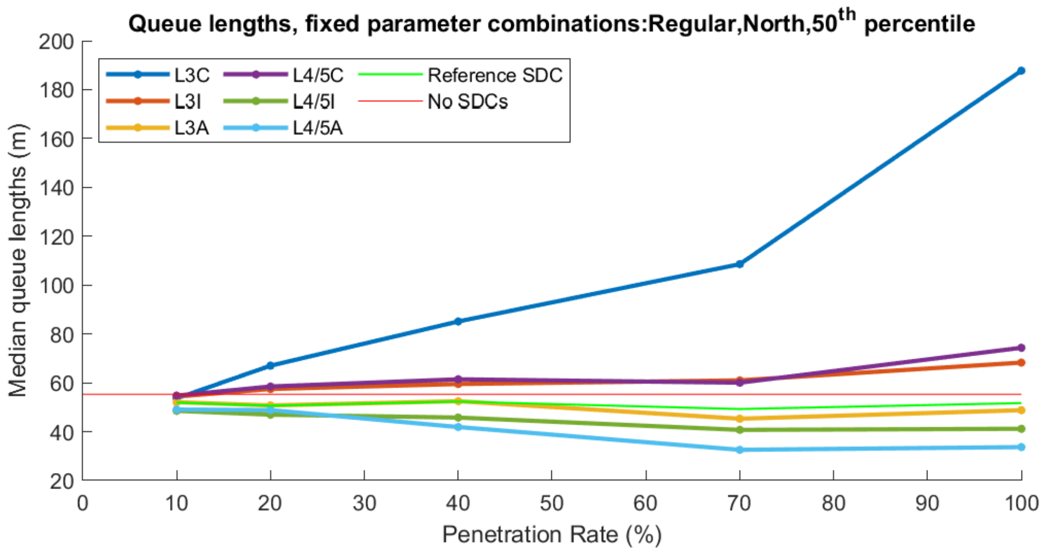



*Figure 17. Median 90th percentile queue lengths of the north entry at various combinations of the parameters at the regular intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

### 4.2.2. The roundabout

The same roundabout is analysed which is used in section 4.1 with the same OD-matrix which is visible in Appendix F: OD-matrices of the intersections.

#### 4.2.2.1. Loss times

When comparing the data in Table 23 and Figure 18 with the data of the regular intersection, it can be stated that SDCs have a more positive impact on the loss times around roundabouts, only the most cautious degree of SDCs has a negative impact on the loss times. Looking at the most aggressive type of SDCs, it can have a positive impact of 65% comparted to the 0% penetration of SDCs. The extreme cautious and aggressive SDC behaviours have a change of 96% negatively and 48% positively respectively, when comparing it to the reference SDC scenario. Interesting to note is the fact that in section 4.1.2, it seemed that there would be a limit to the impact of SDCs at certain penetration rates, but Figure 18 shows that the impact keeps on progressing at higher penetration rates as well.

*Table 23. Loss times of the various combinations of parameters at the roundabout and the relative differences with reference scenarios*

| Combination | Description | Loss times (at 100% penetration) (s) | Relative change compared to 0% penetration | Relative change comparted to 100% penetration of Table 9 |
|---|---|---|---|---|
| - | 0% penetration | 15.3 | - | - |
| - | 100% penetration of vehicles with only Table 9 applied. | 10.3 | 33% | - |
| **1.** | L3 cautious | 20.3 | -33% | -96% |
| **2.** | L3 intermediate | 11.0 | 28% | -6.5% |
| **3.** | L3 aggressive | 9.2 | 40% | 11% |
| **4.** | L4/5 cautious | 11.1 | 27% | -7.6% |
| **5.** | L4/5 intermediate | 7.1 | 53% | 32% |
| **6.** | L4/5 aggressive | 5.4 | 65% | 48% |

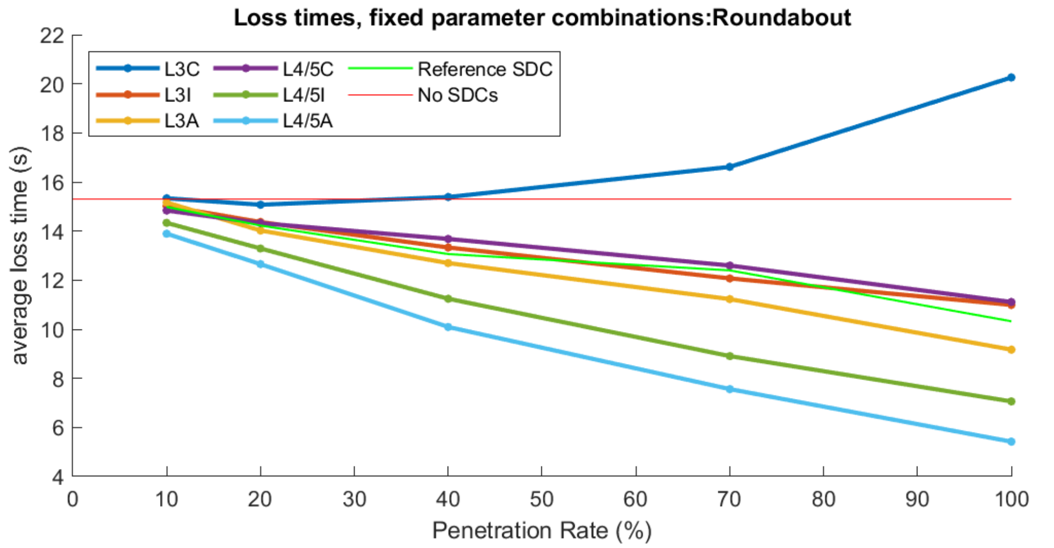



*Figure 18. Loss times of the various combinations of the parameters at the roundabout at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

#### 4.2.2.2. Queue lengths

Figure 19 shows the typical queue length changes at the roundabout. It does not look like an exact copy of the loss times in Figure 18, however, the trends are still visible. Only in the most cautious variation, there is a clear increase in queue lengths. The intermediate and aggressive level 3 and the cautious level 4/5 are somewhat close to the situation of 0% penetration of SDCs, and the level 4/5 intermediate and aggressive show clear decreases of loss times.

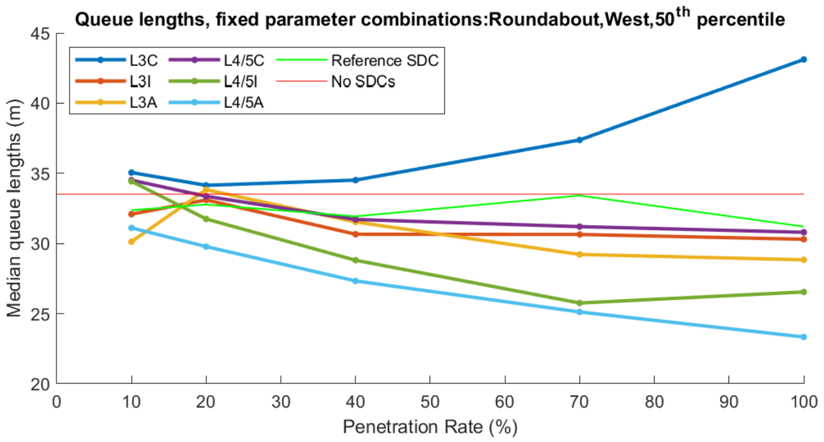



*Figure 19. Median 90th percentile queue lengths of the west entry at various combinations of the parameters at the roundabout at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

### 4.2.3. The signalised intersection

The same signalised intersection is analysed which is used in section 4.1 with the same OD-matrix which is visible in Appendix F: OD-matrices of the intersections.

#### *4.2.3.1. Loss times*

What immediately comes forward from Table 24 and Figure 20, is the fact that the positive impact that the SDCs have on the loss times and queue lengths is by far not as much as at the regular intersection and the roundabout, which is similar to the results of section 4.1.3. The maximum decrease in loss times is only 17%, whereas at the regular intersection and roundabout this was 46% and 65% respectively. This might be caused by the fact that there always is a presence of loss times at a signalised intersection, since all lights turn red at some moment. As discussed in section 2.4.2, this 'fixed loss time at a signalised intersection' has been analysed in order to take it into account, however, this aspect might still influence the degree to which the loss times can decrease.

On the negative side of the spectrum, the loss times are increased clearly in the most cautious scenario, which is explainable through the fact that the cautious SDCs will influence the vehicle throughput a lot by, e.g., keeping a larger headway time and decreased acceleration. Since there is only a limited time a vehicle can cross an intersection per signal sequence, this extra loss time builds up more over time.

*Table 24. Loss times of the various combinations of parameters at the signalised intersection and the relative differences with reference scenarios.*

| Combination | Description | Loss times (at 100% penetration) (s) | Relative change compared to 0% penetration | Relative change comparted to 100% penetration of Table 9 |
|---|---|---|---|---|
| - | 0% penetration | 26.5 | - | - |
| - | 100% penetration of vehicles with only Table 9 applied. | 26.2 | -0.9% | - |
| **1.** | L3 cautious | 38.7 | -46% | -49% |
| **2.** | L3 intermediate | 26.1 | 1.4% | -0.5% |
| **3.** | L3 aggressive | 25.4 | 4.2% | 2.4% |
| **4.** | L4/5 cautious | 27.0 | -2.0% | -4.0% |
| **5.** | L4/5 intermediate | 23.6 | 11% | 9.4% |
| **6.** | L4/5 aggressive | 22.0 | 17% | 15% |

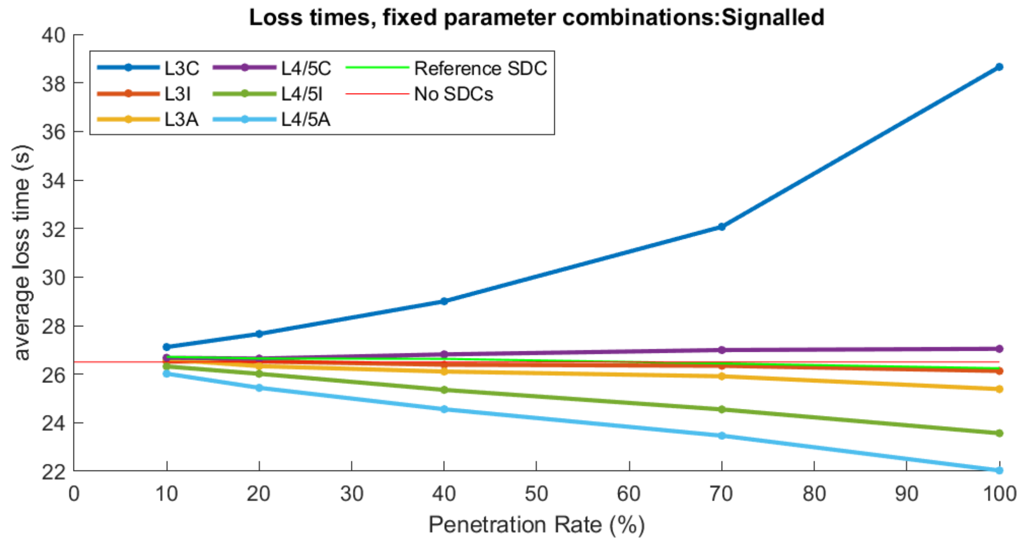



*Figure 20. Loss times of the various combinations of the parameters at the signalised intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

#### *4.2.3.2. Queue lengths*

Figure 21 shows the typical queue length changes at the signalised intersection: the degree of impact is mostly limited, which is alike the loss times. Interesting to note, however, is the fact that even in the cautious cases, the queue lengths seem to shorten at high penetration rates, but the queues are enlarged at 10% penetration. Apart from the most cautious scenario, the queues have a degree of decrease in lengths at the other penetration rates.

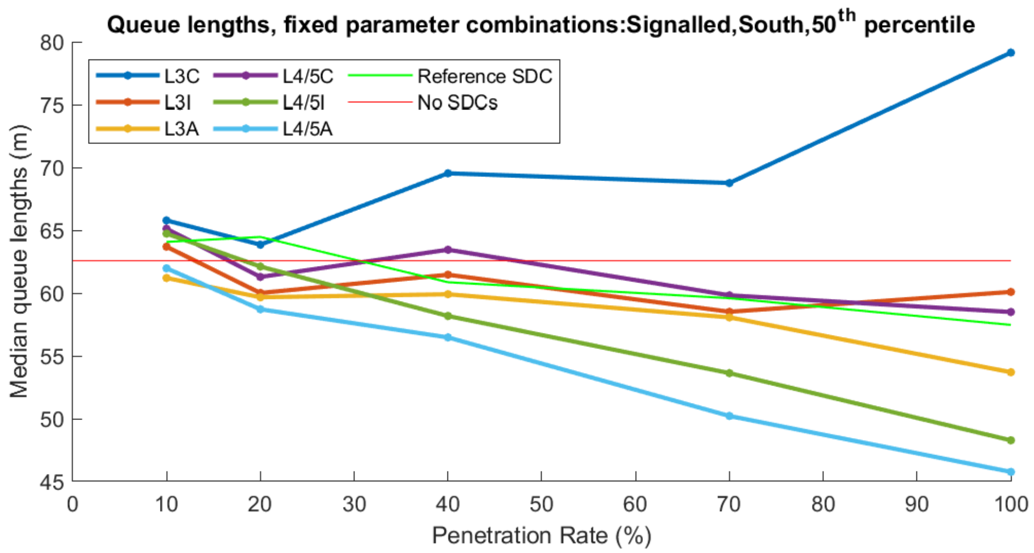



*Figure 21. Median 90th percentile queue lengths of the south entry at various combinations of the parameters at the signalised intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

### 4.2.4. Capacity Changes

The capacity changes give interesting insights on the effects that result from ranging the input flow until the loss times are back at the original level. The most cautious and most aggressive combinations of parameters are analysed together with the Reference SDC scenario in order to see in what range the capacity effects will be. Table 25 shows the results of the capacity analysis.

*Table 25. Changes in input flow when the loss times of the most cautious, most aggressive and Reference SDCs are brought to the same level as the No SDC scenario.*

| Intersection | Capacity change for most cautious SDC | Capacity change for Reference SDC | Capacity change for most aggressive SDC |
|---|---|---|---|
| **Regular** | -7.6% | 2.0% | 8.8% |
| **Roundabout** | -3.1% | 6.5% | 27% |
| **Signalised** | -19% | 0.0% | 32% |

Interestingly, the signalised intersection has the largest changes concerning the capacity, whereas it had the least changes concerning loss times. This is explainable through the fact that the capacity of the signalised intersection is highly dependent on the number of vehicles that can get through the intersection during the green phase. After the signal turns red, a vehicle must wait the entire signal cycle before it has a green light again, so relatively few loss times can be gained or lost compared to other intersections. However, during the green phase itself, vehicles can use it far more effectively with aggressive driving styles, and vice versa with cautious driving styles. Noteworthy, therefore, is the fact that the attempt to get rid of the 'fixed loss time' as explained in section 2.4.2 was not sufficient to clearly analyse the loss times caused by the driving behaviour around the signalised intersection rather than the loss times caused by the traffic signal cycle.

#### 4.2.5. Conclusion

Looking at the data resulting from the combinations of parameters, expected trends arise: the higher the penetration rate of the SDCs, the more the loss times and queue lengths are changed. What is interesting to notice, is the fact that only the most cautious simulated scenario (L3 cautious) has a substantial negative impact on both the loss times (-189%, -33% and -46% for the respective intersections) and the queue lengths. When the degree of cautiousness is increased only one step (L3 intermediate), the outcome is already a lot closer to the 0% penetration rate scenario or even more positively than the 0% penetration rate scenario.

On the positive side of the spectrum, the loss times and queue lengths can decrease substantially. The decrease at the most aggressive scenario is not as big as the loss with the most cautious scenario, however, still the aggressive SDCs manage to decrease the loss times with 46%, 65% and 17% at the respective intersections. Interestingly, the roundabout seems to have the least negative and the most positive effects when SDCs are implemented. This is likely due to the fact that at the regular intersection, the vehicles on the priority road have no great loss times since they can simply continue their drive. At the signalised intersection, vehicles often simply need to await the cycle time. Vehicles form all direction need to slow down, but are not fixed to cycle times.

Noticeable when looking at Figure 16, Figure 17, Figure 18, Figure 19, Figure 20 and Figure 21 concerning the reference SDC scenario, is the fact that it seems to have a clear impact for the loss times of the regular intersection and the roundabout, but it has relatively few impact on the loss times of the signalised intersection and all the queue lengths in general. It can therefore be concluded that the applied combinations of Table 21 cause the main impact on the queues. Concerning the loss times, the reference SDC scenario has a clear impact on the roundabout and regular intersection, from which is possible to conclude that the parameter values of Table 9 have a contribution to the loss times at this type of intersection.

### 4.3. Conclusion

Modelling SDCs gives interesting insights into the impacts which Wiedemann 1999 parameters have on the loss times and queue lengths. Mainly the CC1 headway time parameter is very influential for both criteria. The CC0 standstill distance and CC2 following variation have a main impact on the queue lengths and loss times respectively. CC8, the standstill acceleration, has a negative influence on both criteria when altered negatively. CC9, the acceleration at 80 km/h, has no substantial influence, which can be explained through that vehicles in the urban environments will not drive at speeds of 80 km/h.

These observations have been used to establish six different combinations of parameters describing SDCs of various automation and aggressiveness levels. The outcome of the analyses of these combinations, of which the results of the most cautious and aggressive are visible in Table 26, showed that SDCs have the ability to decrease loss times and queue lengths. The maximum decrease in loss times is of 46% at the regular intersection, 65% at the roundabout and 17% at the signalised intersection. The other scenarios, of which the details are visible in section 4.2, also show decreases in loss times, or minor increases. These relative positive results can be, amongst others, attributed to the parameter values described in Table 9, which functions as a reference with the fixed SDC parameters. The only scenario in which the criteria worsened substantially, was the scenario with the most cautious type of SDC. This scenario caused increases in loss times of 189%, 33% and 46% at the respective intersections. Similar trends are visible with the queue lengths.

*Table 26. Relative results of the most cautious and most aggressive combinations of SDCs concerning loss times, queue lengths and capacity changes at the three analysed intersections.*

| Intersection | Regular | Roundabout | Signalised |
|---|---|---|---|
| **Most cautious loss times** | 189% | 33% | 46% |
| **Most aggressive loss time** | -46% | -65% | -17% |
| **Most cautious queue length, north** | 240% | 197% | 91% |
| **Most aggressive queue length, north** | -39% | -37% | -33% |
| **Most cautious queue length, east** | - | 100% | 5.9% |
| **Most aggressive queue length, east** | - | -43% | -22% |
| **Most cautious queue length, south** | 82% | 16% | 26% |
| **Most aggressive queue length, south** | -42% | -24% | -27% |
| **Most cautious queue length, west** | - | 29% | 6.7% |
| **Most aggressive queue length, west** | - | -30% | -19% |
| **Most cautious capacity change** | -7.6% | -3.1% | -19% |
| **Most aggressive capacity change** | 8.8% | 27% | 32% |

With the use of the loss times, it has been analysed what the effect of SDCs will be on the capacity of the intersections, of which the results are also visible in Table 26. This analysis showed that the largest fluctuation in capacity is visible at the signalised intersection, with a 19% decrease in capacity in the most cautious scenario and a 32% increase in the most aggressive scenario. Noticeable is the fact that the decrease in loss times at the signalised intersection is the least, but the capacity has the largest gain. This can be accredited to the fact that vehicles will have to wait the entire cycle time anyway, which limits the changes, especially the decrease, in loss times. Nevertheless, SDC can make better or worse use of the green phase for aggressive and cautious SDCs respectively, greatly influencing the capacity itself.

In any way, it is possible to say that SDC can have a great impact on the loss times, queue lengths and capacities of different types of intersections. Whether this impact is positive or negative and the degree to which this positivity and negativity is present is dependent on the aggressiveness of the implemented SDCs.

# 5. Discussion

Within the research, some aspects of discussion are encountered. These are elaborated on further within this chapter.

First of all, one of the parts of this research was to discover how SDCs can be modelled. However, any vehicle in VISSIM can already be seen as an SDC, since they behave based on mathematically defined equations. This is alike what real-life SDCs will do. The vehicles in VISSIM are calibrated to, amongst others, Wiedemann parameters, in order to describe real-life vehicle behaviour. Due to the large number of parameters, functions and distributions involved with describing the driving behaviour, it can be stated that VISSIM has a sophisticated way of describing the (human) driving behaviour. Nevertheless, it is important to keep in mind that the description of (regular) vehicles in VISSIM might not be a 100% reproduction of real-life traffic.

Secondly, slow traffic is ignored in this research for simplicity of the model. According to mobility behaviour expert Matthijs Dicke-Ogenia (personal communication, 23 May 2019), slow modes of transport like pedestrians and cyclist will have a key influence on the behaviour of SDCs, especially in mixed environments which are present in many urban environments. In this research, the focus was on intersections where there are separated flows of traffic. Nevertheless, the importance of slow traffic should be considered as an important aspect here as well, since cyclists and pedestrian crossings are key in entering intersections and the flow of traffic around intersections, while they are ignored in this research.

Another aspect of discussion is the use of the Wiedemann 1999 model on the urban intersection scale. As is discussed in chapter 0, the Wiedemann 1974 model is stated to be more suitable for urban traffic and the 1999 model is more suitable for highways. Applying the 1999 model to the urban level, as is done in this research, might not completely mirror the situation on the urban roads to its exact details. The differences in effect on the driving behaviour between the models came forward during this research when a wrong simulation was run with the Wiedemann 1974 model applied to regular cars rather than Wiedemann 1999. The outcomes of the of the different Wiedemann models showed small differences. Nevertheless, the resulting effects of the implementation of SDCs will give good impressions on the relative changes in loss times and queue lengths.

There are variables in the driving behaviour model which are altered to describe SDCs, however they are not ranged. Because no ranges are applied to these parameters, it is not very clear what the effect of these individual parameters are on the loss times and queue lengths, also after the analysis in Appendix I: Analysis of the Progressive Decrease in Loss Times. The variables which are referred to here are visible in Table 9. The variables that may play an important role here are the non-ranged Wiedemann-parameters and the acceleration curve. The acceleration curve has been set to a fixed function for all SDCs in this research. However, just like regular vehicles, different SDCs will have different engines, and therefore different acceleration capabilities. Therefore, the non-ranged parameters in Table 9 might be influencing the behaviour of SDCs is a way that is currently not accounted for.

The SDCs which are modelled in this research all have the same type of behaviour in a single simulation. Nevertheless, it is unlikely that all the SDCs will have identical behaviour. Various automotive companies might have different settings for the behaviour of their cars, and maybe even users of the SDCs might have the ability to set the degree of aggressiveness of their vehicles. This has only been partly accounted for by establishing a small range for the desired speed of vehicles. However, aspects like acceleration curves (as mentioned in the previous paragraph), headway times and behaviour at amber signals might be altered by different automotive companies or users. Since this will lead to less uniformity than the situations simulated in this research, the impact of the various behavioural changes might be different as well.

Connectivity between vehicles themselves and between vehicles and the infrastructure is left out of scope. However, it is quite unlikely that if there are cars that have the ability to drive entirely on their own (level 4/5), those cars do not have any communicational abilities. The focus of this research was solely oriented for the differences behaviour-wise, but communicative vehicles will have different impacts on the traffic operations of the urban road system. It is therefore interesting for future research to look into the effects that communication will have.

Important to keep in mind concerning the results, is the fact that these results are only of the analysis of a single intersection. When these intersections are linked together in a network, different results may occur. Especially since the urban traffic environment is filled with various combinations of intersections after each other, this interplay of intersections is very relevant in the overall analysis of the urban traffic environment.

# 6. Conclusion

This chapter concerns the answers to the research questions visible in section 2.2., based on the outcome of chapters 0. and 4. The various research questions are answered separately in order to create a clear overview of the various aspects of the research. Based on the technical outcomes, a more policy-oriented advice is given as well. The chapter is concluded with recommendations for future topics of research.

## 6.1. Answering the Research Questions

The main research question can be answered after the sub-questions are answered. Therefore, the sub-questions are answered first.

1. *How can SDCs be modelled within VISSIM?*

SDCs can be modelled within VISSIM by altering the parameters which describe the driving behaviour of vehicles as well as the functions and distributions which describe aspects related to driving behaviour. As can be seen in Table 5 and Table 6, there is a wide range of parameters which can be altered to influence the driving behaviour is such a way that an SDC is mimicked. Key parameters in describing driving behaviour of vehicles are the Wiedemann 1999 parameters, since the Wiedemann 1999 model is the basis of driving behaviour is VISSIM. The 10 different Wiedemann 1999 parameters describe different aspects like following distances and oscillation of traveling speeds. Altering these together with other aspects like adjusted acceleration curves and mitigated speed distributions, it is possible to simulate an SDC. An overview of the parameter, function and distribution changes used in this research can be found in Table 9, Table 11 and Table 21.

a. *What behavioural models of vehicles are altered in SDCs compared to regular vehicles?*

SDCs are expected to be up to 100% deterministic, whereas human drivers are very stochastic. Taking this as a starting point, it is possible to define the fact that there will be less oscillations in speed and that SDCs are less prone to reaction time because sensors will give the computer (near) immediate data. (PTV Group, 2017) gives an overview, visible in Table 7, with expected behavioural changes, which are used to define what parameters will change when comparing regular vehicles to SDCs.

b. *How can different levels of automation be modelled in VISSIM?*

Different levels of automation can be modelled in VISSIM with (slight) adjustments to the parameters which are changed to describe the behaviour of SDCs. Since the main focus in this research is on distinguishing level 3 from level 4/5 automation, it is key to understand what the differences between those levels are. This is elaborated on in Table 7. In section 4.2, the various combinations of parameters are established to describe SDCs. More cautious values do not necessarily implicate a level 3 SDC. Nevertheless, it is expected that level 3 SDCs will drive more cautiously, since drivers will need time to respond before taking control after the computer abandons it. Therefore, 2 of the 3 combinations describing level 3 SDCs have the most cautious parameter selections. The exact values of the selected Wiedemann 99 parameters describing the different levels of automation are visible in Table 21.

i. *What parameters of VISSIM are important in modelling different levels of SDCs?*

As becomes clear in Table 5 and Table 6, there are multiple parameters, functions and distributions which are important in describing SDCs. These parameters, functions and distributions all have different influences in describing SDCs. The most important parameters are the Wiedemann 1999 parameters, since they describe the key aspects of driving behaviour. Of those ten parameters, five have been selected as most relevant. These five are:

- CC0, which describes the standstill distance between two vehicles;
- CC1, which describes the headway time;
- CC2, which describes the following variation;
- CC8, which describes the standstill acceleration of the vehicle and
- CC9, which describes the acceleration at 80 km/h.

1. *Can different values of parameters in VISSIM be used to describe specific levels of automation?*

The exact parameter values used to describe the different levels of automation are given in section 4.2. However, at the end of section 3.3 it is stated that the CC0, CC1 and CC2 parameters will have a clear distinct value when analysing a level 3 SDC and a level 4/5 SDC. Level 3 SDCs will probably be somewhat more cautious, since drivers will need to have the ability to interfere, but this does not mean that Level 4/5 will be more aggressive by definition.

2. *What are proper ranges of parameters in VISSIM in modelling SDCs?*

Five Wiedemann 1999 parameters have been ranged for modelling SDCs. The ranges of these parameters are based on previously used parameter values which are found in literature. The resulting ranges can be found in Table 11. The values of the ranges are established around cautious and aggressive values present in literature, in order to have the ability to investigate both sides of the vehicle automation spectrum.

2. *How do SDCs influence the capacity of urban road networks, concerning different types of intersections?*

The influence of SDCs on the capacity and traffic operations of urban road networks is, of course, highly dependent on the type of SDCs which are implemented. A cautious SDC will increase aspects like loss times and queue lengths, whereas an aggressive SDC decreases those. Interesting results show that moderately cautious SDCs might decrease the loss times and queue lengths, which is likely caused by more uniform behaviour of the fleet. Increased penetration rates show progressive effects on the capacity aspects. The roundabout shows promising effects concerning decreases in loss times and queue lengths with aggressive SDCs and relatively few losses with cautious SDCs. The loss times at the signalised intersection are not influenced that much, however the actual capacity is. The results are visualised in section 4.2 and summarized in Table 26.

a. *How do SDCs influence the capacity of different types of intersections when relevant parameters of the SDCs are ranged and various penetration rates are applied?*

SDCs can have a great influence on the loss times, queue lengths and capacity of various types of intersections. However, whether this is a positive or negative effect is largely determined by the aggressiveness of the implemented SDC, which is done by altering the parameter values. Penetration rates cause progressive trends of various results: either a positive or negative trend is enhanced when penetration rates are increased. The results are visualised in section 4.1.

i. *How are the loss times at different intersections effected by ranging the relevant parameters describing SDCs and various penetration rates are applied?*

There is no one way to describe the results of ranging parameters describing SDCs. What however can be stated, is that the loss times are clearly influenced by ranging individual parameters. Especially the CC1, describing the headway time, has a great influence as can be seen in the figures in section 4.1 and Appendix G: Loss Times of the Individually Ranged Parameters: the higher the headway time, the higher the loss times. Besides the CC1, the CC2 parameter, describing the following variation and the

CC8 parameter, describing acceleration at 0 km/h, have a relevant influence on the loss times, both mostly when altered negatively/cautiously.

ii. *How are the queue lengths at different intersections effected by ranging the relevant parameters describing SDCs and various penetration rates are applied?*

It is more difficult to notice trends in the queue lengths when the parameters are changed compared to the trends of the loss times. The CC0 parameter, describing the standstill distance, has the clearest influence as is visible in section 4.1, since the queue lengths are mainly determined by the distances between vehicles at standstill. Besides the CC0, the CC1 and CC2 also seem to have influence on the queue lengths, however to a lesser extend when compared to the CC0 or to the impact they have on the loss times.

iii. *Is there an optimum type of intersection to optimize the capacity of SDCs in urban environments?*

Looking at the various traffic operation aspects in section 4.2 and Table 26, it seems like the roundabout has most positive and least negative impacts on loss times when comparing it to the 0% penetration rate scenario. This might be caused by the continuous flow of traffic around the intersection. Vehicles might simply slip between two vehicles driving on the roundabout when the gap between them is just sufficient rather than waiting for the perfect opportunity to cross. However, communication between vehicles is out of scope and it might be that this gives a different view on 'most optimized intersection'. When vehicles are communicating, the urge to slow down around an intersection becomes none if it simply knows it can continue driving when it enters the intersection, whereas at a roundabout, it simply needs to slow down anyway.

When looking at the actual capacity changes, the roundabout has promising results as well, concerning relatively few loss (-3.1%) with very cautious SDCs and a possibility with aggressive SDCs to increase the capacity substantially (27%). Nevertheless, the largest possible gain is visible at the signalised intersection with an increase in capacity of 32%. On the negative side, the capacity can also be decreased by up to 19% at the signalised intersection, so the most optimum type of intersection depends on the degree of aggressiveness of SDCs.

b. *How do SDCs influence the capacity of different types of intersections concerning different penetration rates of SDCs?*

When regarding capacity, i.e. traffic operations, in terms of loss times, different penetration rates of SDCs will mostly affect the loss times progressively in a positive way, as can be seen in section 4.2. Only the most cautious analysed scenario had a great (more than 20%) negative impact on the loss times. In most cases, the other 5 scenarios had relatively few (less than 5%) negative or a positive impact on the loss times.

i. *Is there a minimum penetration rate which is needed to see a substantial impact (5% change in capacity) on the capacity of road systems when the SDC is introduced?*

When taking the loss times as a capacity reference, it depends on the type of SDC and the type of intersection to determine the minimum penetration rate for a substantial impact. As visible in section 4.2, an SDC with moderate settings will of course need a higher penetration rate in order to see impact, since its behaviour is more similar to regular vehicles. At the signalised intersection, only the most cautious and the two most aggressive scenarios have the 'ability' to surpass the 5% impact limit anyhow. At the roundabout, 5% impact is already achieved with most of the scenarios at 20%

penetration, whereas at the regular intersection this is only achieved at 40% penetration. However, as shown by the analysis of the changes in capacity, the loss times do not have to give the same relative in-/decrease as the capacity, especially when looking at the signalised intersection.

Based on the answers on the sub-questions, it is possible to answer the main question:

*What is the impact of SDCs on the capacity of the urban road network?*

Looking at the outcomes of section 4.2 and the relative results of the most cautious and aggressive alternatives in Table 26, the impact which SDCs will have on the urban traffic network will greatly depend on how either cautiously or aggressive SDCs are implemented in the fleet of vehicles. At lower penetration rates, the impacts are minor, however when penetration rates are increased, the impacts are greatly enhanced. Interestingly, the only scenario in which the loss times and queue lengths are substantially influenced negatively at all intersections, is the most cautious scenario. All the other scenarios, which also include variations which can be labelled 'cautious' have small negative effects or even have positive effects.

The type of intersection plays a role in the degree to which the loss times and queue lengths can be influenced by SDCs. Especially the regular intersection is susceptible for negative effects with cautious SDCs, while roundabouts clearly are most sensitive for effects by aggressive SDCs. Noteworthy is the fact that communication between vehicles has not been analysed in this research, which will influence the traffic operations of specific intersection types.

Lastly, when a translation is made from loss times to capacity changes, it is possible to see that the implementation of SDCs can both have a very negative and positive influence on the overall capacity of the intersections. At the signalised intersection the capacity might decrease by as much as 19% when cautious SDCs are implemented, whereas it is also possible that a gain of 32% is achieved at the same type of intersection. Also noteworthy concerning the capacity changes, is the fact that the capacity can change the most at the signalised intersection, whereas the loss times have the least change there. This can be explained by the fact that it is difficult to change loss times at the signalised intersection a lot because of the cycle of phases, but the green phase can be used either more or less efficiently depending on the type of SDCs.

Whether the effects which are made visible by this research will actually occur on the public road system is highly dependent on how SDCs will be implemented by the automotive industry.

## 6.2. Translating Technical Results to Policy Advice

Looking to the outcomes of the research, it is difficult to point out a straightforward conclusion for advice on mobility policy. As put forward by the results of section 4.2 which are summarized in Table 26, the implementation of SDCs can either result in a decrease in capacity or in an increase in capacity depending on the aggressiveness. A reasonable reaction to a decreasing capacity would be to construct more roads so that the capacity of the entire road system remains the same at least. Vice versa, it is logical to alter public space in a more vehicle limiting way when capacity of the current road increases and a reduction of road surface is possible.

However, concerning the implementation of SDCs, it is key to look at a broader perspective. The first highly autonomous SDCs that will be/are implemented to the fleet will be level 3 SDCs. As is shown in this research, it is highly likely that those will have relative cautious driving behaviour settings. Only later, when the technology is improved, approved and accepted, level 4/5 will be implemented, which will likely be more aggressive. Since there still is a gap of knowledge concerning the aggressiveness of SDCs that the automotive companies will allow, no definite advice can be given on e.g. whether or not it is relevant to construct more roads in order to maintain the accessibility of urban environments on the long term. Besides, the role that the implementation of MaaS might play on the number of vehicles on the road is relevant as well, but that is out of scope completely in this research.

Nevertheless, the results show that for the short term, when there is a low penetration rate of SDCs (10%, 20%), only small negative but mainly positive effects can be noticed. As is visible in the graphs of section 4.2, the effects at lower penetration rates are minor. This observation can be used to advise that no immediate change of policy is needed concerning road construction and the implementation of SDCs. The current lay-out of the urban road system will be suitable at these lower penetration rates. For the long term, when the penetration rate of SDCs increase, it would best to anticipate in a later stadium, when more is known about the behaviour of SDCs.

## 6.3. Recommendations for Future Research

As a result of this research, multiple aspects arose which are interesting to analyse in future researches concerning SDCs.

First of all, communication between vehicles was not incorporated in this research. Nevertheless, it might have very relevant influence in SDCs. Especially if level 4/5 SDCs are implemented to the fleet, it is highly likely that they are equipped with some type of intercommunication. It is therefore relevant to investigate the impact that communication will have in future research.

Secondly, slow traffic is ignored in this research, whereas it might have a relevant influence in the Dutch urban traffic system where, e.g., cars often share the road with cyclists. Future research might therefore focus on this aspect as well.

Thirdly, the SDCs in this research have been set to have a uniform behaviour. However, it is likely that different automotive companies will build SDCs with different aspects of behaviour, or users of SDCs might be able to set some behavioural aspects themselves. Uniformity of the behaviour of the fleet is then lost, which might lead to other results than in this research. A relevant topic of follow-up research might therefore be a more diverse fleet of SDCs.

Fourthly, a fairly simple approach has been used to analyse the effects on capacity. The actual changes on the capacity on one hand and the impacts that the changing capacity has on demands on the other need more sophisticated approaches for more reliable results. Especially since macro-scale researches like (Smit, et al., 2017) have interesting conclusions concerning demands and mileage, it will be an interesting topic for future research to look into the effects of capacity changes on demand for SDCs.

Finally, a key uncertainty in the implementation of SDCs is whether SDCs will have cautious, moderate or aggressive driving styles. Only when this is known, it is possible to give a more steering advice for the long-term concerning accessibility of, and traffic capacity in the urban environment. This is therefore a relevant topic for future research. The degree of aggressiveness is dependent on the choices that automotive companies make. Since these companies might not yet know themselves what will be approvable and acceptable, in-depth research might not be possible. In that case, it is important to stay up to date with any developments in this subject.

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# APPENDIX A: METHODOLOGICAL PROCESS SCHEME

Figure 22 shows the used methodological process scheme for the methodology as described in section 2.2.

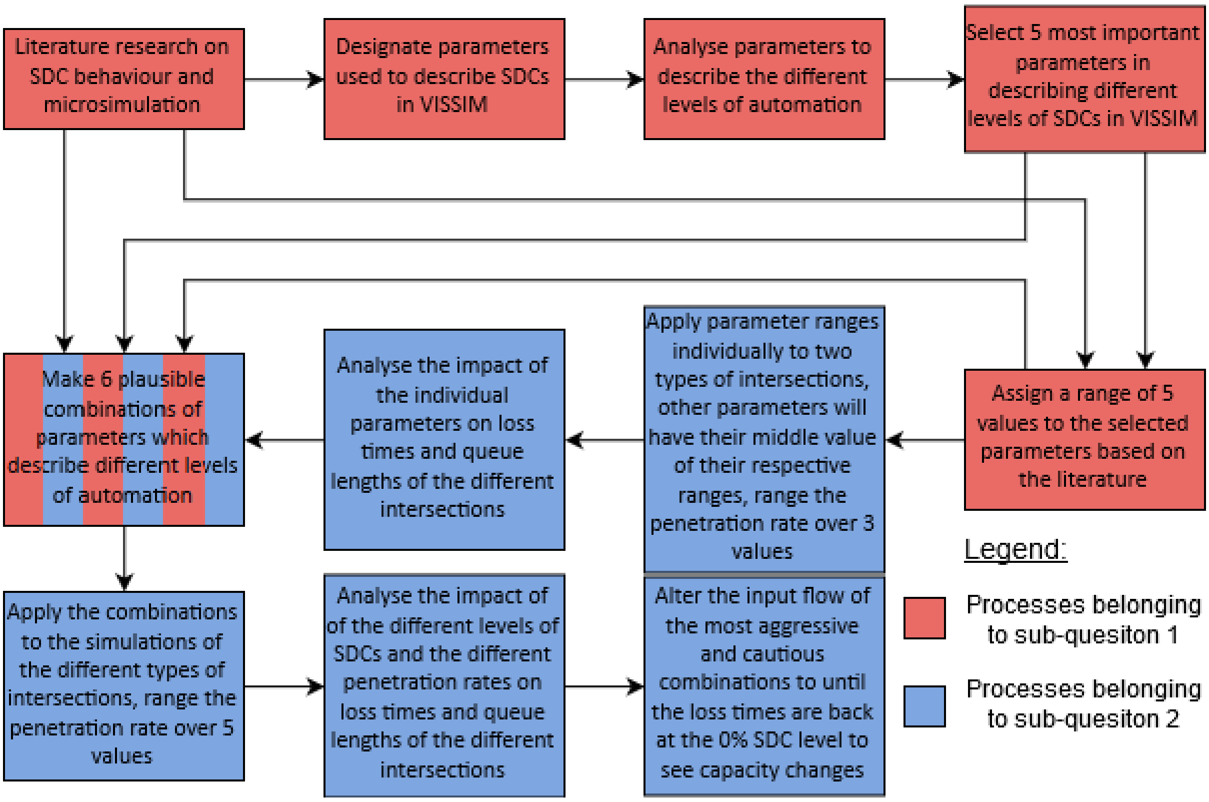



*Figure 22. The flowchart describing the methodological processes of the research.*

# APPENDIX B: FORMULAS APPLIED FOR DATA GATHERING AND PROCESSING

The data which is exported from the simulations are the raw data on individual vehicles, which include loss times of individual vehicles, and the queue counter data collection, which includes the queue lengths during intervals of 60 seconds during the runs. The data for the calculation of the loss times at every intersection is gathered and evaluated by the equations in Table 27, where:

- $s$ is the indicator a specific seed;
- $t_{simulation,s}$ is the current runtime in the simulation of seed s;
- $t_{warm\ up}$ is the warmup time;
- $i$ is the indicator of a specific vehicle;
- $t_{loss\ time,I,s}$ is the loss time of individual vehicle *i* in seed *s*;
- $t_{simulated,I,s}$ is the simulated travel time of individual vehicle *i* in seed *s*;
- $t_{theoretical,I,s}$ is the theoretical, ideal travel time (travel time that would be reached if no other vehicles and no traffic signals are in the network) of individual vehicle *i* in seed *s*;
- $t_{loss\ time,avg,s}$ is the average loss time of vehicles in seed *s*,
- $t_{loss\ time,avg}$ is the average loss time at a specific intersection;
- $n$ is the number of vehicles of which the loss time data is gathered and
- $S$ is the number of seeds used for simulation.

*Table 27. Equations used for the data gathering for and calculation of the loss times.*

| Equation | Description |
|---|---|
| **If:** $t_{simulation,s} \geq t_{warm\ up}$ | Condition for erasing warm-up time. |
| **Then:** $t_{loss\ time,i,s} = t_{simulated,i,s} - t_{theoretical,i,s}$ | |
| $t_{loss\ time,avg,s} = \frac{1}{n} * \sum_{i=1}^{n} t_{loss\ time,i,s}$ | Calculate average loss time in certain seed. |
| $t_{loss\ time,avg} = \frac{1}{S} * \sum_{i=1}^{S} t_{loss\ time,avg,s}$ | Calculate average loss time of all seeds. |

Queue counters are located at all directional lanes of the intersection. The data for calculation of the queue lengths at every intersection is gathered and evaluated by the equations in Table 28, where;

- $s$ is the indicator of a specific seed;
- $t_{simulation,s}$ is the current runtime in the simulation of seed *s*;
- $t_{warm\ up}$ is the warmup time;
- $i$ is the indicator of a specific vehicle;
- $e$ is the indicator of a specific entry direction;
- $q$ is the indicator of a specific queue counter/directional lane;
- $v_{i,s,e,q}$ is the speed of vehicle *i* in seed *s* at entry direction *e* at queue counter *q*;
- $\Delta x_{i,s,e,q}$ is the space headway of vehicle *i* in seed *s* at entry direction *e* at queue counter *q*;
- $Q_{s,e,q}$ is the set of vehicles currently in the queue in seed *s* at entry direction *e* at queue counter *q*;
- $L_{i,s,e,q}$ is the length of vehicle *i* in seed *s* at entry direction *e* at queue counter *q*;
- $l_{queue,step,s,e,q}$ is the queue length at the current simulation step in seed *s* at entry direction *e* at queue counter *q*;
- $l_{queue,minute,max,s,e,q}$ is the maximum queue length in the current runtime minute in the simulation in seed *s* at entry direction *e* at queue counter *q*;

- $l_{queue,minute,90\%,e,q}$ is the 90th percentile queue length in the current runtime minute regarding the different seeds at entry direction *e* at queue counter *q*;
- $l_{queue,minute,90\%,e,max}$ is the 90th percentile queue length in the current runtime minute regarding the different seeds and the maximum regarding the different queue counters at entry direction *e*;
- $l_{queue,90\%,e,max}$ is the median 90th percentile queue length over the entire simulated time regarding the different seeds and the maximum regarding the different queue counters at entry direction *e*;

*Table 28. Equations used for the data gathering for and calculation of the queue lengths.*

| Equation | Description |
|---|---|
| **If:** $t_{simulation,s} \geq t_{warm\ up}$ | Conditions for vehicles joining the queue. |
| **And:** $v_{i,s,e,q} < 5\ km/h$ | |
| **And:** $\Delta x_{i,s,e,q} < 20\ \mathrm{m}$ | |
| **Then:** $i_{s,e,q} \in Q_{s,e,q}$ | |
| **If:** $v_{i,s,e,q} > 10\ km/h$ | Condition for vehicles leaving the queue. |
| **Then:** $i_{s,e,q} \notin Q_{s,e,q}$ | |
| $l_{queue,step,s,e,q} = \sum_{i_{s,e,q}=1}^{\lvert Q_{s,e,q} \rvert} L_{i_{s,e,q}} + \Delta x_{i_{s,e,q}}$ | Calculate queue length during a certain seed, at a certain entry direction, at a certain queue counter. |
| **If:** $l_{queue,step,s,e,q} \geq l_{queue,minute,max,s,e,q}$ | Condition for choosing the maximum queue length per minute |
| **Then:** $l_{queue,minute,max,s,e,q} = l_{queue,step,s,e,q}$ | |
| $l_{queue,minute,90\%,e,q} = P_{90\%}(\{l_{queue,minute,max,*,e,q}\})$ | Take 90th percentile of the queue length regarding seeds. |
| $l_{queue,minute,90\%,e,max} = \max(\{l_{queue,minute,90\%,e,*}\})$ | Take the maximum queue length regarding queue counters of a certain entry direction. |
| $l_{queue,90\%,e,max} = P_{50\%}(\{l_{queue,*,90\%,e,max}\})$ | Take 50th percentile of the queue lengths regarding time. |

# APPENDIX C: THE WIEDEMANN 1999 MODEL

The Wiedemann 1974 and 1999 models assume four different types of driving modes: free driving, approaching, following and breaking (Rossen, 2018; Aghabayk, Sarvi, Young, & Kautzsch, 2013). The mode in which a driver/vehicle is located, is determined by the six thresholds stated in Table 29, and are also visualised in Figure 23.

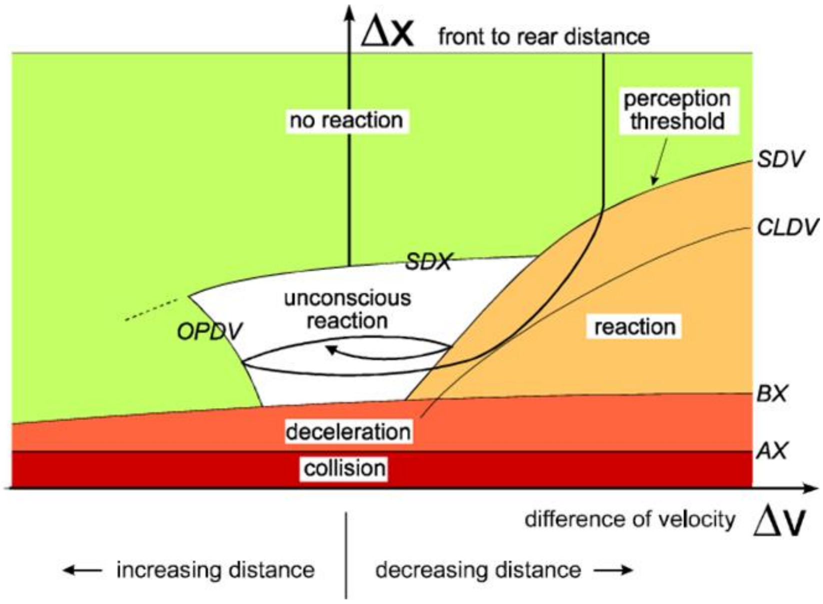



*Figure 23. The schematisation of the car-following model of Wiedemann with one vehicle trajectory visualised (Fellendorf & Vortisch, 2001).*

*Table 29. Explanation of the threshold symbols used in the Wiedemann car-following models.*

| Symbol | Explanation |
|---|---|
| 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 |

The thresholds of Table 29 are defined by the Wiedemann parameters, which are visible in Table 30. Parameters CC0 to CC6 are implemented through equations, parameters CC7 to CC9 are implemented directly in the acceleration behaviour of the vehicles.

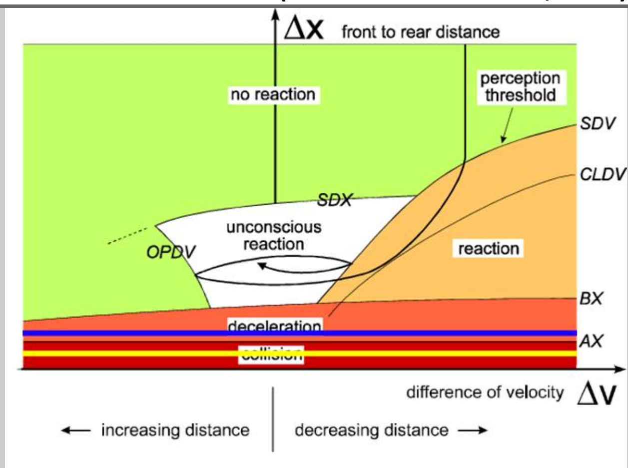
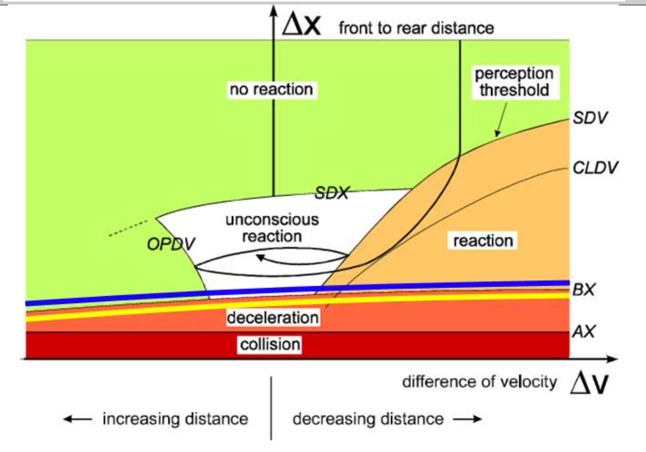
*Table 30. The parameters of the Wiedemann 1999 model with its accompanying descriptions in VISSIM.*

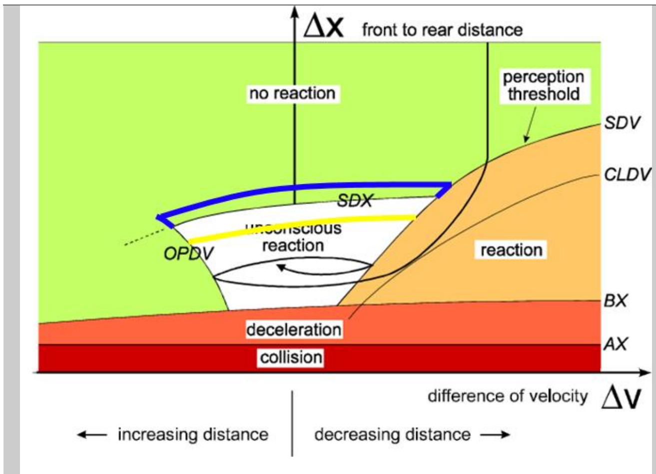
| Parameter | Description | Unit | Implementation in equation (Aghabayk, Sarvi, Young, & Kautzsch, 2013) |
|---|---|---|---|
| CC0 | Standstill distance | m | $AX = L + CC0$ |
| CC1 | Headway time | s | $BX = AX + CC1 * v$ |
| CC2 | Following variation | m | $SDX = BX + CC2$ |

| | | | |
|---|---|---|---|
| CC3 | Threshold for entering ‘following’ | | $(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4$ |
| CC4 | Negative ‘following’ threshold | | $(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4$<br>$CLDV = \frac{CC6}{17000} * (\Delta x - L)^2 - CC4$ |
| CC5 | Positive ‘following’ threshold | | $OPDV = -\frac{CC6}{17000} * (\Delta x - L)^2 - \delta * CC5$ |
| CC6 | Speed dependency of oscillation | | $CLDV = \frac{CC6}{17000} * (\Delta x - L)^2 - CC4$<br>$OPDV = -\frac{CC6}{17000} * (\Delta x - L)^2 - \delta * CC5$ |
| CC7 | Oscillation acceleration | $m/s^2$ | |
| CC8 | Standstill acceleration | $m/s^2$ | |
| CC9 | Acceleration at 80 km/h | $m/s^2$ | |

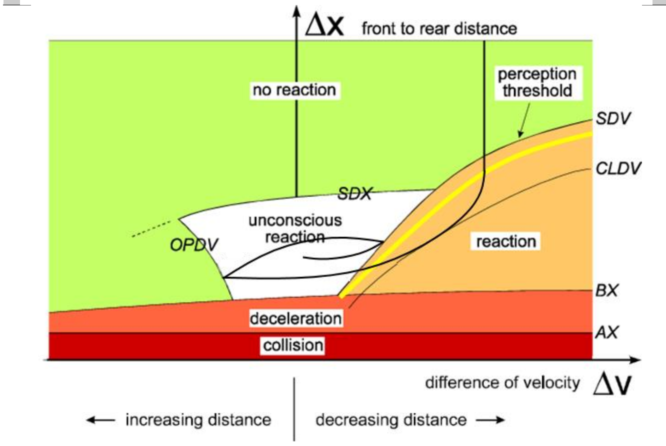
The parameters can be altered in order to change the driving behaviour of the vehicles. The resulting adjustments to the visualisation of the model are presented in Table 31.

*Table 31. Altered visualisations of the Wiedemann 1999 model when the parameters of the model are adjusted.*

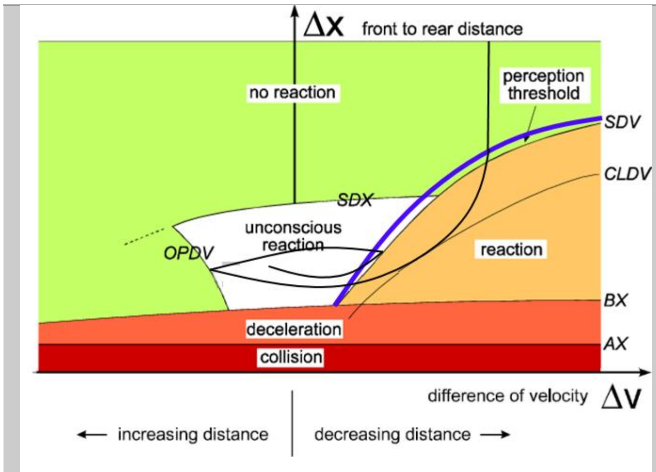
| Visualisation based on (Fellendorf & Vortisch, 2001) | Description |
|---|---|
|  | CC0 is altered. The purple line shows the direct results a higher value of CC0, the yellow line shows a lower value of CC0. When CC0 is altered, the minimum desired distance between two vehicles (AX) is altered, which indirectly also plays a role in determining BX, SDX and SDV. The shapes of BX and SDX change uniformly with the shape changes of AX; a higher CC0 will lead to a higher AX and therefore to a higher BX and SDX. The shape of SDV changes reversely to the shape of AX; a higher CC0 will lead to a higher AX but to a lower SDV. |
|  | CC1 is altered. The purple line shows the direct results a higher value of CC1, the yellow line shows a lower value of CC1. When CC1 is altered, the minimum safe following distance (BX) is changed, which indirectly plays a role in determining SDX and SDV. The shape of SDX changes uniformly with the shape of BX; a higher CC1 will lead to a higher BX and therefore to a higher SDX. The shape of SDV changes reversely to the shape of BX; a higher CC0 will lead to a higher BX but to a lower SDV. |



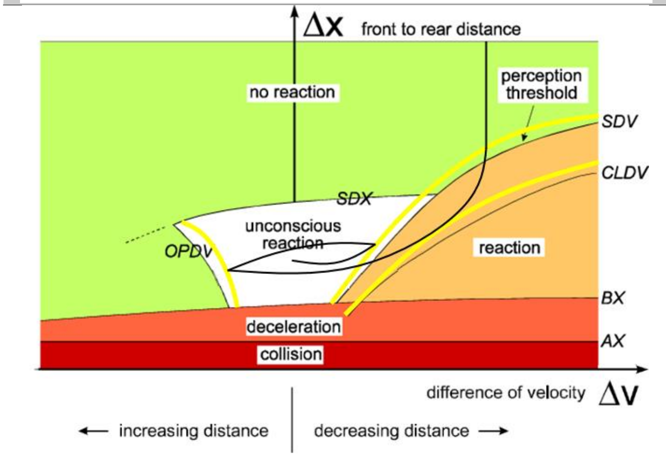

CC2 is altered. The purple line shows the direct results a higher value of CC2, the yellow line shows a lower value of CC2. When CC2 is altered, maximum distance indicating following distance (SDX) is changed, which indirectly plays a role in determining SDV. The shape of SDV changes reversely to the shape of SDX; a higher CC2 will lead to a higher SDX but to a lower SDV.



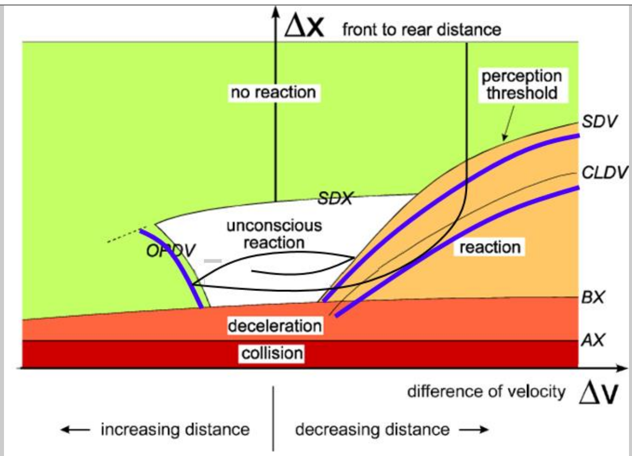

CC3 is altered negatively (closer to 0). The yellow line shows the direct results of a lower value of CC3, which results in a slightly altered the example vehicle trajectory. The perception threshold (SDV) is lowered, so the other vehicle is perceived later in the following process.



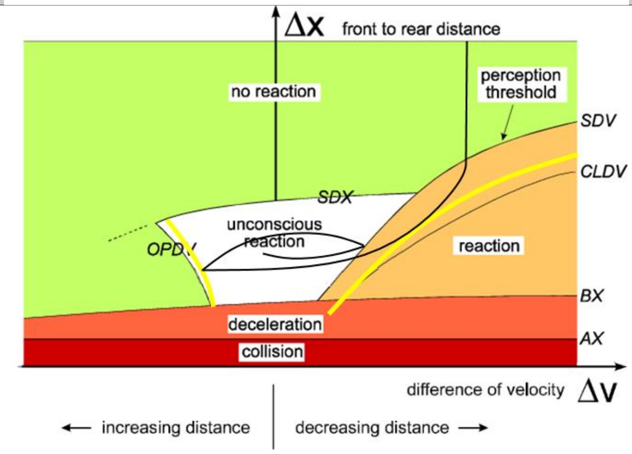

CC3 is altered positively (moved away from 0). The purple line shows the direct results of a higher value of CC3, which results in a slightly altered the example vehicle trajectory. The perception threshold (SDV) is heightened, so the other vehicle is perceived earlier in the following process.



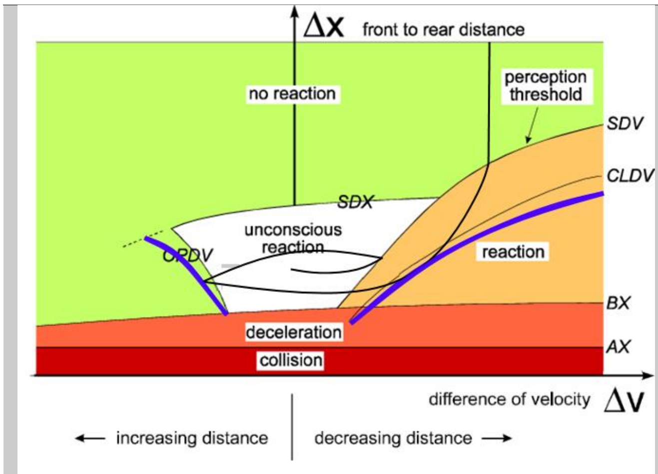

CC4 and CC5 are altered negatively (closer to 0). The yellow line shows the direct result of a lower value of CC4 and CC5, which results in a slightly altered the example vehicle trajectory. The perception threshold (SDV) is heightened, so the other vehicle is perceived earlier in the following process. The reaction threshold (CLDV) is heightened, so braking starts slightly earlier distance-wise. The acceleration threshold (OPDV) is heightened, so the vehicle accelerates earlier.




CC4 and CC5 are altered positively (moved away from 0). The purple line shows the direct result of a higher value of CC4 and CC5, which results in a slightly altered the example vehicle trajectory. The perception threshold (SDV) is lowered, so the other vehicle is perceived later in the following process. The reaction threshold (CLDV) is lowered, so braking starts slightly later distance-wise. The acceleration threshold (OPDV) is lowered, so the vehicle accelerates later.




CC6 is altered negatively. The yellow line shows the direct results of a lower value of CC6, which results in a slightly altered example vehicle trajectory. The reaction threshold (CLDV) is heighted at larger ΔV, so braking start earlier distance-wise. The acceleration threshold (OPDV) is heightened at larger ΔV, so the vehicle accelerates earlier ΔV-wise.




CC6 is altered positively. The purple line shows the direct results of a higher value of CC6, which results in a slightly altered example vehicle trajectory. The reaction threshold (CLDV) is lowered at larger ΔV, so braking start later distance-wise. The acceleration threshold (OPDV) is lowered at larger ΔV, so the vehicle accelerates later ΔV-wise.

# APPENDIX D: RELEVANCE ANALYSIS OF BEHAVIOURAL CHANGES OF SDCS

Table 32 shows the changes of driving behaviour of SDCs when compared to regular vehicles as expected by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017).

*Table 32. Behavioural changes of SDCs compared to regular vehicles as expected by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017), their relevance to this research and the proposed adjustments done by (PTV Group, 2017) and (Stanek, Huang, Milam, & Wang, 2017).*

| Autonomous vehicle behaviour | Relevance | Adjustments to make in VISSIM |
|---|---|---|
| Keep smaller standstill distances | Relevant, since this will occur when SDCs wait at intersections | Change CC0 |
| Keep smaller distances at non-zero speed | Relevant, since this plays an important role in SDCs following other vehicles | Change CC0, CC1 and CC2 |
| Accelerate faster and smoothly from standstill | Relevant, since acceleration from standstill will occur at intersections | Change acceleration functions and CC8 and CC9 |
| Keep constant speed with no or smaller oscillation at free flow | Relevant, since SDCs might not have to stop at certain intersections at certain moments | Use COM interface<br>**Note:** concerning the speed differences between vehicles, the speed distribution can be altered. |
| Follow other vehicles with smaller distance oscillation | Relevant, since speed oscillations are important factors in traffic approaching intersections and crossing intersections | Change CC2<br>**Note:** concerning the speed differences between vehicles, the speed distribution can be altered. |
| Form platoons of vehicles | Not relevant, since platooning involves communication between SDCs | Use COM interface |
| Following vehicles react on green signal at the same time as the first vehicle in the queue | Indirectly relevant, since SDCs might accelerate simultaneously with the car driving directly in front of it, regardless of a green signal | Use COM interface |
| Communicate with other SDCs, i.e. broken-down vehicle and other avoid it | Not relevant, since communication is out of the scope | Use COM interface |
| Communicate with the infrastructure, i.e. vehicles adjusting speed profile to reach a green light at signals | Not relevant, since communication is out of the scope | Use COM interface |
| Perform more co-operative lane change as lane changes could occur at higher speed co-operatively | Not relevant, since lateral movement is not of importance in the situation to analyse and communication is out of the scope | Switch cooperative lane change and change maximum speed difference and maximum collision time |

| | | |
|---|---|---|
| Smaller lateral distances to vehicles or objects in the same lane or on adjacent lanes | Small relevance, since this might be useful at directional lanes at intersections | Change default behaviour when overtaking on the same lane and define exceptions for vehicle classes |
| Exclusive SDC lanes, with and without platoons | Not relevant, since the focus is on a case where SDCs and regular vehicles are both present on the same road | Define blocked vehicle classes for lanes |
| Drive as Communicative SDC on the selected routes (or areas) and as conventional human controlled vehicles on the other routes, i.e. Volvo DriveMe project | Not relevant, since communication is out of the scope | Use different link behaviour types and driver behaviour for vehicle classes |
| Divert vehicles already in the network onto new routes and destinations; i.e. come from a parking place or position in the network to pick up a rideshare app passenger on demand | Not relevant, since such movements will not occur at a single intersection | Use COM interface |

# APPENDIX E: EXPLANATION OF THE IMPLEMENTATION OF SDCS IN VISSIM

In this appendix, an explanation is given on how SDCs are applied as vehicles in existing models in VISSIM. It is a step-by-step description of the way SDCs are implemented in the models used in this research. Clicks on certain buttons are written **boldly**. The places in this guide where the parameters to alter (penetration rates and Wiedemann 99 parameters) are changed are <u>underlined</u>.

1. **Base Data** > **Vehicle Types**
    a. Create a new type of vehicle and name it SDC.
    b. Check in the overview what colour distribution is used for the regular cars.
2. **Base Data** > **Distributions** > **Color**
    a. Edit the colour distribution for the regular cars. Only the colour black should remain.
    b. Add a colour distribution for the SDCs. Name it SDCs. Only the colour white should be part of it, in order to visually distinguish regular cars and SDCs.
3. **Base Data** > **Vehicle Types**
    a. Select the accompanying colour distribution for the vehicle type SDC.
4. **Base Data** > **Vehicle Classes**
    a. Add a vehicle class and name it SDC.
    b. Add the vehicle type SDC to the vehicle class SDC.
5. **Traffic** > **Vehicle composition**
    a. Select the existing composition Car.
    b. Remove the unnecessary vehicle types in the right-side window. Only one vehicle type concerning regular cars should remain.
    c. Add the vehicle type SDC to the composition Car. The composition should now exist out of one vehicle type describing regular cars and the vehicle type SDC.
    d. Change the <u>*penetration rate*</u> of the vehicle types by changing the relative flow.
6. **Base Data** > **Functions** > ***Deceleration functions***
    a. Duplicate the deceleration function of the regular Car.
    b. Rename it to SDC.
    c. Select the deceleration function SDC. In the right-side window, alter the yMin and yMax to the same value as Y.
    d. Do this for the other deceleration function as well.
7. **Base Data** > **Functions** > ***Acceleration functions***
    a. Duplicate the acceleration function of the regular Car.
    b. Rename it to SDC.
    c. Select the acceleration function SDC. In the right-side window, alter the yMin to the same value as Y.
    d. Set the yMax at the corresponding X value as visible in Table 33.

*Table 33. The used acceleration function for an SDC in VISSIM.*

| X | yMax |
|---|---|
| 0.00 | 4.50 |
| 10.00 | 4.10 |
| 20.00 | 3.70 |
| 30.00 | 3.40 |
| 40.00 | 3.10 |
| 50.00 | 2.85 |

| | |
|---|---|
| 60.00 | 2.65 |
| 70.00 | 2.40 |
| 80.00 | 2.25 |
| 90.00 | 2.10 |
| 100.00 | 1.95 |
| 110.00 | 1.70 |
| 120.00 | 1.30 |
| 130.00 | 1.10 |
| 140.00 | 0.80 |
| 150.00 | 0.50 |
| 160.00 | 0.00 |

   e. Do this for the other acceleration function as well.

8. **Base Data** > **Distributions** > **Time**
   a. Add five new time distributions.
   b. Name the new time distributions accordingly to the headway time which is implemented for the SDC and add SDC to the name.
   c. Set the standard deviation of the new time distributions to 0.
   d. Set the mean of the new time distributions to their respective values according to the headway times.
9. **Right click Desired Speed Decisions > Show list**
   a. Check the desired speed distributions related to regular cars.
   b. If none are present, place them at the start of the input road segments.
10. **Base Data** > **Distributions** > **Desired speed**
    a. Duplicate the desired speed distributions related to regular cars.
    b. Add 'SDC' to the name of the duplicated speed distributions.
    c. Delete possible excess rows in the right-side window. Only two rows should remain.
    d. Edit the X values to maximum 5% below and 5% above the desired average speed.
    e. Make sure the FX of the first row is 0 and the FX of the second row is 1.
11. **Right click Desired speed Decisions > Show list**
    a. Add the newly created desired speed distributions of the SDCs to the speed decisions.
12. **Repeat steps 9 to 11 for the Reduced Speed Areas**
    a. Use the Reduced Speed Areas instead of the Desired Speed Decisions
13. **Traffic** > **Vehicle composition**
    a. In the right-side window, select the desired initial speed distribution for the SDC.
14. **Base Data** > **Driving behaviour**
    a. Duplicate the link type(s) used in the model for regular cars.
    b. Add SDC to the name of the duplicated link type(s).
15. **Right click on the SDC link type** > **Edit**
    a. Select the Wiedemann 99 parameters as car following model.
    b. Alter the *Wiedemann 99 parameters* accordingly to the desired values.
    c. Change the maximum look ahead distance to 160 metres.
    d. Change the number of observed vehicles to 3.
16. **Base Data** > **Link behaviour types**
    a. Add a link behaviour type named 'Mixed Traffic'.
    b. In the right-side screen, add the regular car vehicle classes and the SDC vehicle class.
    c. Select the accompanying driving behaviour for the respective vehicle classes.
17. **Right click on Links** > **Show list**
    a. Edit the link behaviour type of the links which SDCs have access to, to Mixed Traffic.

# APPENDIX F: OD-MATRICES OF THE INTERSECTIONS

In this appendix, the OD-matrices of the various analysed intersections are visible. The OD-matrices of the regular intersection and roundabout are scaled based on the available data of the Aalsmeerderweg – Machineweg intersection in Aalsmeer, the Netherlands. The OD-matrices of the signalised intersection are scaled based on the initial analysis of the N214/N216 intersection.

## APPENDIX F.1: OD-MATRIX OF THE REGULAR INTERSECTION

*Table 34. OD-matrix used with the assessment of the regular intersection in vehicles per hour.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 122.5 | 105 | 15 | **242.5** |
| **East** | 58.75 | | 315 | 310 | **683.75** |
| **South** | 62.5 | 141.25 | | 160 | **363.75** |
| **West** | 36.25 | 283.75 | 25 | | **345** |
| **Total** | **157.5** | **547.5** | **445** | **485** | |

## APPENDIX F.2: OD-MATRIX OF THE ROUNDABOUT

*Table 35. OD-matrix used with the assessment of the roundabout in vehicles per hour.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 127.4 | 109.2 | 15.6 | **252.2** |
| **East** | 61.1 | | 327.6 | 322.4 | **711.1** |
| **South** | 65.0 | 146.9 | | 166.4 | **378.3** |
| **West** | 37.7 | 295.1 | 26.0 | | **358.8** |
| **Total** | **163.8** | **569.4** | **462.8** | **504.4** | |

## APPENDIX F.3: OD-MATRICES OF THE SIGNALISED INTERSECTION

Because the traffic assignment at the signalised intersection is a dynamic assignment, a different matrix is applied for every 15 minutes of the simulation.

*Table 36. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the 15-minute-warm-up and the first 15 minutes of the simulation.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 42.6 | 206.4 | 79.0 | **328.0** |
| **East** | 10.1 | | 22.7 | 518.9 | **551.8** |
| **South** | 168.5 | 31.0 | | 163.8 | **363.4** |
| **West** | 30.7 | 374.9 | 136.8 | | **542.4** |
| **Total** | **209.3** | **448.6** | **365.9** | **761.8** | |

*Table 37. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the second 15 minutes of the simulation.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 48.5 | 235.1 | 90.0 | **373.6** |
| **East** | 11.5 | | 25.9 | 591.0 | **628.4** |
| **South** | 191.9 | 35.3 | | 186.6 | **413.8** |
| **West** | 34.9 | 427.0 | 155.8 | | **617.7** |
| **Total** | **238.4** | **510.8** | **416.7** | **867.6** | |

*Table 38. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the third 15 minutes of the simulation.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 56.7 | 274.9 | 105.2 | **436.8** |
| **East** | 13.5 | | 30.3 | 691.0 | **734.8** |
| **South** | 224.4 | 41.3 | | 218.2 | **483.9** |
| **West** | 40.8 | 499.3 | 182.1 | | **722.3** |
| **Total** | **278.7** | **597.3** | **487.3** | **1014.4** | |

*Table 39. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the fourth 15 minutes of the simulation.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 49.8 | 241.4 | 92.4 | **383.7** |
| **East** | 11.8 | | 26.6 | 607.0 | **645.4** |
| **South** | 197.1 | 36.3 | | 191.6 | **425.1** |
| **West** | 35.9 | 438.6 | 160.0 | | **634.4** |
| **Total** | **244.8** | **524.7** | **428.0** | **891.1** | |

*Table 40. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the fifth 15 minutes of the simulation.*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 50.9 | 246.7 | 94.5 | **392.1** |
| **East** | 12.1 | | 27.2 | 620.3 | **659.6** |
| **South** | 201.5 | 37.1 | | 195.8 | **434.4** |
| **West** | 36.7 | 448.2 | 163.5 | | **648.4** |
| **Total** | **250.2** | **536.2** | **437.4** | **910.6** | |

*Table 41. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the sixth 15 minutes of the simulation*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 48.3 | 234.0 | 89.6 | **371.9** |
| **East** | 11.5 | | 25.8 | 588.3 | **625.5** |
| **South** | 191.1 | 35.2 | | 185.7 | **412.0** |
| **West** | 34.8 | 425.1 | 155.1 | | **614.9** |
| **Total** | **237.3** | **508.5** | **414.8** | **863.6** | |

*Table 42. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the seventh 15 minutes of the simulation*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 53.9 | 261.1 | 100.0 | **414.9** |
| **East** | 12.8 | | 28.8 | 656.3 | **697.9** |
| **South** | 213.2 | 39.3 | | 207.2 | **459.6** |
| **West** | 38.8 | 474.2 | 173.0 | | **686.0** |
| **Total** | **264.7** | **567.3** | **462.8** | **963.5** | |

*Table 43. OD-matrix used with the assessment of the signalised intersection in vehicles per hour for the eighth and ninth 15 minutes of the simulation*

| Origin↓/Destination→ | North | East | South | West | Total |
|---|---|---|---|---|---|
| **North** | | 50.6 | 245.2 | 93.9 | **389.6** |
| **East** | 12.0 | | 27.0 | 616.3 | **655.3** |
| **South** | 200.2 | 36.9 | | 194.6 | **431.6** |
| **West** | 36.4 | 445.3 | 162.4 | | **644.2** |
| **Total** | **248.6** | **532.7** | **434.6** | **904.8** | |

# Appendix G: Loss Times of the Individually Ranged Parameters

In this appendix, the resulting graphs of the absolute and normalised loss times of the individually ranged parameters, are visible. The graphs are ordered per intersection and per penetration rate. Note that the y-axis values differ per graph.

## Appendix G.1: Loss Times at the Regular Intersection

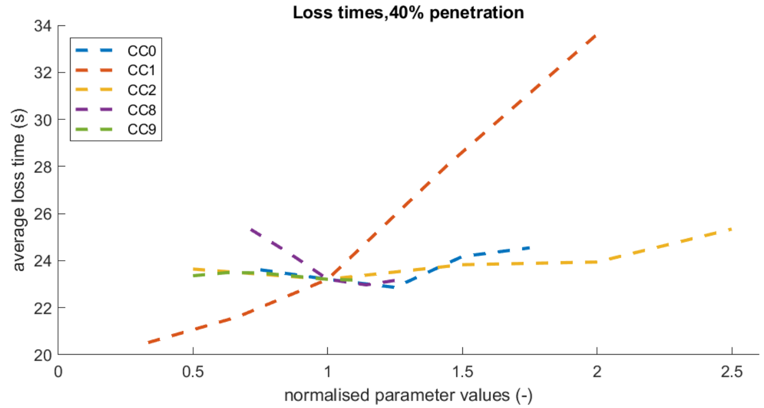



*Figure 24. Absolute loss times plotted against normalised parameters for the regular intersection at 40% penetration of SDCs.*

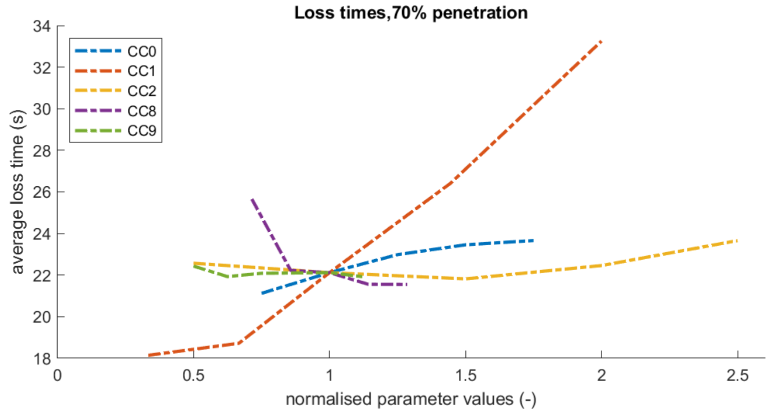



*Figure 25. Absolute loss times plotted against normalised parameters for the regular intersection at 70% penetration of SDCs.*

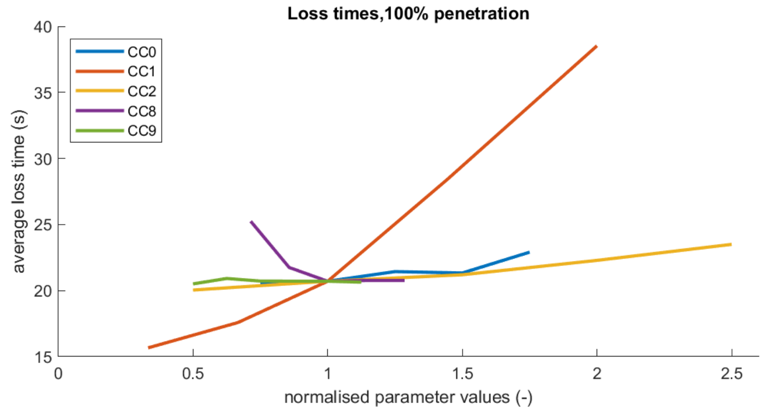



*Figure 26. Absolute loss times plotted against normalised parameters for the regular intersection at 100% penetration of SDCs.*

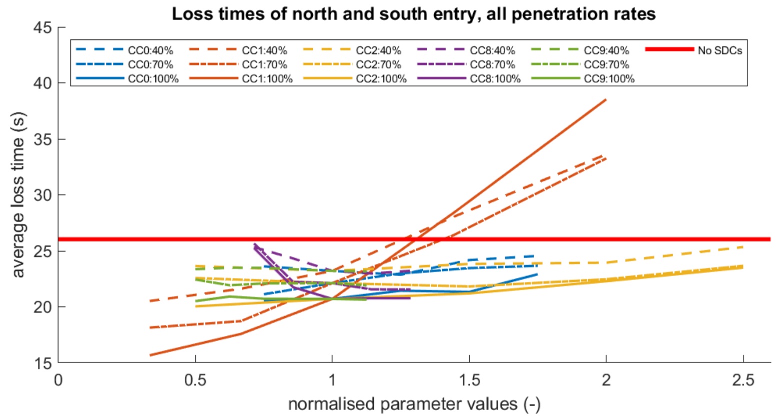



*Figure 27. Absolute loss times plotted against normalised parameters for the regular intersection, combination of penetration rates.*

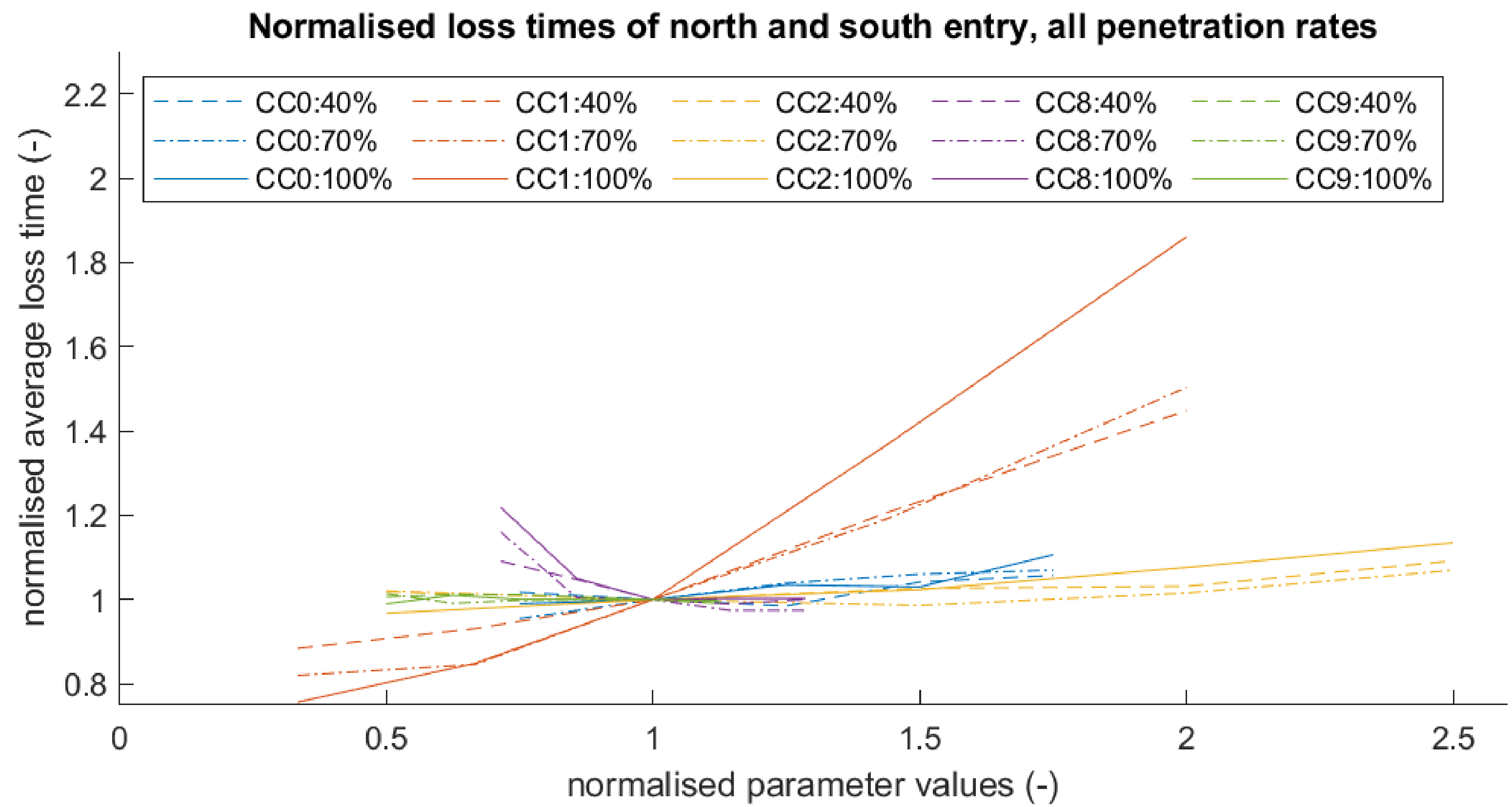



*Figure 28. Normalised differences in loss times plotted against normalised parameters for the regular intersection, combination of penetration rates.*

## Appendix G.2: Loss Times at the Roundabout

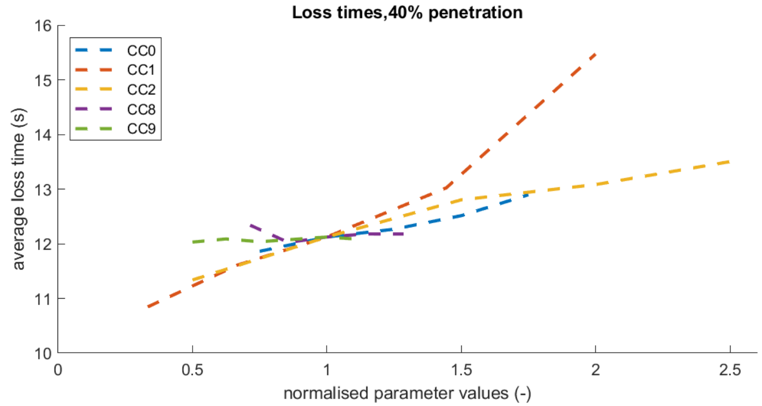



*Figure 29. Absolute loss times plotted against normalised parameters for the roundabout at 40% penetration of SDCs.*

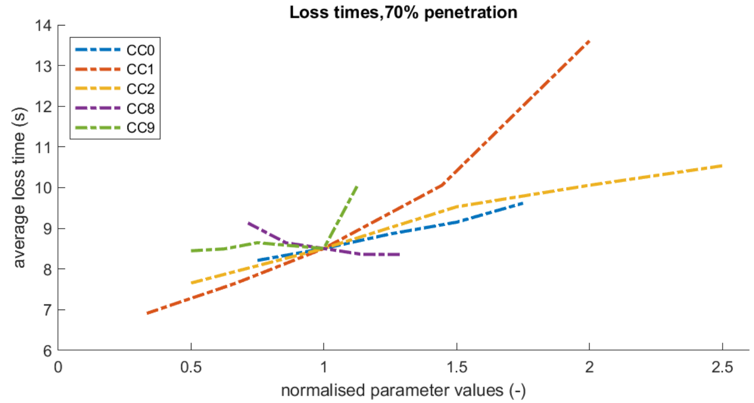



*Figure 30. Absolute loss times plotted against normalised parameters for the roundabout at 70% penetration of SDCs.*

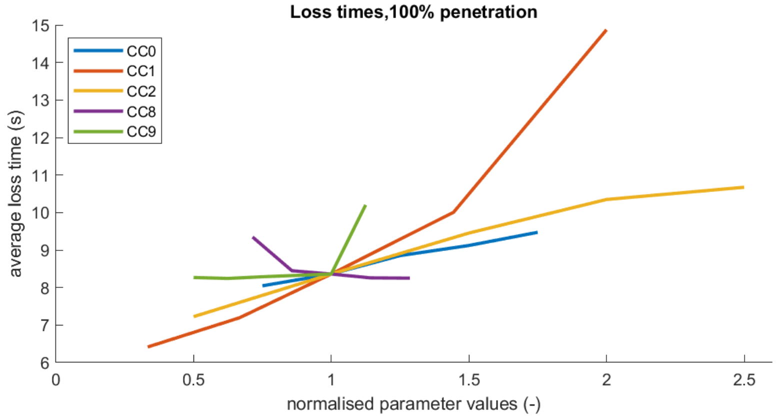



*Figure 31. Absolute loss times plotted against normalised parameters for the roundabout at 100% penetration of SDCs.*

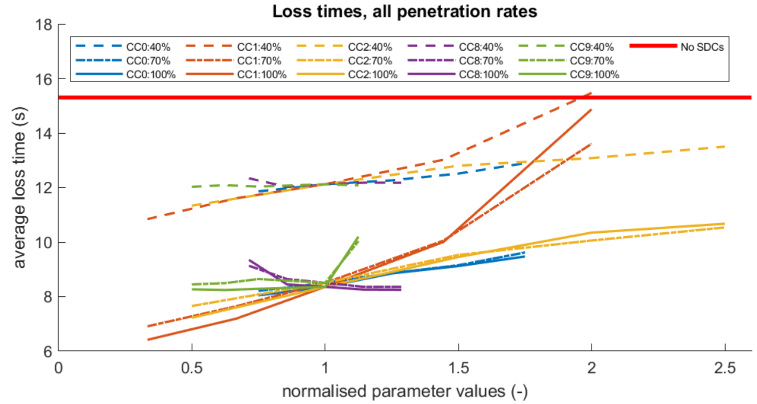



*Figure 32. Absolute loss times plotted against normalised parameters for the roundabout, combination of penetration rates.*

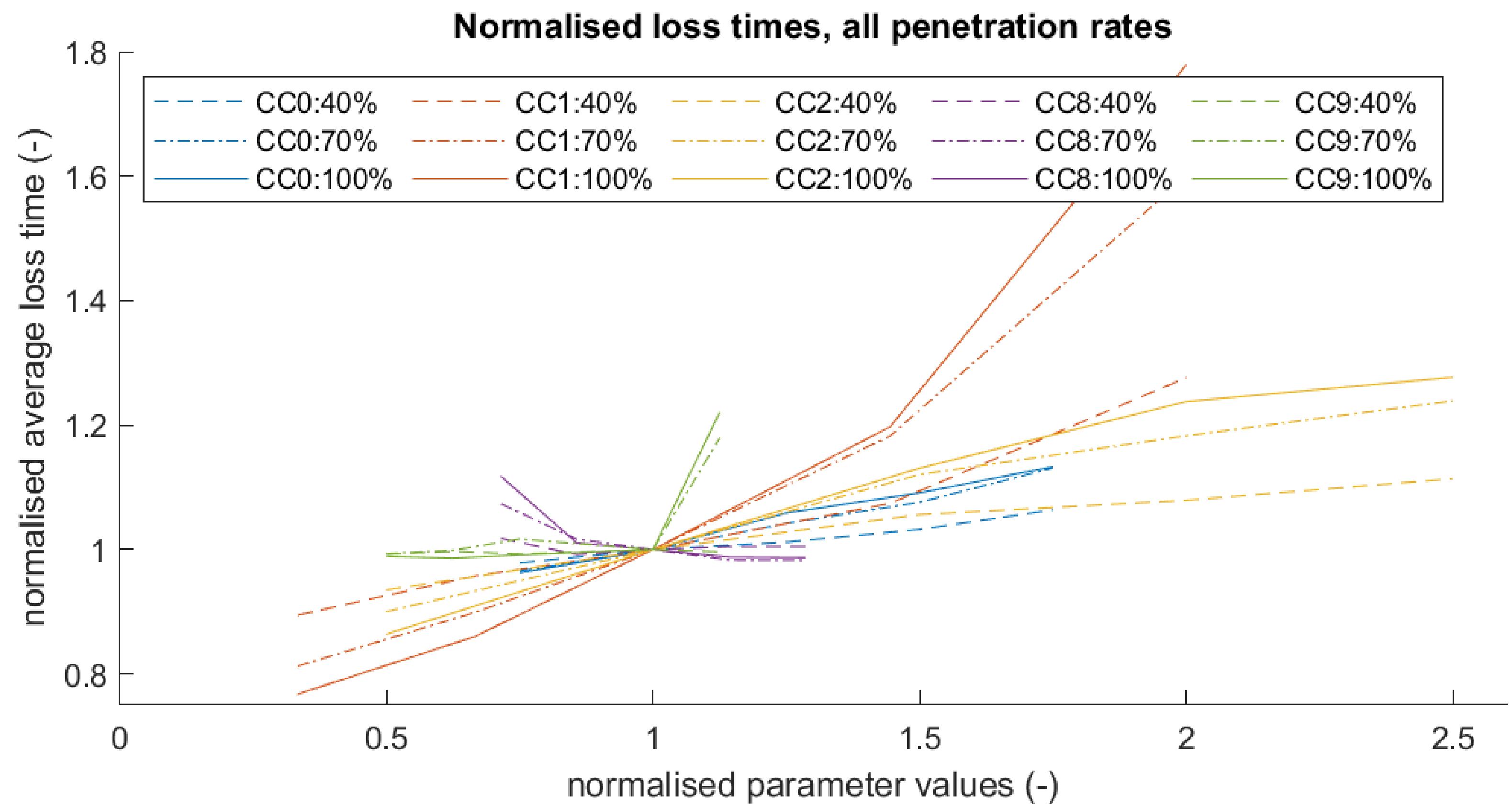



*Figure 33. Normalised differences in loss times plotted against normalised parameters for the roundabout, combination of penetration rates.*

## Appendix G.3: Loss Times at the Signalised Intersection

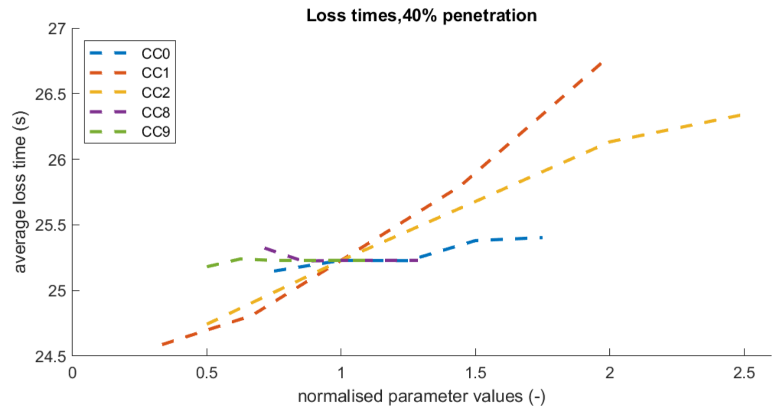



*Figure 34. Absolute loss times plotted against normalised parameters for the signalised intersection at 40% penetration of SDCs.*

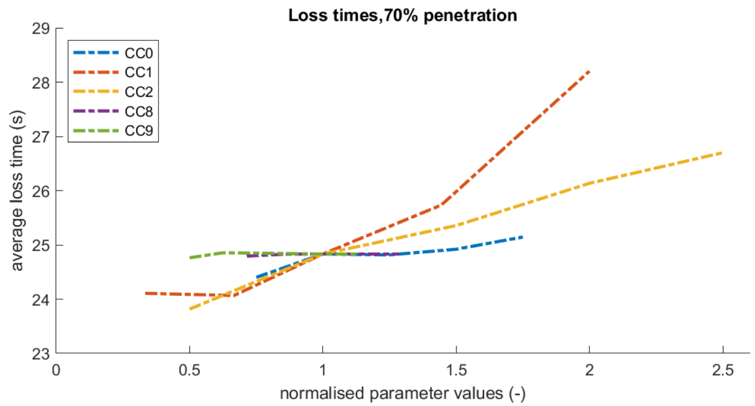



*Figure 35. Absolute loss times plotted against normalised parameters for the signalised intersection at 70% penetration of SDCs.*

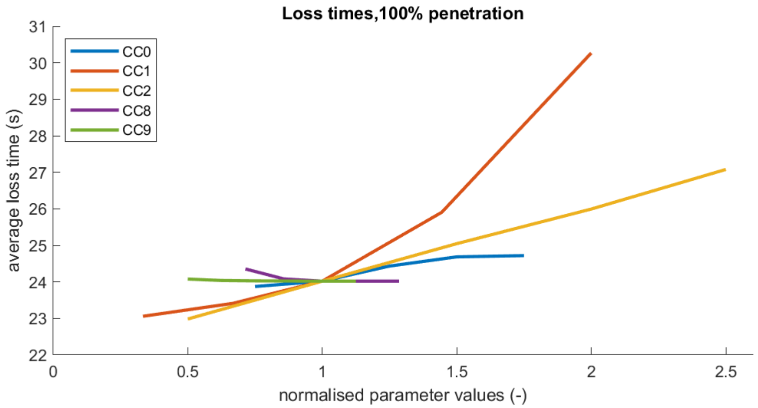



*Figure 36. Absolute loss times plotted against normalised parameters for the signalised intersection at 100% penetration of SDCs.*

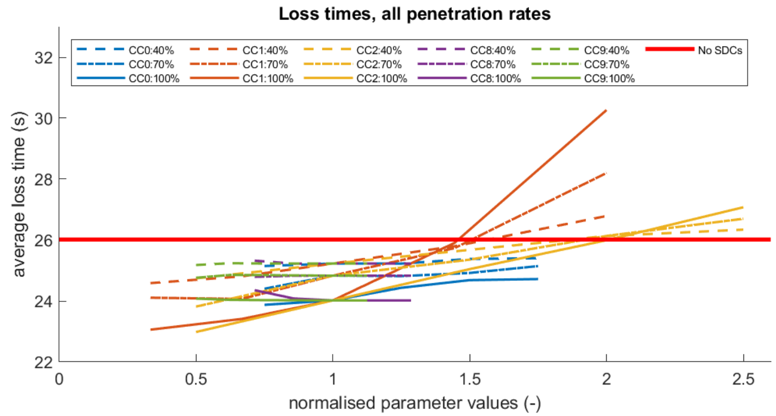



*Figure 37. Absolute loss times plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

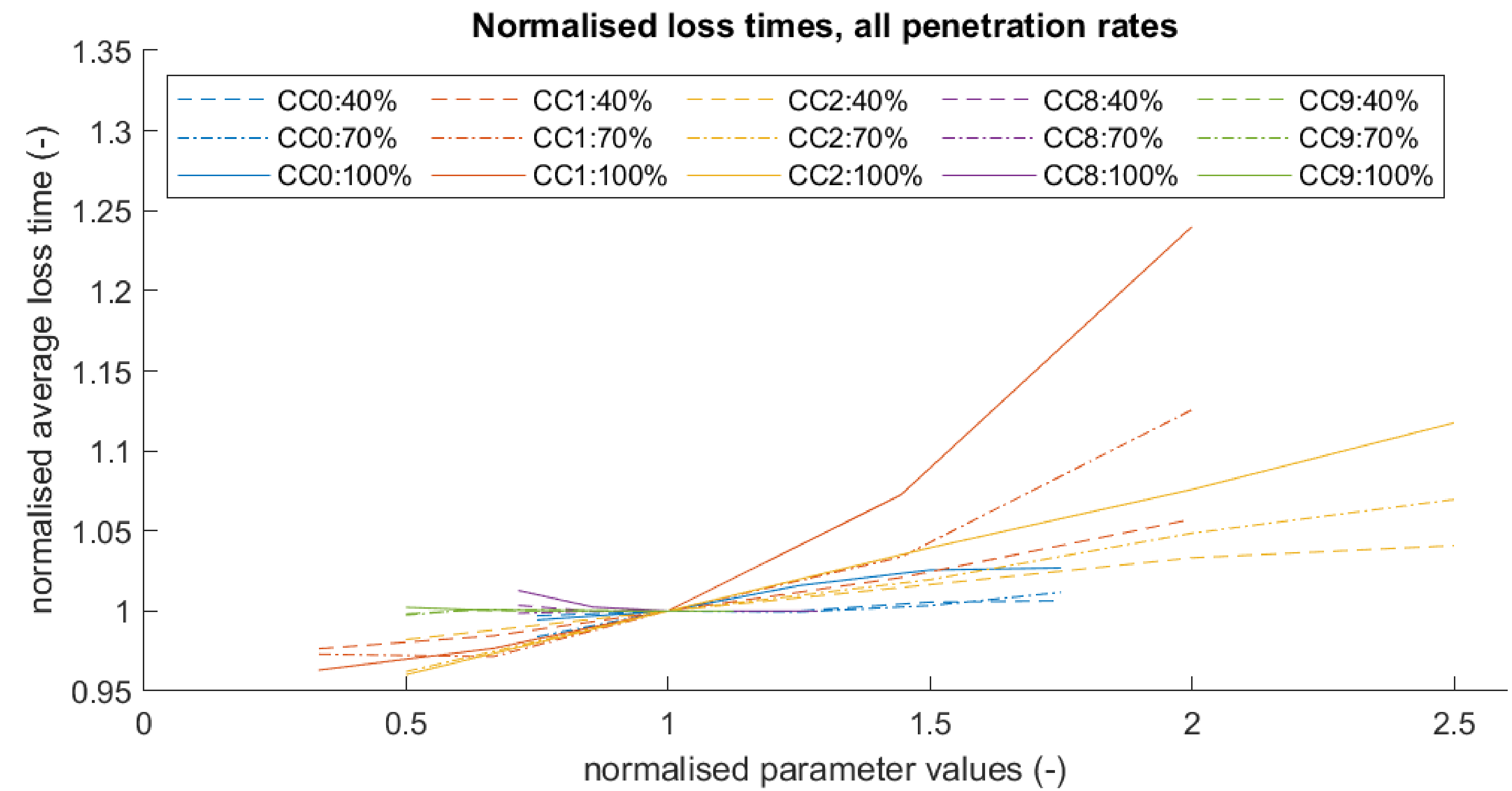



*Figure 38. Normalised differences in loss times plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

# Appendix H: Queue Lengths of the Individually Ranged Parameters

In this appendix, the resulting graphs of the queue lengths of the first series of simulations, where the parameters are ranged individually, are visible. The graphs are ordered per intersection, per intersection entry and per penetration rate.

## Appendix H.1: Queue Lengths at the Regular Intersection

Since the regular intersection concerns a priority road, the queues of the priority road are not analysed. Only the north and south side entries are analysed.

## Appendix H.1.1: Queue Lengths at the Regular Intersection, North Entry

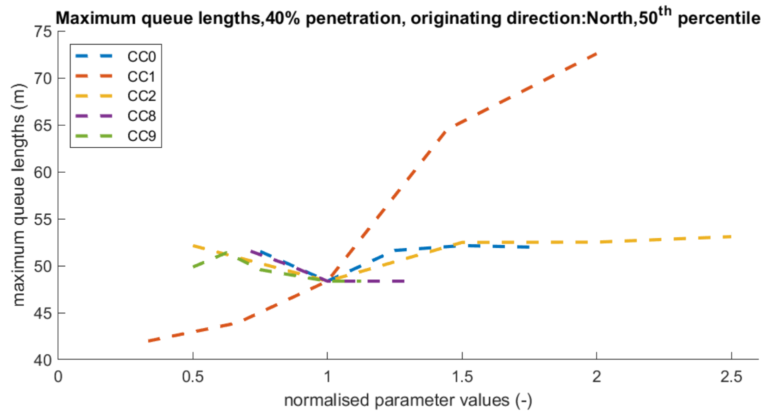



*Figure 39. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the regular intersection at 40% penetration of SDCs.*

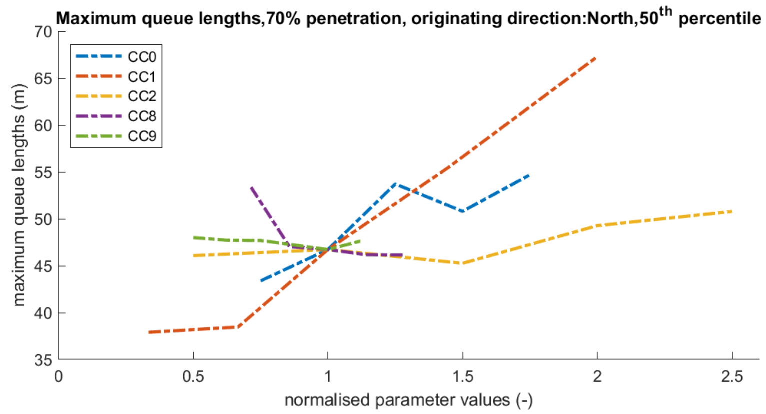



*Figure 40. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the regular intersection at 70% penetration of SDCs.*

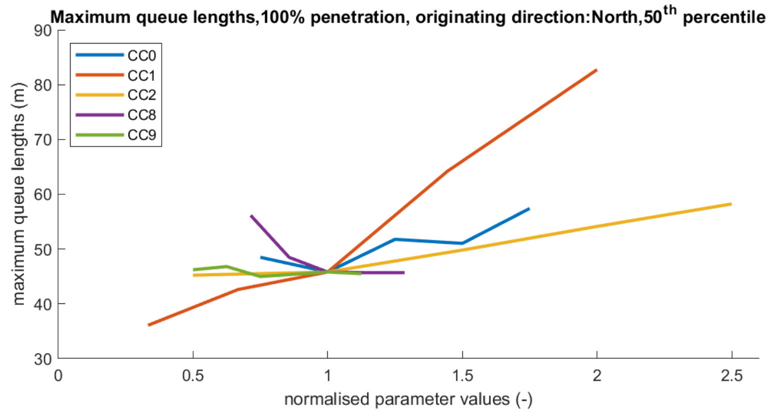



*Figure 41. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the regular intersection at 100% penetration of SDCs.*

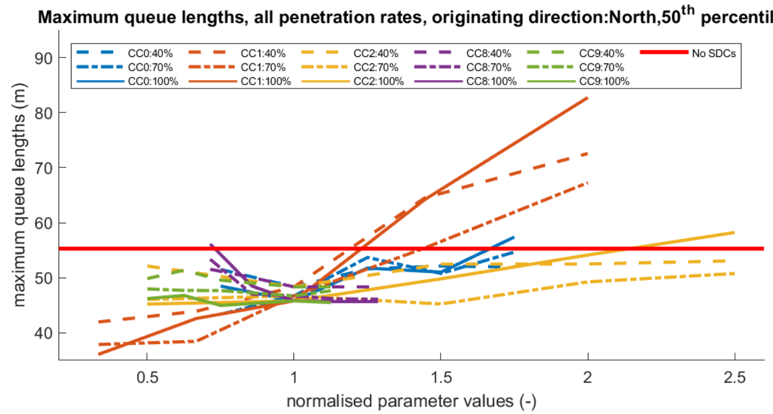



*Figure 42. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection, combination of penetration rates.*

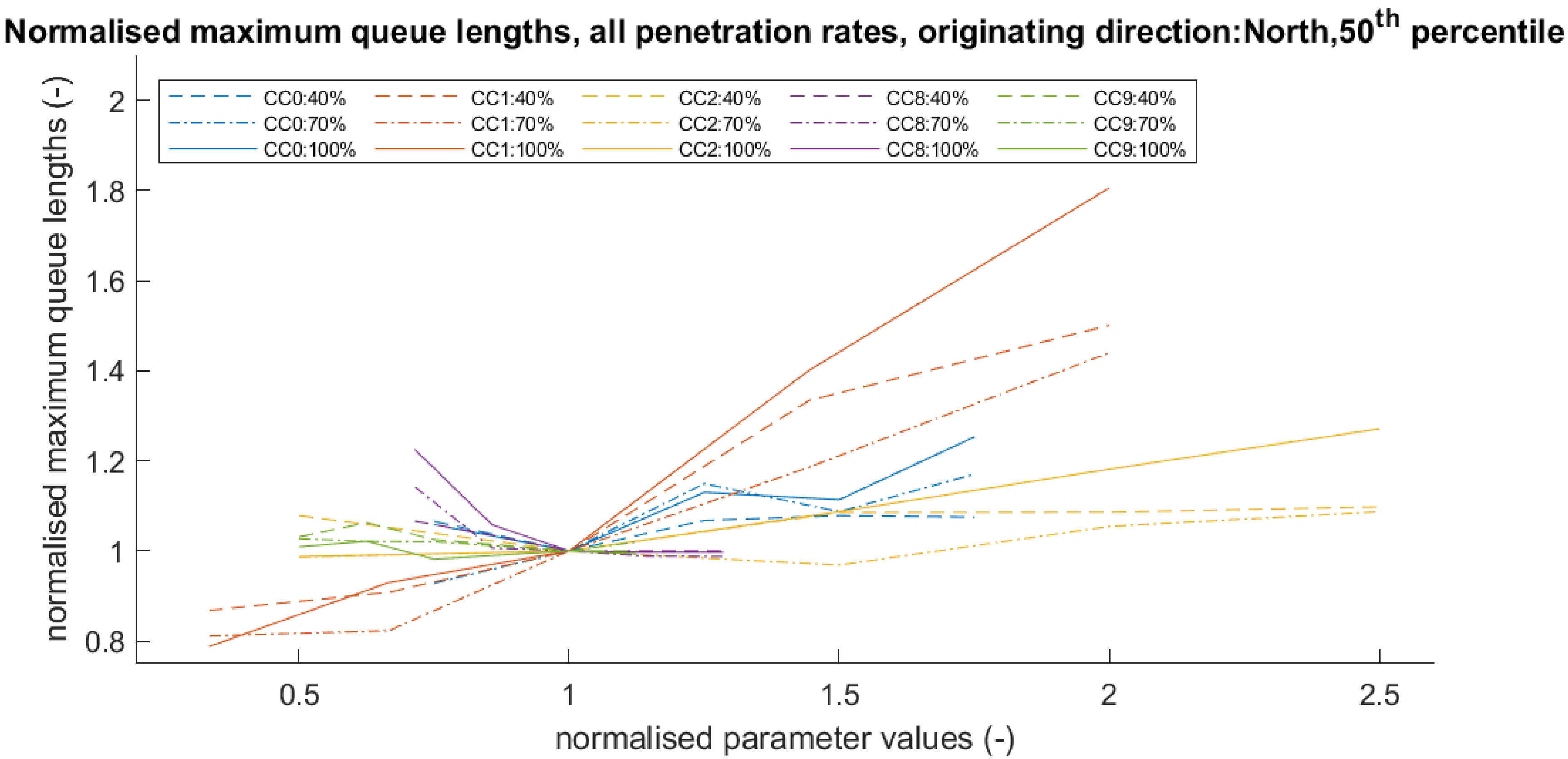



*Figure 43. Normalised median 90th percentile queue lengths of the north entry plotted against normalised parameters for the regular intersection, combination of penetration rates.*

## Appendix H.1.2: Queue Lengths at the Regular Intersection, South Entry

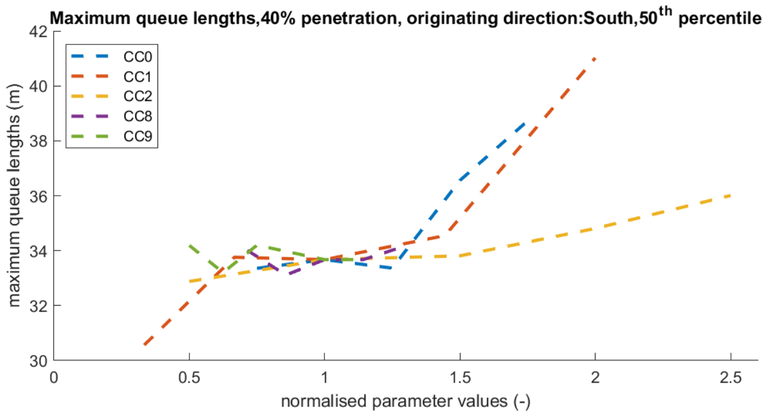



*Figure 44. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection at 40% penetration of SDCs.*

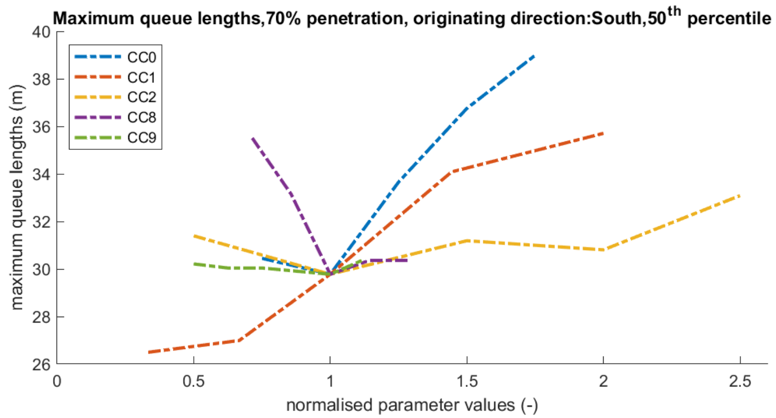



*Figure 45. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection at 70% penetration of SDCs.*

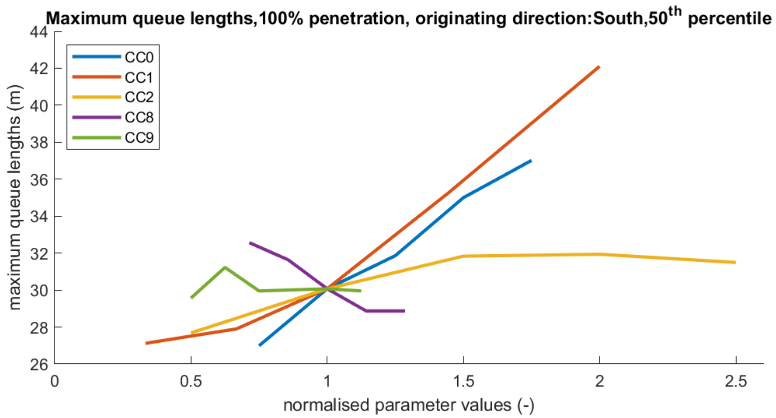



*Figure 46. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection at 100% penetration of SDCs.*

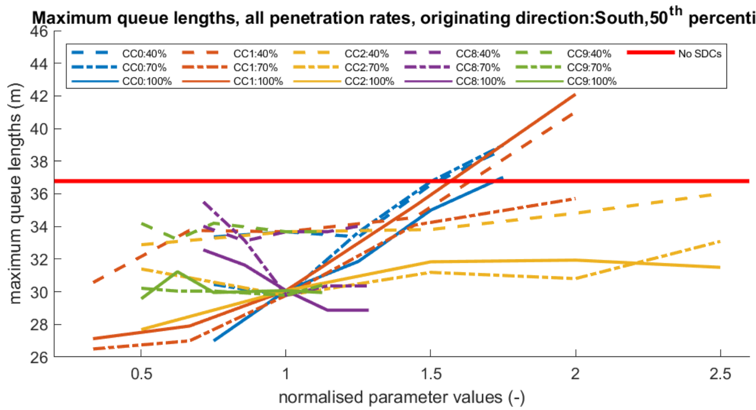



*Figure 47. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection, combination of penetration rates.*

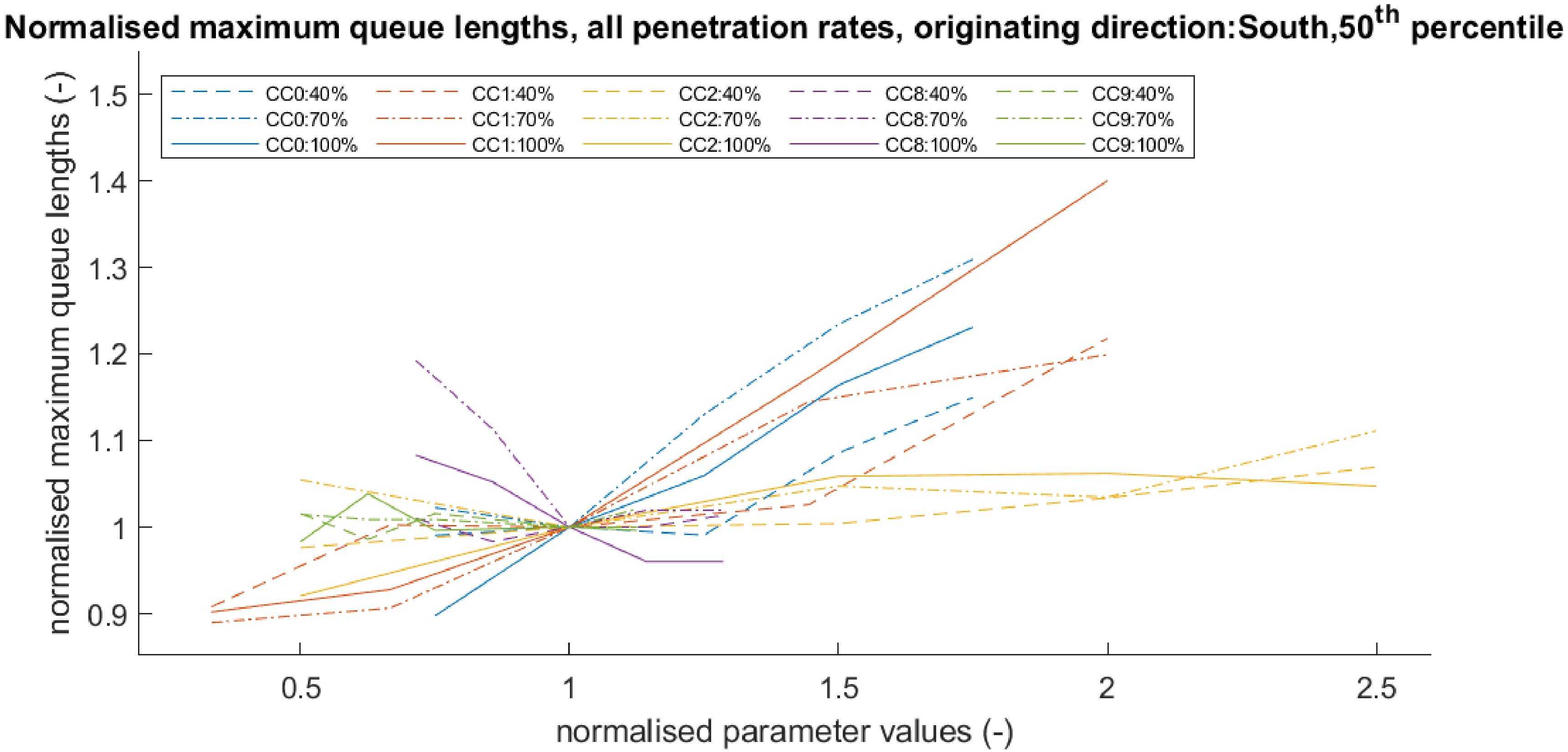



*Figure 48. Normalised median 90th percentile queue lengths of the south entry plotted against normalised parameters for the regular intersection, combination of penetration rates.*

## Appendix H.2: Queue Lengths at the Roundabout

### Appendix H.2.1: Queue Lengths at the Roundabout, North Entry

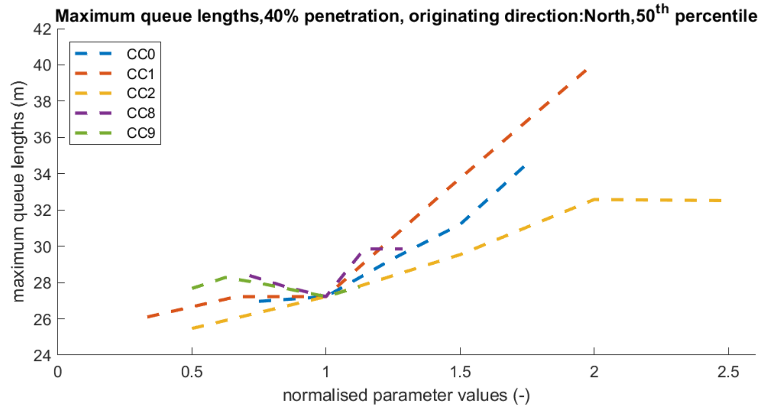



*Figure 49. 50th percentile values of the maximum queue lengths of the north entry plotted against normalised parameters for the roundabout at 40% penetration of SDCs.*

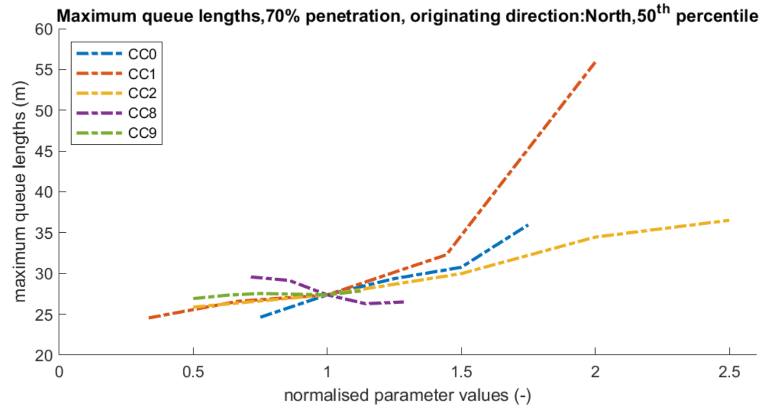



*Figure 50. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the roundabout at 70% penetration of SDCs.*

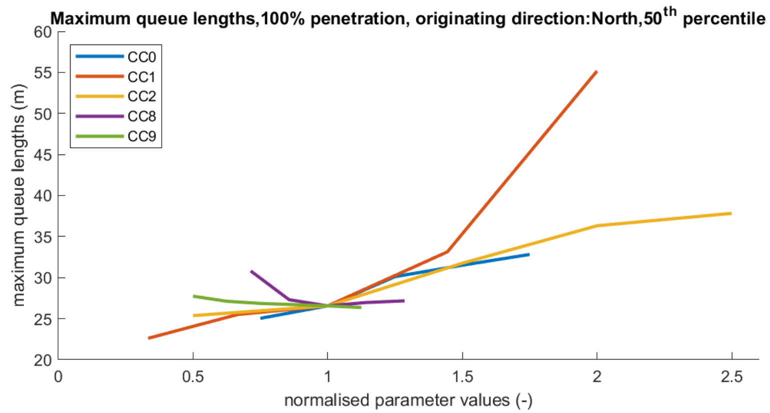



*Figure 51. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the roundabout at 100% penetration of SDCs.*

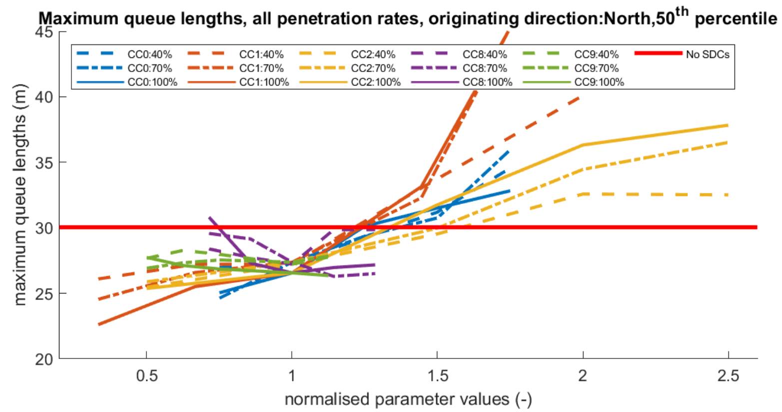



*Figure 52. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the roundabout, combination of penetration rates. The CC1 70% and CC1 100% lines continue outside this zoom to values of 55.9 m and 55.2 m respectively.*

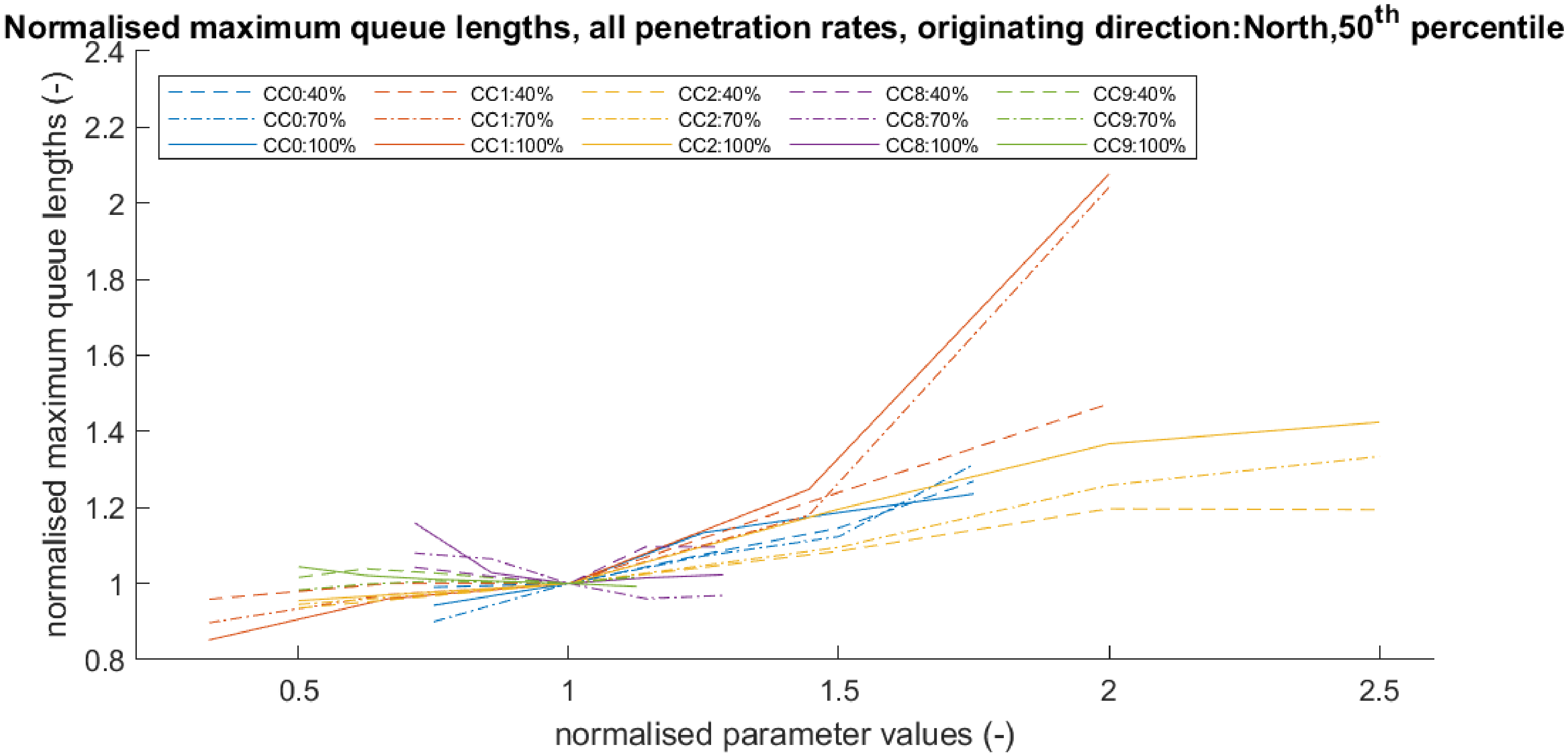



*Figure 53. Normalised median 90th percentile queue lengths of the north entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

## Appendix H.2.2: Queue lengths at the Roundabout, East Entry

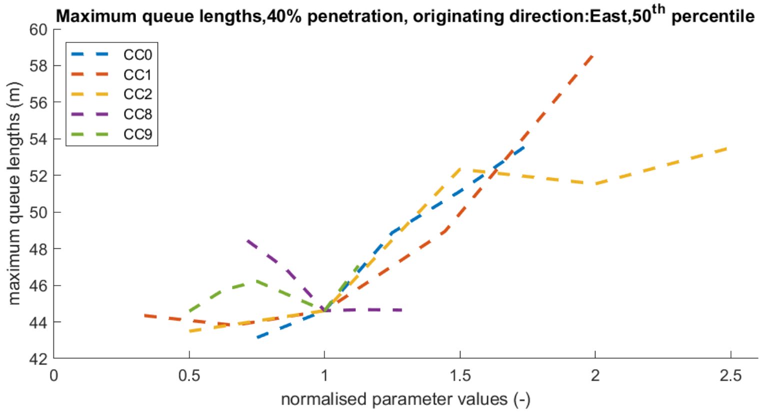



*Figure 54. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the roundabout at 40% penetration of SDCs.*

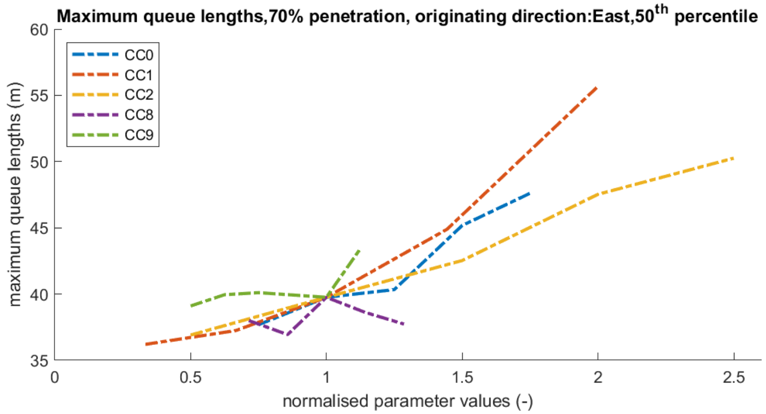



*Figure 55. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the roundabout at 70% penetration of SDCs.*

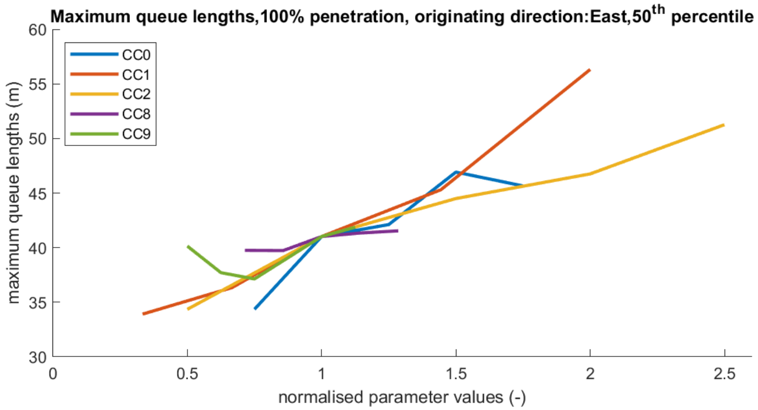



*Figure 56. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the roundabout at 100% penetration of SDCs.*

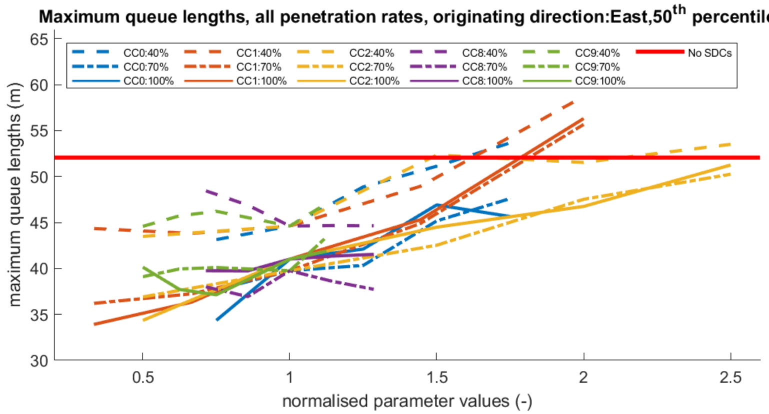



*Figure 57. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

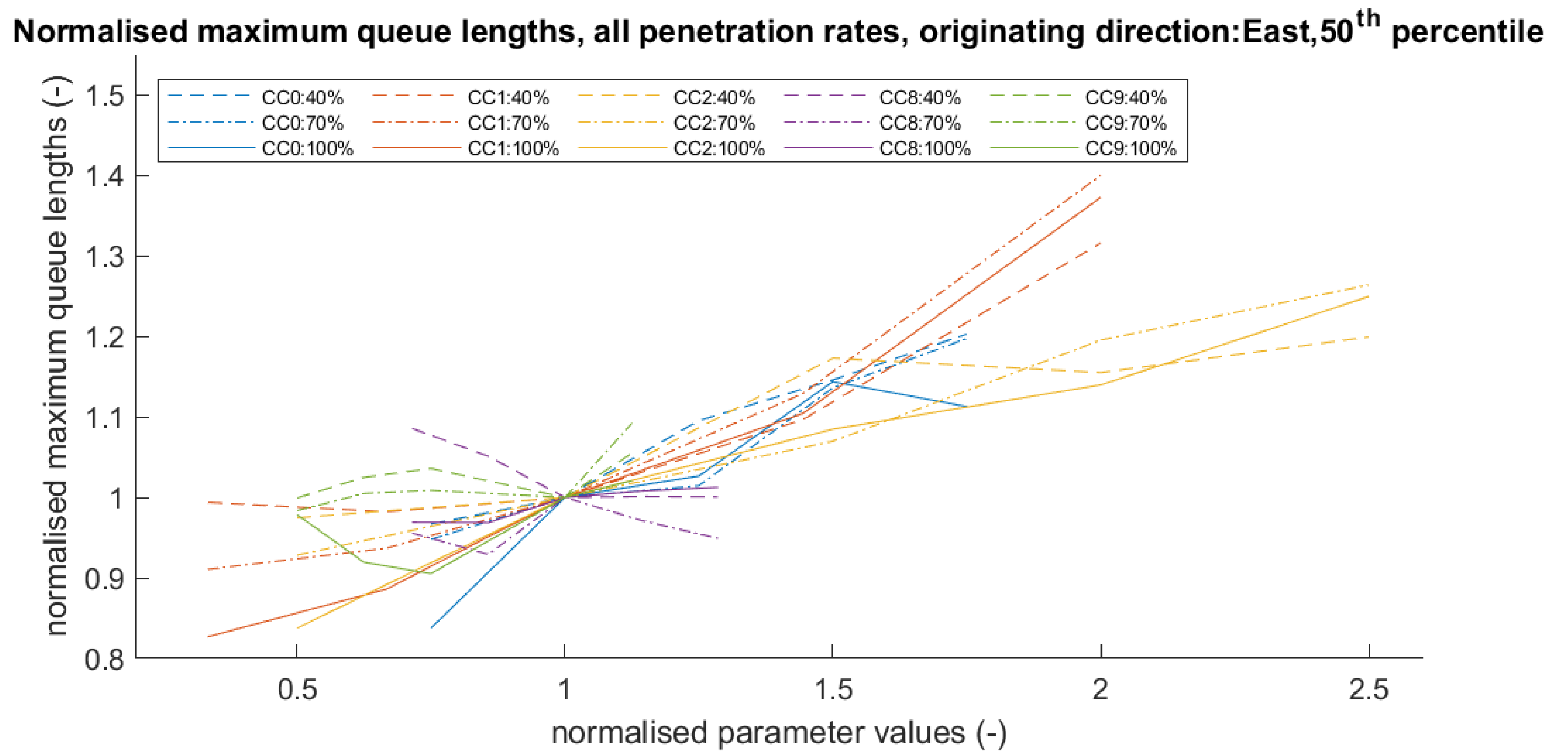



*Figure 58. Normalised median 90th percentile queue lengths of the east entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

## Appendix H.2.3: Queue Lengths at the Roundabout, South Entry

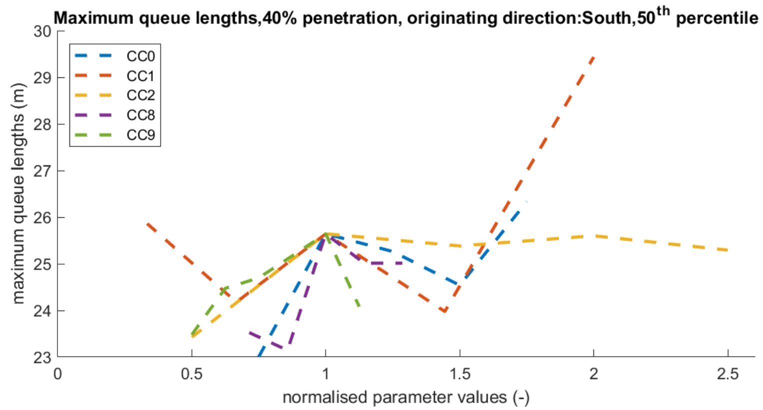



Figure 59. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the roundabout at 40% penetration of SDCs.

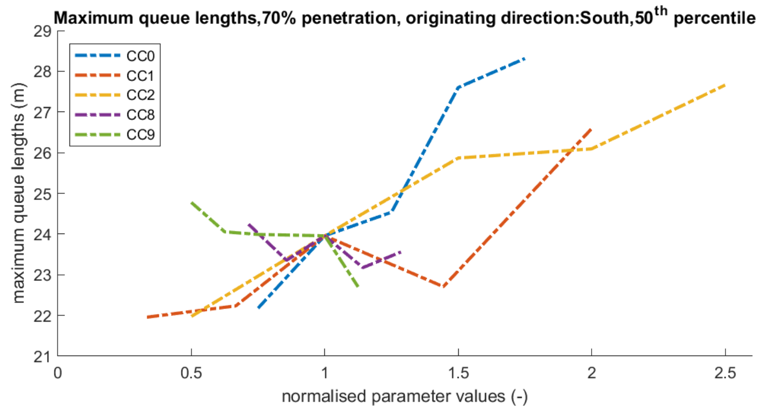



Figure 60. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the roundabout at 70% penetration of SDCs.

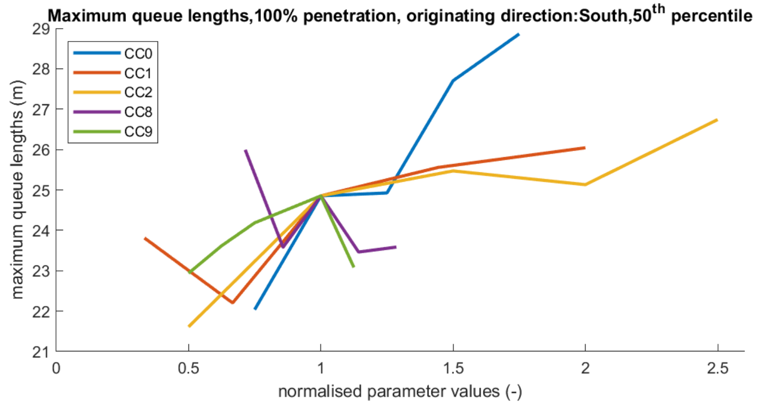



Figure 61. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the roundabout at 100% penetration of SDCs.

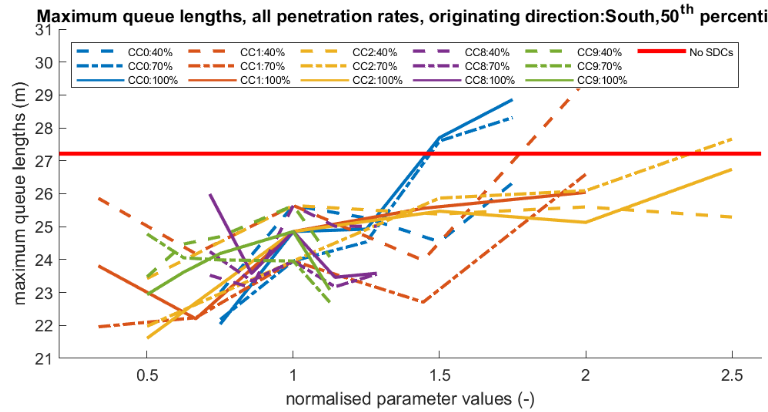



Figure 62. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the roundabout, combination of penetration rates.

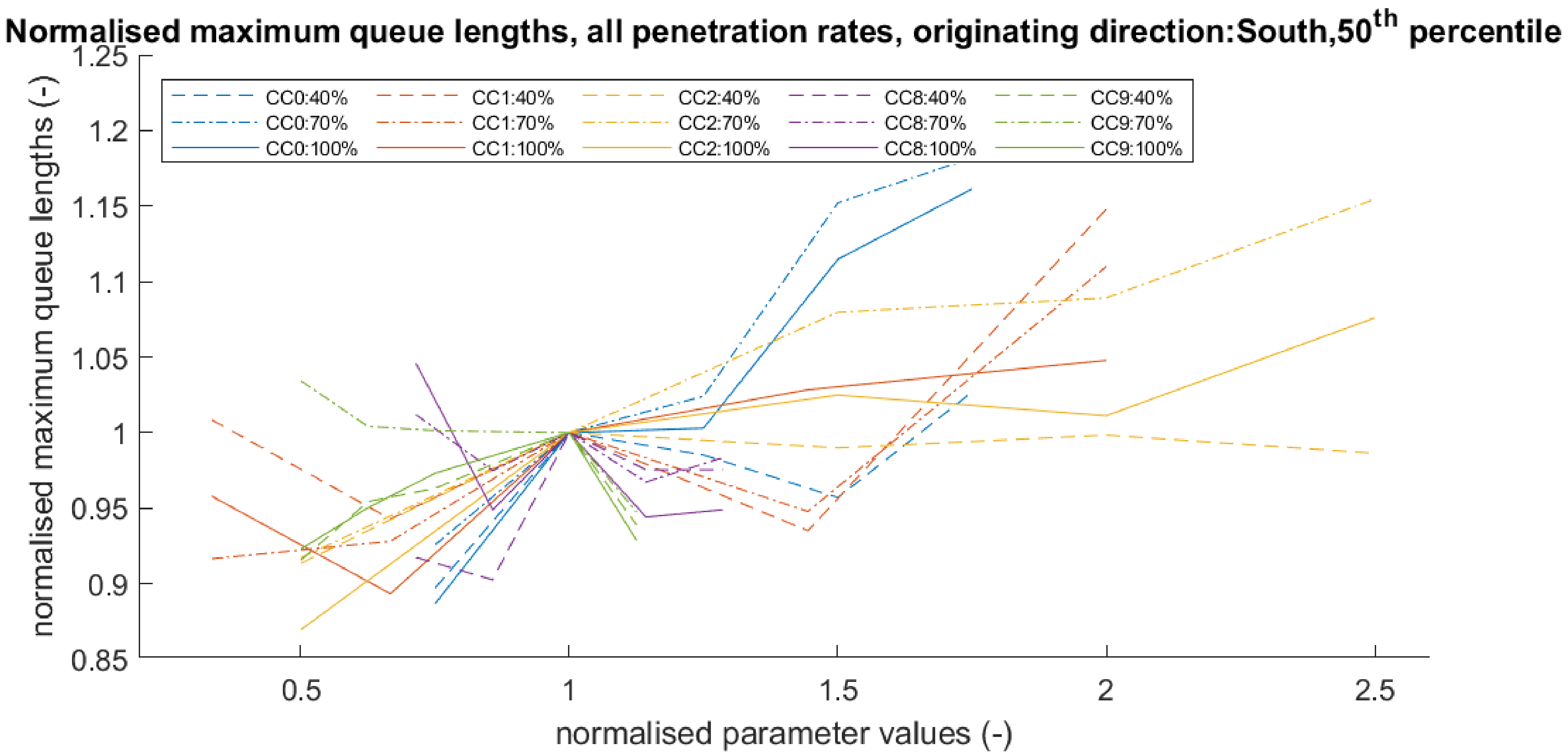



*Figure 63. Normalised median 90th percentile queue lengths of the south entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

## Appendix H.2.4: Queue Lengths at the Roundabout, West Entry

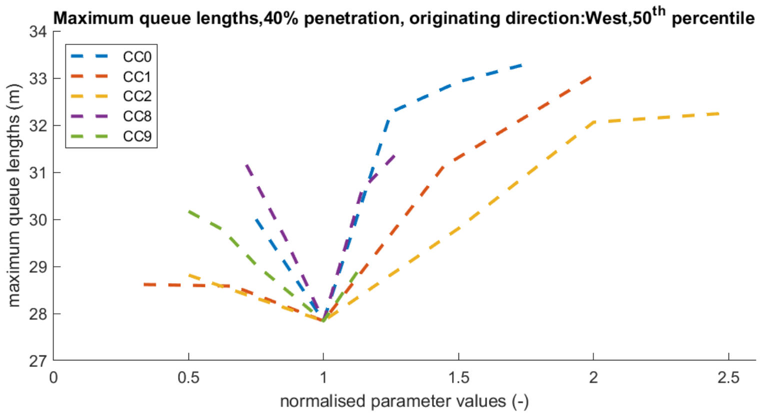



*Figure 64. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the roundabout at 40% penetration of SDCs.*

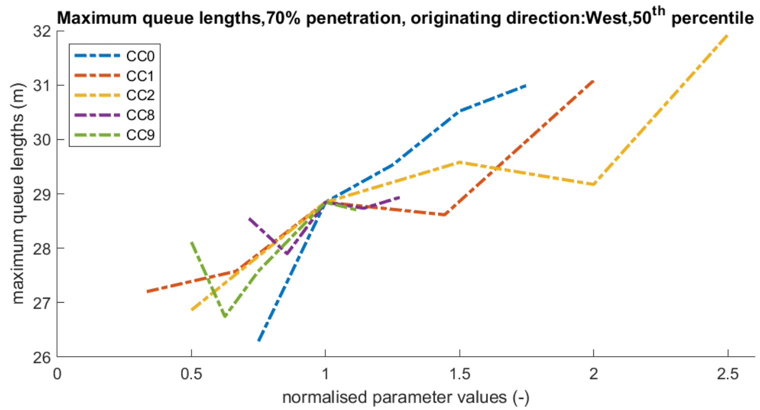



*Figure 65. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the roundabout at 70% penetration of SDCs.*

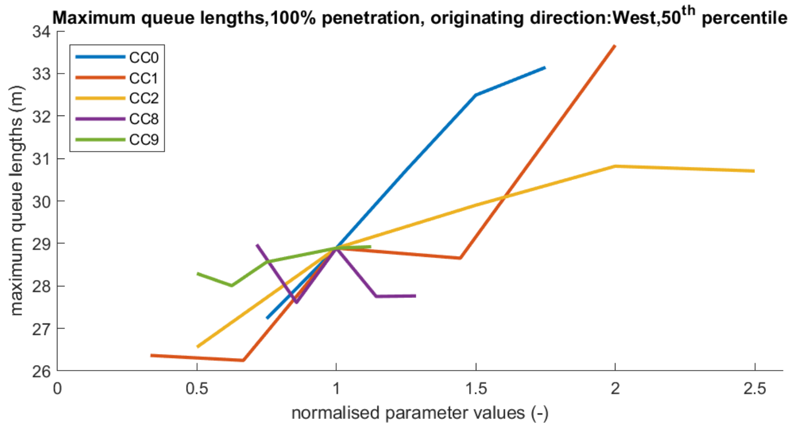



*Figure 66. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the roundabout at 100% penetration of SDCs.*

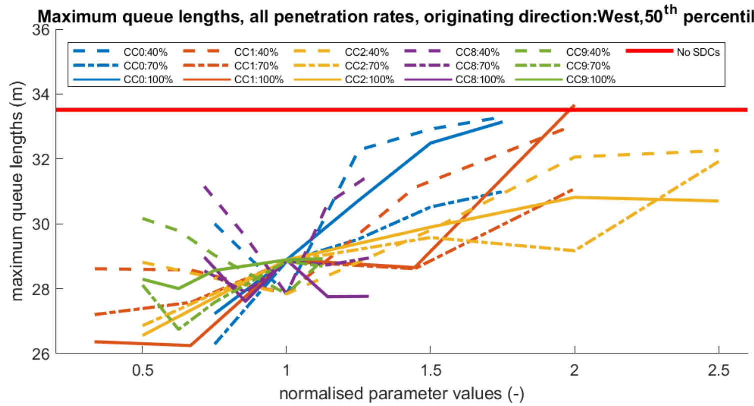



*Figure 67. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

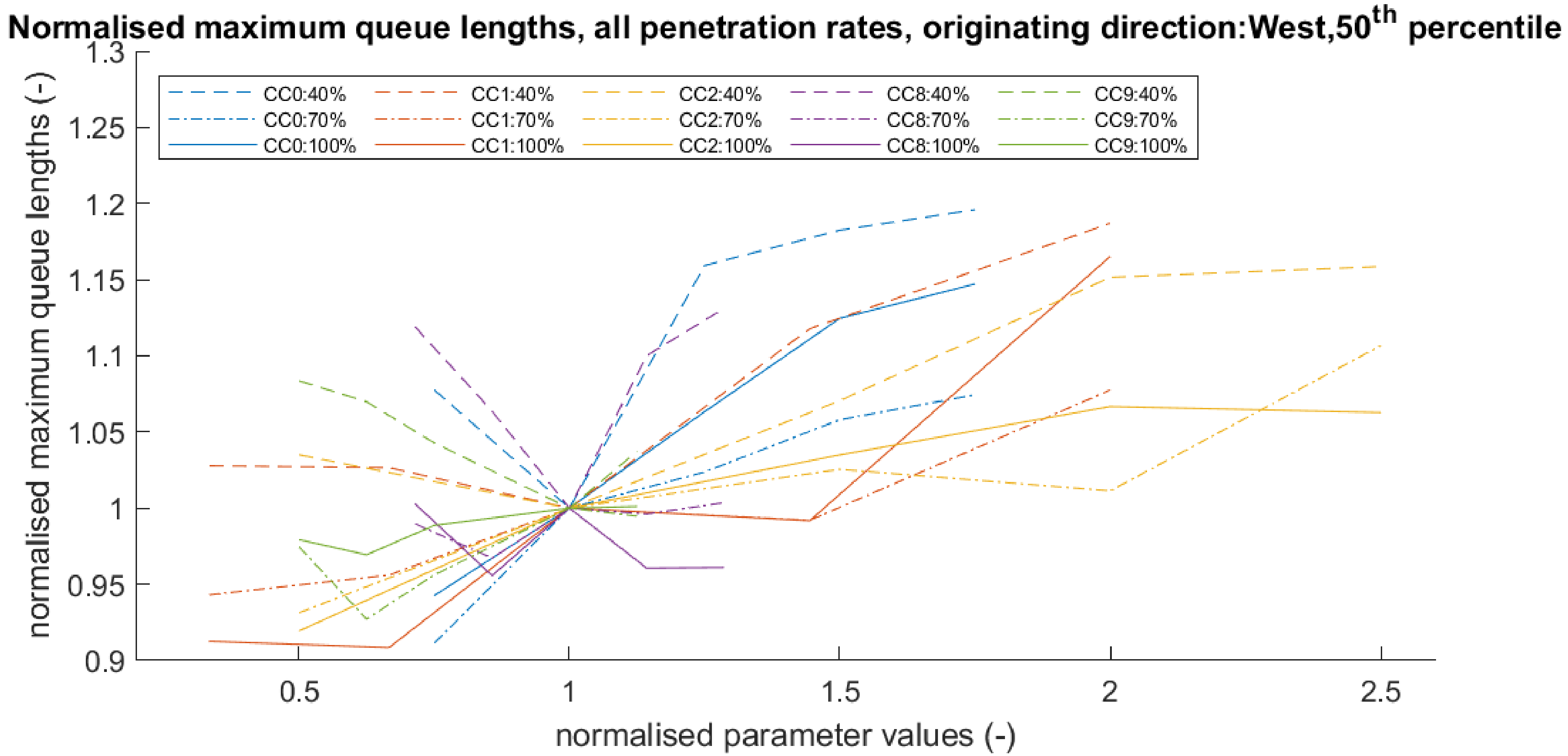



*Figure 68. Normalised median 90th percentile queue lengths of the west entry plotted against normalised parameters for the roundabout, combination of penetration rates.*

## Appendix H.3: Queue Lengths at the Signalised Intersection

### Appendix H.3.1: Queue Lengths at the Signalised Intersection, North Entry

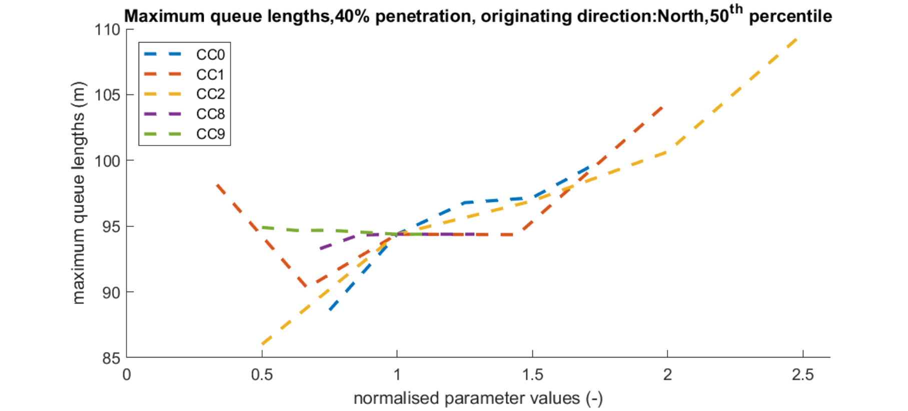



*Figure 69. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the signalised intersection at 40% penetration of SDCs.*

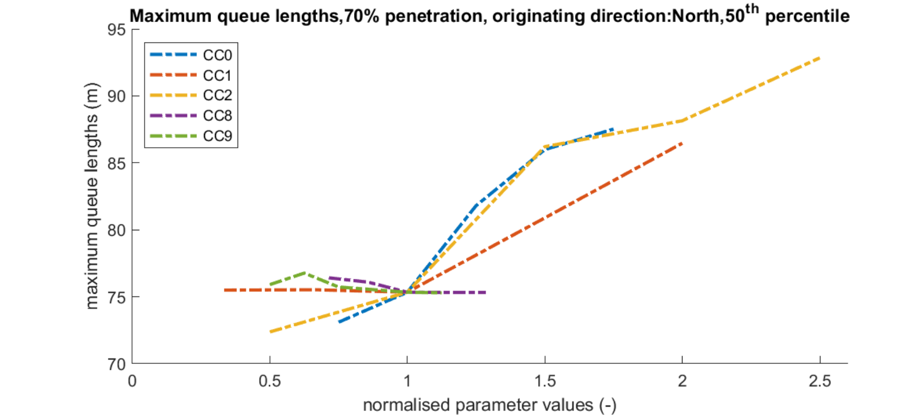



*Figure 70. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the signalised intersection at 70% penetration of SDCs.*

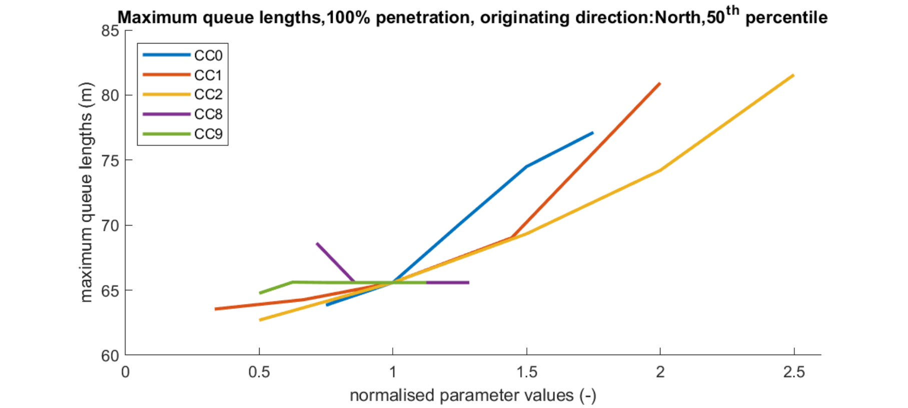



*Figure 71. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the signalised intersection at 100% penetration of SDCs.*

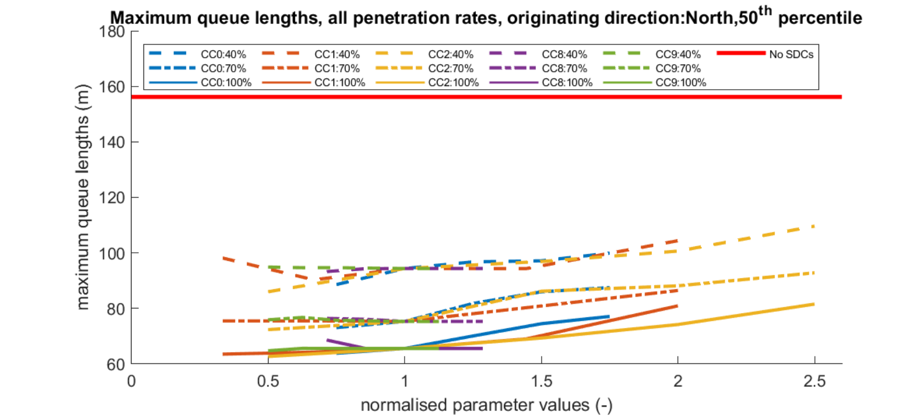



*Figure 72. Median 90th percentile queue lengths of the north entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

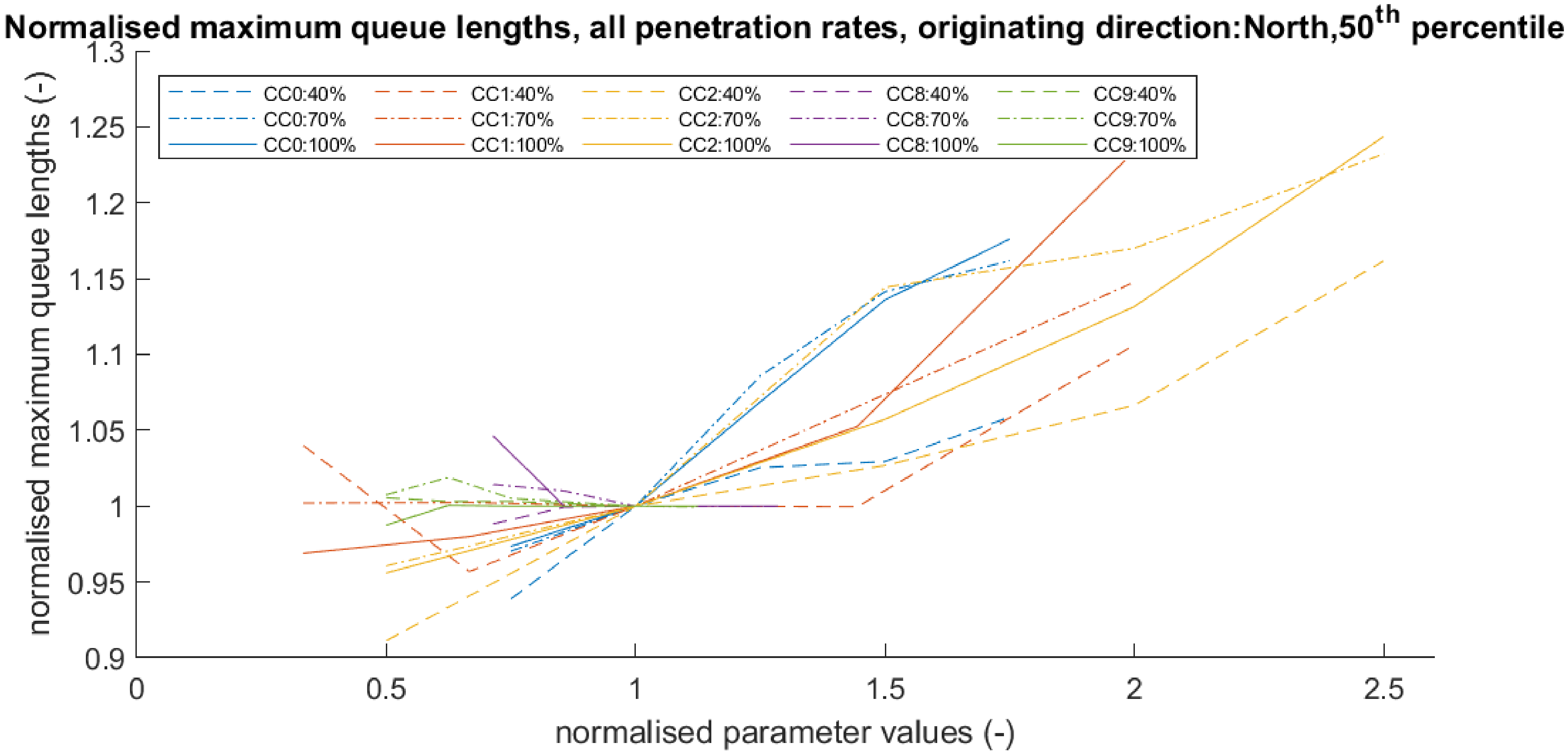



*Figure 73. Normalised 50th percentile values of the maximum queue lengths of the north entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

## Appendix H.3.2: Queue lengths at the Signalised Intersection, East Entry

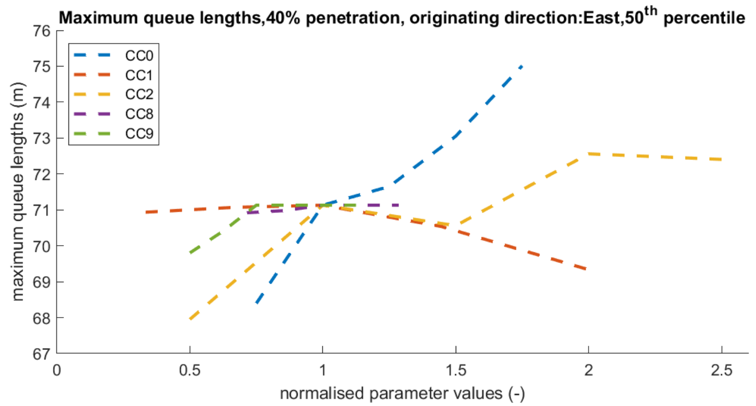



*Figure 74. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the signalised intersection at 40% penetration of SDCs.*

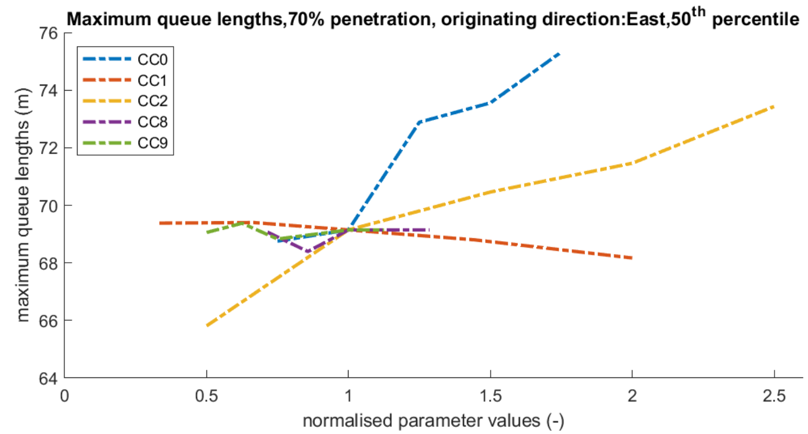



*Figure 75. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the signalised intersection at 70% penetration of SDCs.*

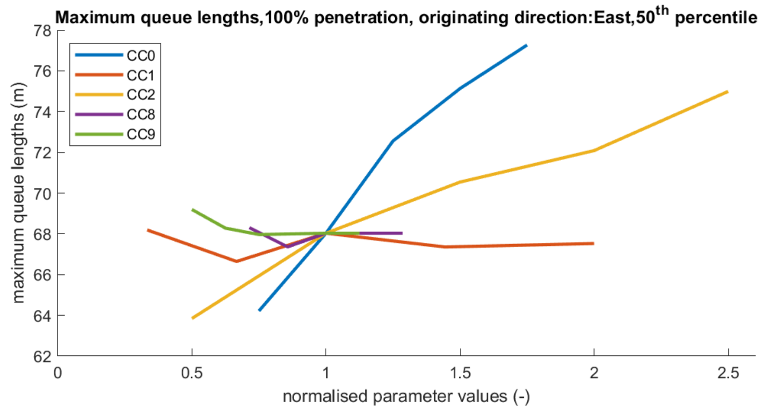



*Figure 76. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the signalised intersection at 100% penetration of SDCs.*

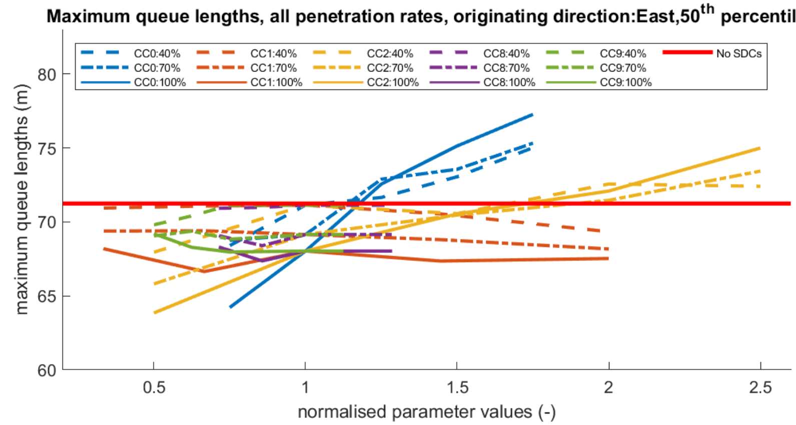



*Figure 77. Median 90th percentile queue lengths of the east entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

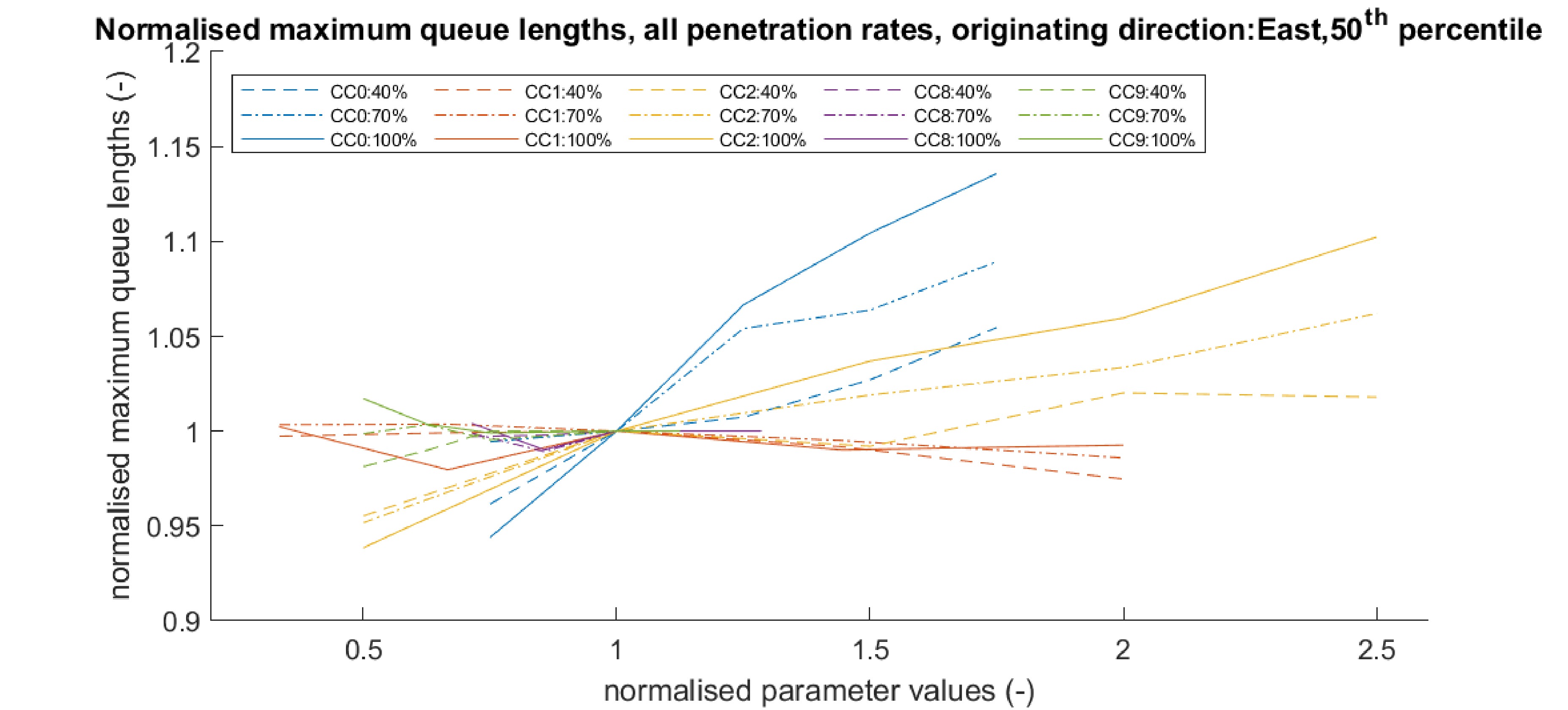



*Figure 78. Normalised median 90th percentile queue lengths of the east entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

## APPENDIX H.3.3: QUEUE LENGTHS AT THE SIGNALISED INTERSECTION, SOUTH ENTRY

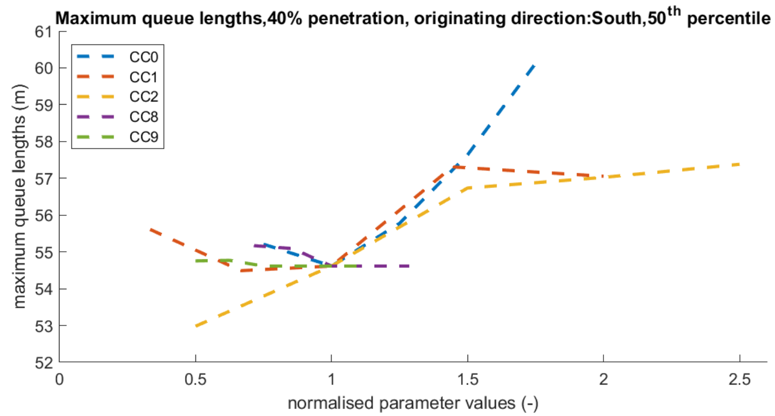



*Figure 79. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection at 40% penetration of SDCs.*

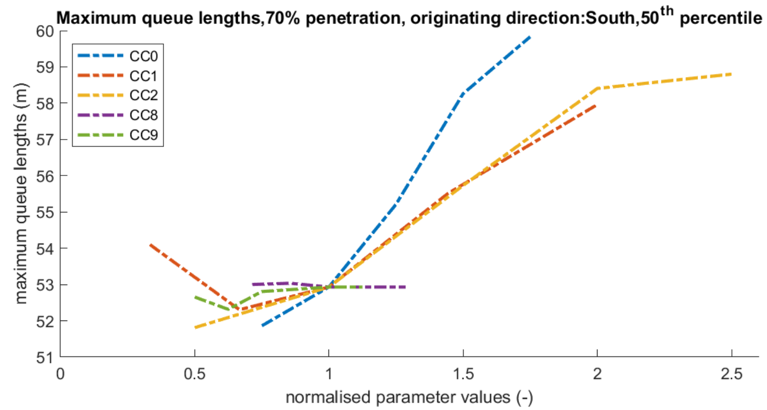



*Figure 80. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection at 70% penetration of SDCs.*

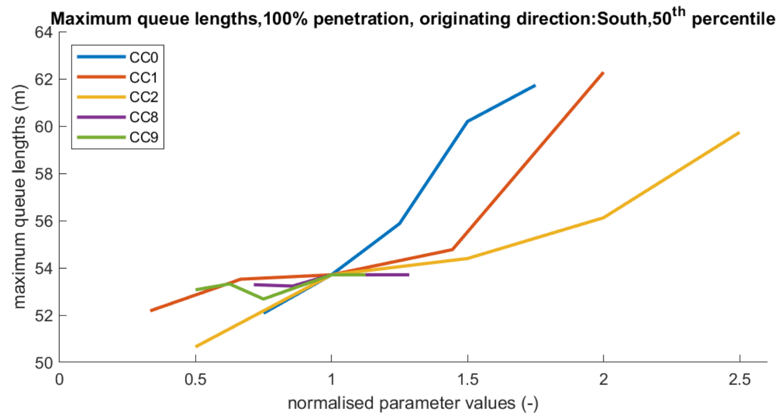



*Figure 81. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection at 100% penetration of SDCs.*

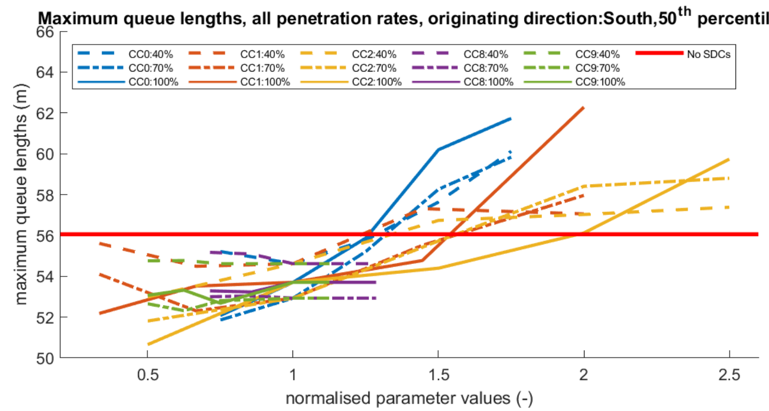



*Figure 82. Median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

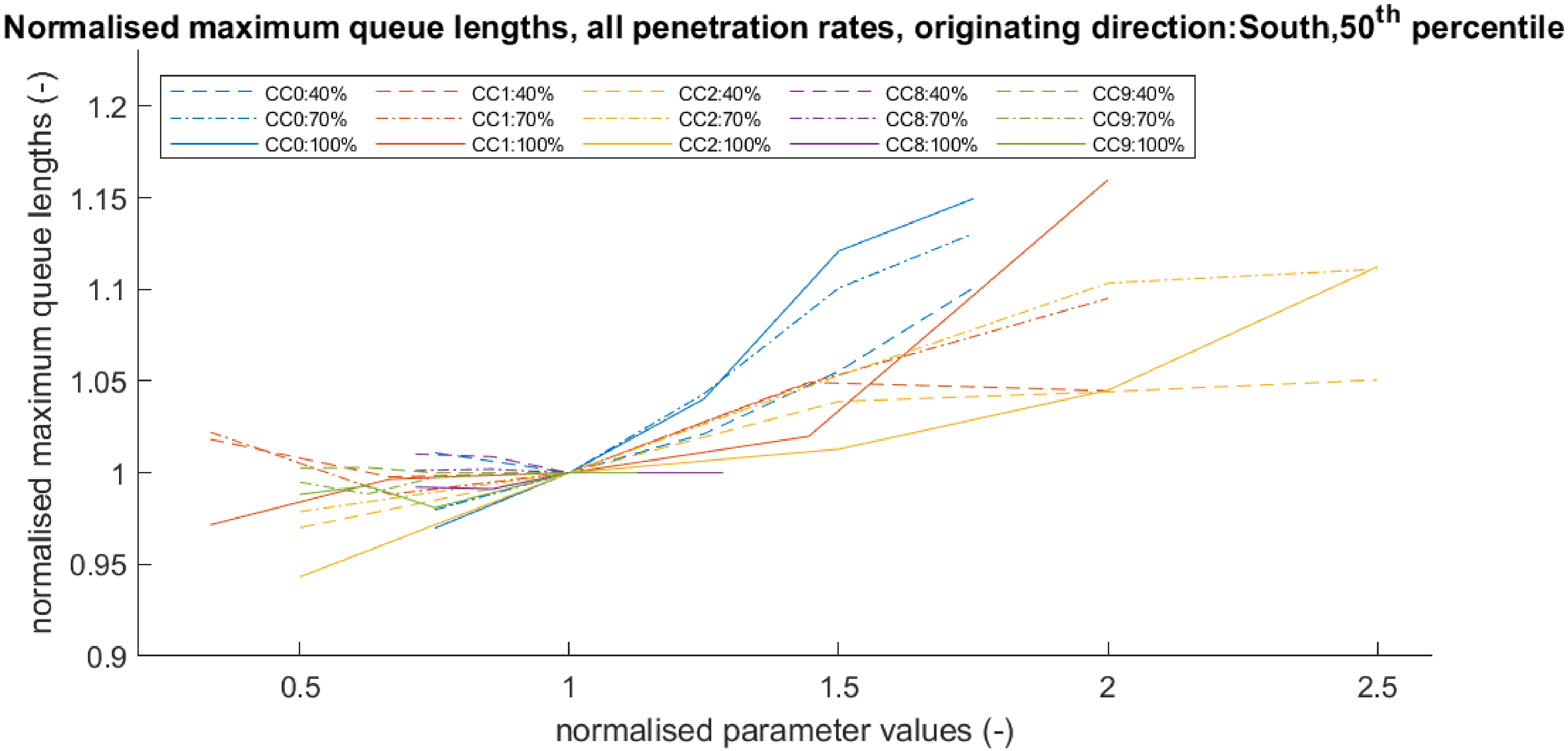



*Figure 83. Normalised median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

## Appendix H.3.4: Queue Lengths at the Signalised Intersection, West Entry

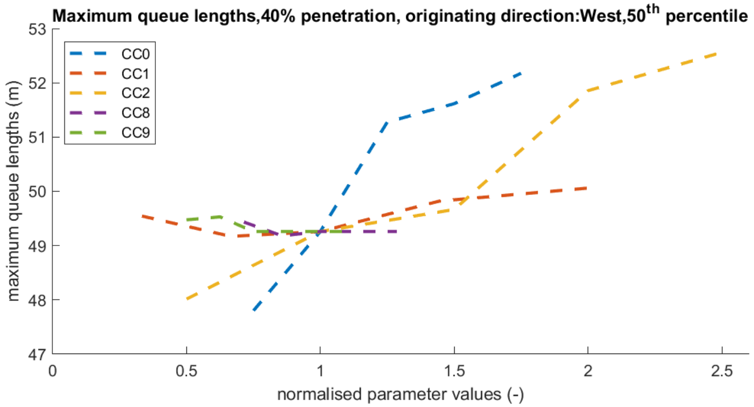



*Figure 84. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the signalised intersection at 40% penetration of SDCs.*

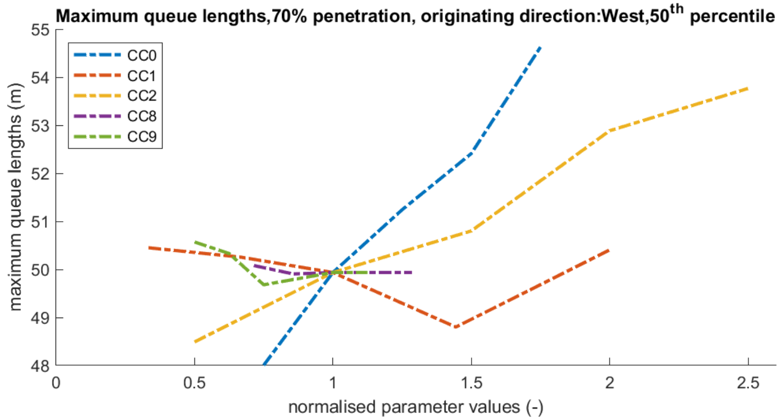



*Figure 85. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the signalised intersection at 70% penetration of SDCs.*

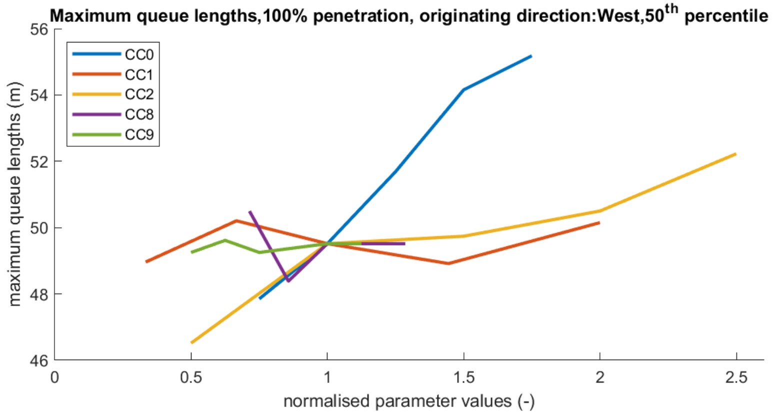



*Figure 86. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the signalised intersection at 100% penetration of SDCs.*

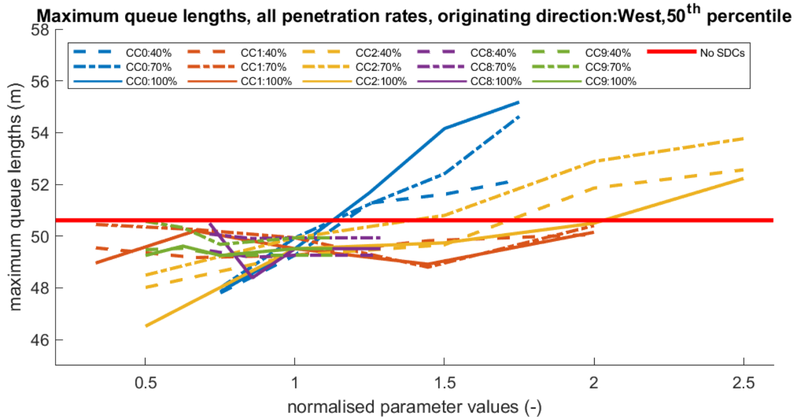



*Figure 87. Median 90th percentile queue lengths of the west entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

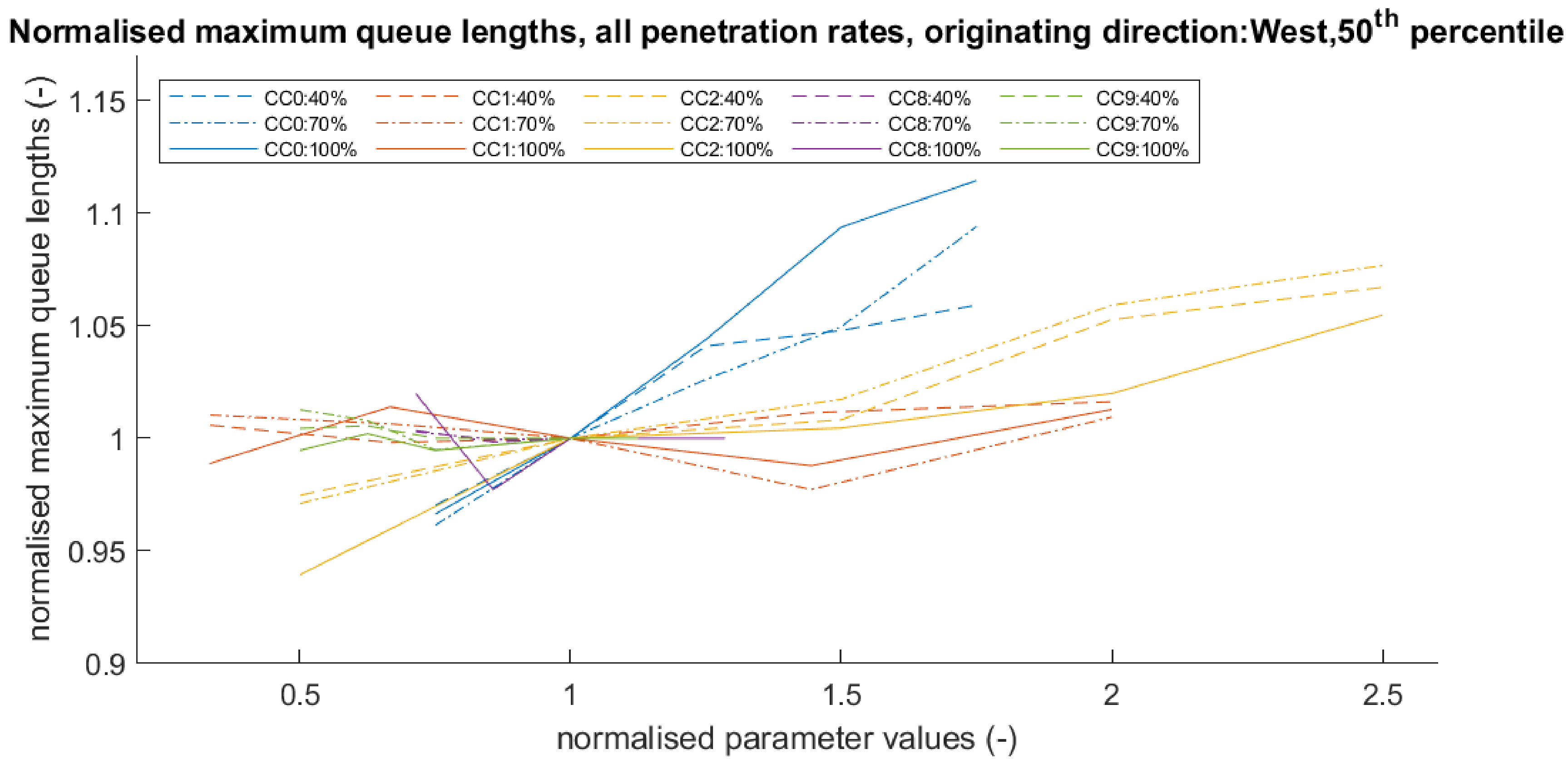



*Figure 88. Normalised median 90th percentile queue lengths of the south entry plotted against normalised parameters for the signalised intersection, combination of penetration rates.*

# Appendix I: Analysis of the Progressive Decrease in Loss Times

Figure 4, Figure 8, Figure 12, Table 13, Table 15 and Table 18 show a progressive decrease in loss times when the penetration rate is increased, also when parameter values are selected that are similar to regular vehicles. This decrease must therefore be caused by the non-ranged parameters described in Table 9. Of these parameters, the CC3, describing the following threshold, the CC6, describing the speed dependency of oscillation, and the Desired speed distributions seem most interesting, since they are altered in a more aggressive way compared to regular vehicles. These

## Appendix I.1: Set-Up of the Analysis

For this analysis, a penetration rate of 70% chosen at the regular, since the results of the different penetration rates are the clearest there. The parameters are ranged according to the values visible in Table 44. The other parameters have the value as described by Table 9 and the default SDC values of Table 11.

*Table 44. The ranged values for the CC3 and CC6 parameters. Highlighed in orange are the default values for the SDC.*

<table>
<tr><th>Parameter</th><th>Unit</th><th>Value 1</th><th>Value 2</th><th>Value 3</th><th>Value 4</th><th>Value 5</th><th colspan="2">Regular cars</th></tr>
<tr><td>CC3</td><td>-</td><td>-15</td><td>-12</td><td>-8</td><td>-4</td><td>0</td><td colspan="2">-8</td></tr>
<tr><td>CC6</td><td>-</td><td>0</td><td>4</td><td>8</td><td>11.44</td><td>16</td><td colspan="2">11.44</td></tr>
<tr><td rowspan="6">Desired speed distribution</td><td rowspan="6">Linear range in % around 50 km/h</td><td rowspan="6">+/-0</td><td rowspan="6">+/-2</td><td rowspan="6">+/-5</td><td rowspan="6">+/-8</td><td rowspan="6">+/-10</td><td colspan="2">Non-linear</td></tr>
<tr><td>V (m/s)</td><td>Fx (%)</td></tr>
<tr><td>45</td><td>0</td></tr>
<tr><td>50</td><td>25</td></tr>
<tr><td>55</td><td>80</td></tr>
<tr><td>60</td><td>100</td></tr>
</table>

## Appendix I.2: Results of the Analysis

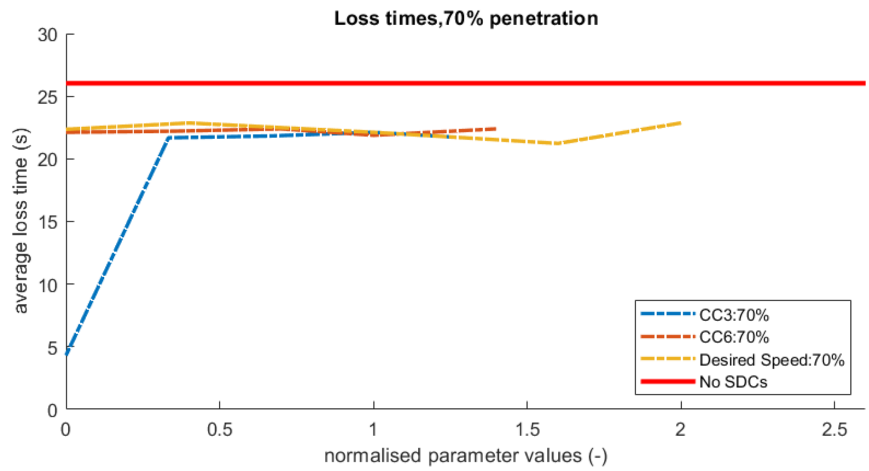



*Figure 89. Absolute loss times plotted against normalised parameters for the CC3 and CC5 parameters and the desired speed distribution at the regular intersection.*

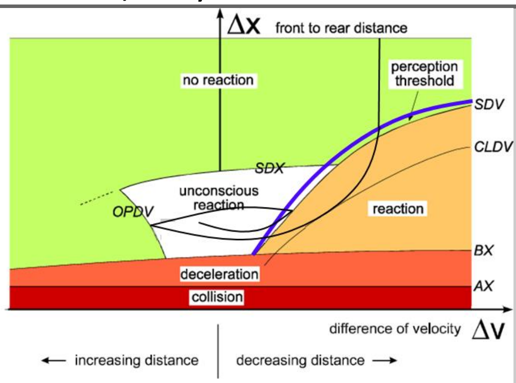
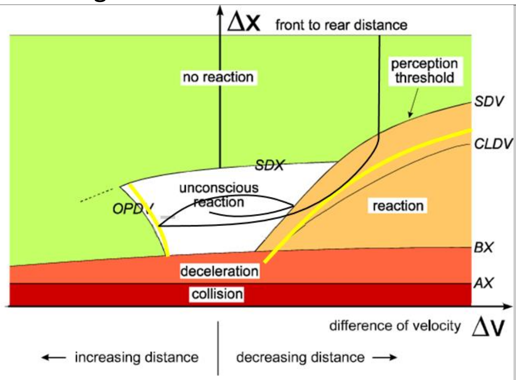
In Figure 89, the lines show the effect when only the labelled parameter is ranged and the other parameters are set on their default value. The CC6 parameter is normalised by the 11.44 value. Looking at Figure 89, the CC3 and CC6 parameters and the desired speed distributions do not seem to be the cause of the general decrease in loss times visible in the other analysed scenarios in section 4.1. It is possible to make this conclusion since all the dotted lines in Figure 89 do not cross the 'No SDC' line. Only when this would be the case, one of the parameter would have caused the steady drop throughout the different penetration rates, since it would also point out that the parameter would be capable of letting the loss times stay around the original scenario where no SDCs are present.

# APPENDIX J: CHANGED WIEDEMANN 1999 MODELS FOR VARIOUS COMBINATIONS

The used parameter combinations in Table 21 in section 4.2 will lead to changes in the Wiedemann 1999 model visualisation when compared to regular vehicles. This appendix presents how these changes will work out. Note the fact that the CC7, CC8 and CC9 parameters are not discussed in this appendix, since they do not influence the visualisation of the model, but rather the individual behaviour of a vehicle within the model.

The original Wiedemann 1999 model is presented in Appendix C: The Wiedemann 1999 Model. First of all, it is important to see how the on-ranged parameters of Table 9 change the starting point of the Wiedemann model visualisation. The parameters which have influence on the visualisation and the resulting changes are visible in Table 45. The resulting changes can be deducted from Appendix C: The Wiedemann 1999 Model.

*Table 45. Effects on the Wiedemann 1999 Model visualisation by the parameter values of Table 9, based on (Fellendorf & Vortisch, 2001)*

| Parameter | SDC value | Regular car value | In-/decrease | Effect on visualisation based on (Fellendorf & Vortisch, 2001) |
|---|---|---|---|---|
| **CC3** | -12 | -8 | Increase (further away from 0) |  |
| **CC4/5** | (-) 0.35 | (-) 0.35 | No change | No change |
| **CC6** | 0 | 11.44 | Decrease |  |

These changes result in the visualisation visible in Figure 90.

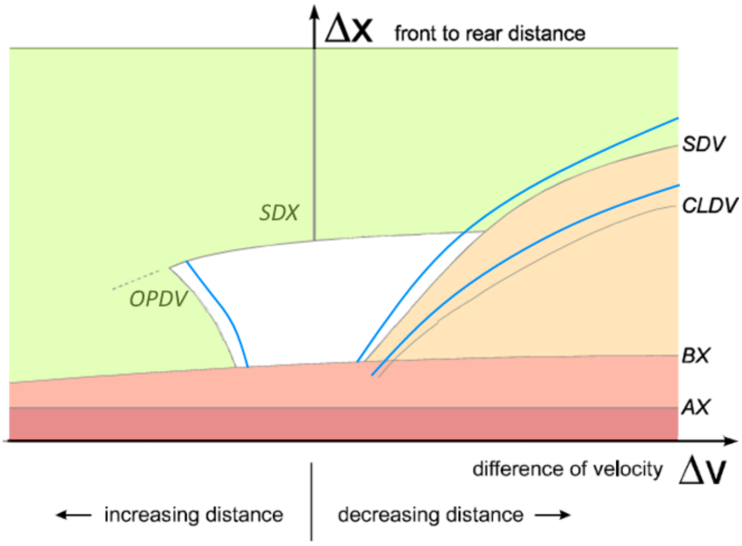


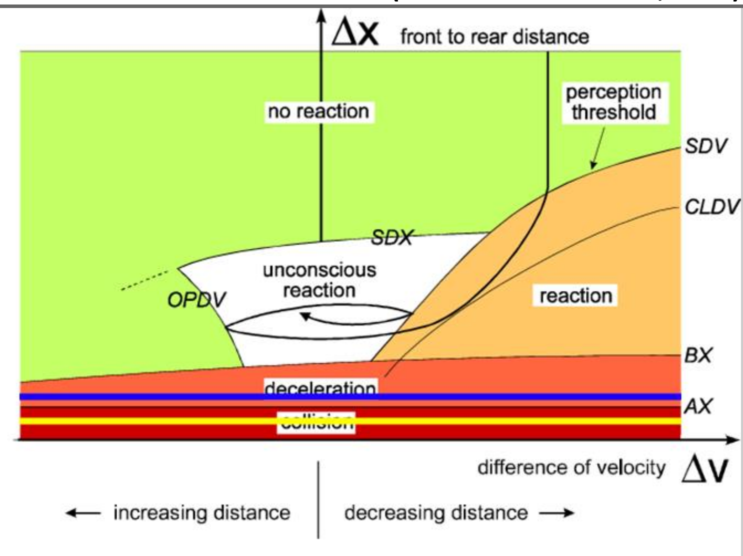

*Figure 90. Visualisation of the changes made by Table 9 to the Wiedemann 1999 model.*

With this starting point it is possible to what the individual effects of the combinations in Table 21 are. This is done by identifying the changes to the parameters compared to regular vehicles in Table 46, subsequently determining the effect which an individual parameter change will have in Table 47 and will be concluded by composing the final behavioural models.

*Table 46. The values for the CC0, CC1 and CC2 parameters and the indication whether the change (ch.) between the selected value (val.) is larger than (>), equal to (=), smaller than (<) or a lot smaller than (<<) the value for regular vehicles.*

| Parameter | Regular vehicle | Comb. 1 | | Comb. 2 | | Comb. 3 | | Comb 4. | | Comb 5. | | Comb 6. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Val. | Ch. | Val. | Ch. | Val. | Ch. | Val. | Ch. | Val. | Ch. | Val. | Ch. |
| **CC0** | 1.0 | 1.5 | > | 1.25 | > | 1.0 | = | 1.25 | > | 0.75 | < | 0.75 | < |
| **CC1** | 0.9 | 1.8 | > | 1.3 | > | 0.9 | = | 1.3 | > | 0.6 | < | 0.3 | << |
| **CC2** | 4.0 | 5.0 | > | 2.0 | < | 3.0 | < | 3.0 | < | 2.0 | < | 1.0 | << |

*Table 47. Effects on the changes of the CC0, CC1 and CC2 parameters when increased and decreased.*

| Parameter | Legend | Effect on visualisation based on (Fellendorf & Vortisch, 2001) |
|---|---|---|
| **CC0** | Increased (purple)<br>Decreased (yellow) |  |

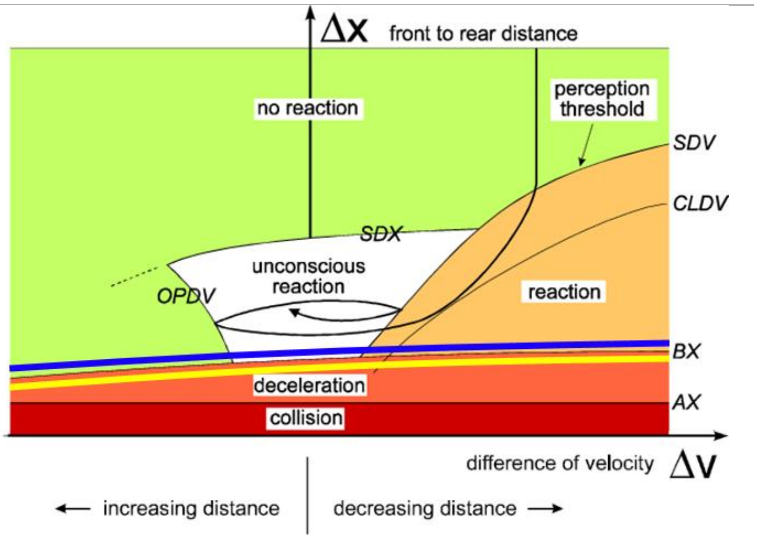
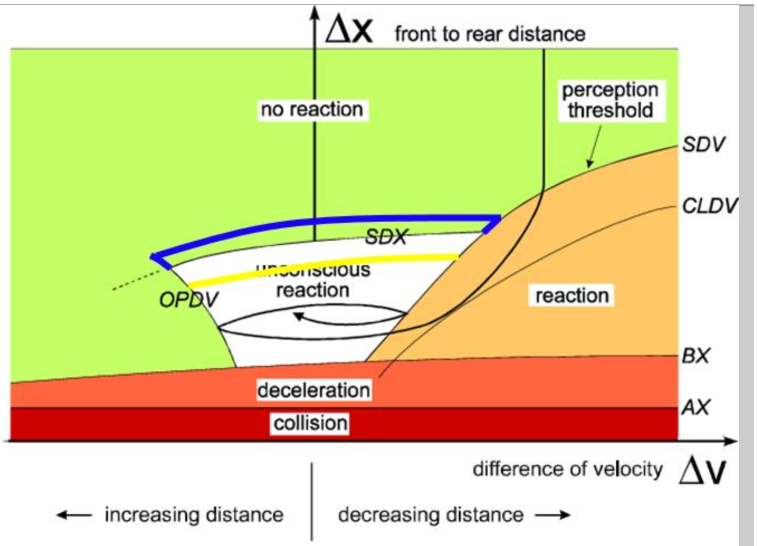
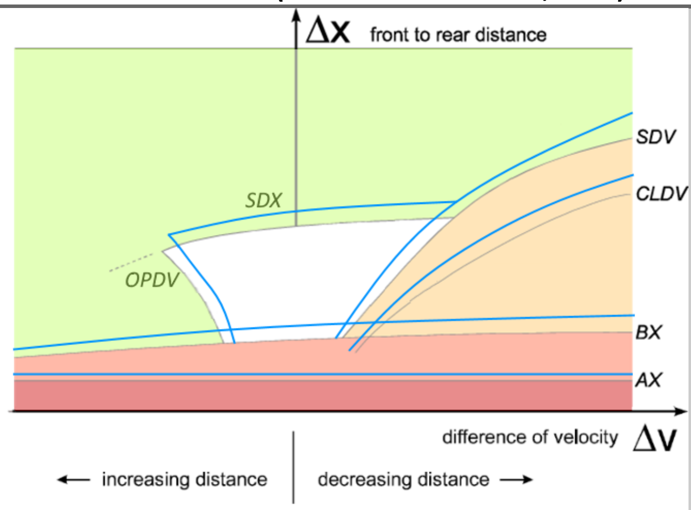
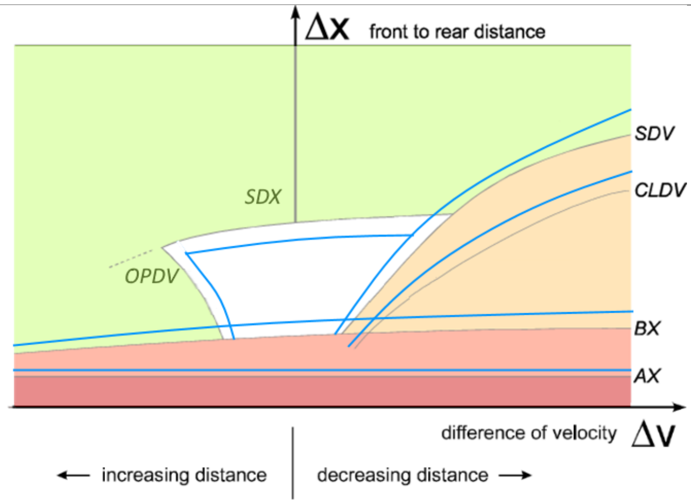
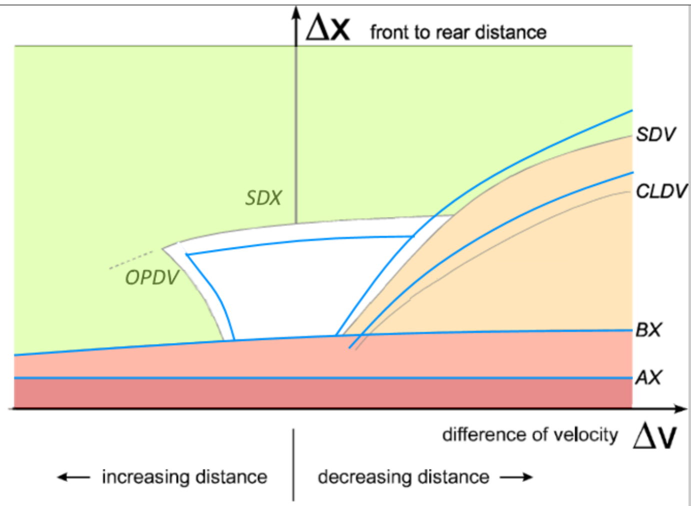
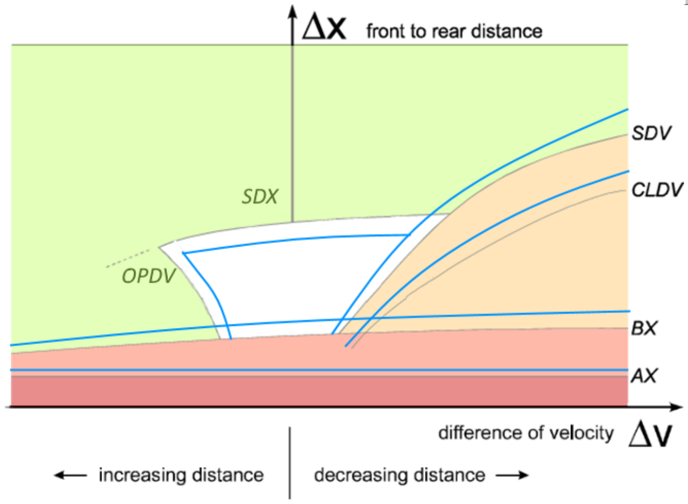
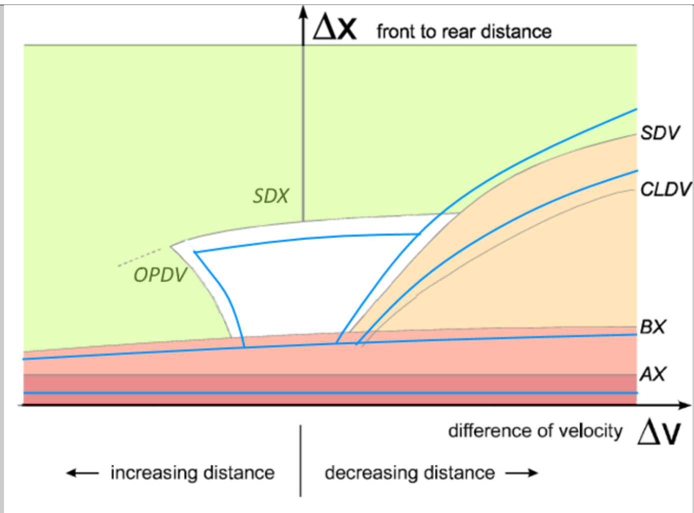
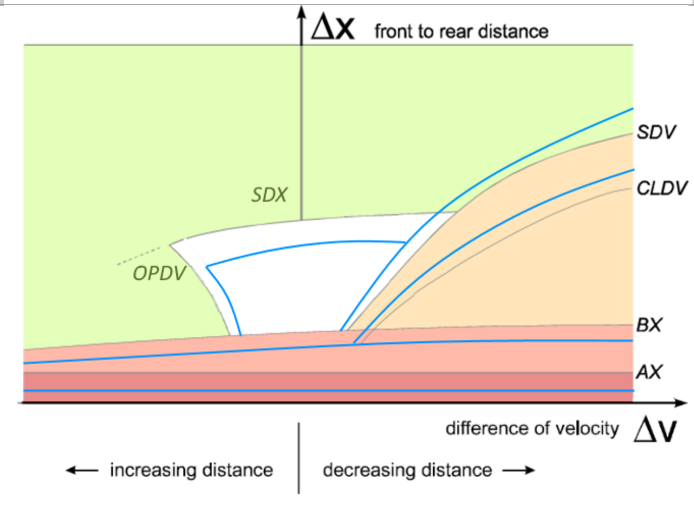
| | | |
|---|---|---|
| **CC1** | Increased (purple)<br>Decreased (yellow) |  |
| **CC2** | Increased (purple)<br>Decreased (yellow) |  |

*Table 48. Changes caused by the various combinations of parameters as stated by Table 21. The blue lines indicate the new visualisation of the model.*

| **Combination** | **Visualisation based on (Fellendorf & Vortisch, 2001)** | |
|---|---|---|
| **1.** |  | The entire structure of the model is shifted upwards, meaning that vehicles will respond earlier distance-wise to start its following behaviour. Besides, it will try to maintain a larger headway at all times, causing the peloton to be longer overall. |

| | | |
|---|---|---|
| **2.** |  | The change between combinations 2 and 1 is that the SDX line, is places closer to the Δv axis. This causes the SDC to respond in an earlier stage, i.e. with a smaller front to rear distance, to stay in the following regime. Nevertheless, a larger headway is kept at all times compared to regular vehicles. |
| **3.** |  | The change between combinations 3 and 2 is that the AX and BX lines are set to the default values. The SDC therefore allows a shorter minimum front to rear distance when compared to combination 2. |
| **4.** |  | Combination 4 is very similar to combination 2, however the SDX function is lowered even more. The SDC responds in an even earlier stage to stay in the following regime. |

| | | |
|---|---|---|
| **5.** |  | Combination 5 incorporated a lowered AX and BX values which cause the SDC to hold smaller headways than when compared to regular vehicles. Besides, SDX is lowered, which causes the SDC to respond earlier to stay in the following regime, similar to combinations 2 and 4. |
| **6.** |  | Combination 6 is similar to combination 5, but with an even lowered value for BX and SDX. This results in the SDC responding even later when closing in on a leading vehicle Moreover, it also responds quicker to stay in the following regime. |

# Appendix K: Loss Times of the Combined Parameters

In this appendix, the resulting graphs of the absolute loss times of the combined parameters, are visible. The graphs are ordered per intersection. Note that the y-axis values differ per graph.

## Appendix K.1: Loss Times at the Regular Intersection

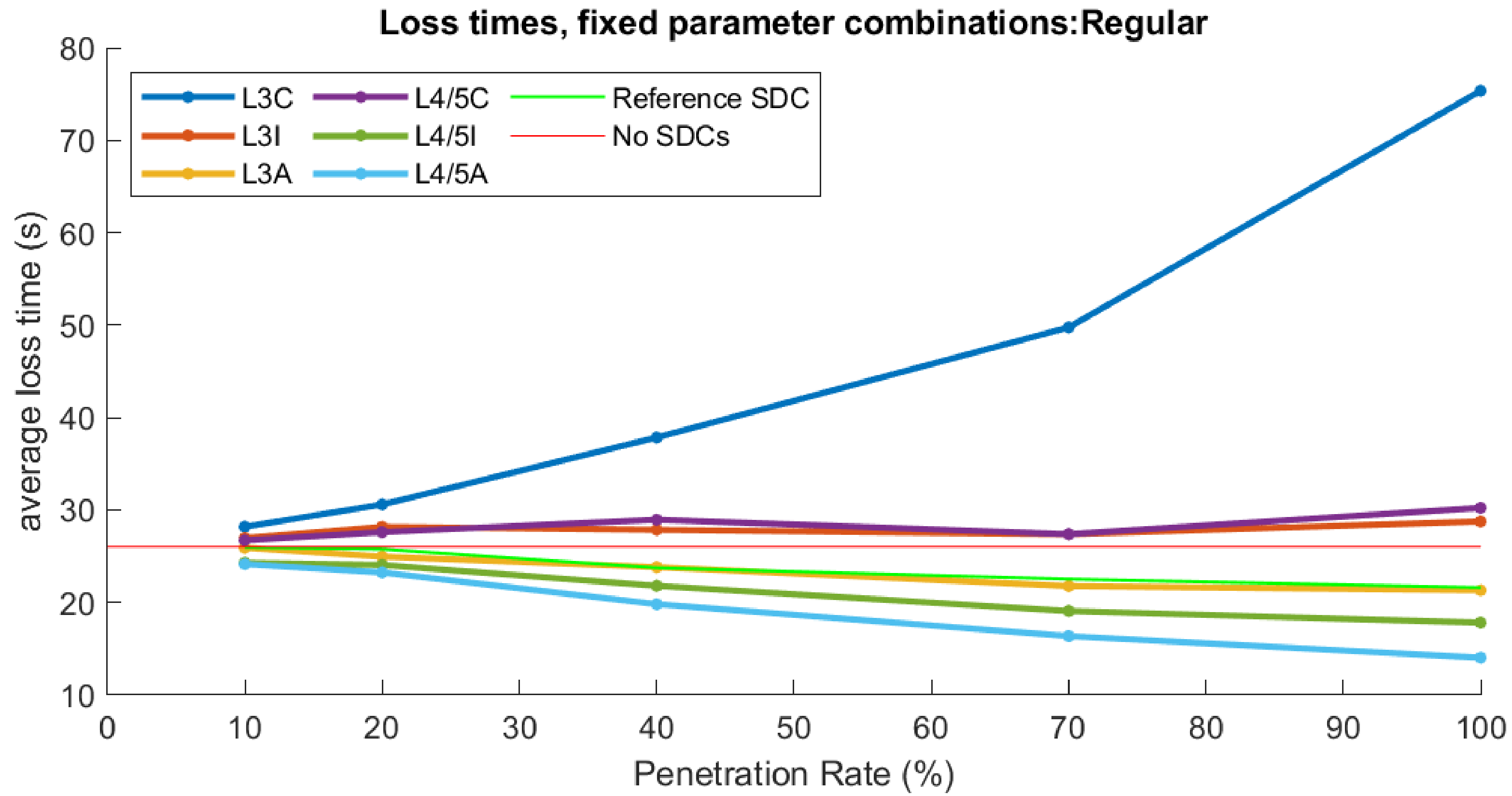



*Figure 91. Loss times of the various combinations of the parameters at the regular intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

## APPENDIX K.2: LOSS TIMES AT THE ROUNDABOUT

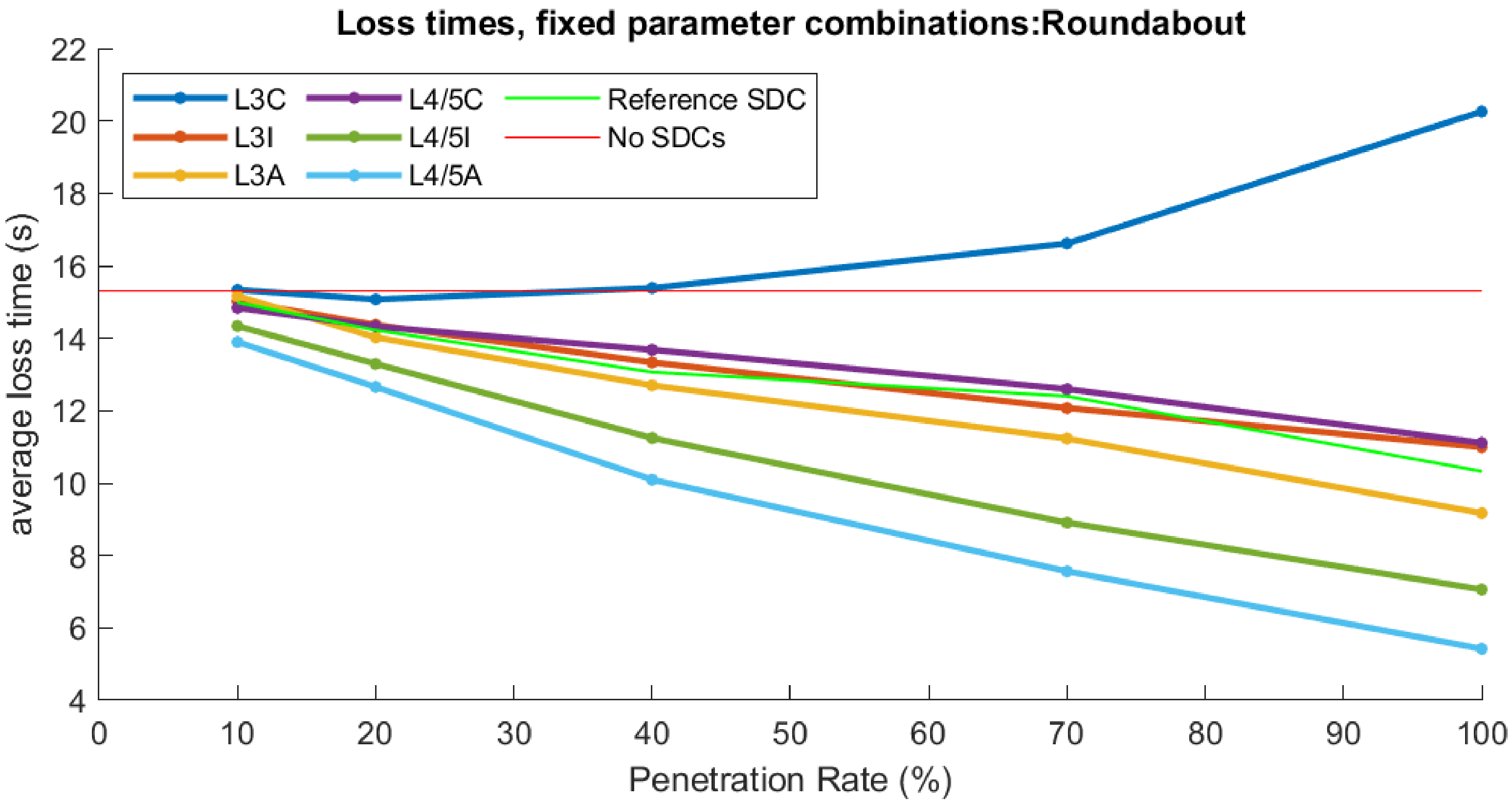



*Figure 92. Loss times of the various combinations of the parameters at the roundabout at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

## APPENDIX K.3: LOSS TIMES AT THE SIGNALISED INTERSECTION

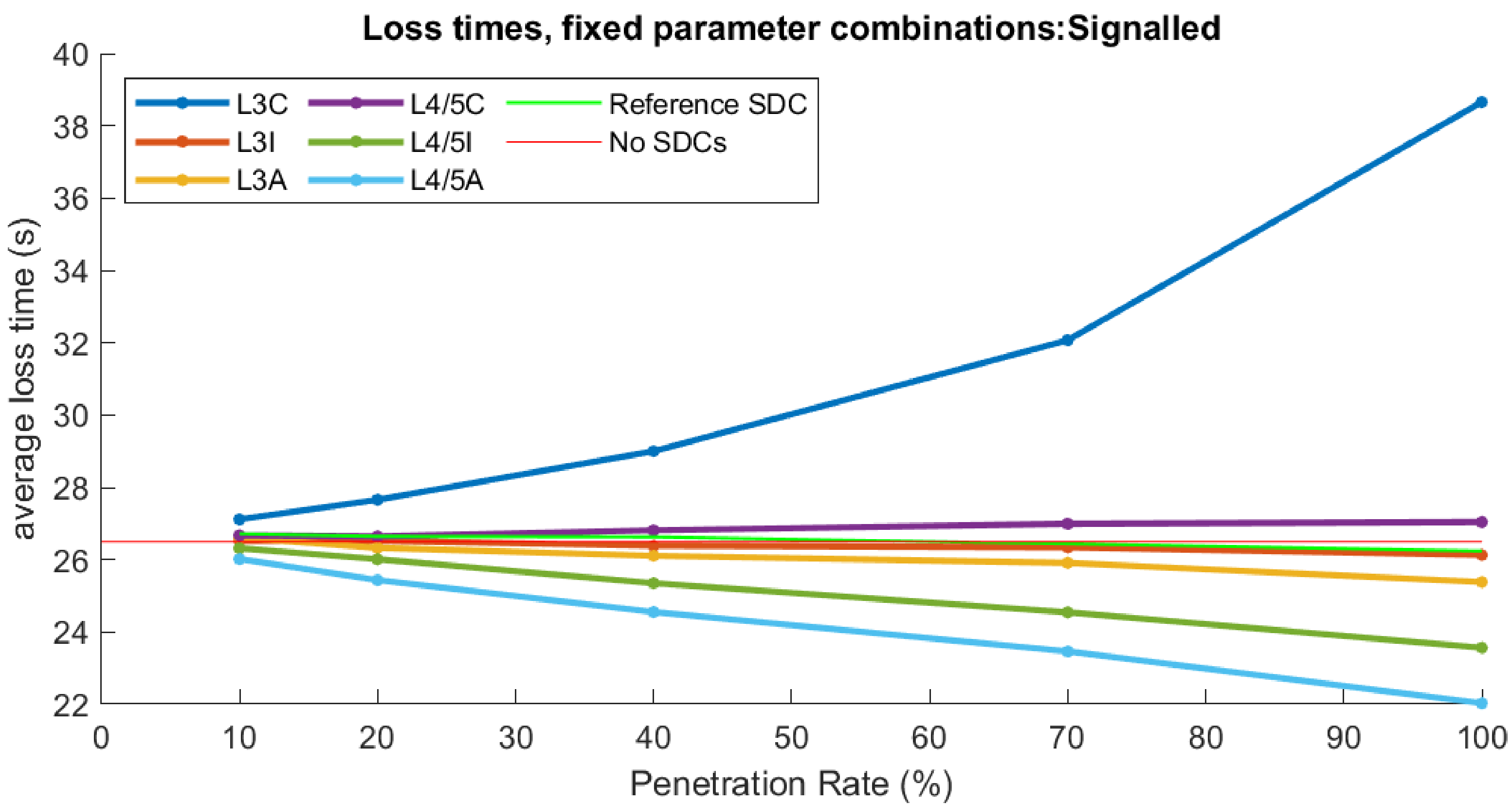



*Figure 93. Loss times of the various combinations of the parameters at the signalised intersection at multiple penetration rates visualised. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

# APPENDIX L: QUEUE LENGTHS OF THE COMBINED PARAMETERS

In this appendix, the resulting graphs of the queue lengths of the second series of simulations, where the parameters are combined, are visible. The graphs are ordered per intersection and per intersection entry.

## APPENDIX L.1: QUEUE LENGTHS AT THE REGULAR INTERSECTION

Since the regular intersection concerns a priority road, the queues of the priority road are not analysed. Only the north and south side entries are analysed.

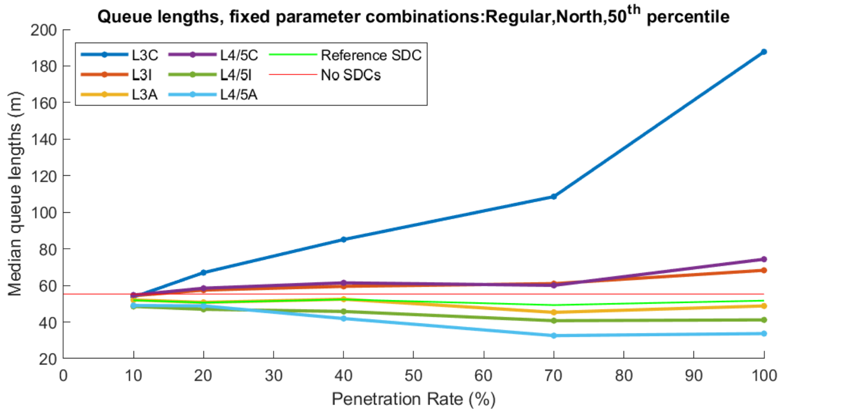



*Figure 94. Median 90th percentile queue lengths of the north entry plotted against penetration rate for the regular intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

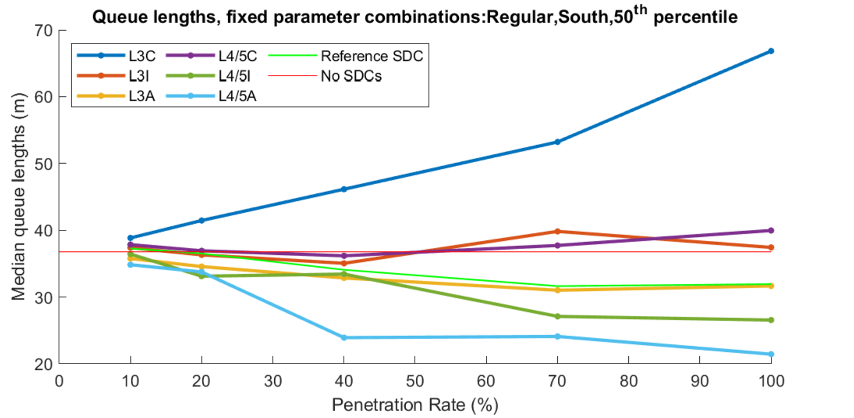



*Figure 95. Median 90th percentile queue lengths of the south entry plotted against penetration rate for the regular intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

## APPENDIX L.2: QUEUE LENGTHS AT THE ROUNDABOUT

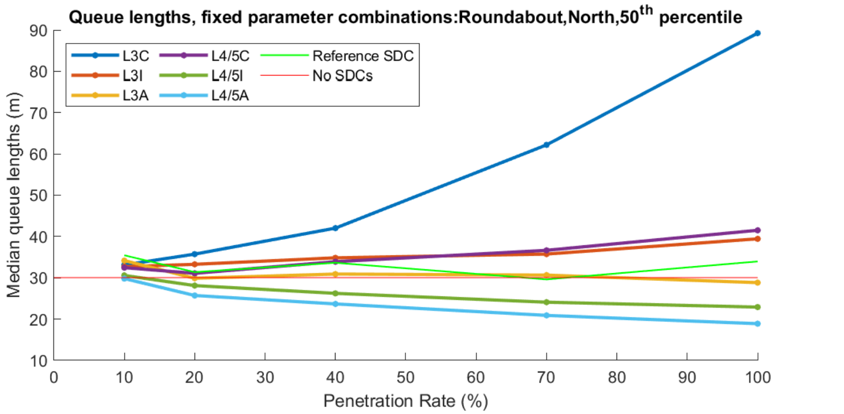



*Figure 96. Median 90th percentile queue lengths of the north entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

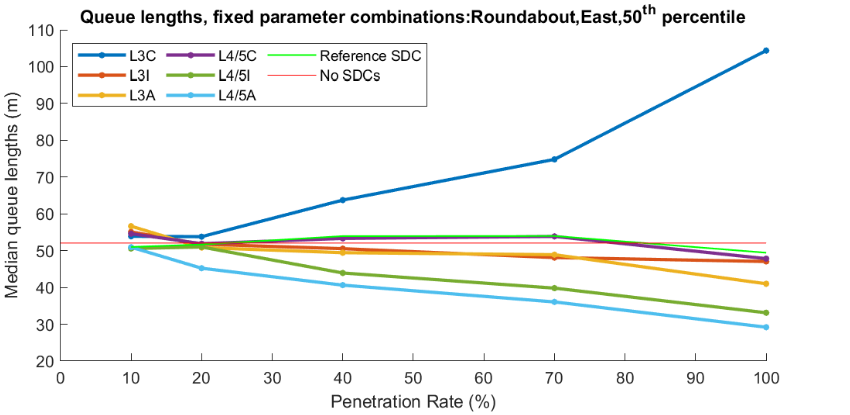



*Figure 97. Median 90th percentile queue lengths of the east entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

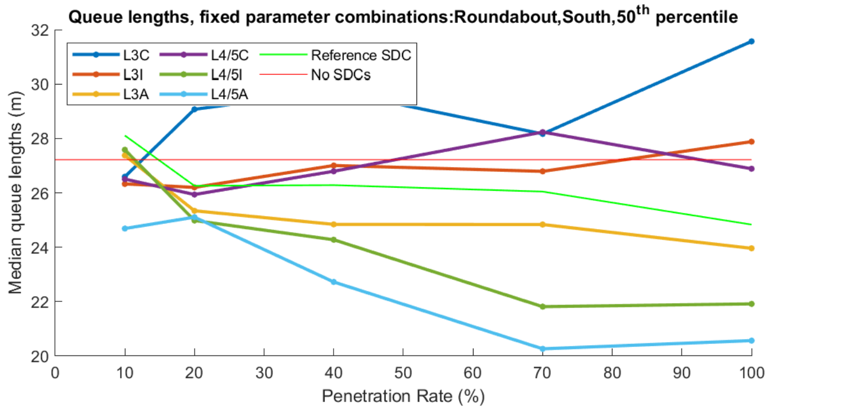



*Figure 98. Median 90th percentile queue lengths of the south entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

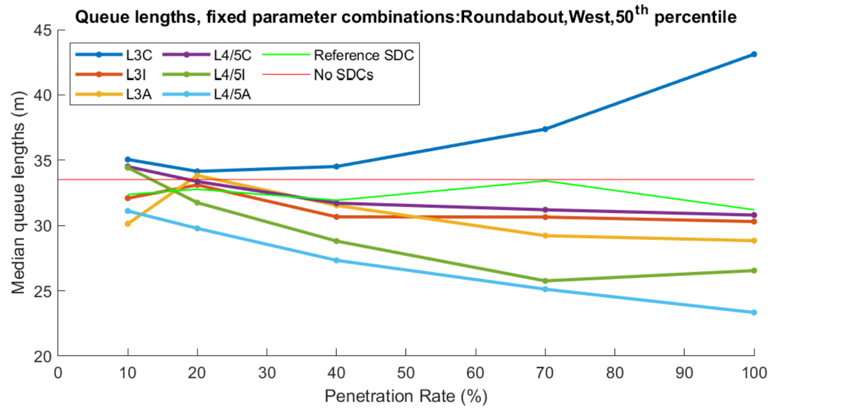



*Figure 99. Median 90th percentile queue lengths of the west entry plotted against penetration rate for the roundabout. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

## Appendix L.3: Queue Lengths at the Signalised Intersection

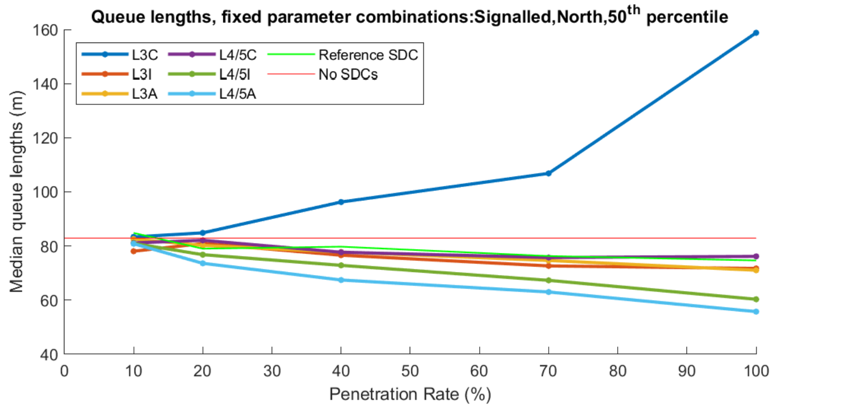



*Figure 100. Median 90th percentile queue lengths of the north entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied.*

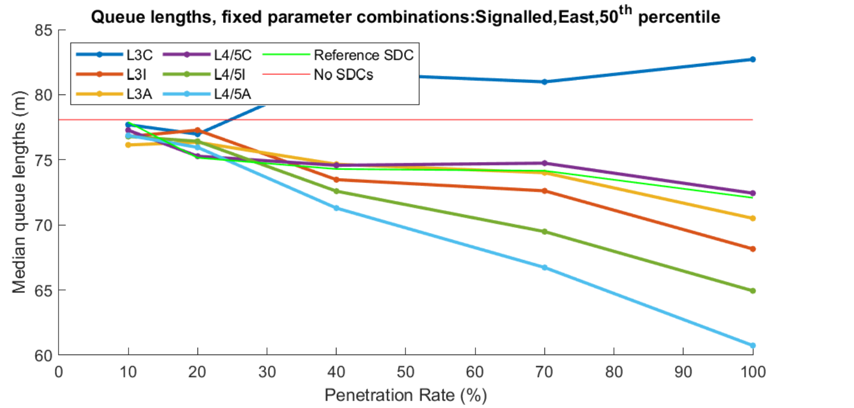



*Figure 101. Median 90th percentile queue lengths of the east entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

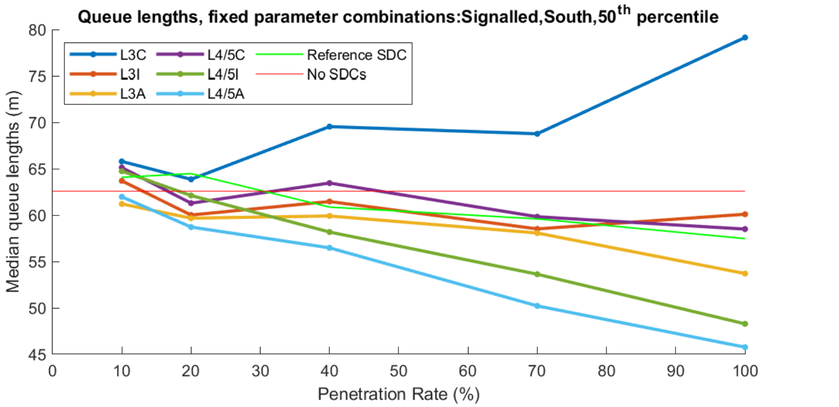



*Figure 102. Median 90th percentile queue lengths of the south entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

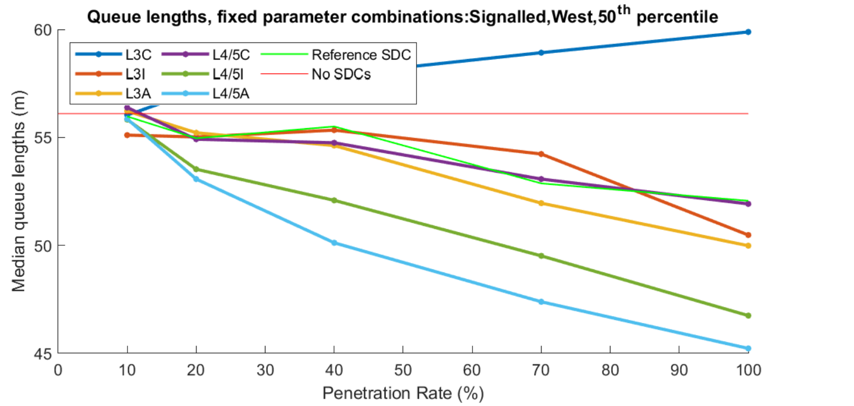



*Figure 103. Median 90th percentile queue lengths of the west entry plotted against penetration rate for the signalised intersection. The 'Reference SDC' scenario is the scenario where only Table 9 is applied*

# Appendix M: Feedback to Personal Development Goals

Since this chapter concerns personal information, it has been removed from the publicly published version of the thesis.

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# Appendix N: Matlab-Scripts Used for Data Analysis

Four Matlab scripts have been used for the data analysis of the loss times and queue lengths in section 4.1. These are two self-established functions used for the loading, filtering and analysis of the data and two scripts that call these functions and plot the figures.

The scripts used for the analysis of the loss times and queue lengths in section 4.2 is very similar, but there has been an elaboration for the penetration rates and the analysis concerning penetration rate on one hand and assessment criterion on the other.

## Appendix N.1: Function Avg_Loss_Time.m

```
function [avg_loss,max_loss,std_loss] =
Avg_Loss_Time(foldloc,docfold,para,para_values,seeds,warm_up,int_type)
%docloc = general location of folder containing the loss time data;
%docname = basic name of the file (without extension);
%warm_up = warm-up time in seconds.

%% Base Data
filename = cell(10,5);
readvector = {'001','002','003','004','005','006','007','008','009','010'};
docname = cell(1,5);
%% Edit string data

%establish basic folders and names of the files
for q = 1:para_values
    if q < 10
        if mod(q,5) == 0
            docname(q) = {strcat('\P',num2str(5),'\s00000',num2str(q))};
        else
            docname(q) = {strcat('\P',num2str(mod(q,5)),'\s00000',num2str(q))};
        end
    elseif q >= 10
        if mod(q,5) == 0
            docname(q) = {strcat('\P',num2str(5),'\s0000',num2str(q))};
        else
            docname(q) = {strcat('\P',num2str(mod(q,5)),'\s0000',num2str(q))};
        end
    end
end

%combine folderlocation and filenames to complete path
for n = 1:seeds
    filename(n) = {strcat(foldloc,char(docfold),char(docname(para)),'_',char(readvector(n)),'.rsr')};
end

%% Load Data
loss = [];

for l = 1:seeds
    s = dir(char(filename(l)));
    %disp(char(filename(l)))
    if s.bytes > 50000
        loss = [loss;dlmread(char(filename(l)),';',9,0)];
    else
        disp(filename(l))
    end
end

%sort data on entry time of vehicle
loss = sortrows(loss);

%% Analyse data

% Erase priority road at regular intersection
if int_type == 1
    for m = 1:length(loss)
        if (loss(m,2) >=120 && loss(m,2) <130) || (loss(m,2) >=140 && loss(m,2) <150)
            loss(m,:) = NaN;
        end
    end
end
loss(any(isnan(loss),2),:) = [];

% Erase warm-up time
for i = 1:length(loss)
    if loss(1,1) < warm_up
        loss(1,:) = [];
    end
end

%% Output
```

```
avg_loss = mean(loss(:,6));
max_loss = max(loss(:,6));
std_loss = std(loss(:,6));
```

## APPENDIX N.2: FUNCTION GETQUEUES.M

```
function [output] = GetQueues(foldloc,docloc,seeds,counters,intervals,int_type,t,j,k)
%foldloc = general folder location
%docloc = specific document location

%% Base Data
n = 0;                                                  %counter for north
e = 0;                                                  %counter for east
s = 0;                                                  %counter for south
w = 0;                                                  %counter for west


num_counters = counters;                                %number of diffent queue counters
num_intervals = intervals;                              %number of time intervals
notread = [21,2,20+seeds*num_counters*num_intervals,8]; %determining the rows and columns that should not
be read from the .att-files

% Empty arrays
average = zeros(1620,7);
stdev = zeros(1620,7);
max_value = zeros(1620,7);
min_value = zeros(1620,7);
average_1 = zeros(405,7);
stdev_1 = zeros(405,7);
max_v_1 = zeros(405,7);
average_2 = zeros(810,7);
stdev_2 = zeros(810,7);
max_v_2 = zeros(810,7);
average_3 = zeros(1215,7);
stdev_3 = zeros(1215,7);
max_v_3 = zeros(1215,7);
average_4 = zeros(1620,7);
stdev_4 = zeros(1620,7);
max_v_4 = zeros(1620,7);

%% Load Data
disp(strcat(char(docloc)))
queues = dlmread(strcat(foldloc,char(docloc)),';',notread);


%% Analyse Data

% Remove gridlocks

if int_type == 1 && t == 2 && j == 2 && k == 1
    queues([9*num_counters*num_intervals+1:10*num_counters*num_intervals],:) = [];
    queues([7*num_counters*num_intervals+1:8*num_counters*num_intervals],:) = [];
elseif int_type == 1 && t == 2 && j == 2 && k == 2
    queues([7*num_counters*num_intervals+1:8*num_counters*num_intervals],:) = [];
end

% Sorting

queues = sortrows(queues,2);
queues = sortrows(queues,3);

% Grouping per queue counter

for a = 1:length(queues)
    if queues(a,2) >= 10 && queues(a,2) <= 19
        n = n + 1;
        queues_n(n,1) = queues(a,2);
        queues_n(n,2) = queues(a,3);
        queues_n(n,3) = queues(a,5);
    elseif queues(a,2) >= 20 && queues(a,2) <= 29
        e = e + 1;
        queues_e(e,1) = queues(a,2);
        queues_e(e,2) = queues(a,3);
        queues_e(e,3) = queues(a,5);
    elseif queues(a,2) >= 30 && queues(a,2) <= 39
        s = s + 1;
        queues_s(s,1) = queues(a,2);
        queues_s(s,2) = queues(a,3);
        queues_s(s,3) = queues(a,5);
    elseif queues(a,2) >= 40 && queues(a,2) <= 49
        w = w + 1;
        queues_w(w,1) = queues(a,2);
        queues_w(w,2) = queues(a,3);
        queues_w(w,3) = queues(a,5);
    end
```

```
end

% 90th percentile value per seed

for b = 1:length(queues_e)/seeds
    if int_type == 1
        if b > length(queues_n)/seeds
            queues_e_s(b,1) = queues_e(b*seeds,1);
            queues_e_s(b,2) = queues_e(b*seeds,2);
            queues_e_s(b,3) = prctile(queues_e([1+seeds*(b-1):b*seeds],3),90);

            queues_w_s(b,1) = queues_w(b*seeds,1);
            queues_w_s(b,2) = queues_w(b*seeds,2);
            queues_w_s(b,3) = prctile(queues_w([1+seeds*(b-1):b*seeds],3),90);
        else
            queues_n_s(b,1) = queues_n(b*seeds,1);
            queues_n_s(b,2) = queues_n(b*seeds,2);
            queues_n_s(b,3) = prctile(queues_n([1+seeds*(b-1):b*seeds],3),90);

            queues_e_s(b,1) = queues_e(b*seeds,1);
            queues_e_s(b,2) = queues_e(b*seeds,2);
            queues_e_s(b,3) = prctile(queues_e([1+seeds*(b-1):b*seeds],3),90);

            queues_s_s(b,1) = queues_s(b*seeds,1);
            queues_s_s(b,2) = queues_s(b*seeds,2);
            queues_s_s(b,3) = prctile(queues_s([1+seeds*(b-1):b*seeds],3),90);

            queues_w_s(b,1) = queues_w(b*seeds,1);
            queues_w_s(b,2) = queues_w(b*seeds,2);
            queues_w_s(b,3) = prctile(queues_w([1+seeds*(b-1):b*seeds],3),90);
        end
    else
        queues_n_s(b,1) = queues_n(b*seeds,1);
        queues_n_s(b,2) = queues_n(b*seeds,2);
        queues_n_s(b,3) = prctile(queues_n([1+seeds*(b-1):b*seeds],3),90);

        queues_e_s(b,1) = queues_e(b*seeds,1);
        queues_e_s(b,2) = queues_e(b*seeds,2);
        queues_e_s(b,3) = prctile(queues_e([1+seeds*(b-1):b*seeds],3),90);

        queues_s_s(b,1) = queues_s(b*seeds,1);
        queues_s_s(b,2) = queues_s(b*seeds,2);
        queues_s_s(b,3) = prctile(queues_s([1+seeds*(b-1):b*seeds],3),90);

        queues_w_s(b,1) = queues_w(b*seeds,1);
        queues_w_s(b,2) = queues_w(b*seeds,2);
        queues_w_s(b,3) = prctile(queues_w([1+seeds*(b-1):b*seeds],3),90);
    end
end

% Maximum length per entry

% The signalled intersection has 3 directional lanes per entry
if int_type == 3
    for c = 1:length(queues_e_s)/3
        queues_n_max(c,1) = queues_n_s(c*3,1);
        queues_n_max(c,2) = queues_n_s(c*3,2);
        queues_n_max(c,3) = max(queues_n_s([1+3*(c-1):c*3],3));

        queues_e_max(c,1) = queues_e_s(c*3,1);
        queues_e_max(c,2) = queues_e_s(c*3,2);
        queues_e_max(c,3) = max(queues_e_s([1+3*(c-1):c*3],3));

        queues_s_max(c,1) = queues_s_s(c*3,1);
        queues_s_max(c,2) = queues_s_s(c*3,2);
        queues_s_max(c,3) = max(queues_s_s([1+3*(c-1):c*3],3));

        queues_w_max(c,1) = queues_w_s(c*3,1);
        queues_w_max(c,2) = queues_w_s(c*3,2);
        queues_w_max(c,3) = max(queues_w_s([1+3*(c-1):c*3],3));
    end
% The regular intersection has 1 directional lane at the N/S entries and 2 at the E/W entries
elseif int_type == 1
    for d = 1:length(queues_e_s)/2
        if d > length(queues_n_s)
            queues_e_max(d,1) = queues_e_s(d*2,1);
            queues_e_max(d,2) = queues_e_s(d*2,2);
            queues_e_max(d,3) = max(queues_e_s([1+2*(d-1):d*2],3));

            queues_w_max(d,1) = queues_w_s(d*2,1);
            queues_w_max(d,2) = queues_w_s(d*2,2);
            queues_w_max(d,3) = max(queues_w_s([1+2*(d-1):d*2],3));
        else
            queues_n_max(d,1) = queues_n_s(d,1);
            queues_n_max(d,2) = queues_n_s(d,2);
            queues_n_max(d,3) = max(queues_n_s([1+(d-1):d],3));

            queues_e_max(d,1) = queues_e_s(d*2,1);
```

```
            queues_e_max(d,2) = queues_e_s(d*2,2);
            queues_e_max(d,3) = max(queues_e_s([1+2*(d-1):d*2],3));

            queues_s_max(d,1) = queues_s_s(d,1);
            queues_s_max(d,2) = queues_s_s(d,2);
            queues_s_max(d,3) = max(queues_s_s([1+(d-1):d],3));

            queues_w_max(d,1) = queues_w_s(d*2,1);
            queues_w_max(d,2) = queues_w_s(d*2,2);
            queues_w_max(d,3) = max(queues_w_s([1+2*(d-1):d*2],3));
        end
    end
 % The roundabout has 1 directional lane per entry
else
    for f = 1:length(queues_e_s)
        queues_n_max(f,1) = queues_n_s(f,1);
        queues_n_max(f,2) = queues_n_s(f,2);
        queues_n_max(f,3) = max(queues_n_s([1+(f-1):f],3));

        queues_e_max(f,1) = queues_e_s(f,1);
        queues_e_max(f,2) = queues_e_s(f,2);
        queues_e_max(f,3) = max(queues_e_s([1+(f-1):f],3));

        queues_s_max(f,1) = queues_s_s(f,1);
        queues_s_max(f,2) = queues_s_s(f,2);
        queues_s_max(f,3) = max(queues_s_s([1+(f-1):f],3));

        queues_w_max(f,1) = queues_w_s(f,1);
        queues_w_max(f,2) = queues_w_s(f,2);
        queues_w_max(f,3) = max(queues_w_s([1+(f-1):f],3));
    end
end
%% Output

% Export the median and 90th percentile value to the calling Matlab script
output(1,:) = prctile(queues_n_max(:,3),50);
output(2,:) = prctile(queues_n_max(:,3),90);

output(3,:) = prctile(queues_e_max(:,3),50);
output(4,:) = prctile(queues_e_max(:,3),90);

output(5,:) = prctile(queues_s_max(:,3),50);
output(6,:) = prctile(queues_s_max(:,3),90);

output(7,:) = prctile(queues_w_max(:,3),50);
output(8,:) = prctile(queues_w_max(:,3),90);
```

## Appendix N.3: Script Loss_Times.m

```
%% Initialisation
clear;clc;close all
tic

% Adjustable data
pr = 1;                     %selected penetration rate from vector below
para = 1;                   %selected parameter from vector below
min_pen = 1;                %minimum analysis penetration rate: 1 = 40%, 2 = 70%, 3 = 100%
max_pen = 3;                %maximum analysis penetration rate: 1 = 40%, 2 = 70%, 3 = 100%
min_para = 1;               %minimum parameter to analyse: 1 = CC0, 2 = CC1, 3 = CC2, 4 = CC8, 5 = CC9
max_para = 5;               %maximum parameter to anlayse: 1 = CC0, 2 = CC1, 3 = CC2, 4 = CC8, 5 = CC9
seeds = 10;                 %amount of seeds used
min_par_v = 1;              %minimum parameter value to anlyse: P1, P2, P3, P4, P5
max_par_v = 5;              %maximum parameter value to anlyse: P1, P2, P3, P4, P5
para_values = 25;           %amount of parameter values
conflict_time = 2;          %confict loss time at signalled intersection
int_type = 1;               %type of intersection analysed: 1 = Regular, 2 = Roundabout, 3 = Signalled


%adjustable for figures
savefigure = 0;             %determine if the figures are saved: 0 = no, 1 = yes
savenormfigure = 0;         %determine if the normalised figures are saved: 0 = no, 1 = yes
floataxis = 0;              %let Matlab determine y-axis values: 0 = no, 1 = yes

% Input data
warm_up = 900;              %warm-up time in seconds
para_names = {'CC0','CC1','CC2','CC8','CC9'}; %names of parameters
pen_rates = [40, 70, 100];  %penetration rates
docnames = {'001','002','003','004','005','006','007','008','009','010'}; %names of the files
colours = [[0, 0.4470, 0.7410];[0.8500, 0.3250, 0.0980];[0.9290, 0.6940, 0.1250];[0.4940, 0.1840,
0.5560];[0.4660, 0.6740, 0.1880]];
intersection = {'Regular','Roundabout','Signalled'}; %types of intersection
ax_values(1,1,:) = [0 2.6 15 45]; %axis values
ax_values(1,2,:) = [0 2.6 .75 2.3];
ax_values(2,1,:) = [0 2.6 6 18];
ax_values(2,2,:) = [0 2.6 .75 1.8];
ax_values(3,1,:) = [0 2.6 22 33];
```

```
ax_values(3,2,:) = [0 2.6 .95 1.35];


% Empty arrays
docfold = cell(3,5);
all_legend = cell(3,5);
norm_para = zeros(5);
loss_times = zeros(length(pen_rates),length(para_names),length(seeds));
max_loss = zeros(length(pen_rates),length(para_names),length(seeds));
std_loss = zeros(length(pen_rates),length(para_names),length(seeds));
no_sdc = [];
n_fig = 0;                    %counter for figures

%% Load Data

% Parameter Values
all_parameters = load('parameters.txt');

%% Establish file paths

%location of the folders with the data
foldloc = strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor Jaar 4\Module 12, BSc-opdracht\02. Modelleren\02. Data Analyse\03. Data\Raw Data\',char(intersection(int_type)),'\');

%defining the various data folders
for m = 1:length(pen_rates)
    for p = 1:length(para_names)
        docfold(m,p) = {strcat(num2str(pen_rates(m)),'\',char(para_names(p)))};
    end
end

%% Data Analysis

% Normalise parameter
parameters = all_parameters;
parameters(:,1) = [];
norm_para = parameters./all_parameters(:,1);

% Get average loss times

for n = min_pen:max_pen
    for j = min_para:max_para
        for k = min_par_v:max_par_v
            [loss_times(n,j,k),max_loss(n,j,k),std_loss(n,j,k)] = Avg_Loss_Time(foldloc,docfold(n,j),((j-1)*5+k),para_values,seeds,warm_up,int_type);
        end
    end
end


% Normalise average loss times
for b = min_para:max_para
    for c = min_par_v:max_par_v
        if b == 1 || b == 3
            norm_loss_times(:,b,c) =  loss_times(:,b,c) ./ loss_times(:,b,2) ;
        elseif b == 2 || b == 4
            norm_loss_times(:,b,c) =  loss_times(:,b,c) ./ loss_times(:,b,3) ;
        elseif b == 5
            norm_loss_times(:,b,c) =  loss_times(:,b,c) ./ loss_times(:,b,4) ;
        else
            error;
        end
    end
end

% Read regular vehicle data
for l = 1:seeds
    no_sdc = [no_sdc;dlmread(char(strcat(foldloc,'00\S000001_',docnames(l),'.rsr')),';',9,0)];
end

% Erase priority road at regular intersection
if int_type == 1
    for m = 1:length(no_sdc)
        if (no_sdc(m,2) >=120 && no_sdc(m,2) <130) || (no_sdc(m,2) >=140 && no_sdc(m,2) <150)
            no_sdc(m,:) = NaN;
        end
    end
end
no_sdc(any(isnan(no_sdc),2),:) = [];

no_sdc_avg = mean(no_sdc(:,6));
no_sdc_max = max(no_sdc(:,6));
no_sdc_std = std(no_sdc(:,6));

% Substract conflict loss times at signalled intersection
if int_type == 3
    loss_times = loss_times - conflict_time;
    max_loss = max_loss - conflict_time;
```

```
    no_sdc_avg = no_sdc_avg - conflict_time;
    no_sdc_max = no_sdc_max - conflict_time;
end

% Calculate relative change at normalised = 1
rel_gain(1,1) = no_sdc_avg;
rel_gain(1,2) = 0;
for w = min_pen:max_pen
    rel_gain(w+1,1) = loss_times(w,1,2);
    rel_gain(w+1,2) = (rel_gain(1,1)-rel_gain(w+1))/rel_gain(1,1)*100;
end
rel_gain
toc
%% Plot data
tic

% Legend of plots

for u = min_pen:max_pen
    for v = min_para:max_para
        all_legend(u,v) = strcat (para_names(v),':',num2str(pen_rates(u)),'%');
    end
end

% Absolute values

for s = min_pen:max_pen+1
    %call figures
    n_fig = n_fig + 1;
    figure('units','normalized','outerposition',[0 0 0.5 0.5])
    figure(n_fig)
    clf(n_fig)
    %plotting data
    hold on
    for t = min_para:max_para
        if s == 1
            plot(norm_para(t,:),squeeze(loss_times(s,t,:)),'--','Color',colours(t,:),'LineWidth',2);
        elseif s == 2
            plot(norm_para(t,:),squeeze(loss_times(s,t,:)),'-.','Color',colours(t,:),'LineWidth',2);
        elseif s == 3
            plot(norm_para(t,:),squeeze(loss_times(s,t,:)),'-','Color',colours(t,:),'LineWidth',2);
        elseif s == 4
            plot(norm_para(t,:),squeeze(loss_times(s-3,t,:)),'--','Color',colours(t,:),'LineWidth',1.5);
            plot(norm_para(t,:),squeeze(loss_times(s-2,t,:)),'-.','Color',colours(t,:),'LineWidth',1.5);
            plot(norm_para(t,:),squeeze(loss_times(s-1,t,:)),'-','Color',colours(t,:),'LineWidth',1.5);
        end
    end
    %add explainatory elements & save figures
    xlabel('normalised parameter values (-)')
    ylabel('average loss time (s)')
    if s <4
        title(strcat('Loss times,',num2str(pen_rates(s)),'% penetration'))
        legend(para_names(min_para:max_para),'Location','northwest')
        xlim([0 2.6])
        if s == 1 && savefigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Loss_times_',num2str(pen_rates(s)),'.p
ng'))
        elseif s == 2 && savefigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Loss_times_',num2str(pen_rates(s)),'.p
ng'))
        elseif s == 3 && savefigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Loss_times_',num2str(pen_rates(s)),'.p
ng'))
        end
    elseif s == 4
        %plot the 0%-penetration scenario
        plot([0,2.6],[no_sdc_avg,no_sdc_avg],'r','LineWidth',2.5);
        %add explainatory elements & save figures
        if int_type == 1
            title('Loss times of north and south entry, all penetration rates')
        else
            title('Loss times, all penetration rates')
        end
        legend(char({char(all_legend),'No SDCs'}),'Location','northwest','NumColumns',6,'FontSize',6.5)
        if floataxis == 0
            axis(squeeze(ax_values(int_type,1,:,:)))
        else
            xlim([0 2.6])
        end
        if savefigure == 1
            saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Loss_times_All.png'))
        end
    end
    hold off
end
```

```
% Normalised values

for s = min_pen:max_pen+1
    %call figures
    n_fig = n_fig + 1;
    if s < 4
        figure('units','normalized','outerposition',[0 0 0.5 0.5])
    elseif s == 4
        figure('units','normalized','outerposition',[0 0 .5 .5])
    end
    figure(n_fig)
    clf(n_fig)
    %plotting data
    hold on
    for t = min_para:max_para
        if s == 1
            plot(norm_para(t,:),squeeze(norm_loss_times(s,t,:)),'--','Color',colours(t,:));
        elseif s == 2
            plot(norm_para(t,:),squeeze(norm_loss_times(s,t,:)),'-.','Color',colours(t,:));
        elseif s == 3
            plot(norm_para(t,:),squeeze(norm_loss_times(s,t,:)),'-','Color',colours(t,:));
        elseif s == 4
            plot(norm_para(t,:),squeeze(norm_loss_times(s-3,t,:)),'--','Color',colours(t,:));
            plot(norm_para(t,:),squeeze(norm_loss_times(s-2,t,:)),'-.','Color',colours(t,:));
            plot(norm_para(t,:),squeeze(norm_loss_times(s-1,t,:)),'-','Color',colours(t,:));
        end
    end
    %add explainatory elements & save figures
    xlabel('normalised parameter values (-)')
    ylabel('normalised average loss time (-)')
    if s <4
        title(strcat('Normalised loss times,',num2str(pen_rates(s)),'% penetration'))
        legend(para_names(min_para:max_para),'Location','northwest')
        xlim([0 2.6])
        if s == 1 && savenormfigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Norm_loss_times_',num2str(pen_rates(s)
),'.png'))
        elseif s == 2 && savenormfigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Norm_loss_times_',num2str(pen_rates(s)
),'.png'))
        elseif s == 3 && savenormfigure == 1

saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Norm_loss_times_',num2str(pen_rates(s)
),'.png'))
        end
    elseif s == 4
        if int_type == 1
            title('Normalised loss times of north and south entry, all penetration rates')
        else
            title('Normalised loss times, all penetration rates')
        end
        legend(char({char(all_legend)}),'Location','northwest','NumColumns',6)
        if floataxis == 0
            axis(squeeze(ax_values(int_type,2,:,:)))
        else
            xlim([0 2.6])
        end
        if savenormfigure == 1
            saveas(figure(n_fig),strcat(pwd,'\',char(intersection(int_type)),'\Norm_loss_times_All.png'))
        end
    end
    hold off
end

toc
```

## Appendix N.4: Script Queues.m

```
%% Initialisation
clear;clc;close all
tic

% Input data
readvector = {'001','002','003','004','005','006','007','008','009','010'};
para_names = {'CC0','CC1','CC2','CC8','CC9'};
para_names_c = {'C0','C1','C2','C8','C9'};              %first C removed for scripting reasons
para_value_names = {'P1','P2','P3','P4','P5'};
pen_rates = [40, 70, 100];                              %penetration rates
directions = [1:4];                                     %directions to drive at intersection
direction_names = {'North','East','South','West'};     %names of the directions
percentiles = [50,90];                                  %percentiles NOT INPUT FOR GETQUEUES!
colours = [[0, 0.4470, 0.7410];[0.8500, 0.3250, 0.0980];[0.9290, 0.6940, 0.1250];[0.4940, 0.1840,
0.5560];[0.4660, 0.6740, 0.1880]];
```

```
intersection = {'Regular','Roundabout','Signalled'};%types of intersection
docname = {'Kuv_linksaf - C','EnkelLZinVoorrang_Aalsmeer_OS_SDC - C','TAG020_CC0 - C'};
counters = [6, 4, 12];
intervals = [60, 60, 135];

% Adjustable data
min_pen = 1;                %minimum analysis penetration rate: 1 = 40%, 2 = 70%, 3 = 100%
max_pen = 3;                %maximum analysis penetration rate: 1 = 40%, 2 = 70%, 3 = 100%
min_para = 1;               %minimum parameter to analyse: 1 = CC0, 2 = CC1, 3 = CC2, 4 = CC8, 5 = CC9
max_para = 5;               %maximum parameter to anlayse: 1 = CC0, 2 = CC1, 3 = CC2, 4 = CC8, 5 = CC9
min_par_v = 1;              %minimum parameter value to anlyse: P1, P2, P3, P4, P5
max_par_v = 5;              %maximum parameter value to anlyse: P1, P2, P3, P4, P5
seeds = 10;
int_type = 1;               %type of intersection analysed: 1 = regular, 2 = roundabout, 3 = signalled

%input for figures
perc = 1;                   %analysed percentile, 1 = 50, 2 = 90.
dir = 3;                    %analysed origin direction, 1 = north, 2 = east, 3 = south, 4 = west.
savefigure = 1;             %determine if the absolute figures are saved: 0 = no, 1 = yes
savenormfigure = 1;         %determine if the normalised figures are saved: 0 = no, 1 = yes
floataxis = 0;              %let matlab determine y-axis values: 0 = no, 1 = yes

% Empty arrays
filename = cell(10,5);
docloc = cell(3,5);
queues = zeros(3,5,5,8);
norm_queues = zeros(3,5,5,8);
n_fig = 0;                  %counter for figures

%% Load Data

% Parameter Values
all_parameters = load('parameters.txt');

%% Establish file paths

% Location of the folders with the data
foldloc = strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor Jaar 4\Module 12, BSc-
opdracht\02. Modelleren\02. Data Analyse\03. Data\Raw Data\',char(intersection(int_type)),'\');

% Defining the file locations and names
for m = min_pen:max_pen
    for p = min_para:max_para
        for q = min_par_v:max_par_v
            docloc(m,p,q) =
{strcat(num2str(pen_rates(m)),'\',char(para_names(p)),'\P',num2str(q),'\',char(docname(int_type)),char(pa
ra_names_c(p)),'_P',num2str(q),'_Queue Results_010.att')};
        end
    end
end

%% Data Analysis

% Normalise parameter
parameters = all_parameters;
parameters(:,1) = [];
norm_para = parameters./all_parameters(:,1);

% Load queues
for n = min_pen:max_pen
    for j = min_para:max_para
        for k = min_par_v:max_par_v
            queues(n,j,k,:) =
GetQueues(foldloc,docloc(n,j,k),seeds,counters(int_type),intervals(int_type),int_type,n,j,k);
        end
    end
end


% Normalise queues
for b = min_para:max_para
    for c = min_par_v:max_par_v
        if b == 1 || b == 3
            norm_queues(:,b,c,:) =  squeeze(queues(:,b,c,:))./squeeze(queues(:,b,2,:));
        elseif b == 2 || b == 4
            norm_queues(:,b,c,:) =  squeeze(queues(:,b,c,:))./squeeze(queues(:,b,3,:));
        elseif b == 5
            norm_queues(:,b,c,:) =  squeeze(queues(:,b,c,:))./squeeze(queues(:,b,4,:));
        else
            error;
        end
    end
end

% Read regular vehicle data
no_sdc = GetQueues(foldloc,strcat('00\',char(docname(int_type)),'C0_P1_Queue
Results_010.att'),seeds,counters(int_type),intervals(int_type),int_type,1,1,1);
```

```
% Calculate relative change at normalised = 1

rel_gain(1,1) = no_sdc(1+(dir-1)*2 + (perc-1));
rel_gain(1,2) = 0;
for w = min_pen:max_pen
    rel_gain(w+1,1) = queues(w,1,2,1+(dir-1)*2 + (perc-1));
    rel_gain(w+1,2) = (rel_gain(1,1)-rel_gain(w+1))/rel_gain(1,1)*100;
end
rel_gain

toc
%% Plot data
tic

% Legend of plots

for u = min_pen:max_pen
    for v = min_para:max_para
        all_legend(u,v) = strcat (para_names(v),':',num2str(pen_rates(u)),'%');
    end
end

% Absolute values

for s = min_pen:max_pen+1
    %call figures
    n_fig = n_fig + 1;
    figure('units','normalized','outerposition',[0 0 0.5 0.5])
    figure(n_fig)
    clf(n_fig)
    %plotting data
    hold on
    for t = min_para:max_para
        if s == 1
            plot(norm_para(t,:),squeeze(queues(s,t,:,1+(dir-1)*2 + (perc-1))),'--
','Color',colours(t,:),'LineWidth',2);
           xlim([0 2.6])
        elseif s == 2
            plot(norm_para(t,:),squeeze(queues(s,t,:,1+(dir-1)*2 + (perc-1))),'-
.','Color',colours(t,:),'LineWidth',2);
            xlim([0 2.6])
        elseif s == 3
            plot(norm_para(t,:),squeeze(queues(s,t,:,1+(dir-1)*2 + (perc-1))),'-
','Color',colours(t,:),'LineWidth',2);
            xlim([0 2.6])
        elseif s == 4
            plot(norm_para(t,:),squeeze(queues(s-3,t,:,1+(dir-1)*2 + (perc-1))),'--
','Color',colours(t,:),'LineWidth',2);
            plot(norm_para(t,:),squeeze(queues(s-2,t,:,1+(dir-1)*2 + (perc-1))),'-
.','Color',colours(t,:),'LineWidth',2);
            plot(norm_para(t,:),squeeze(queues(s-1,t,:,1+(dir-1)*2 + (perc-1))),'-
','Color',colours(t,:),'LineWidth',2);
        end
    end
    %add explainatory elements & save figures
    xlabel('normalised parameter values (-)')
    ylabel('maximum queue lengths (m)')
    if s <4
        title(strcat('Maximum queue lengths,',num2str(pen_rates(s)),'% penetration, originating
direction:',char(direction_names(dir)) ,',',num2str(percentiles(perc)) ,'^t^h percentile'))
        legend(para_names,'Location','northwest')
        if savefigure == 1
            saveas(figure(n_fig),strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor
Jaar 4\Module 12, BSc-opdracht\02. Modelleren\02. Data Analyse\03. Data\Matlab queues\',...

char(intersection(int_type)),'\',char(direction_names(dir)),'\Queue_',num2str(pen_rates(s)),'_',char(dire
ction_names(dir)),'_',num2str(percentiles(perc)),'.png'))
        end
    elseif s == 4
        %plot 0%-penetration scenario
        plot([0,2.6],[no_sdc(1+(dir-1)*2 + (perc-1)),no_sdc(1+(dir-1)*2 + (perc-
1))],'r','LineWidth',2.5);
        %add explainatory elements & save figures
        title(strcat('Maximum queue lengths, all penetration rates, originating
direction:',char(direction_names(dir)) ,',',num2str(percentiles(perc)) ,'^t^h percentile'))
        if floataxis == 0
            axis([0.2 2.6 26 46])
        else
            xlim([0 2.6])
        end
        legend(char({char(all_legend),'No SDCs'}),'Location','northwest','NumColumns',6,'FontSize',6.5)
        if savefigure == 1
            saveas(figure(n_fig),strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor
Jaar 4\Module 12, BSc-opdracht\02. Modelleren\02. Data Analyse\03. Data\Matlab
queues\',char(intersection(int_type)),'\',char(direction_names(dir)),'\Queue_All_Penetration_Rates_',char
(direction_names(dir)),'_',num2str(percentiles(perc)),'.png'))
        end
    end
```

```
    hold off
end

% Normalised values

for s = min_pen:max_pen+1
    %call figures
    n_fig = n_fig + 1;
    if s < 4
        figure('units','normalized','outerposition',[0 0 0.5 0.5])
    elseif s == 4
        figure('units','normalized','outerposition',[0 0 0.5 0.5])
    end
    figure(n_fig)
    clf(n_fig)
    %plotting data
    hold on
    for t = min_para:max_para
        if s == 1
            plot(norm_para(t,:),squeeze(norm_queues(s,t,:,1+(dir-1)*2 + (perc-1))),'--
','Color',colours(t,:));
            xlim([0 2.6])
        elseif s == 2
            plot(norm_para(t,:),squeeze(norm_queues(s,t,:,1+(dir-1)*2 + (perc-1))),'-
.','Color',colours(t,:));
            xlim([0 2.6])
        elseif s == 3
            plot(norm_para(t,:),squeeze(norm_queues(s,t,:,1+(dir-1)*2 + (perc-1))),'-
','Color',colours(t,:));
            xlim([0 2.6])
        elseif s == 4
            plot(norm_para(t,:),squeeze(norm_queues(s-3,t,:,1+(dir-1)*2 + (perc-1))),'--
','Color',colours(t,:));
            plot(norm_para(t,:),squeeze(norm_queues(s-2,t,:,1+(dir-1)*2 + (perc-1))),'-
.','Color',colours(t,:));
            plot(norm_para(t,:),squeeze(norm_queues(s-1,t,:,1+(dir-1)*2 + (perc-1))),'-
','Color',colours(t,:));
        end
    end
    %add explainatory elements & save figures
    xlabel('normalised parameter values (-)')
    ylabel('normalised maximum queue lengths (-)')
    if s <4
        title(strcat('Normalised maximum queue lengths,',num2str(pen_rates(s)),'% penetration,
originating direction:',char(direction_names(dir)) ,',',num2str(percentiles(perc)) ,'^t^h percentile'))
        legend(para_names,'Location','northwest')
        if savenormfigure == 1
            saveas(figure(n_fig),strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor
Jaar 4\Module 12, BSc-opdracht\02. Modelleren\02. Data Analyse\03. Data\Matlab queues\',...

char(intersection(int_type)),'\',char(direction_names(dir)),'\Norm_queue_',num2str(pen_rates(s)),'_',char
(direction_names(dir)),'_',num2str(percentiles(perc)),'.png'))
        end
    elseif s == 4
        title(strcat('Normalised maximum queue lengths, all penetration rates, originating
direction:',char(direction_names(dir)) ,',',num2str(percentiles(perc)) ,'^t^h percentile'))
        if floataxis == 0
            axis([0.2 2.6 0.85 1.55])
        else
            xlim([0 2.6])
        end
        legend(char({char(all_legend)}),'Location','northwest','NumColumns',6,'FontSize',6.5)
        if savenormfigure == 1
            saveas(figure(n_fig),strcat('C:\Users\ivobr\OneDrive\Documenten\Universiteit Twente\Bachelor
Jaar 4\Module 12, BSc-opdracht\02. Modelleren\02. Data Analyse\03. Data\Matlab
queues\',char(intersection(int_type)),'\',char(direction_names(dir)),'\Norm_queue_All_Penetration_Rates_'
,char(direction_names(dir)),'_',num2str(percentiles(perc)),'.png'))
        end
    end
    hold off
end

toc
```