Master Thesis

Dedicated traffic management system for truck and vehicle platooning on intersections.

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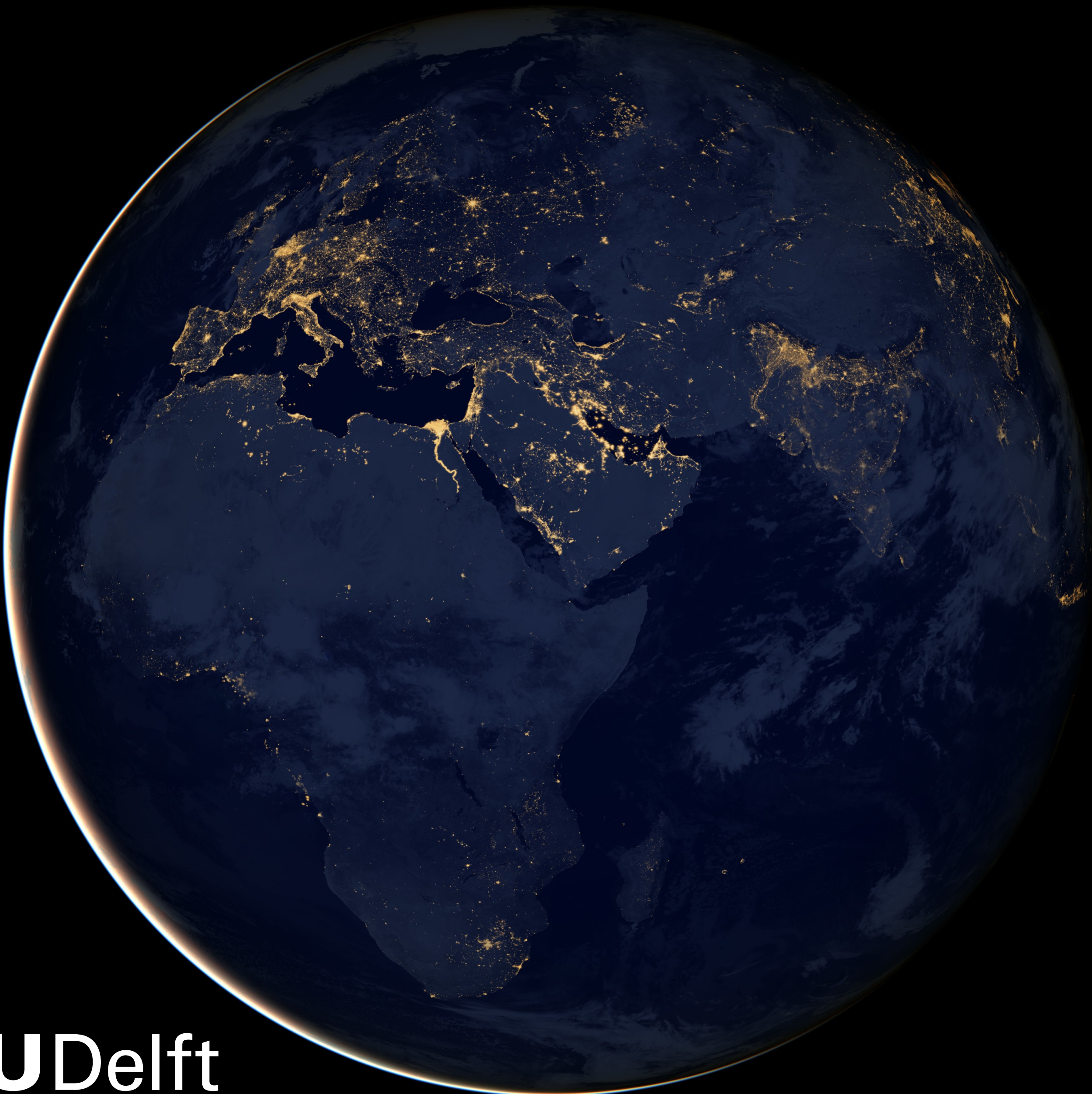
R.J.M. Menken



Delft University of Technology

TU Delft

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Dedicated traffic management system for truck and vehicle platooning on intersections.

by

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Project duration:	June 13, 2022 – June, 2023	
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Preface

This thesis is the concluding part of my Master of Science programme Transport & Planning at the Delft University of Technology. My specialisation during this degree was on road traffic systems, which focuses on the operations and management of private traffic flows, such as cars, trucks and active modes (pedestrians and cyclists), in varying traffic conditions.

This thesis was commissioned by the Province of Noord-Holland, which is responsible for the regional infrastructure. During this process, I aimed to develop a dedicated traffic management system, which uses vehicle connectivity and platooning capabilities to improve the traffic flow on an existing intersection located in the province. This is done by firstly conducting a literature study, which is then followed by the development of the system and a microsimulation. The objective was to provide the Province with a recommendation on how future developments could be implemented to intersection signal control systems in order to improve traffic flows.

There are multiple persons I would like to thank for their support and contributions to this thesis, starting with my daily supervisors Henk Taale and Boris Kock. Henk, as my supervisor from the TU Delft, provided invaluable guidance throughout the project. Our biweekly meeting not only ensured that I stayed on track, it also allowed for fruitful discussions and valuable insights. Boris, my supervisor from the Province of Noord-Holland, provided me with invaluable feedback, insights, guidance and the necessary resources at every stage of the thesis.

Furthermore, I would like to thank Simeon Calvert and Marco Rinaldi, who are both members of the committee. They have provided me with valuable input and feedback. Their expertise and engagement during the committee meetings, such as the kick-off, mid-term and green-light meetings, were of huge value in the creation of this thesis. I would also like to thank Cyril Cappendijk for providing me the information about the used traffic control systems on the corridor.

Finally, I would like to express my appreciation to the Province of Noord-Holland for providing with the right resources to conduct this research. I hope that the findings from this thesis are valuable to their ongoing efforts in optimizing and improving the traffic and transport systems in the region.

R.J.M. Menken
Delft, Wednesday 14th June, 2023

Summary

Congestion is a major problem on the Dutch road networks, which is a widely researched topic. Multiple factors contribute to this increasing congestion, examples of these are increasing traffic demands and inefficient traffic signal control. The focus of this research is on arterial traffic networks consisting of signalized intersections. The effects of two innovations that aim to reduce congestion have been evaluated, which are intelligent traffic signal control using the data of connected vehicles and truck/vehicle platooning. Research has shown promising results in both areas, but there are still some gaps to be filled. Especially in the area of truck/vehicle platooning on intersections and the combination of intelligent intersection control and truck/vehicle platooning. These two innovations have therefore been combined in this study to develop a dedicated traffic management system that leverages vehicle connectivity and platooning capabilities to control the traffic on a signalized intersection. The objective of this study is to determine the traffic flow effects that this system has in mixed traffic conditions. This leads to the following main research question:

What dedicated traffic management system can potentially improve the traffic flows on a logistic corridor where truck platoons drive in mixed traffic (consisting of regular and connected vehicles) and what are the traffic flow effects on this corridor when the system is implemented?

The effectiveness of this dedicated traffic management has been determined by doing a microsimulation on an existing logistic corridor. This study is commissioned by the Province of Noord-Holland, so the chosen corridor for this is located in Noord-Holland. This corridor is a part of the logistic corridor between the largest flower auction in the world, Royal FloraHolland, and the A4 highway. The used part of the corridor consists of three intersections, from which the intersection between the N201 and Koolhovenlaan has been used to implement the dedicated traffic management system. The currently used signal controller on this intersection is a vehicle-actuated signal controller, which uses measurements done by induction loops to update the signal phase and timings plan. The intersection is also a part of a field experiment where freight traffic is granted priority based on vehicle connectivity.

Categorization of Intersection Control

Intersection control in combination with connected (and autonomous) vehicles is a widely researched topic. An overview of the categorization of the different types of intersection control systems has been made in this study. This overview has been used to filter the right articles that serve as an inspiration for the development of the dedicated traffic management system. Intersection control is firstly differentiated into the way that the time-space conflicts between crossing vehicles are separated, which can be signalized intersection management (SIM) using signalization or autonomous intersection management (AIM) using advanced driver guidance based on connected autonomous vehicles. The dedicated traffic management that has been developed in this study must be suitable for both connected vehicles with platooning capabilities and non-connected manually driven vehicles. The focus of this study is therefore on SIM.

Intersection control can be further categorized by the hierarchical layer it belongs to. Three hierarchical layers can be distinguished from each other, which are the corridor coordination layer, intersection management (trajectory planning) layer and vehicle control layer. The focus of this research is on the traffic control on a single intersection, which is the second layer. This layer can be categorized into three signal control methods, which are:

1. **Advanced driver guidance based on CAV's**
   The driver (Connected vehicle) or the vehicle control system (Connected autonomous vehicle) is instructed on how to properly operate the vehicle. These instructions are based on the signal and vehicle data.

2. **Advanced traffic signal control with CAV's**
   The signal timing and phases can be optimized by the signal control system based on CV data in order to improve the intersection performance.
3. **Signal vehicle coupled control based on CAV's**
   The signal vehicle coupled control (SVCC) system can optimize the vehicle operations and signal timing and phases simultaneously under the CAV environment.

The second category is the most suitable for this study, since this can be used in mixed traffic conditions. This category can be further differentiated into:

1. Actuated traffic signal enhanced using CAV's data.
2. Platoon-based traffic signal control based on CAV's coordination.
3. Planning-based traffic signal control based on CAV's coordination (including transit priority traffic signal control enhanced by CAV's coordination).

From these categories, the Platoon-based traffic signal control based on CAV's coordination is the most suitable for the dedicated traffic management system, since this leverages vehicle platooning capabilities as well.

The results of the filtering steps based on the categorization of intersection control using vehicle connectivity (and automation) are two articles that served as the main inspiration for the dedicated traffic management system:

Traffic signal control by leveraging Cooperative Adaptive Cruise Control (CACC) vehicle platooning capabilities. - Liu et al. (2019)
This is cooperative signal control algorithm, that leverages datasets from CACC-equipped vehicles and from fixed traffic sensors to estimate future traffic conditions. These are then used to optimize the green split by allocating more green time to platoons of CACC-equipped vehicles. The objective of this system is to maximize the intersection throughput.

Signal Timing Optimization with Connected Vehicle Technology: Platooning to Improve Computational Efficiency. - Liang et al. (2018)
This proposed system utilizes the information of connected vehicles arriving at an intersection to identify naturally occurring platoons. The next step of the system is to identify the optimal departure sequence of these platoons and adjust the green and cycle times accordingly. The objective is to maximize the discharge of the intersection.

Dedicated Traffic Management System

Properties from both articles have been used for the development of the dedicated traffic management system. This system is suitable for traffic that consists of both manually driven vehicles and vehicles that are equipped with cooperative adaptive cruise control (CACC), which are able to form platoons and communicate with each other and the infrastructure. The communication with infrastructure is used by the system to keep track of the real-time speed and location of these vehicles. Furthermore, the system uses fixed traffic signals to count the number of manually driven vehicles between two CACC-equipped vehicles.

Trigger Events
The algorithm starts by doing some checks regarding the CACC-equipped vehicles that are on one of the four approaches and within a certain range (within the zone of interest). If any of the following three trigger events occur, the algorithm will start.

1. A connected vehicle enters the zone of interest.
2. A connected vehicle comes to a complete stop.
3. A connected vehicle departs from the zone of interest.

Speed and Location Estimation
In case that the algorithm kicks off, it starts by sorting all vehicles per lane by their distance from the intersection stop line. The next step is the speed and location estimation of the manually driven vehicles. This is done for the manually driven vehicles between two CACC-equipped vehicles, based on the driving status of these CACC-equipped vehicles, which can be either driving, or stopped in queue. This results in four different cases:

- Both the upstream and downstream vehicle are driving: **Case 1**.
- Both the upstream and downstream vehicle are in a waiting queue: **Case 2**.
- The downstream vehicle is stopped and the upstream vehicle is driving: **Case 3**.
- The downstream vehicle is driving and the upstream vehicle is stopped: **Case 4**.

Each case has a different method for estimating the speed and location of each manually driven vehicle between the two CACC-equipped vehicles. The end result of this step is a list per lane containing the speed and location of all vehicles that are within the zone of interest.

Green split optimization
This is then used for the next step, the green split optimization. The green split and the cycle time have been optimized by maximizing the objective function, which is to maximize the intersection throughput. For a given green split, the intersection throughput can be calculated by predicting the distance each vehicle can travel during the upcoming signal cycle (a cycle of all four signal phases, including the currently active phase). This calculation uses the speed and location of all vehicles, as well as the green and intergreen times of the given green split. This has to be done for multiple green splits in order to find the one with the highest throughput. A genetic algorithm has been applied to reduce the computation times, while still finding a solid green split.

Simulation Results

To test the effectiveness of the dedicated traffic management system, a microsimulation using the PTV Vissim software has been done. Three different main scenarios have been used during this simulation:

1. ***Base scenario***: No CACC-equipped vehicles and a vehicle actuated signal controller.
2. ***Platoon scenario***: CACC-equipped vehicles under different penetration rates and a vehicle actuated signal controller.
3. ***DTM scenario***: CACC-equipped vehicles under different penetration rates and the dedicated traffic management system.

The Platoon and DTM scenarios were split up further into different penetration rates of CACC-equipped trucks and both CACC-equipped cars and trucks. However, the traffic volumes were the same for all scenarios. The scenarios were compared to each other by three key performance indicators (KPI's): the total delay, the average travel time and the average number of stops.

The results show that truck platooning alone does not bring a significant benefit in terms of the traffic flow KPI's. This is likely caused by the fact that trucks are only a small part of the traffic composition and have therefore trouble to form platoons 'on the fly'. The total delay and average travel time decrease when both cars and trucks are able to form platoons under different penetration rates. These results are stronger with higher penetration rates of CACC-equipped vehicles. However, the number of stops do increase for these scenarios. This is caused by the fact that long platoons cause disturbances near bottlenecks and weaving becomes harder for vehicles that have to change lanes.

The dedicated traffic management system does have a negative impact on the traffic flows around the intersection when only trucks are equipped with CACC under low penetration rates. This shows that the system does not work properly under low overall penetration rates of CACC-equipped vehicles. However, the dedicated traffic management system does outperform the base scenario once a certain threshold of overall penetration rate has been surpassed. Nonetheless, this is not the case for the number of stops, similarly to the Platoon scenarios.

When comparing the DTM scenarios to the Platoon scenarios, the results show that a vehicle actuated signal controller outperforms the dedicated traffic management system significantly with only truck platooning under the lowest penetration rates. After a certain threshold of overall penetration rate has been surpassed, the dedicated traffic management system performs better. However, this is not the case at the highest overall penetration rate (80% and higher), where the difference between both is negligible or the vehicle actuated signal controller performs better depending on the KPI.

Contents

1 Introduction

1.1. Problem Statement

The Dutch road network is becoming more congested. Car traffic is estimated to increase between 11 and 30 percent in the Netherlands between the years 2014 and 2030. This increase is 19% up to 45% between the years 2014 and 2040 (Hilbers et al., 2020). The effects of Covid 19 have not been included in this estimation. It is expected that this will damp the increase in car traffic by 2% (Kennisinstituut voor Mobiliteitsbeleid, 2021). The main reason for this increase is the increase in population and wealth and the equal or lower driving costs. Freight traffic is expected to moderately increase with 13% between the years 2014 and 2030 (Hilbers et al., 2020). These effects are not influenced by the consequences of Covid 19 (Kennisinstituut voor Mobiliteitsbeleid, 2021). This higher traffic volume has some negative side effects. A part of these negative side effects are an increase in congestion, a higher fuel consumption and the risk of traffic accidents.

Inefficient traffic control on intersections is another factor that leads to an increase in traffic congestion, deteriorating mobility, more fuel consumption and reduced safety. Connected (and autonomous) vehicles provide the opportunity to improve the traffic control performance of signalized intersections (Guo et al., 2019). Firstly, because vehicle connectivity can be utilized for a better traffic state estimation. This can then be used for optimizing the intersection controller (Guo et al., 2019, Zhong et al., 2021, Gholamhosseinian and Seitz, 2022). Different types of C(A)V-based traffic signal control methods have been proposed in literature. Those showed generally positive results regarding the improvement of traffic flows and reducing fuel consumption.

Another innovation following from vehicle connectivity and automation that can improve the traffic flows, fuel economy and safety is vehicle platooning. The main advantages of platooning lie in emission and energy reduction (Calvert et al., 2019). However, some literature state that vehicle platooning can have a positive effect on traffic flows, which is mostly caused by the smaller headways between vehicles (Zhang et al., 2020).

This research focuses on combining the two innovations that are mentioned above: advanced intersection control based on vehicle connectivity and truck/vehicle platooning. The focus of the truck platoons has been on trucks equipped with connected adaptive cruise control (CACC). These trucks are able to form platoons while driving near each other. The effectiveness of these concepts have been determined by performing a microsimulation on a part of a real logistic corridor.

1.2. Logistic Corridor

During this research a dedicated traffic management system has been developed for truck/vehicle platoons. This system will be simulated on a part of a real logistic corridor to determine its effectivity regarding traffic flows. The considered corridor is located between Royal FloraHolland and the A4 highway (see figure 1.1) and has been introduced in this section. The total length of this corridor is 8.5

kilometres.

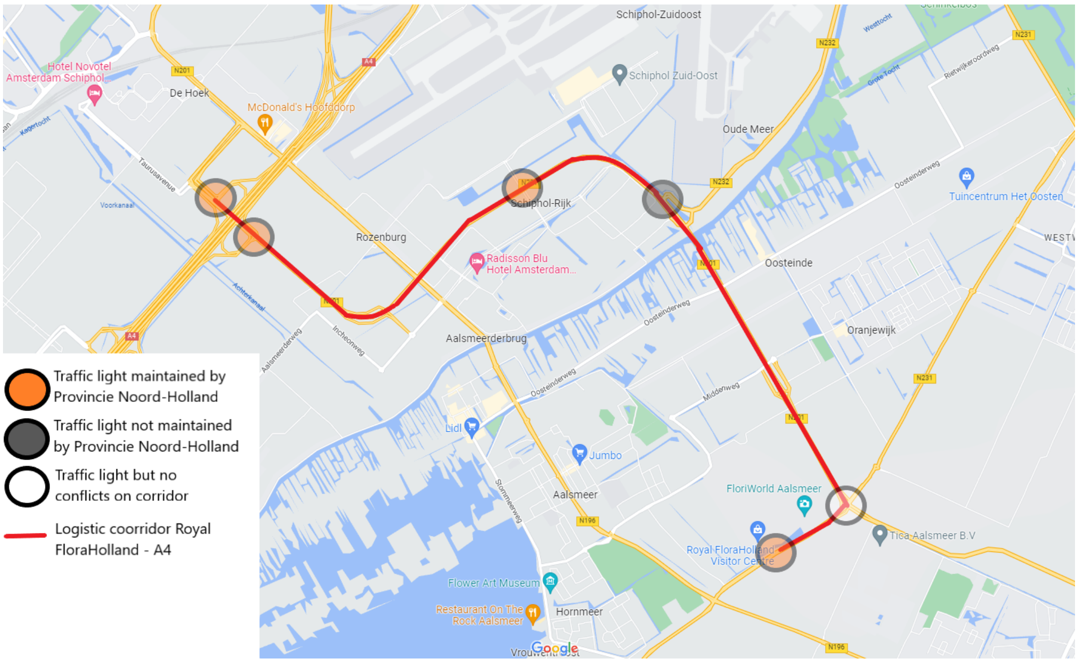


Figure 1.1: The logistic corridor between Royal FloraHolland and the A4 highway.

Royal FloraHolland Aalsmeer is the largest flower auction in the world with average daily sales of 43 million flowers and 5 million plants (Visit Aalsmeer, 2022). This generates a lot of freight traffic on the surrounding road network. The focus of this research is one of the routes that the trucks drive, which follows the arterial roads N201 and N231 between Royal FloraHolland and the A4 highway. This route contains 6 signalised intersections from which one has no conflicts on the corridor due to a fly over (presented by the white circle in figure 1.1). Four of the six signalised intersections on the corridor are maintained by the Province of Noord-Holland (presented by the orange circles in figure 1.1). These intersections are part of a field experiment (CTC: Connected Transport Corridor) (Editor DMI, 2022), where some trucks are connected to the traffic lights. The connection is used to give the trucks priority and prevent some stops at the intersections. The grey coloured intersection (figure 1.1) on the corridor is not maintained by the Province of Noord-Holland and is not a part of the CTC experiment either.

Royal FloraHolland is not the only source that generates freight traffic on and nearby the corridor, since the corridor is also located next to Schiphol Airport and Schiphol Logistics Park, which also generates a significant amount of freight traffic.

The choice for this particular corridor is motivated by the ongoing CTC experiments. This master thesis is part of an internship at the Province of Noord-Holland, which installs and maintains the intelligent traffic lights for this project. Therefore, it is a logical step to choose the logistic corridor that is part of the experiment performed by the Province of Noord-Holland. This choice will offer the province valuable insight into the possible traffic flow effects that an enhanced intelligent traffic signal controller can provide.

1.3. Research Objective

The congestion on the logistic corridor between Royal FloraHolland and the A4 highway is increasing. The objective of this research is to develop a dedicated traffic management (DTM) system using vehicle connectivity and platooning capabilities, and to evaluate the impact it has on the traffic flows on an intersection. Mixed traffic conditions that consists of cars and heavy trucks have been considered for this. In order to determine the extra benefits of the DTM system, the effects that truck and/or vehicle platooning have were evaluated separately as well.

Both intersection traffic control in combination with vehicle connectivity and truck/vehicle platooning are well researched topics. However, there is still a gap in research regarding the combination of both topics. So another objective is to contribute to this research and fill in a part of this research gap.

1.4. Research Questions

The research objective that has been formulated in the previous section results into the following main research question:

What dedicated traffic management system can potentially improve the traffic flows on a logistic corridor where truck platoons drive in mixed traffic (consisting of regular and connected vehicles) and what are the traffic flow effects on this corridor when the system is implemented?

In order to completely answer this main research question, multiple aspects have to be looked into. These aspects have been included in the sub research questions:

1. *What are possible intersection traffic control types that can be used for partially connected traffic?*
2. *What is the state-of-the-art of truck-platooning in arterial and urban traffic?*
3. *What are the requirements for a dedicated intersection control system that controls mixed traffic which partially consists of truck platoons?*
4. *Which of the researched advanced intersection control systems are the most suitable for the logistic corridor?*
5. *What are the properties of the dedicated traffic management system that will be used on the intersection on the logistic corridor?*
6. *What micro-simulation software can be used for simulating the effectiveness of the dedicated traffic management system on the logistic corridor?*
7. *What is the effectiveness of the current traffic control strategy on the intersection on the logistic corridor?*
8. *What is the effectiveness of platooning on an intersection on the logistic corridor?*
9. *What is the effectiveness of the proposed dedicated traffic management system when it is implemented to an intersection on the logistic corridor?*

1.5. Methodology & Thesis Outline

Different steps have to be executed in order to answer all research questions from section 1.4. This section presents the methodology for this research. Furthermore, the outline of the thesis has been given in this section as well.

1.5.1. Literature Study

The research is initiated with a literature study, which is performed in chapter 2. Upon completing this literature study, sub-research question 1 and sub-research question 2 have been addressed and answered.

The first objective of the literature study is to enhance the understanding of intersection control systems that utilize vehicle connectivity in heterogeneous traffic conditions. Various kinds of these intersection control systems have been explored within the literature. This study elaborates the characteristics, which are used to distinguish the different intersection control systems. Subsequently, this serves as the basis to define the requirements for the DTM system that have been developed in this thesis.

The second objective of the literature study is to get more familiar with the state-of-the-art of truck/vehicle platooning (in mixed traffic), so that the properties of these systems can be applied to the model that has been created later on during the research. Furthermore, the potential benefits of platooning near and on intersections have been explored.

1.5.2. Development of the Dedicated Traffic Management System
After completing the literature study, the DTM system that has been applied to the logistic corridor can be formulated. This answers sub-research questions 3, 4 and 5, which has been done in chapter 3.

Based on the identified characteristics of the available intersection control systems discussed in the literature study, the requirements for the DTM system have been determined. From these requirements, the most suitable articles proposing an intersection control system have been identified. These serve as the primary source of inspiration for formulating the properties of the DTM system that has been developed in this thesis.

1.5.3. Model Development
After determining the properties of the dedicated traffic management system for the intersection on the logistic corridor, the model to simulate the effectiveness of this system can be developed. This is done in chapter 4.

The effectiveness of the dedicated traffic management system has been determined by performing simulations. The first step in doing this was to determine which simulation software package can be used for this, which has been done by comparing different options based on multiple criteria.

After determining the micro-simulation software package, the model creation can be started. The road network of the corridor has been implemented into the model. The intersection control system that is used in practice has been recreated into the model, which can be used for determining the traffic flow effects on the corridor when no measures are applied. The DTM system that has been developed in the previous step of the research has been implemented into the model as well.

Different vehicle types have been implemented into the model to create a more realistic simulation. For the base scenario, the current traffic volume and composition have been used. The data for this has been retrieved from the Province of Noord-Holland. For other scenarios the connected vehicles with platooning capabilities have to be modelled by adapting the vehicle properties.

A face validation has been performed to check if the model is an accurate representation of the real system. Based on this some parameters have been adapted if necessary.

1.5.4. Results, Conclusion & Recommendations
The next step is to run the microsimulation using different scenarios. These scenarios were chosen such that all sub-research questions can be answered. The results that follow from these simulation runs were used to answer sub-research questions 7, 8 and 9, which has been done in chapter 5 and appendix D and F.

Based on these results, the conclusions regarding the performance of truck/vehicle platooning and the DTM system have been drawn in chapter 5.3.

Chapter 6 provides a summarized answer to all sub-research questions based on this report. Then the limitations of the research and recommendations have been given.

1.6. Scope
This study focuses on both signalized intersection control in combination with vehicle connectivity and truck/vehicle platooning. The main focus has been on the development of the dedicated traffic management system. However, the performance of truck/vehicle platooning has been evaluated as well.

The effectivity of the developed DTM system has been tested by doing a microsimulation on a real logistic corridor. However, this corridor has been narrowed down within the simulation model, due to time and computational constraints. The length of the used corridor is 4.9 kilometres instead of the 8.5 kilometres of the whole corridor. The system has been implemented to only one intersection, which is the intersection between the N201 and the Koolhovenlaan. The two surrounding intersections have been a part of the model as well, but those have not been evaluated. The part of the logistic corridor that has been used in the microsimulation model is presented in figure 1.2.

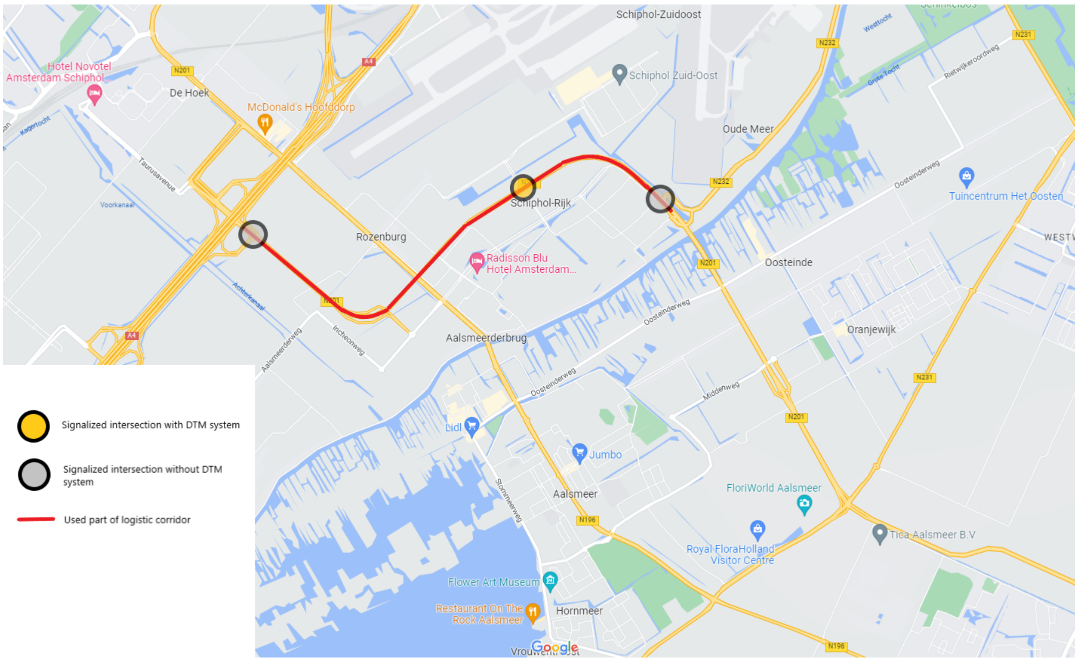


Figure 1.2: The part of the logistic corridor between Royal FloraHolland and the A4 highway that will be used in the microsimulation model.

2
Literature Review

The literature review has been done in this chapter. Firstly, a brief description of the current state of traffic signal control has been given in section 2.1. This describes the current state of intersection control and provides some examples of intelligent intersection control that is being tested/applied in reality. Section 2.2 describes the different type of intersection control systems using connected (and autonomous) vehicle data that have been described in literature. Finally, section 2.3 gives an insight into truck/vehicle platooning.

2.1. Current State of Intersection Control

Before new innovations in traffic signal control can be explored, a brief summary of the current state of intersection control will be given in this section. The intersection that will be considered in this study is managed using a vehicle actuated signal controller.

A vehicle actuated signal controller uses sensors to measure the current upstream traffic state of the intersection. This is used to update the signal phase and timings plan. The most common sensors that are used for this are induction loops (Box and Waterson, 2010). There are multiple functionalities that these are used for at signalized intersection in the Netherlands (van Dijck et al., 2018). Firstly, to detect the presence of a vehicle, which can be used for a green request. This can be done with the head loop, which is located one or two metres before the stop line, or by loops which are located further away from the stop line. Short inductive loops can be used for counting vehicles. Another function of the induction loop is to measure the headway between vehicles. This can be used for:

- Green time extension for discharging the queue.
- Green time extension for arriving vehicles.
- Green time extension for safely ending the green phase.

The efficiency of traditional vehicle actuated signal controllers can be improved in multiple areas. Firstly, by coordinating adjacent signalized intersections (Hamilton et al., 2013). Secondly, by utilizing the advancements in vehicle connectivity and automation (Guo et al., 2019), which will be discussed in section 2.2.

As stated in chapter 1.1, some field experiments regarding intelligent traffic management are being executed on the considered logistic corridor (Editor DMI, 2022). This experiment is a part of the Connected Transport Corridor (CTC). Within the experiment, freight traffic will get priority on the specific intersections where the intelligent traffic signal controllers (iVRI's) are installed. The expected benefits of this experiment are time savings for the equipped trucks. Moreover, some environmental benefits are expected as well, since the trucks will save fuel by having to brake less, which will also marginally reduce noise pollution in the area.

Another project that implements intelligent traffic lights in the Netherlands is performed by the Partnership Talking Traffic (Talking Traffic, 2022). The idea of this project is to transform traffic signal controllers

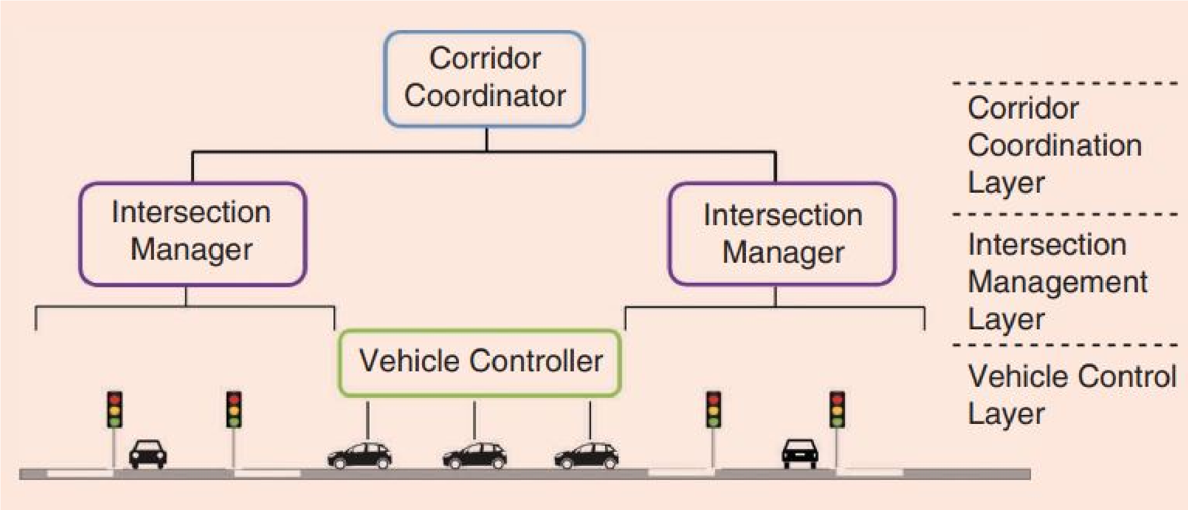


Figure 2.1: The three hierarchical layers for intersection management (Zhong et al., 2021)

to intelligent traffic signal controllers (iVRI's). These iVRI's use the smartphone data of nearby road users. From this data, the traffic volumes, traffic composition, arrival times and routes can be determined. This is used as extra input for the signal controller to improve traffic management and data exchange with road users. For instance, the time when a traffic light will turn green can be communicated to road users so that they can adjust their speed accordingly. Benefits of this system are improved comfort, improved traffic flows and lower emissions.

2.2. Categorization of Intersection Control

Extensive research has been conducted on intersection control. The introduction of vehicle connectivity and automation resulted in even more research areas regarding intersection control. This section will give an insight into the categorization of the research into this topic.

2.2.1. SIM and AIM

The single most important task of intersection management is to separate the time-space conflicts among the crossing vehicles. This will ensure safety between multiple conflicting traffic streams with the objective to reduce the delay as much as possible. Two types of intersection control can be differentiated from each other (Zhong et al., 2021). Firstly, signalized intersection management (SIM) which manages the traffic on an intersection by assigning priority to a group of vehicles with traffic control signals. Autonomous intersection management (AIM) is the second type. Vehicles are considered individually within this intersection management type.

Connected and automated vehicles (CAV's) are expected to play a substantial role in mitigating traffic accidents, congestion and pollution on intersections (Antonio and Maria-Dolores, 2022). However, the exact role CAV's have in this can be different in each type of intersection management. Within SIM, the real-time CAV traffic data is incorporated into the signal controller so that it can adapt the signal phase and timing (SPaT) plans accordingly. Within AIM on the other hand, the intersection can be signal free, due to vehicle connectivity.

2.2.2. Hierarchical Layers

The next point on which intersection control can be categorized are the hierarchical layers. Three hierarchical layers can be distinguished from existing intersection management: Corridor Coordination Layer, Intersection management (Trajectory Planning) Layer, and Vehicle Control Layer. These layers are visualized in figure 2.1 and will be explained in this section.

Corridor Coordination Layer
The first layer is corridor coordination layer, which is responsible for the coordination between multiple consecutive intersections. This kind of coordination is common practice on a major arterial under SIM (Zhong et al., 2021). Fixed-time SPaT plans are commonly used in practice to achieve this corridor coordination. A green wave is an example of the corridor coordination layer (Trigion, 2022).

Another real-world example of a traffic control system in the corridor coordination layer is the Split Cycle Offset Optimisation Technique (SCOOT) (Department for Transport, 1995). The system uses data obtained from fixed traffic sensors to adjust signal timings accordingly. It optimises the split, cycle and offset of multiple intersections in an urban traffic network. This also assures coordination between multiple intersections.

Intersection Management (Trajectory Planning) Layer
The second layer is responsible for determining and communicating the order at which (groups of) vehicles can traverse the intersection. Under AIM, this layer determines the sequence in which vehicles can cross the intersection. This is done by allocating the limited space-time resources of an intersection to determine the trajectory of each individual vehicle. Therefore, AIM is often called trajectory planning (Zhong et al., 2021).

Under SIM, the order in which vehicle groups can cross the intersection is determined in this layer. The signal phases that have conflicting movements are alternated based on a predefined phase sequence (Zhong et al., 2021).

Vehicle Control Layer
The final layer is the vehicle control layer, which focuses on the speed and direction of an individual vehicle. The importance of this layer is increasing with the introduction of advanced driver assistance systems (ADAS). This shifts the vehicle control away from the human driver to automated systems. Ultimately, it is expected that CAV's take over all control of the vehicle.

2.2.3. Advanced Traffic Control in the CAV Environment

The intersection management (trajectory planning) layer can be further categorized into three signal control methods, which has been done by Guo et al. (2019). However, these methods do require (partial) vehicle connectivity and automation. The goal is to improve the intersection performance (e.g. reducing fuel consumption or travel times). The three signal control methods are listed below:

1. The driver (CV) or the vehicle control system (CAV) is instructed on how to properly operate the vehicle. These instructions are based on the signal and vehicle data.
2. The signal timing and phases can be optimized by the signal control system based on CV data in order to improve the intersection performance.
3. The signal vehicle coupled control (SVCC) system can optimize the vehicle operations and signal timing and phases simultaneously under the CAV environment.

2.2.4. General Optimization Problem

The three intersection control methods discussed in section 2.2.3 can be formulated by a general arterial traffic control problem as an optimization problem (Li et al., 2014), which has been done by Guo et al. (2019). Within this problem a certain performance index J, which is usually mobility- or sustainability-based, will be optimized over a finite time horizon [0, K]. This generalized optimization problem that is given in this section, will be applied in section 2.2.5 to three different signal control methods than have been discussed in section 2.2.3.

The abbreviations used are as follows:

- J is the performance index over a finite time horizon [0, K]. J is usually mobility or sustainability based, or a combination of both.
- x(k) are the state variables.
- d(k) are the environmental inputs.

- The decision variables are a sequence of control inputs u(0), u(1), ··· u(K).
- Constraints include initial conditions, traffic flow dynamics and vehicle dynamics.

The problem can be formulated as follows:

$$min_{u(k)} J = f[x(K)] + \sum_{k=1}^{K} g[x(k), u(k), d(k)]$$

Subject to

(i) State equation

$$x(k+1) = x(k) + h[u(k), d(k)], k = 1, \cdots K-1$$

(ii) Initial and end state conditions

$$x(1) = x_0, x(K) = x_K$$

(iii) Constraints of state, environment and input variables

$$\varphi[x(k), x(k), d(k)] \in \Omega, k = 1 \cdots K$$

2.2.5. General Optimization Problem Applied to Intersection Management

The previously formulated optimization problem can be applied to the three types of single intersection management methods that are formulated in section 2.2.3. The state variables, control inputs, environmental inputs and constraints differ between the methods.

Advanced Driver Guidance based on CAV's

When the previous optimization problem is being applied to this control method, the following state variables, control inputs, environmental inputs and constraints are used.

- **State variables**: the vehicle speeds and positions.
- **Control inputs**: vehicle accelerations and turn angles.
- **Environmental inputs**: signal timings and phases.
- **Constraints**: certain conditions, for example the physical limits of accelerations, speed and turn angles.

Different optimal solutions can be achieved from this optimization problem, which depends on the objective. These are achieved by speed guidance and are mostly to reduce fuel consumption or mobility based (Guo et al., 2019). When CAV's are considered instead of CVs, the driving strategies are executed by the automated systems. This takes away some of the uncertainty caused by human control.

Advanced Traffic Signal Control with CAV's

The following state variables, control inputs, environmental inputs and constraints are derived from applying the general optimization problem to this control method:

- **State variables**: queue length, travel time.
- **Control inputs**: Signal phase and timing plans.
- **Environmental inputs**: the arrival vehicles (actuated and planning-based control), arrival platoons (platoon-based control).
- **Constraints**: cycle length, and minimum and maximum green times.

The advanced traffic signal control method with CAV's is typically designed for a single intersection. This can then be extended to corridors, and even networks. In order to account for coordination between intersections, the objective function will have to altered as well.

The objective function can be derived by two methods for corridors and networks. These methods differ to each other regarding the information that is available at the individual intersections. First of all, the centralized methods, where the optimization problem is formulated by summing the objectives of the intersections or by defining a general objective for all intersections combined. The second method is the distributed method. For this method it is assumed that the traffic information of the neighbouring intersections is known. This acts as the environmental input for the optimization problem. The benefit of this method is that it requires less computational capacity. However, it does not help to reach the global optimization results.

Guo et al. (2019) found that three advanced CAV-based traffic signal control types can be specified by the general optimization problem. These are listed below and will be described in this section.

1. Actuated traffic signal enhanced using CAV's data.
2. Platoon-based traffic signal control based on CAV's coordination.
3. Planning-based traffic signal control based on CAV's coordination (including transit priority traffic signal control enhanced by CAV's coordination).

These control methods differ from each other in the way that the future traffic states are predicted based on the CAV's data.

1. **The actuated (adaptive) traffic signal control** estimates the current traffic states such as the queue lengths. Then the future traffic measures (e.g., average volume) are predicted based on the control decisions (such as to extend or terminate certain phases) that could be generated. It is considered to be a passive method, since it does not make a detailed prediction of future traffic states. It does only adjust the signal phase and timings plan according to current traffic states.

An example of actuated traffic signal control systems using C(A)V data is an adaptive intersection management system proposed by Gradinescu et al. (2007). This system uses wireless communication between vehicles and fixed controller nodes on the intersection. This system uses the data that vehicles send to the infrastructure through V2I communication to estimate the demand on each approach of the intersection, which is then used for calculating the optimal cycle length for the signal controller. Test results of this system show that it brings improvements in terms of total delay and emissions in comparison to a real pre-timed signal controller.

2. The problem is simplified by **the platoon-based signal control method** by categorizing the individual vehicles into a (pseudo) platoon. The arrivals or trajectories of these platoons are then predicted and the timing plan is adjusted accordingly.

Different platoon-based traffic signal control methods have been proposed. Examples of these are written by:

- Pandit et al. (2013), where a platoon-based 'oldest arrival first' algorithm for an intersection management system is proposed. This method has a positive effect on the total delay in the system when the traffic inflow rates are not large and the penetration rate of connected vehicles is high enough. Downsides of this research are that it is only tested on a single four-legged intersection under homogeneous traffic conditions.
- He et al. (2012), where a platoon-based arterial (network) traffic signal control is presented that works for multiple modalities. This model has been simulated with the PTV VISSIM software (PTV Group, 2021) under both under-saturated and over-saturated conditions. The results regarding the average vehicle delay are positive for the proposed method under a penetration rate of 40% or higher.
- Xie et al. (2011), who proposed a platoon-based self-scheduling algorithm for real-time traffic management on a network. This algorithm generates two possible actions, which are to extend or terminate the current phase. The goal is to keep the formed platoons moving rather than clearing the queues. The proposed method performed well on bottleneck intersections and for coordination of the vehicle flows between intersections.
- Bashiri et al. (2018), where a reservation-based intersection control system is introduced that derives optimal schedules for vehicle platoons. This system has been simulated on a single four-legged intersection with homogeneous traffic. The results show that the system has a positive effect on the delay and throughput on the intersection compared to the regular intersection control.

- Liang et al. (2018), where a platoon-based intersection control system for mixed traffic is introduced. This system uses the information of CV's to form naturally occurring platoons, which are used to optimize the intersection control. The system sends instructions the platoon leading vehicles, which must be an autonomous vehicle, regarding the acceleration and deceleration behaviour. This system has been simulated on a single four-legged intersection under different penetration rates. The results show that the average delay is significantly reduced with a CV penetration rate of 40% or higher.

3. The detailed individual trajectories of the vehicles are taken into account by the **planning-based signal control**. The signal timing and phases are optimized in a forward time horizon.

An example of a planning-based signal control system is proposed by Feng et al. (2015), where a optimization-based real-time traffic signal control method is proposed. This system assumes that the speed and location of a CV is known. The upstream part of the road leading towards an intersection is divided into three regions, free-flow, deceleration and queuing. This is then used to estimate the driving status of all unequipped vehicles. Based on this an arrival scheme of all vehicles is created, which is then used to optimize the green split, using a two-level optimization model. The results show that this system can reduce the total delay by 16.3% under a high traffic demand in comparison to a vehicle actuated signal controller.

Signal Vehicle Coupled Control (SVCC) based on CAV's
The research in traffic signal control and vehicles was traditionally done in separation from each other. Individual vehicle characteristics were not considered in the research in traffic signal control. However, traffic signal control and vehicle control depend on each other in reality. This is because drivers react to the traffic signals and this influences the vehicle performance, such as fuel consumption and emissions. Moreover, in actuated control, the signal timings are adjusted by the traffic flows caused by individual vehicles.

The introduction of connected vehicles allows a better information exchange between vehicles and signals. This used to be quite limited in the past, when only the arrival of a set of vehicles could be detected by the sensors of the signal controller. The signal controller communicated back to the vehicles close to the intersection by changing the signal colour. Therefore, the concept of implementing a coupled signal and vehicle control has been possible with the introduction of CAV's, since the signal controller and vehicles can exchange real-time information.

When the general optimization problem is applied to this control method, the state variables, control inputs, environmental inputs and constraints are as follows:

- **State variables**: queue length, travel time and vehicle states (for example the throttle and exhaust system states or the battery state (if the vehicle is electric)).
- **Control inputs**: signal timings and phases, and the vehicle trajectories.
- **Constraints**: minimum/ maximum green times, cycle lengths and car following models.

The optimization problem of Signal Vehicle Coupled Control is more complex than for Advanced Driver Guidance based on CAV's and Advanced Traffic Signal Control with CAV's, since it involves both linear and nonlinear states, discrete and continuous control inputs, and other complex constraints.

2.3. (Truck) Platooning

Vehicle platooning is not a new concept, since the first research in the topic started in the 1970s (Martinez-Diaz et al., 2021). The first large-scale pilot test was performed in California in the 1990s. Due to the research and development in vehicle connectivity and cooperation, vehicles are able to communicate to each other through short range wireless communication. This allows the introduction of cooperative adaptive cruise control (CACC), which led to the development of 'vehicle platooning' and 'truck platooning' (Calvert et al., 2019).

2.3.1. Platooning Classification

There are five criteria that are used to classify platoons (Martinez-Diaz et al., 2021), which are listed below. These are then subdivided into multiple categories.

1. Vehicle type
   - Homogeneous
     Only similar vehicles in terms of their size and automation type can form a platoon.
   - Heterogeneous
     Different vehicle types can form a platoon together.
2. Platoon size
   - Finite
     The maximum platoon length is a finite number.
   - Infinite
     The maximum platoon length in infinite.
3. Information flow topology
   - Nearest vehicles
     Each vehicle receives/exchanges information from/with the n vehicles ahead.
   - Nearest vehicles and leader
     Each vehicle receives/exchanges information from/with the n vehicles ahead, plus the leader.
4. Formation policy
   - Opportunistic (on the fly)
     Only the CAV's that happen to drive consecutively in a lane can form a platoon.
   - Cooperative
     All CAV's that are in a certain range will attempt to join a platoon.
   - Online, dynamic or in real time
     A CAV announces its destination and/or route before it will start or during the journey.
   - Offline, static or scheduled
     CAV trips are announced in before a trip.
   - Merging policies
     Accelerate, decelerate or hybrid strategies.
5. Following policy
   - Constant space gap
     A fixed space gap is held between the following vehicles.
   - Constant time gap
     A fixed time gap is held between following vehicles.
   - Variable gap
     A variable space or time gap is held between following vehicles based of for instance the road features.

2.3.2. Benefits

Literature has described several benefits that vehicle platooning can provide. This section will give a brief summary of those (expected) benefits.

The improvement of traffic flows is one of the potential benefits that platooning can bring, which is the main focus of this research. Most of the traffic flow improvements are expected due to the small headways between the vehicles while maintaining a relatively high speed. The extend of the traffic flow benefits depends on the exact scenario, e.g. the penetration rate of C(A)V's, the platoon length, the car-following policies, the infrastructure, etc. (Martinez-Diaz et al., 2021).

The focus of this research is on platooning near and on signalized intersections, which are bottlenecks in an urban and regional traffic networks. Lioris et al. (2017) state that the bottleneck capacity of an intersection can be increased by 200 to 300 percent if vehicles cross the intersection as a platoon. However, in order to reach this, a 100% market penetration of CACC equipped vehicles and enough road capacity to store the growing queues in front of intersections are required. Moreover, the delay and travel time experienced by the vehicles will not be effected despite the increase in demand. Another research in vehicle platooning is performed by Kockelman et al. (2016). The results show that the combination of vehicle platooning and intelligent traffic control could potentially increase the capacity by 200 up to 300 percent compared to the current intersection management.

However, most research regarding vehicle and/or truck platooning has been done for freeway traffic. Results show that this drastically increase the road capacity under the right conditions (Kockelman et al., 2016; Sala and Soriguera, 2020). However, not all studies show traffic flow benefits for vehicle platooning. Calvert et al. (2019) have evaluated the traffic flow effects of truck platooning on a Dutch highway. however, this research did not show improved traffic flows in the network when truck platooning is applied. The results are slightly negative with a traffic demand below 80% and a large negative effect is observed under congested traffic conditions. Another risk of vehicle platooning is that long platoons could cause congestion if their integrity is lost near bottlenecks (Martinez-Diaz et al., 2021). This could increase the number of acceleration/deceleration maneuvers around platoons by vehicles that are not a part of the platoon, since it is harder to merge to a different lane (Calvert et al., 2019). Furthermore, the number of acceleration/deceleration maneuvers of the platooning vehicles itself could also increase to maintain the platoon.

Other benefits of vehicle platooning that have been in literature are reduced fuel consumption and emissions (Brummitt and Khan, 2022; Zhang et al., 2020), increased safety (Alam et al., 2015) and lower labour costs (Janssen et al., 2015).

2.4. Conclusion

The literature review is kicked-off with a short overview of the currently used intersection control systems. Then some examples of projects that aim to improve these systems using vehicle connectivity (and automation) were given. The objective of this section is to serve as an introduction into this research that dives deeper into intelligent intersection control, which has been combined with truck/vehicle platooning in this study.

Section 2.2 provided an overview into the categorization of intersection control in combination with connected vehicles. This is used in section 3.1 to filter out the right articles proposing an intersection control system that is used as the main inspiration for the development of the DTM system for this study.

Vehicle platooning can be classified differently based on multiple categories, as stated in section 2.3. These categories are used in section 4.2.1 to explain the properties of the cars and trucks that are able to form platoons in the microsimulation model. Furthermore, section 2.3 stated that vehicle platooning could bring potential traffic flow benefits near and on intersections. However, more research in this area is still required. Hence, this research dives deeper into this topic of truck/vehicle platooning in combination with intelligent intersection control that utilizes connected vehicle data.

3

Development of Dedicated Traffic Management System

The categorization of intersection management, as described in chapter 2.2, is used for filtering the right literature that serves as the main inspiration for developing the dedicated traffic management system in this study. This chapter then continues with a brief summary of the articles found. Following from this summary, the most important aspects of both articles are combined and the dedicated traffic management system has been formulated.

3.1. Filtering Intersection Management Literature

The first step that has been elaborated in chapter 2.2 is the choice between signalized intersection management (SIM) and autonomous intersection management (AIM). For this research, literature about SIM is considered, since AIM will only work under a 100% penetration rate of connected (and autonomous) vehicles.

The second choice that had to be made is on which hierarchical layer the intersection management has to serve. The main focus of this thesis is on a single intersection within a logistic corridor. This means that the focus is on the 'intersection management' layer.

Single intersection management in combination with vehicle connectivity can be subdivided further into three categories. These have been explained in detail in chapter 2.2.5 using the general optimization problem. From the three categories, the focus of this thesis is on the second type: 'Advanced traffic signal control based on CAV's, since the focus is on traffic signal control and not on vehicle control.

This control method can be differentiated further by the way that the future traffic state is predicted as is explained in chapter 2.2.5. Since intersection traffic control is combined with truck platooning for this research, literature about the Platoon-based traffic signal control based on CAV coordination is considered.

Following from this filtering steps, two articles stood out. These were used as the main inspiration for the development of the dedicated traffic management system. These articles are:

- Traffic signal control by leveraging Cooperative Adaptive Cruise Control (CACC) vehicle platooning capabilities.
  Liu et al. (2019)
- Signal Timing Optimization with Connected Vehicle Technology: Platooning to Improve Computational Efficiency
  Liang et al. (2018)

The remaining of this chapter gives a summary of the important properties proposed by both articles.

Then the most important properties are combined and the dedicated traffic management system is formulated.

3.2. Traffic Signal Control by Leveraging CACC Vehicle Platooning Capabilities

This is a cooperative signal control algorithm proposed by Liu et al. (2019). It gathers data sets by CACC-equipped vehicles and traditional fixed traffic sensors, which it uses to predict the future traffic states. The signal timings are adapted based on these predicted future traffic states. This algorithm assumes homogeneous traffic conditions, where only car traffic is considered in combination with CACC-equipped cars under various penetration rates.

3.2.1. Objective Function

The objective is to maximize the overall throughput of the intersection. This is chosen above minimizing the overall delay, because it allows the optimization problem to be largely simplified. Minimizing the overall delay requires the prediction of all vehicle trajectories. To make this prediction, a comprehensive sensor network is needed to measure the real-time speed and location of each vehicle. Furthermore, a powerful computer is required for all calculations to determine the optimal solution. Throughput maximization depends on estimating the number of vehicles that can pass the intersection during the length of a cycle. For this, the number of vehicles that queue up and how the queue discharges during the green phase need to be determined. Simple kinematic theory and traffic wave theories can be used for this process, which simplifies the problem compared to minimizing the overall delay.

The objective function will be optimized by allocating optimal green times to the different phases. The signal controller depends the green time allocation on two factors: the total number of vehicles queued on each intersection approach and the highest local CACC market penetration. The intersection approach with the highest number of queued vehicles will require a longer green time within the cycle to let more vehicles pass the intersection. If there are similar queue lengths on two or more intersection approaches, the direction with the most CACC equipped vehicles will be favoured by the algorithm due to the fact that the throughput of that direction will be higher.

Liu et al. (2019) have implemented the cooperative signal control to an 8-phase traffic controller, which is shown in figure 3.1. The following signal phase and timing constraints have been considered:

$$\sum_{l=1}^{4}(g_l + t_{yr}) = C$$

$$\sum_{l=5}^{8}(g_l + t_{yr}) = C$$

$$\sum_{l=1}^{2}(g_l + t_{yr}) = \sum_{l=5}^{6}(g_l + t_{yr})$$

$$\sum_{l=3}^{4}(g_l + t_{yr}) = \sum_{l=7}^{8}(g_l + t_{yr})$$

Where:

- C: the cycle length.
- l: the phase ID.
- g: the green time.
- t_{yr}: the yellow and all red time

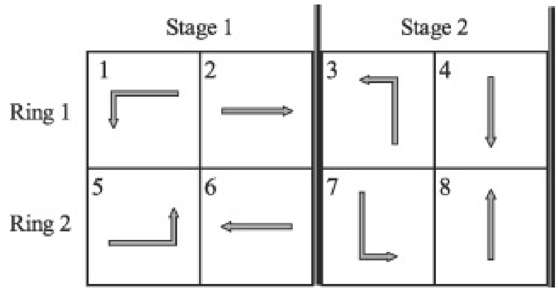


Figure 3.1: The 8-phase traffic controller used by Liu et al. (2019).

3.2.2. Vehicle Distance Prediction

For the implementation of this algorithm, it is required to estimate the distance the subject vehicle can travel during the upcoming signal cycle. This depends on the fact whether a vehicle will make it through the green light or not. Two situations in which this can happen are assumed by the algorithm, for which different calculation methods are used. Firstly, if the vehicle can keep cruising up to the intersection stop line. Secondly, if the vehicle will join a waiting queue and will then have to accelerate again. So depending on the situation, the distance the subject vehicle can travel is calculated.

3.2.3. Speed and Location Estimation

The calculations that are formulated in section 3.2.2 require the speed and location of the subject vehicle as input.

In order to perform the calculations that are required to predict the distance that the subject vehicle can travel, the speed and location of this subject vehicle is required. The CACC-equipped vehicles can send this data directly to the intersection controller through V2I communication. However, the data of the manually driven vehicles has to be collected by fixed sensors (e.g. loop detectors). Within this algorithm, it is assumed that the speed and location of the first and last vehicle are known. For the first vehicle, this can be collected by the sensors located at the intersection. For the last vehicle, this has to be collected by more upstream sensors. For instance, the departure sensors at the upstream intersection can send this data to the intersection controller. The following equations show the relation between the speed and position of the final vehicle and the measurement data of the upstream sensor. It is assumed that the vehicles drive at a constant speed. However, this assumption does not hold in oversaturated traffic conditions where vehicles cannot drive at free flow speed.

$$v_0^{last} = v_{measure}$$

$$d_0^{last} = d_{sensor} - v_{measure} * (t_0 - t_{measure})$$

Where:

- $v_{measure}$: the measured speed when the last vehicle passes the upstream sensor.
- d_{sensor}: the distance between the upstream sensor and the intersection stop line.
- $t_{measure}$: the time stamp at which the last vehicle passes the upstream sensor.

The upstream fixed traffic sensors will also be used for counting the number of manually driven vehicles between two CACC equipped vehicles. The speed and location of the manually driven vehicles between two CACC equipped vehicles is estimated in four cases. The cases differ from each by the driving states of the first CACC-equipped vehicle that is ahead of the manually driven vehicle and the first CACC-equipped vehicle behind. Two driving states are assumed, which are either stopped in queue or driving. This leads then to four different cases:

- Both the upstream and downstream vehicles are driving: **Case 1**.
- Both the upstream and downstream vehicles are in a waiting queue: **Case 2**.
- The downstream vehicle is stopped and the upstream vehicle is driving: **Case 3**.
- The downstream vehicle is driving and the upstream vehicle is stopped: **Case 4**.

3.2.4. Implementation of the Algorithm

The proposed traffic signal control algorithm is executed at the start of each signal cycle, where the signal phase and timings plan (SPaT) of the intersection is updated. The algorithm iterates through the possible green splits among all eight phases until the optimal solution with the maximum throughput has been found. In case of no demand in one of the directions, the phase is skipped. A fixed and pre-determined cycle length is assumed in this algorithm. Per iteration step, the speed location and CACC string status data is collected for all CACC vehicles within the communication range of the intersection. Furthermore, the speed and count data of the manually driven vehicles is collected by the upstream fixed sensors. Both data sets are then used to determine the speed and location of all manually driven vehicles with the methods that are mentioned in section 3.2.3. The next step is to predict the distance that each vehicle travels in the upcoming cycle with the methods from section 3.2.2. Finally, the number of vehicles that can pass the intersection per direction is determined.

The computation speed of the algorithm is increased by adopting a heuristic method. The speed is further increased by only considering integer numbers when calculating the green splits. Furthermore, once the objective function starts to decline the search for more green splits will be stopped. The end result of the algorithm is an updated green split. Figure 3.2 shows all the steps that are taken in the algorithm.

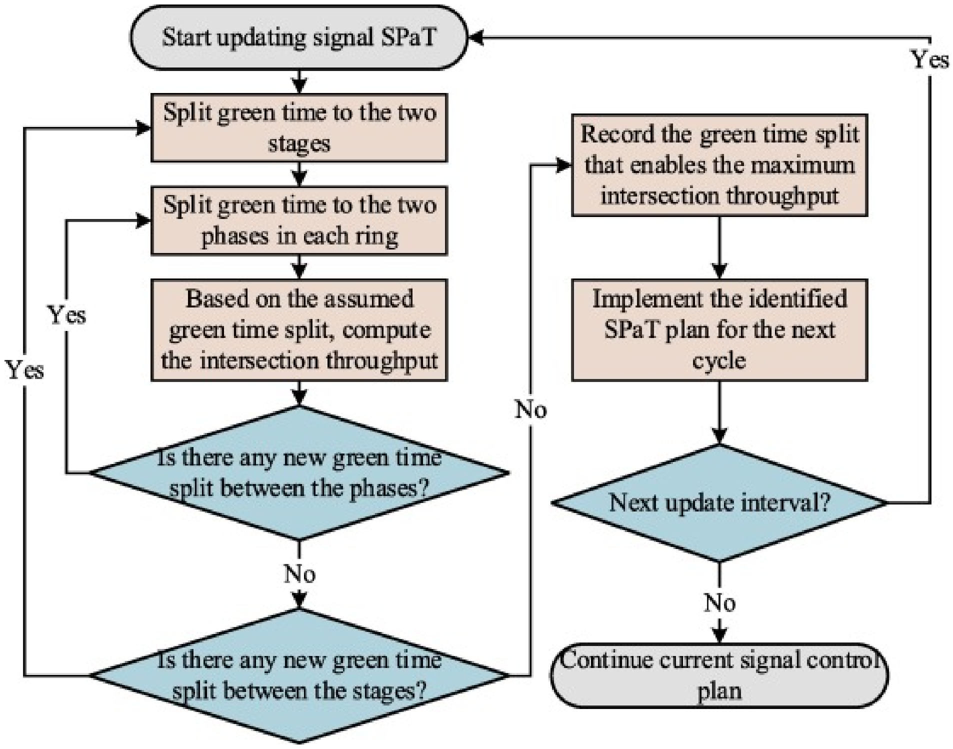


Figure 3.2: The flowchart of the traffic signal control algorithm.

3.3. Signal Timing Optimization with Connected Vehicle Technology: Platooning to Improve Computational Efficiency

Liang et al. (2018) have proposed a real-time traffic signal optimization algorithm that is suitable for mixed traffic with CAV's and manually driven vehicles. This algorithm utilizes the information from the CAV's to identify naturally occurring platoons that arrive at the intersection. These are then used to select the optimal signal timings in order to minimize the total vehicle delay.

3.3.1. Algorithm Explanation

The proposed algorithm consists of two optimization levels. The upper level is responsible for determining the optimal departure sequence of the vehicles waiting for or approaching the intersection. The lower level provides a longitudinal trajectory guidance to a subset of the CAV's while traversing the intersection.

Three different vehicle types are considered within the algorithm. First of all, the manually driven vehicles which are unable to communicate with the intersection controller. Secondly, the CV's that are able to communicate their speed and location information with the intersection controller. However, the intersection controller cannot directly control the longitudinal trajectory of these vehicles. The last considered vehicle type is the CAV, which is able to communicate its speed and location towards the intersection controller and its longitudinal trajectory can be controlled.

The algorithm uses the estimated arrival times of the C(A)V's that are within the communication range as input. These arrival times are updated every time that one of the following two events occur. the first event is when a new C(A)V enters one of the intersection approaches. The second event is when a C(A)V has to stop in the queue on one of the intersection approaches. The number of manually driven vehicles on each approach is determined with the use of the C(A)V information. This is calculated by the number of C(A)V's that are stopped and the distance between the last C(A)V and the stop line. The manually driven vehicles that are identified with this method are included into the set of considered vehicles for the algorithm.

The following part of the algorithm consist of three steps. Within these steps the algorithm identifies the naturally occurring platoons, determines the optimal departure sequence and provides a subset of the AV's with the longitudinal trajectory guidance.

Step 1: Platoon Identification
The information obtained from C(A)V's is used to identify naturally occurring platoons that arrive or are stopped on one of the intersection approaches. The identification criteria of a platoon are the headways and spacings of C(A)V's and/ or identified manually driven vehicles on each intersection approach. These headways and spacings are compared to a critical threshold value that has been pre-defined. Strings of vehicles that have headways or spacings lower than the threshold value are assumed as a platoon. The headway is used for identifying driving platoons, while the spacing is used for identifying platoons stopped in the waiting queue. However, manually driven vehicles can only be detected by C(A)V's while standing still.

Step 2: Optimal Platoon Departure Sequence Selection
This step has to objective to minimize vehicle delay by determining the ideal sequence of platoons that depart from each intersection approach. This algorithm does not consider individual vehicle departure sequences, but it is based on the identified vehicle platoons instead. It is assumed that the vehicles within a platoon will discharge through the intersection together. However, these platoons may break if the maximum green time has been triggered. Two methods can be used to determine the optimal departure sequence of the platoons. These methods have been proposed by Yang et al. (2016) in a previous study. The difference is that for this algorithm vehicle platoons are considered, while in the previous study the vehicles were considered individually. Considering platoons reduces the computational complexity, since less departure sequences have to be considered.

The first method to identify the optimal departure sequence is an enumeration method, where all possible platoon departure combinations are identified and evaluated. The second method is a branch-and-bound method where an intelligent tree search algorithm is used to identify the optimal departure sequence.

Step 3: Longitudinal Trajectory Guidance
Within this step longitudinal trajectory guidance is provided to a subset C(A)Vs to minimize the total number of stops without increasing the vehicle delay. Trajectory design is performed for each departure sequence identified by either of the two methods in step 2. The trajectory guidance is only provided to the lead AV in a platoon to reduce computational complexity. The trajectories of the other vehicles are indirectly influenced by the controller, since those will have to follow the lead vehicle.

The trajectory design is initiated by calculating the expected time it will take for each AV to reach the intersection (t_e) for each considered departure sequence. This time is equal to the maximum of the start of the green time or the time at which the final vehicle traverses through the intersection and some minimum discharge headway combined. Once this is known, the speed at which the AV needs to travel to reach the stop line at t_e can be calculated and communicated towards the vehicle.

3.4. Dedicated Traffic Management System Properties

The properties of the dedicated traffic management system that will be implemented on the intersection between the N201 and Koolhovenlaan are discussed in this paragraph. These properties are based on the previously discussed systems in paragraphs 3.2 and 3.3. So this chapter dives deeper into these properties and it discusses the adaptations that have been made to the systems of both articles in order to create the DTM system.

3.4.1. System input

In order for the algorithm to work as intended, information regarding the speed and location of each vehicle is required. This information is provided to the system by the connected vehicles and the fixed traffic sensors.

Connected Vehicle Data

CACC-equipped vehicles that are in range on one of the intersection approaches are considered to be within the zone of interest, for which the length is determined in section 3.5. These are able to share their data with the traffic controller. The system will use the location and speed data as input. Furthermore, the CACC string status will be used as input.

Fixed Traffic Sensor Data

The information regarding the manually driven vehicles will be obtained by fixed traffic sensors. This data will be less accurate since it can only be measured at fixed locations and not be updated real time as is the case for the connected vehicles. These sensors will count the number of vehicles that have crossed it and determine the vehicle type by the length of the vehicle. Two vehicle types are considered, namely cars and trucks. These will be gathered separately per lane so that the data is more accurate. Once a connected vehicle has passed the sensor, the count will be reset to zero. The count and order of preceding manual vehicles will be stored by the connected vehicle so that it can be used for the real time location and speed estimation of the manually driven vehicles.

This count of manually driven vehicles will be updated further down the zone of interest. This is done to account for possible lane changes of either the manually driven vehicles or the CACC-equipped vehicles.

3.4.2. Start of Algorithm

The traffic control system proposed by Liu et al. (2019) starts at the beginning of each signal cycle, while the traffic control system proposed by Liang et al. (2018) starts if one of two trigger events have taken place. The DTM algorithm will start if a trigger event has taken place. Compared to the system of Liang et al. (2018), an extra trigger event has been added, which is the third.

1. **A connected vehicle enters the zone of interest.**
   This increases the set of connected vehicles that must be considered by the intersection controller.
2. **A connected vehicle comes to a complete stop.**
   This allows the algorithm to determine the total length of the queue that consists of conventional and connected vehicles.
3. **A connected vehicle departs from the zone of interest.**
   Similarly to the first trigger event, the total set of considered connected vehicles by the algorithm has to be updated. Due to this similarity to the first trigger event, it has been added to the DTM system.

If there is not a new trigger event, the algorithm will not update itself. Therefore the green split determined during the previous trigger event will remain until one of these three trigger events occur.

3.4.3. Objective Function

The objective function used in the DTM system is similar to that used by Liu et al. (2019), where the overall throughput of the intersection is maximized. This objective function is as follows:

$$Max \sum_{i=1}^{M} \sum_{j=1}^{N} \delta_{ij}$$

Where:

- M: the number of intersection approaches.
- N: the number of vehicles in an intersection approach.
- i: approach ID.
- j: vehicle ID.
- δ_{ij} = 1 if a vehicle if a vehicle can cross the intersection during the next cycle and 0 if otherwise.

This objective functions is equivalent to the minimization of the queue lengths of all intersection approaches combined:

$$Queue = N + Q_{in} - Q_{out}$$

Q_{in} is the inflow of traffic into the queue and Q_{out} is the outflow of traffic of the queue that traverses the intersection. N and Q_{in} are determined by the traffic intensities within the network, while Q_{out} is the only parameter than can be influenced by the intersection controller. To reduce the total queue lengths, the intersection throughput should be maximized. The intersection controller does this by maximizing the number of vehicles leaving the intersection during a cycle. A vehicle is considered leaving the intersection, if it has crossed the stop line.

The method of how this objective function has been implemented is slightly altered compared to that of Liu et al. (2019), which uses a eight-phase traffic controller (figure 3.1). However, the DTM system uses a four-phase signal controller. The cycle length is variable and is determined by the length of each phase and the required transition times between the phases, which is similar to the method proposed by Liang et al. (2018). This means that the cycle length of the upcoming cycle is updated each time that the algorithm is executed. This is subject to the following constraints:

$$\sum_{l=1}^{4} (g_l + t_{yr}) = C$$

$$g_l \leq g_{lmax}$$

Where:

- C: the cycle length.
- l: the phase ID.
- g: the green time.
- g_{lmax}: the maximum green time for phase l.
- t_{yr}: the yellow and all red time

Moreover, if a phase is already active, the green time assigned to it cannot be larger than the maximum green time minus the time the specific phase has already been green.

As stated, the DTM system uses four signal cycles, which have been predetermined and are based on the preferred phase order of the real vehicle actuated signal controller. Table 3.1 shows the direction numbers that belong to each phase. Which direction belongs to each number has been clarified in section 4.2.

Table 3.1: The directions that belong to each signal phase.

Phase	Directions
1	1, 2, 7, 8
2	3, 9
3	4, 5, 10, 11
4	6, 12

3.4.4. Speed and Location Estimation

The algorithm starts once a trigger event has occurred. The first step for this algorithm is to sort the data of each vehicle per lane and in the right order regarding the distance towards the intersection stop line of each vehicle. This is kicked off by sorting the connected vehicles, since those positions are known. As explained in section 3.4.1 the order and number of manually driven vehicles that have crossed the fixed traffic sensors are passed to the first connected that crosses the sensor. This can then be used for the speed and location estimation of the manually driven vehicles.

For this the method proposed by Liu et al. (2019) is used. This method estimates the speed and location of all manually vehicles between two CACC-equipped vehicles based on the driving states of the CACC-equipped vehicles. Four cases are used as explained in section 3.2.3. However, the speed and location data for the manually driven vehicles that could be measured by upstream fixed traffic sensors will not be used for this estimation. So only the speed and location data of CACC-equipped vehicles are used within the estimation.

The DTM system is suitable for mixed traffic, which consists of both cars and trucks. To account for this, the used method is slightly adapted. Therefore, the average length used in the method is different based on the amount of cars and trucks driving between two CACC-equipped vehicles. Whether the manually driven vehicles are cars or trucks, is measured by the fixed traffic sensors (section 3.4.1).

The end result of this step is a sorted list per lane containing the location, driving speed and vehicle type ((connected) car or truck).

Case 1

In this case, both the upstream and downstream CACC vehicles are moving, which is visualized in figure 3.3. The assumption is made that the manually driven vehicles in between are moving in cruising speed as well. It is also assumed that the headway between the vehicles will not change. Linear interpolation is applied to estimate the speed of the vehicles in between:

$$v_k = V_0 + \frac{V_1 - V_0}{HW} * k * h_{avg}$$

$$x_k = X_0 + \sum_{p=1}^{k} v_p * h_{avg}$$

$$h_{avg} = \frac{HW}{N_m + 1}$$

Where:

- k: the number of the manually driven vehicle.
- v_k: the speed of manually driven vehicle k.
- x_k: the location of manually driven vehicle k.
- V_0 and V_1: the speed of the downstream and upstream CACC vehicles.
- X_0 and X_1: the location of the downstream and upstream CACC vehicles.
- HW: the headway between the upstream and downstream CACC vehicles.
- h_{avg}: the average headway of the manually driven vehicles between the downstream and upstream CACC vehicles.
- N_m: the number of manually driven vehicles between the downstream and upstream CACC vehicles.

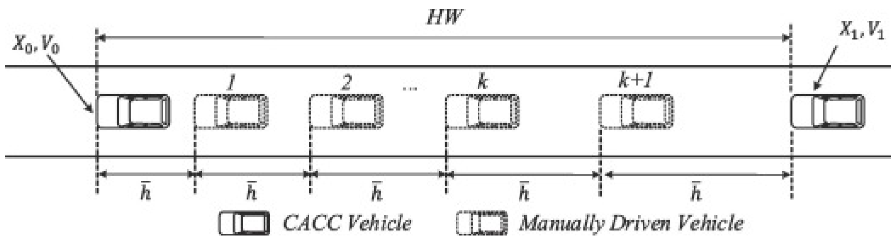


Figure 3.3: Speed and location estimation: Case 1

Case 2
For this case, both the upstream and downstream CACC are stopped, which is visualized in figure 3.4. Regarding the in between manually driven vehicles, it is assumed that those are stopped as well. A jam gap is maintained between those vehicles. The location of each manually driven vehicles is calculated by the following equations:

$$x_k = X_0 + k * (l_{avg} + d_{jam})$$

$$d_{jam} = \frac{D - (N_m + 1) * l_{avg}}{N_m + 1}$$

Where:

- D: the distance between the front bumpers of the upstream and downstream CACC vehicles.

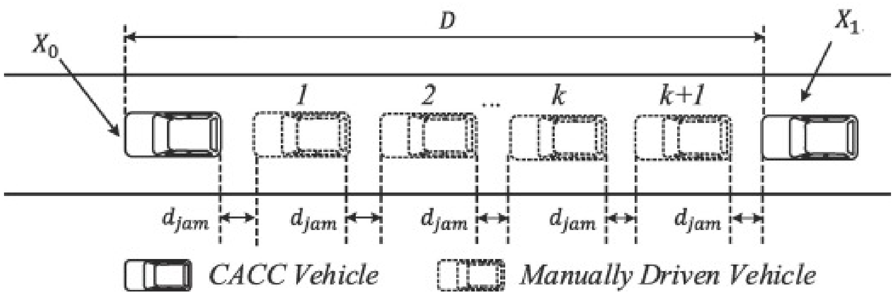


Figure 3.4: Speed and location estimation: Case 2

Case 3
For this case, the downstream CACC vehicle is stopped, while the upstream CACC vehicle is still moving. This means that the downstream vehicle is already in the queue before the intersection, while the upstream vehicle is about to join the queue. The status of the manually driven vehicles in between in not known. So the first step is to identify the number of those vehicles that are stopped in the queue. Their positions can then be computed in the same method as used in case 2. The position and speed of the other vehicles is calculated with the method of case 1. The number of manually driven vehicles stopped in the queue is calculated by the following statistic function:

$$n_{queue} = \sum_{n=1}^{N_m} n * (1-p)^{n-1} * p$$

Where:

- p: the CACC market penetration.

After determining the number of stopped vehicles, the following equations can be applied to determine the speed and location of the vehicles:

$$v_k = \begin{cases} 0, & \text{if vehicle k is in the queue} \\ \frac{v_1}{HW} * (k - n_{queue}) * h_{avg}, & \text{otherwise} \end{cases}$$

$$x_k = \begin{cases} X_0 + k * (l_{avg} + d_{jam}), & \text{if vehicle k is in queue} \\ X_0 + D + \sum_{p=n_{queue}+1}^{k} v_p * h_{avg}, & \text{otherwise} \end{cases}$$

$$h_{avg} = \frac{(X_1 - X_0) - D}{0.5V_1} * \frac{1}{N_m - n_{queue} + 1}$$

$$HW = (N_m - n_{queue} + 1) * h_{avg}$$

$$D = n_{queue} * (l_{avg} + d_{jam})$$

Where:

- D: the distance between the downstream CACC vehicle and the bumper of the final vehicle in the queue.

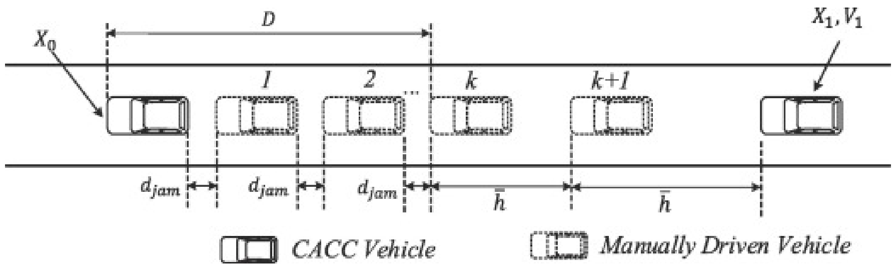


Figure 3.5: Speed and location estimation: Case 3

Case 4

Within case 4, the downstream CACC vehicle is moving and the upstream CACC vehicle is still stopped. This happens when the downstream vehicle is leaving the queue, while the upstream vehicle is still waiting for its predecessing vehicle(s) to accelerate. Similarly to case 3, the status of the manually driven in between is not known. Therefore, it is necessary to determine which of those already started moving. For this, the shockwave theory is applied:

$$n_{moving} = U_{wave} * (t_0 - t_{start})$$

Where:

- t_{start}: the time at which the downstream CACC vehicle starts accelerating.

t_{start} is obtained through V2I communication. The equations of case 1 are used to calculated the speed and location of the manually driven vehicles. The speed and location of the vehicles still waiting in queue can be calculated with the method introduced in case 2:

$$v_k = \begin{cases} 0, & \text{if vehicle k is in queue} \\ V_0 = \frac{V_0}{HW} * k * h_{avg}, & \text{otherwise} \end{cases}$$

$$x_k = \begin{cases} X_0 + \sum_{p=1}^{n_{moving}} v_p * h_{avg} + (k - n_{moving}) * (l_{avg} + d_{jam}), & \text{if vehicle k is in queue} \\ X_0 + \sum_{p=1}^{k} v_p * h_{avg}, & \text{otherwise} \end{cases}$$

$$h_{avg} = \frac{(X_1 - X_0) - D}{0.5V_0} * \frac{1}{n_{moving} + 1}$$

$$HW = (n_{moving} + 1) * h_{avg}$$

$$D = (N_m - n_{moving} + 1) * (l_{avg} + d_{jam})$$

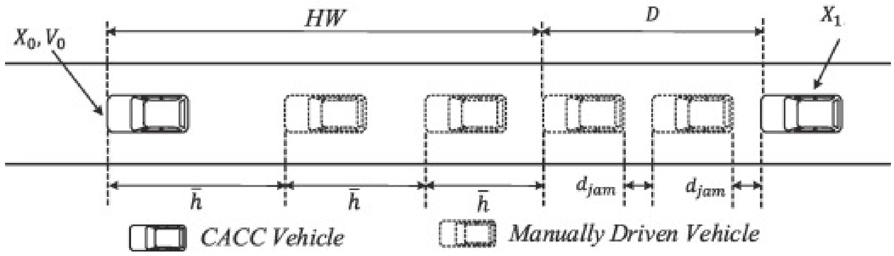


Figure 3.6: Speed and location estimation: Case 4

3.4.5. Determine Optimal Green Split

The data obtained in the previous step will be used for the final step in the algorithm, which is to determine the optimal green split and resulting cycle time for the upcoming cycle, which consists of all four signal phases and the intergreen times. The objective function is to maximize the total throughput of the intersection. This means that the location, speed and vehicle type data in combination with a given green split should be translated into the total intersection throughput. This process will be explained in this section.

To convert this vehicle and green split data into the intersection throughput, the vehicle distance prediction method proposed by Liu et al. (2019) will be applied. This method was created for traffic that consists of cars and CACC equipped cars. Therefore, some adaptations have to be made in order to make the method suitable for traffic that also consists of (CACC equipped) trucks. As stated before, the fixed traffic sensors determine if a vehicle is a car or truck by measuring the vehicle length. If this car is connected or not can directly be send to the traffic control system. Based on this, some properties used in the functions that are explained further down this section are different. These properties are the comfortable deceleration rate, the (average) reaction time, the acceleration rate and the acceleration time.

Vehicle Travel Distance Prediction

The first step in determining the optimal green split is to determine per vehicle if it can keep cruising during the upcoming signal cycle or that it will have to join a waiting queue for a given green split. If the following constraint is satisfied, the vehicle can keep cruising and the corresponding constraints can be applied. If otherwise, the vehicle will have to join the queue and the acceleration constraints will have to be applied.

$$L_{queue} + D_{buffer} < D_{eff}$$

$$L_{queue} = (l + d_{jam}) * N_{pre}$$

$$D_{buffer} = \frac{v_0^2}{2b_{comfort}}$$

$$D_{eff} = d_0 - v_0 * (t_{eff} - t_0)$$

Where:

- l: the average vehicle length.
- d_{jam}: the jam gap.
- $b_{comfort}$: the comfortable deceleration.
- v_0: the cruising speed at the beginning of the cycle.
- D_{buffer}: the distance needed by the subject vehicle to decelerate from cruising speed to standstill.
- D_{eff}: the distance between the subject vehicle and the intersection after it starts driving in cruising speed (v0) until the effective green starts.
- t_{eff}: the start of the effective green time.

The start of the effective green time (t_{eff}) can be estimated with the use of the traffic wave theory:

$$t_{eff} = t_g + \frac{N_{manual}}{U_{wave}} + \tau$$

$$U_{wave} = \frac{1}{\tau_{avg}}$$

Where:

- t_g: the start time of the next green phase
- N_{manual}: the number of preceding manual driven vehicles in the queue.
- U_{wave}: the propagation speed of the acceleration wave [number of vehicles/ sec.]
- τ_{avg}: the average reaction time of the preceding manual vehicles.
- τ: the reaction time of the subject vehicle.

If the effective distance (D_{eff}) is larger than the queue length and the buffer distance combined, the subject vehicle does not have to wait in the queue and it can keep cruising. Otherwise, the vehicle will have to decelerate to wait the queue for the next cycle.

The next step in the algorithm is to determine whether a vehicle can make it through the intersection or not for a given green split. Two methods are used for this, which are based on the fact if the vehicle can keep cruising or that it join the waiting queue.

Vehicle keeps cruising

For this method it is required to know whether a vehicle will make it through the green light during a cycle or not. This depends on the fact whether a vehicle will make it past the stop line while driving in cruising speed during the next cycle. This is described by the following constraints.

$$\delta_{ij} = \begin{cases} 1, & \text{if } D_{cruise} > d_0 \\ 0, & \text{otherwise} \end{cases}$$

$$D_{cruise} = v_0 * (t_r - t_0)$$

Where:

- D_{cruise}: the distance a vehicle can travel while driving in cruising speed until the start of the next red phase.
- d_0: the distance of the subject vehicle to the intersection's stop line at the beginning of the cycle.
- v_0: the subject vehicle's speed at the beginning of the cycle.
- t_r: the start time of the next red phase.
- t_0: the beginning time of a cycle.

Vehicle joins queue

However, the other possibility is that a vehicle will join the back of a queue during the next cycle, which means that it cannot cover the distance towards the stop line in cruising speed. Therefore, the vehicle will have to accelerate again once the signal turns green. If this is the case, the following constraints will be applied:

$$\delta_{ij} = \begin{cases} 1, & \text{if } D_{acc} > d_{Lqueue} \\ 0, & \text{otherwise} \end{cases}$$

$$D_{acc} = \begin{cases} 0.5 * a_{ij} * g_{eff}^2, & \text{if } t_{acc} < g_{eff} \\ 0.5 * a_{ij} * t_{acc}^2 + v_{free} * (g_{eff} - t_{acc}), & \text{otherwise} \end{cases}$$

Where:

- D_{acc}: the distance a vehicle can travel after leaving the queue.
- L_{queue}: queue length.
- a_{ij}: the anticipatory acceleration of a vehicle that accelerates back to free flow speed.
- t_{acc}: the time a vehicle needs to accelerate to free flow speed.
- v_{free}: the free flow speed
- g_{eff}: the effective green time for the vehicle (the time between the start of the acceleration and the signal turning red).

In order to find the best green split, multiple green splits have to be considered. The easiest method is to do this is to use a naive method, where all different green splits are considered. However, the downside of this method is that it requires the most computational effort. Therefore, a more computational efficient should be applied. Liu et al. (2019) use a heuristic method for this, where the algorithm stops iterating through different green splits if the objective function starts declining. A different method is used for the DTM system, which is a genetic algorithm (GA). This is a suitable method for this particular optimization problem. Appendix A explains in more detail what a GA is. Section 3.5 explains how the GA is applied for the green split optimization of the DTM system.

3.5. Apply Dedicated Traffic Management Algorithm

This section describes how the properties the dedicated traffic management (DTM) system from section 3.4 was implemented. These properties are divided into multiple steps, which are presented as a flowchart in figure 3.7. The goal of the algorithm is to optimize the green time distribution between the four signal phases.

The vehicles that are considered for the dedicated traffic management system must be inside of the so-called zone of interest. This is a zone that consists of the four approaches of the intersection. The length of the zone of interest is designed based on the free flow speed of the network and the maximum cycle length of the signal controller. The length is such that a vehicle can travel from the entry point of the zone towards the exit point of the zone, which is the intersection stop line, in one cycle. Here the maximum cycle length is assumed, which is the sum of the maximum green time per phase and the amber and clearance times. The length of the zone of interest is shorter for both approaches on the Koolhovenlaan, since these are not long enough. These are approaches 2 and 4 in figure 4.2 from section 4.2.

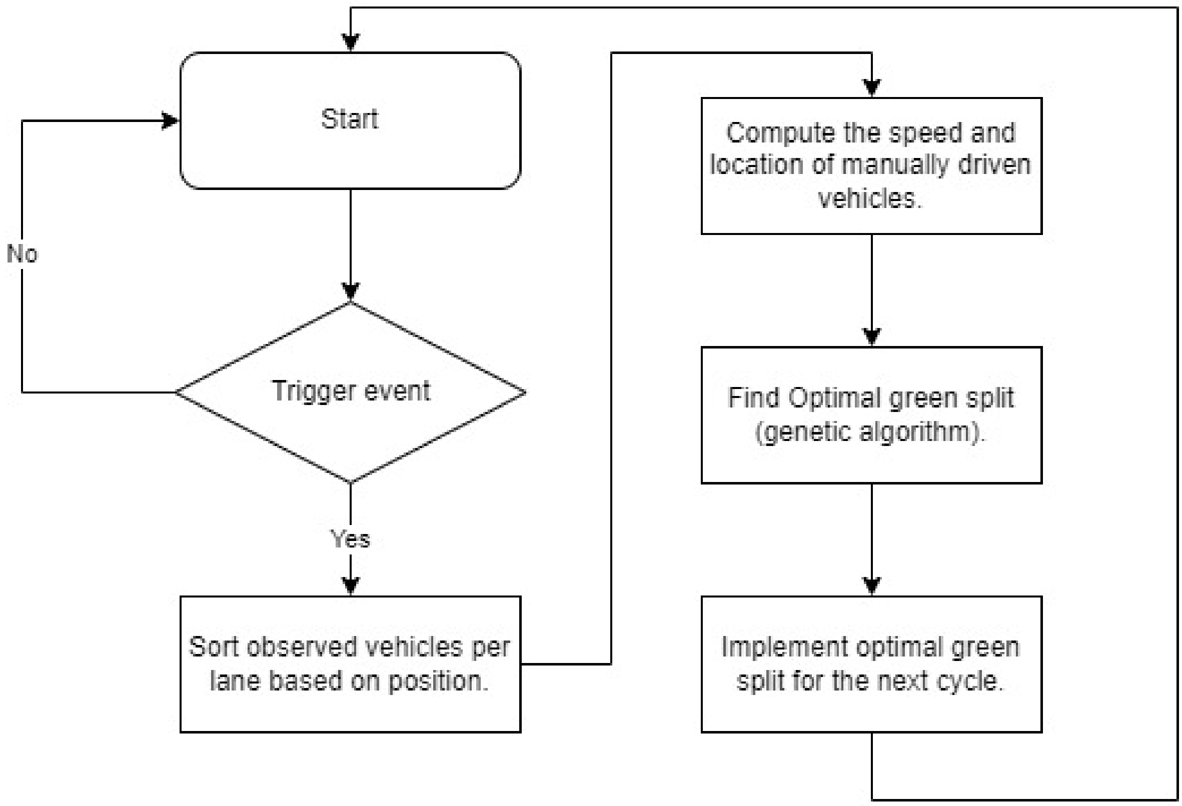


Figure 3.7: Steps that are taken in the dedicated traffic management algorithm.

3.5.1. Trigger events

The algorithm kicks off once a trigger event happens. The system has three different trigger events as is determined in section 3.4:

1. A connected vehicle enters the zone of interest.
2. A connected vehicle comes to a complete stop.
3. A connected vehicle departs from the zone of interest.

These trigger events will be implemented into the Vissim model with the use of event-based scripts, which will be written in the programming language Python. This event-based script will be activated in a certain interval, which has been set to once every five simulation seconds.

The trigger event function will start by checking if there are any vehicles in the Vissim network. If this is the case, the function will loop through each vehicle in the network. Then for each vehicle it is checked whether the vehicle is connected or not. Based on this different follow-up steps are taken.

Connected Vehicles

For each of the connected vehicles it will be checked whether a trigger event has taken place. First of all, it is checked if the connected vehicle is on one of the four links that enter the zone of interest (one link for each intersection approach). If this is the case, it is checked if the vehicle has passed the coordinates of the specific intersection approach where the zone of interest starts. This means that the connected vehicle has entered the zone of interest. However, it could be the case that this has already happened during one of the previous trigger event checks. Therefore, the vehicle number of the considered connected vehicle is compared to a list with all connected vehicles that are in the zone of interest. If the vehicle number is not yet in this list, it means that it has just entered the zone of interest and a trigger event has occurred. The vehicle number will then be appended to this list.

For the second trigger event it is checked if the connected vehicle is on one of the links that leave the zone of interest. These are the connector links on the intersection in the Vissim model. If a vehicle is on one of those, it has just passed the intersection stop line and will leave the intersection. If this condition is satisfied it must be checked if the vehicle number of the considered connected vehicle is still in the list of vehicle that are in the zone of interest. If so, it means that a trigger event has occurred and the vehicle will also be removed from this list.

Regarding the third trigger event, it is checked if a connected vehicle has entered a waiting queue. For this the Vissim parameter 'InQueue' will be used. This parameter is True if a vehicle is in a waiting queue and False otherwise (PTV Group, 2021). First of all, it is checked if the considered connected vehicle is on one of the links that are a part of the zone of interest. If so and the vehicle has satisfied the 'InQueue' condition, its vehicle number is compared to a list containing all vehicles that are inside of the zone of interest and waiting in queue. If the vehicle number is not yet a part of this list, it means that the vehicle has just entered a waiting queue and a trigger event has occurred. This vehicle number will then be appended to the list. However, if the vehicle does not satisfy the 'InQueue' condition, it's vehicle number is still compared to the vehicles in queue list. If the vehicle number is a part of the list, it will be removed.

If for one of the connected vehicles a trigger event has occurred, the code will continue with the next steps of the algorithm. If this is not the case, the code will stop after completing the final steps of the trigger event function and will be reactivated during the next trigger event check.

Non-Connected Vehicles

The trigger event function will do some checks for the non-connected vehicles as well. These checks act as the road-side traffic sensors in reality. The information coming from these checks will be used for the manual vehicle position and speed estimations later on in the algorithm. The first check during this step is similar to the check that has been done in trigger event 1. So it is reviewed if the non-connected vehicle is on one of the four links entering the zone of interest and if it has passed the coordinate of the specific link where the zone of interest starts. Then it is checked if the vehicle number of this non-connected vehicle is already in the list of manual vehicles that are in the zone of interest. If not, the vehicle number will be appended to this list. The vehicle type (car or truck) will be appended to a different list that stores this data per link and lane. This creates a list per lane with the vehicles types in order that those have passed the entering point of the zone of interest. Once a connected vehicle enters the zone of interest, this data for the lane it is driving on is passed to it. The list for this lane will then be cleared. So the location of the fixed traffic sensors is at the entering point of the zone of interest for each approach. Currently, there are no sensors located at this point, so new sensors are required. These could either be new induction loops or cameras for instance.

The manual vehicle count will be updated further in the zone of interest to partially account for lane changes. This will be done at the location of the far induction loops that are already installed in the road.

Finally, it is checked for the considered non-connected vehicle if it is on one of the links that leave the zone of interest. If this is the case and the vehicle number is in the list of manual vehicles that are in the zone of interest, it will be removed from this list.

3.5.2. Vehicle Sorting

The first step in the algorithm after a trigger event is to sort all connected vehicles in the zone of interest based on their lane and longitudinal position. This will result in a sorted list containing all relevant information per vehicle for the next steps in the algorithm. The way that is done in the model will be described in this section.

The end result of this step is a sorted list that contains the relevant information per connected vehicle. So this step is kicked off by creating the empty list. It will be an nested list, which is a list containing lists. The main list in this case contains four sublists, one sublist per intersection approach. These sublists will then get multiple sublists again. Approach 1 and 3 have 6 lanes and will therefore get 6 sublists. Approach 2 and 4 have 4 lanes and will therefore have 4 sublists.

After creating this main list, the vehicle sorting function will loop through the list that contains each connected vehicle that is is range. This is the same list that is used in the previous step, trigger events. For each vehicle it is checked on which intersection approach it is driving, followed by the check on which lane of this approach the vehicle is driving. Then the relevant information of this vehicle is appended to the correct sublist of the main list. This relevant information consists of:

1. Vehicle number.
2. Link number.
3. Lane number.
4. The position of the vehicle in metres. This position is the distance from the intersection stop line.
5. The InQueue parameter.
6. Speed of the vehicle in m/s.
7. Number of preceding manually driven cars.
8. Number of preceding manually driven trucks.
9. The order of the preceding manually driven cars and trucks.
10. Length of the vehicle in metres.
11. Vehicle type (connected car or connected truck).

Once this list is completed with all connected vehicles that are driving in the zone of interest, all sublists will be sorted based on the position of the connected vehicles.

3.5.3. Speed and Location Estimation

This step continues with sorted vehicle information list that is created in the previous step, vehicle sorting. It will transform this list into a new one that contains the speed, location and vehicle type of each vehicle in the zone of interest, the manually driven vehicles included.

The start of this step is similar to the previous step, where an empty nested list is created. There is one difference, which is that the list in this case is not divided per intersection approach, but per signal phase. The reasoning for this is that this is required for the next step in the algorithm where the intersection throughput will be calculated.

Once the main list is created, the function will loop through each item in the sorted vehicle information list. Then the driving situation for the considered vehicle and its trailing vehicle will be determined. This is done with the 'InQueue' variable. Based on these driving situations, the method required to estimate the speed and location of the manually driven vehicles that are in between is determined:

- Both the upstream and downstream vehicle are driving: **Case 1**.
- Both the upstream and downstream vehicle are in a waiting queue: **Case 2**.
- The downstream vehicle is stopped and the upstream vehicle is driving: **Case 3**.
- The downstream vehicle is driving and the upstream vehicle is stopped: **Case 4**.

These speed and location estimation methods are similar to the methods used by Liu et al. (2019), which are described in chapter 3.2.3. This section will describe how these method is applied and slightly adapted to this model. Some adaptations had to be made in order to change the model to suit mixed traffic, which consists in this case of heavy trucks and cars.

Case 1
Before the speed and location of the vehicles can be calculated, the constant values have to be determined, which is the average headway (h_{avg}) in this case. The headway between the two connected vehicles is required for this. However, this is not yet known and has to be calculated by dividing the distance between the vehicles by the speed of the following connected vehicle. After this, the speed and location of each manually driven vehicle can be calculated using the formulas described in chapter 3.2.3. These values will be appended to a corresponding list so that those can be appended to the main list of the speed and location estimation function in the code.

Case 2
All vehicles are standing in queue when case 2 is applied. Therefore, only the location of the manually driven vehicles has to be estimated. Before this can be done, the average vehicle length (l_{avg}) and the standstill distance (d_{jam}) between the vehicle have to be determined. l_{avg} will be calculated with the same method described by Liu et al. (2019). For d_{jam} the value from the Vissim model will be used, which is 2 metres. Then the locations of the manually driven vehicles can be calculated and appended to the corresponding list.

Case 3
Case 3 will be applied when the leading connected vehicle is in queue while the trailing connected vehicle is still driving. The constant values that are required for this method are:

- n_{queue}: the number of manually driven vehicles that are in the queue.
  For this, the market penetration of connected vehicles is required. This is calculated in the trigger event function by dividing the number of connected vehicle by the number of non-connected vehicles in the zone of interest.
- D: the distance between the downstream CACC vehicle and the bumper of the final vehicle in the queue.
  d_{jam} and l_{avg} are required to calculate D. d_{jam} is set to 2 metres and l_{avg} is calculated based on the vehicle types of the manually driven vehicles between the two connected vehicles. The cars that are used in the Vissim model have a default length between 3.75 and 4.76 metres. So the average of 4.26 metres is used for a cars. Trucks have a length of 15.965 metres in the Vissim model so that value is used.
- h_{avg}: the average headway between the driving vehicles.
- HW: the headway between the two connected vehicles.

After calculating the constant values, the speed and location for each manually driven vehicle can be calculated using the corresponding formulas from section 3.2.3.

Case 4
Case 4 is applied when the leading connected vehicle is driving/ accelerating, while the trailing connected vehicle is still standing in queue. To determine the speed and location of the non-connected vehicles in between, the following constant values have to be determined first:

- n_{moving}: the number of moving vehicles.
  The shockwave theory is used to determine the number of manually driven vehicles that are moving.
- D: the distance between the first non-connected vehicle in queue and the upstream connected vehicle.
  This is dependent on N_m, n_{moving}, d_{jam} (2 metres) and the average vehicle length. However in some cases it might happen that D is larger than the distance between the two connected vehicles, which is not possible in practise. If this happens, N_m will be reduced by 1 vehicle until it stops from happening.
- HW: The headway between the downstream connected vehicle and the most upstream moving manually driven vehicle.
- h_{avg}: The average headway between the moving vehicles.

After defining the constant values, the formulas described in section 3.2.3 will be filled in per manually driven vehicles to create two lists: one containing the speed and one containing the location of each vehicle.

End Result
After looping through each connected vehicle and calculating the speed and location of all manually driven vehicles, a complete list containing the speed, location and vehicle type of each vehicle in the zone of interest is obtained. This list is divided into multiple sublists per phase, which are then divided into multiple sublists per lane. The items within these sublists are sorted per lane. This list will be used for the next step in the algorithm which is to determine the optimal green split.

3.5.4. Green Split Optimization

As stated in chapter 3.4.5 a genetic algorithm will be used for finding the optimal green split and cycle time. The aspects of which a genetic algorithm consists out of are listed below. Appendix A gives a more detailed explanation of this algorithm.

- Genetic representation of a solution
- Population
- Fitness function
- Selection
- Crossover
- Mutation

These aspects are represented in the different steps that are taken in the genetic algorithm. Figure 3.8 shows a flowchart of the different steps that have been taken in the algorithm. This section will give a further explanation into how these steps have been applied to this green time optimization problem.

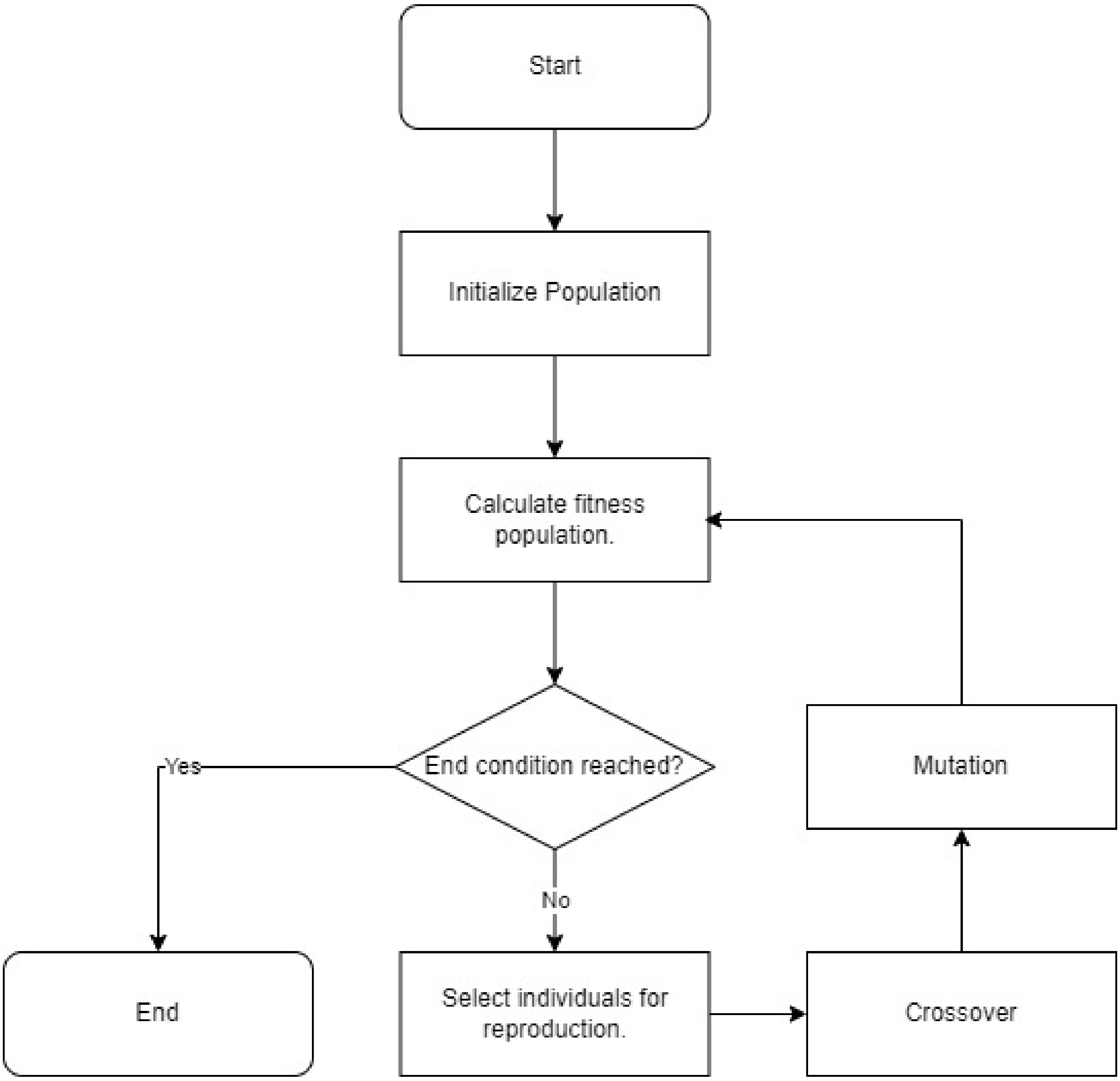


Figure 3.8: Steps that are taken in the genetic algorithm for the green split optimization.

Initialize Population
The first step in the algorithm is the initialization where the first population consisting of a number of candidate solutions is generated. The exact number for this will be determined during the calibration of the parameters (section 4.2.3). Each candidate solution represents a green split. Therefore, a value encoding scheme will be applied. This will represent the genome as a string of values, which represent the green times for each signal phase. In this case, integer numbers are used as the resolution for the green times. The traffic on the intersection is managed by a four-stage signal controller. Therefore, a candidate solution will consist of four different green times. The population is generated using a random generation method. So each phase will have a random green time chosen from the range starting at zero seconds and ending at the maximum green time for that phase. For the active phase the maximum value is the maximum green time minus the time that the phase is already green.

Fitness Function
The next step in the algorithm is to create the fitness function, which is used to evaluate the candidate solutions. In this case, the fitness function is the objective function, which has the objective to maximize the total intersection throughput during the next cycle (all four signal phases including the currently active phase). However, only the objective function will not be enough to solve the problem, since the green split and cycle time (which is the sum of the green split and the intergreen times) should be

translated into the intersection throughput. Therefore, the method and functions explained in chapter 3.2.2 will be applied to determine the intersection throughput for a certain cycle length and greens split. How this method is exactly applied will be explained in further detail in chapter 3.5.5.

End Condition
After calculating the fitness of each candidate solution it will be checked whether the end condition has been satisfied or not. If so, the algorithm will be terminated and the solution with the highest fitness will be implemented into the signal controller. Else, the algorithm will continue with the next steps of the genetic algorithm. This specific version of the genetic algorithm has two end conditions from which one has to be satisfied. Firstly, if the fitness (the intersection throughput for the next cycle) is equal to the total number of vehicles in the zone of interest. The second end condition is whether the maximum number of iterations has been reached. This will prevent the algorithm from endlessly iterating in the case that there is no optimal solution where all vehicles in the zone of interest can traverse the intersection during the next cycle. The maximum number of iterations will be determined during the calibration of the genetic algorithm.

Selection
Based on the outcomes of the fitness function the parents for the next generation will be selected. The most common and simple selection technique is the roulette wheel selection (Mirjalili, 2019). However, the problem with this method is that there is a probability that the method converges into a local optimum (Katoch et al., 2021). Therefore, a modified version of the roulette wheel selection will be used instead, which is Linear Rank Selection (LRS) (Jebari and Madiafi, 2013). This method bases its choice on the rank of an individual instead of its fitness. The individual with the highest fitness gets rank n and the individual with the lowest fitness gets rank 1. The probability of an individual being selected is as follows:

$$p(i) = \frac{rank(i)}{n * (n-1)}$$

Where:

- n: the population size.

A rank selection method reduces the probability that a solution prematurely converges into a local optimum.

Crossover
Once the parents have been selected, the child solutions can be generated. These child solutions will consist of a combination of the genetic information of both parents. This genetic operator is called crossover. The review conducted by Katoch et al. (2021) suggests that a uniform, arithmetic, single point or N-point crossover method should be applied when a value encoding scheme is used. In the case of the green time optimization problem, the genome only consists of four genes. Therefore, a single point crossover will be applied, which is the simplest form of crossover. The crossover point will be randomly selected for each child solution that is produced. Each pair of parents will produce two child solutions. The genes of both parents that are not used in the first child solution are used in the second child solution.

Mutation
After generating the child solutions, mutation will be applied to those genomes. According to Katoch et al. (2021), the most optimal mutation method for a value encoding scheme is displacement. However, this is not an optimal method for this case, since each gene has a different maximum value. Interchanging genes could violate these maximum values and result in infeasible solutions. Therefore, a point mutation will be applied to this case. Here a certain gene has the probability to mutate, which will be set to a low value. This ensures that the child solutions will not be a set of whole new random individuals, but some diversity will be added to the newer generations. The exact mutation probability will be determined during the calibration steps. For each gene it will be determined whether it will mutate or not based on this probability. If the gene will mutate, a certain value will be added to or subtracted

from the value of the gene. However, the value of the gene may not be lower than 0 seconds or exceed the maximum green time for that phase. The value in which the gene will mutate will be picked from a range: [0 – maximum value]. The maximum value will be determined during the calibration steps.

Once the mutation step has been concluded the population for the next generation is ready. This population will then be used for the next iteration of the algorithm. All the previously explained steps from the fitness function onwards will be repeated until the end condition has been reached. The individual with the highest fitness that comes out of the algorithm contains the green split that will be applied in the signal controller.

3.5.5. Fitness Function

The fitness function will transform each candidate solution from the population into a fitness value, which is the total intersection throughput for the next cycle of the signal controller. The speed and location information for each vehicle in the zone of interest is required for this step. So the fitness function continues with the list created in the speed and location estimation step from section 3.5.3.

The steps that are taken in this fitness function are mainly from the vehicle travel distance prediction method designed by Liu et al. (2019). This method is discussed in chapter 3.2.2. In order to implement the method into this green time optimization problem some adaptations have to be made. This chapter will discuss how the method has been implemented into the Vissim micro simulation model. Figure 3.9 shows the different steps that are taken.

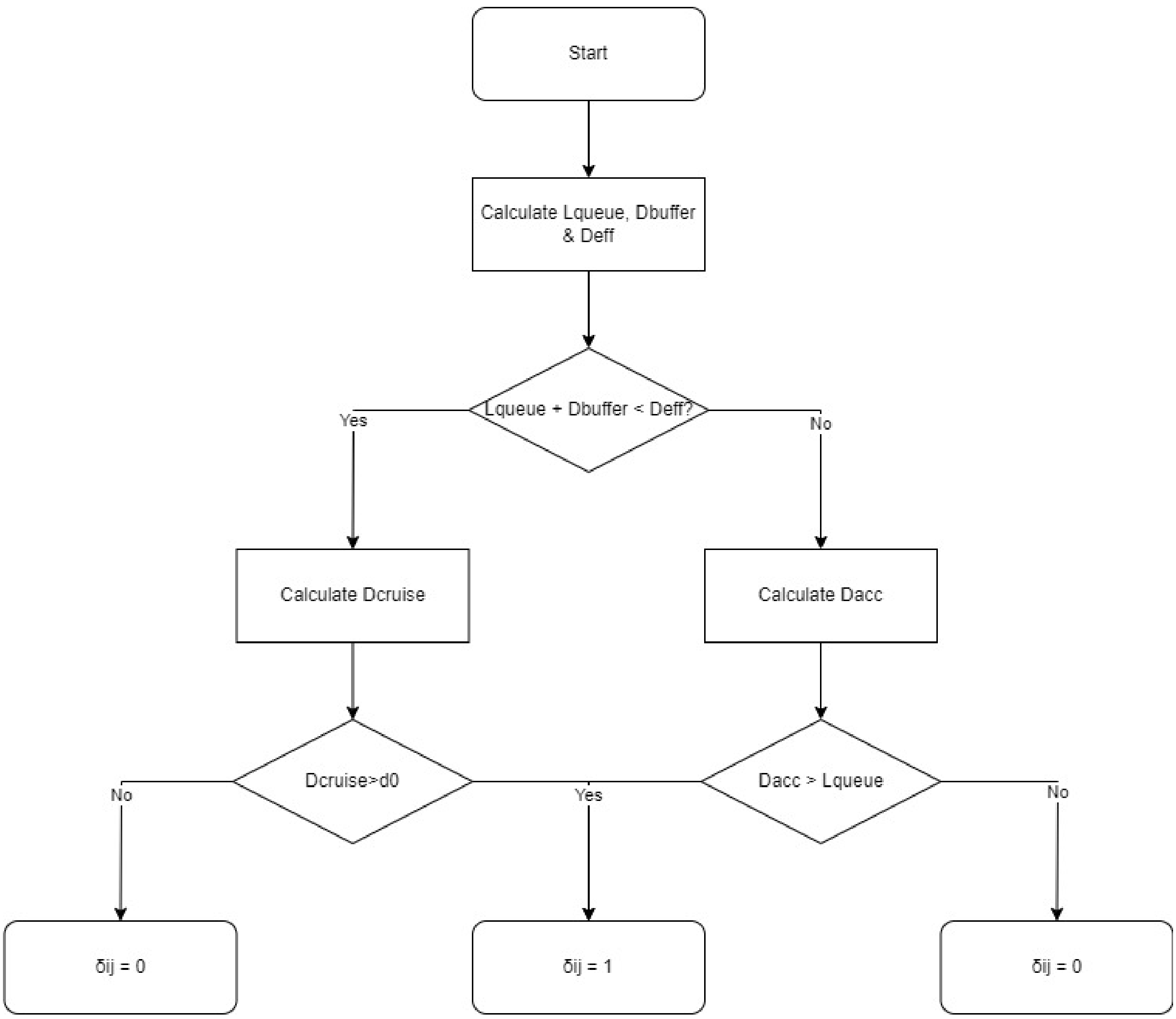


Figure 3.9: Steps that are taken in the fitness function.

Prior to the steps from figure 3.9, the genome of candidate solution has to be transformed into the green start time and green end time for each signal phase. Currently, the genome consists of four values, which are the the green time durations of each phase. The green start and end times are dependent on the green duration, clearance times and amber time.

The steps from figure 3.9 are taken per vehicle in the zone of interest. So in the code a loop is created over each item in the vehicle speed and location list from the speed and location estimation step (section 3.5.3). For each vehicle the queue length of the vehicles that are in front of it on the same lane (L_{queue}), the distance required by the considered vehicle to come to a complete stop (D_{buffer}) and the distance between the considered vehicle and the intersection stop line after the vehicle keeps cruising with v_0 until the effective green time starts (D_{eff}) need to be determined. The required values to calculate L_{queue}, D_{buffer} and D_{eff} are:

- The average vehicle length (l_{avg}).
  This is calculated per lane up to the currently considered vehicle.
- The standstill distance between vehicles (d_{jam}).
  This is set to 2 metres, since this is the average standstill distance in the Vissim model.
- The number of preceding vehicles (N_{pre}).
  This can be read from the data of the lane that the considered vehicle is driving in.
- The initial driving speed (v_0).
  This value can be directly taken from the data of the considered vehicle.
- The comfortable deceleration rate ($b_{comfort}$).
  This value is taken from the Vissim model. It is 2.75 m/s^2 for cars and 1.25 m/s^2 for trucks.
- The initial position of the considered vehicle (d_0).
  This value can be directly taken from the data of the considered vehicle.
- The start time of the green phase that belongs to the lane that the considered vehicle is driving on (t_0).
  This value is determined in the first step of the fitness function, where the genome of the candidate solution is transformed into the green start and end times for each signal phase.

The final variable that is required is the start of the effective green time (t_{eff}). This value can be estimated using the traffic wave theory, for which the following variables are required:

- The start of the green time (t_g).
- The number of preceding manually driven vehicles (N_{manual}).
  This can be read from the data of the lane the considered vehicle is driving in.
- The reaction time of the considered vehicle (τ).
  This is dependent on the vehicle type and platooning status if the vehicle is equipped with CACC.
- The average reaction time of the manually driven vehicles (τ_{avg}).
  This value can be directly taken from the Vissim model and it is 1.2 seconds.

With all these values determined the formulas to calculate L_{queue}, D_{buffer} and D_{eff} can be filled in. The step that follows is to determine whether the considered vehicle can keep cruising of whether it will have to decelerate to join the queue. Depending on this outcome different steps have to be taken afterwards.

In the case that the vehicle can keep cruising, the distance it can cover (D_{cruise}) has to be calculated. All required variables (v_0, t_r and t_0) are already known. Then it can be determined whether the considered vehicle can make it through the intersection during the next cycle or not depending on the fact if D_{cruise} is larger than d_0 or not. δ_{ij} will be set to 1 if the vehicle makes it through and to 0 if not.

If a vehicle is not able to keep cruising, the acceleration distance (D_{acc}) is required. This will be compared to the queue length that has already been calculated to check if the considered vehicle can make it through the intersection during the next cycle. Firstly, the speed the considered vehicle is driving at t_{eff} needs to be determined. It is assumed that the vehicle starts decelerating once it is L_{queue} + D_{buffer} away from the intersection stop line and it decelerates with the comfortable deceleration rate until t_{eff} starts. Then from that point onwards, it is assumed that the vehicle starts accelerating. The acceleration rate is dependent of the driving speed of the vehicle. A linear acceleration is assumed. This results in the acceleration distance, which can than be compared to the queue length. δ_{ij} will be set to 1 if the vehicle makes it through the intersection and to 0 if not.

These steps will be repeated for each vehicle in the zone of interest. All δ_{ij} values will be summed and this results in the total fitness for the candidate solution.

4

Simulation Model Development

Chapter 3 described the properties and methods of the dedicated traffic management system on the Intersection between the N201 and Koolhovenlaan. This chapter has gone into more detail regarding the microsimulation model that has been used to test the effectivity of the DTM system. First, the microsimulation software package that is used for this study has been determined in section 4.1. Then the most important aspects of the model used have been described in this chapter.

4.1. Micro Simulation Software

A micro simulation will be performed to test the effectivity of the dedicated traffic management system. Within a microscopic traffic model, the vehicles and its dynamics are modelled individually (Lopez et al., 2018). These dynamics include among other things the speed, position, individual driving behaviour and route choice (Hollander and Liu, 2008). Microscopic models provide the highest level of detail in comparison to meso- and macroscopic models. However, it has a higher computational complexity (Calvert et al., 2016).

There are a variety of microscopic simulation models available, with each its pros and cons. This section will provide an analysis into the available options and then the choice for which model to use for this research project will be made. It will therefore answer the following sub-research question:

What micro-simulation software can be used for simulating the effectiveness of the dedicated traffic management system on the logistic corridor?

Five different micro simulation software packages will be compared with each other, which are listed below. Diallo et al. (2021) have made an extensive comparison between these simulation tools. This will serve as a guideline for the comparison that will be made in this section.

- MATSim (Multi-Agent Transport Simulation Toolkit)
- SUMO (Simulation of Urban Mobility)
- Aimsun Next (Advanced Interactive Microscopic Simulator for Urban and Nonurban networks)
- PTV Vissim (Planung Transport Verkehr AG Verkehr In Stadten - SIMulationsmodell)
- GAMA (Gis Agent-based Modelling Architecture)

GAMA is a generic Multi-Agent System (MAS) Simulator, this means that it can be adapted to serve multiple objectives, such as modelling road traffic. The other four simulation packages are solely developed for simulating road traffic. These five simulation packages are not the only available options within the literature. However, these are the most commonly used and will therefore be discussed in this study.

A multi-criteria analysis will be performed to define the most suitable simulation tool for this research. Five criteria will be considered:

1. **Nature of the software**
   Within this category it is compared whether the software package is open-source and free to used or that a licence has to be purchased. Moreover, it is compared whether the simulation software works on different operating systems (Windows, Linux and Mac OS).
2. **Creation of road network and transport demand**
   This category compares the ease at which a road network and transport demand can be created in the simulator. It contains the following four criteria: Visual tool integrated, network from open street map (OSM), transport demand and public transport network and scheduling.
3. **Quality of visualization of the simulation**
   The first two criteria within this category are whether the model can be viewed in 2D and 3D. The third criterium is realism. However, this depends on the expectations of the modeller. Realism can be seen at the macroscopic and microscopic level. At the macroscopic level, it can relate to the observed traffic flow variables, such as the density, traffic flow rate, average speed, etc. At the microscopic level, it can relate to agent (vehicles, pedestrians) dynamics. The final criterium is the required memory for the model. It is assumed that a software package passes this criterium if less than 16 GB of RAM is required.
4. **Documentation and users's interface**
   This category compares the different simulators on the available documentation, help and the graphical user interface (GUI). The following criteria belong to this category: online, PDF, forum, conference, community, training and GUI.
5. **Modeler's specifications**
   Within this category, it is compared how well the simulator can be adapted to the modeler's requirements. It contains the following criteria: model micro/ meso, scaling, user and mode characteristics, statistics output, intermodality, calibration, dynamic behaviours, API, source code access.

Each category has been given a coefficient to indicate its importance. A 1 – 5 scale has been used, where 1 indicates that the category is not important and 5 indicates that the category is highly mandatory. Then for each category a mark is given to the individual simulators based on the number of criteria that are met by the simulator. These scales and marks given to the simulators are then used to assign the final score, which is done with the following formula:

$$Score = \frac{\sum_{cat \in [1..n]} mark_{cat} * coeff_{cat}}{\sum_{cat \in [1..n]} coeff_{cat}}$$

So the first step is to assign the coefficients to the five categories that are considered. This is done in table 4.1, where the coefficients used in the research of Diallo et al. (2021) are given together with the coefficients that will be used in this research. The main difference between the two is that the first category, nature of software, is neglected in this study. The reason for this is that the TU Delft has the licenses of some of simulators, such as PTV Vissim. Furthermore, a computer using Windows operating system will be used for the simulation, so it is not relevant whether a simulator runs on Linux or Mac OS. The other categories are still relevant in the choice for the microscopic simulator that will be used for this study.

Table 4.1: Assignment of the coefficients.

Category	Coefficient Diallo et al. (2021)	New coefficient
1	4	X
2	5	5
3	3	3
4	4	4
5	5	5
Total	21	17

Then the marks for each category can be given to each simulator, which is done in table 4.2. For the study of Diallo et al. (2021), where the first category is included, it can be concluded that SUMO has scored the highest, followed by MATSim, Aimsun Next, PTV Vissim and GAMA. However, when the first category of criteria is neglected, PTV Vissim has the highest score. Therefore, PTV Vissim will be chosen as the microscopic simulation software for this study.

Table 4.2: The scores of the microscopic simulation software packages for the study of Diallo et al. (2021) and this study.

Simulator	Cat. 1	Cat.2	Cat. 3	Cat.4	Cat. 5	Mark Diallo et al. (2021)	New mark
SUMO	10	10	5	7	9	8.48	8.12
MATSim	10	8	3	10	8	8.05	7.59
Aimsun Next	7	8	10	6	7	7.48	7.59
PTV Vissim	4	8	10	9	7	7.48	8.29
GAMA	10	5	8	9	4	6.9	6.18

4.2. Model Design

Section 4.1 has concluded that the PTV Vissim microscopic simulation software will be used for creating the model. This section will describe the important aspects of the network that has been created in this simulator. Furthermore, the vehicle types that are used in the model will be elaborated.

The corridor that will be simulated consists of three intersections. The dedicated traffic management system will be applied to only one of these three intersection, which is the intersection between the N201 and Koolhovenlaan (number 1 in figure 4.1). The other two intersections that are included in the corridor are between Hoofddorpdreef/ Rozenburgdreef and the on- and offramp of the A4 highway (number 2 in figure 4.1) and between Rijkerdreef and Fokkerweg (number 3 in figure 4.1). These intersections have the objective to create a more bunched traffic flow towards the intersection N201 and Koolhovenlaan.

Figure 4.1: The part of the logistic corridor with the intersection indicated.

The intersection between the N201 and the Koolhovenlaan uses a vehicle actuated signal controller in reality. This signal controller is largely copied into the model, including an identical sensor layout. The vehicle actuated signal controller will be used for the base scenarios during the simulation experiments. The other two intersections do not have an important role in the simulation. Therefore a simple fixed-time signal controller has been implemented into the model for these intersections.

Figure 4.2 visualises the intersection between the N201 and Koolhovenlaan in the PTV Vissim model. The red numbers indicate each approach. The directions are numbered differently. Direction 1 is the right turning direction on approach 1. Direction 2 is the ongoing direction on approach 1 and direction 3 is the left turning direction on approach 1. The right turning direction on approach 2 is numbered with 4. This continues up to direction 12, which is the left turning direction on approach 4.

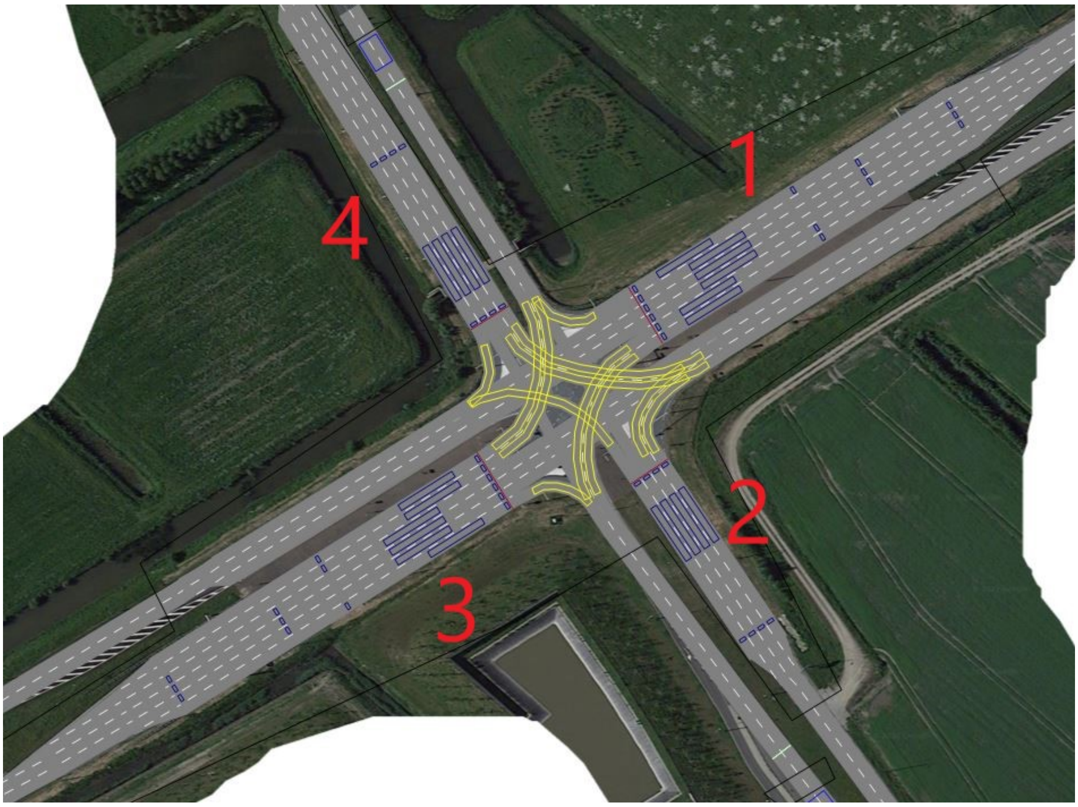


Figure 4.2: The intersection between the N201 and Koolhovenlaan in the PTV Vissim network. The red numbers indicate the approach numbers.

4.2.1. Vehicle Types

Four vehicle types will be used in the Vissim model, which are cars, trucks and CACC-equipped cars and trucks. The properties of these vehicle types will be elaborated in this section

Cars and trucks will be a default vehicle type in the PTV Vissim model. Nothing will be changed regarding the cars. The length of a car ranges between 3.75 and 4.76 metres. The same is true for the trucks that are used in the model, except that the length has been changed. This has been done so that the length matches the maximum length of a truck in combination with a trailer in the Netherlands, which is 18.75 metres (evofenedex, 2023).

The CACC-equipped cars and trucks have the same properties as the regular cars and trucks. However, they are able to form a platoon. For this, the default Vissim platooning functionality has been used with the default values (PTV Group, 2021). In terms of the vehicle platooning classification by Martinez-Diaz et al. (2021), which has been explained in chapter 2.3.1, the platoon size is finite with a maximum platoon size of 8 vehicles. A cooperative formation policy is applied for the platooning formation with an approach distance of 250 metres. A variable gap is held between platooning vehicles, which is 0.60 seconds or 2.00 metres. Only homogeneous platoons can be formed, which means that CACC-equipped cars can only form a platoon with other CACC-equipped cars and the same holds for CACC-equipped trucks.

4.2.2. Scenarios and Traffic Volume

This section will discuss the scenarios that will be run during the microsimulation. There are three main scenarios:

1. ***Base scenario***: No CACC-equipped vehicles and a vehicle actuated signal controller.
2. ***Platoon scenario***: CACC-equipped vehicles under different penetration rates and a vehicle actuated signal controller.

3. ***DTM scenario***: CACC-equipped vehicles under different penetration rates and the dedicated traffic management system.

For each scenario, runs with a simulation period of 3 hours have been done. The traffic volumes are real traffic volumes on the logistic corridor from the week of 12-09-2022 - 16-09-2022. For these volumes, the busiest hour has been determined, which is Tuesday 13-09-2022 between 08:00 and 09:00. These volumes will be used for the simulation, including the hour prior and after this busiest hour.

All scenarios will have identical traffic volumes, with the only exception being the penetration rates that are different. The penetration rates per scenario are given in table 4.3. Each sub-scenario will simulated 10 times to account for the stochasticity of the Vissim model. The results of these simulations that are used in chapter 5 are the averages of the 10 simulation runs. An analysis into the exact amount of required scenarios has been made afterwards, which can be found in appendix E.2.

Table 4.3: The penetration rates per scenario.

Name	% CACC-equipped cars	% CACC-equipped trucks
Base	0	0
Platoon	0	20
Platoon	0	40
Platoon	0	60
Platoon	0	80
Platoon	0	100
Platoon	20	20
Platoon	40	40
Platoon	60	60
Platoon	80	80
Platoon	100	100
DTM	0	20
DTM	0	40
DTM	0	60
DTM	0	80
DTM	0	100
DTM	20	20
DTM	40	40
DTM	60	60
DTM	80	80
DTM	100	100

The PTV Vissim model will use dynamic assignment for the traffic input and route choice of all vehicles within the network. For this an OD-matrix has to be created, which consists of 10 zones. All OD-matrices for the cars and trucks are in appendix C. These tables will be adjusted based on the penetration rates per scenario. The location of each zone within the network has been visualised in figure 4.3. The name of each zone is presented in table 4.4.

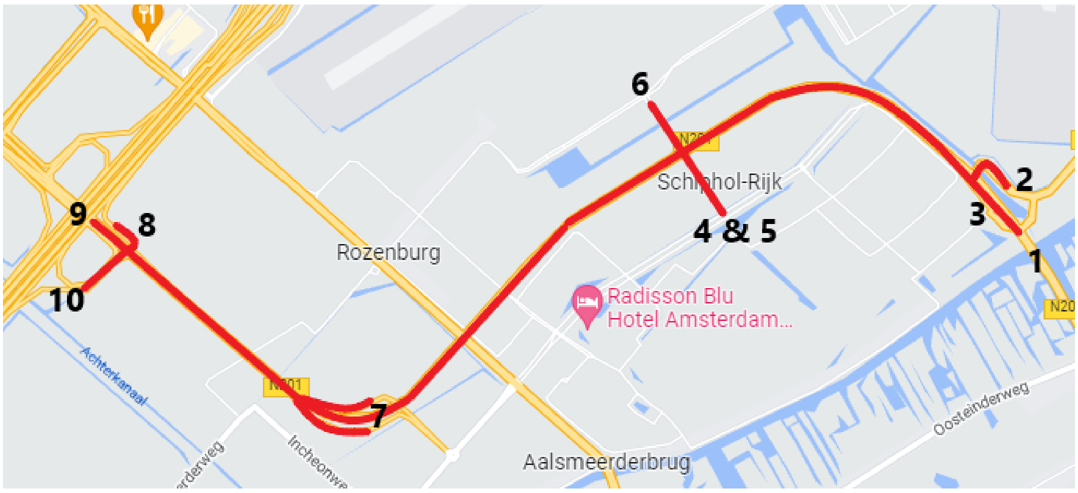


Figure 4.3: The logistic corridor including the zone numbers

Table 4.4: The zone numbers and corresponding names.

Zone nr.	Name
1	N201 Rijkdreef Oost
2	Fokkerweg
3	Oude Meer
4	Koolhovenlaan l
5	Koolhovenlaan r
6	Cargo Entrance
7	Rozenburg
8	Rozenburgdreef
9	Hoofddorpdreef
10	A4

4.2.3. Genetic Algorithm Calibration

The performance of the genetic algorithm (GA) for a specific optimization problem depends on several aspects. A part of these aspects are the used methods for generating the initial population, selection, crossover and mutation. The method choices for this green split optimization problem have already been clarified in section 3.5.4 and are left unchanged. Another part of these aspects are the fixed numbers for some of the parameters, which have to be calibrated as well. This process has been described in this section. The parameters are:

- The initial population size.
- The mutation probability.
- The mutation value.
- The maximum number of iterations.

The objective of the GA calibration is find the solution with the highest fitness in the least amount of iterations as possible.

Calibration Experiment Description

The calibration process has been performed by running a single simulation run with a higher traffic volume than that is used for the simulation of the three main scenarios (see appendix C for the OD-matrices that contain these traffic volumes). The used traffic volume in the GA calibration is twice as high. The reason for this is that the number of vehicles in the zone of interest higher, which makes it harder for the GA to determine the highest fitness value. Therefore, a better result analysis can be performed, which results in the optimal settings for the GA. The used penetration rate of the CACC-equipped vehicles is

40% for both CACC-equipped cars and trucks. This creates a mixed traffic composition, where there are enough CACC-equipped vehicles to provide the algorithm of the speed and location data, while there are still a lot of manually driven vehicles for the speed and location estimation.

The results found by the GA calibration were not yet implemented into the signal controller in this step, since the objective is to find the optimal settings of the GA in order to find the optimal fitness in as little iterations as possible. Therefore, a simple fixed-time signal controller has been used on the intersection during the GA calibration simulation run, which is good enough to manage the traffic on the intersection during this calibration simulation. This fixed-time signal controller uses the maximum green times for each signal phase.

Different scenarios are created to test the impact that the GA parameters have on the performance of the algorithm. These scenarios are presented in table 4.5. The mutation probability ranges from 0.1 to 0.5, the mutation values are 5 and 10, and the population size ranges from 6 to 20. The maximum number of iterations has been kept high (100 iterations) to determine how many iterations are required.

Table 4.5: The scenarios for the genetic algorithm calibration.

Scenario	Mutation probability	Mutation value	population size
1	0.1	5	6
2	0.3	5	6
3	0.5	5	6
4	0.1	5	10
5	0.3	5	10
6	0.5	5	10
7	0.1	5	14
8	0.3	5	14
9	0.5	5	14
10	0.1	5	20
11	0.3	5	20
12	0.5	5	20
13	0.1	10	6
14	0.3	10	6
15	0.5	10	6
16	0.1	10	10
17	0.3	10	10
18	0.5	10	10
19	0.1	10	14
20	0.3	10	14
21	0.5	10	14
22	0.1	10	20
23	0.3	10	20
24	0.5	10	20

As mentioned earlier this section, a single simulation run has been done during the GA calibration. After a half hour warm-up period, the GA calibration has been performed each simulation second for two simulation minutes. During each step, every GA scenario from table 4.5 has been executed. A genetic algorithm uses stochasticity in multiple steps, such as the population initialization, selection, crossover and mutation. To account for this stochasticity, each scenario has been run 10 times per time step that the GA calibration is performed. The average results of these 10 runs were used in the result analysis step. The relevant results are the maximum fitness value of each scenario and run, and the average number of required iterations to reach this maximum fitness. Scenarios that have the highest maximum fitness results obviously perform the best. The first generation at which this maximum fitness is reached is also important since this tells the speed at which the algorithm converges into the global optimum. This reduces the number of iterations required for the genetic algorithm and therefore increases the computational speed.

Calibration Experiment Results
Once all simulation runs have been performed, the gathered data can be processed. For each scenario a histogram with the required iterations to reach the final fitness has been created (see Appendix B for this). This final fitness is not always the global optimum, since it could occur that more than 100 iterations were required to reach it. Tables 4.6 and 4.7 show the average required iterations and the maximum fitness results for each mutation probability, mutation value and population size. The average of these required iterations and maximum fitness per parameter is presented in table 4.8.

Table 4.6: The average required iterations to reach the final fitness per scenario.

Mutation probability	0.1		0.3		0.5	
Mutation value	5	10	5	10	5	10
6	12.56	11.65	6.87	8.71	5.21	5.86
10	6.39	6.09	2.81	3.2	1.75	2.36
14	3.23	4.26	1.52	1.88	1.14	1.43
20	1.62	2.13	0.84	0.95	0.67	0.76

Table 4.7: The maximum fitness value per scenario.

Mutation probability	0.1		0.3		0.5	
Mutation value	5	10	5	10	5	10
6	4475.8	4477.4	4495.7	4493.7	4496.8	4496.9
10	4494.2	4493.4	4496.4	4496.7	4497	4497
14	4496.1	4495.7	4496.9	4497	4497	4497
20	4497	4496.9	4497	4497	4497	4497

Table 4.8: The average of the required iterations and maximum fitness value per GA parameter.

Mutation probability	**Avg. required iterations**	**Avg. Max. fitness**
0.1	6.0	4490.8
0.3	3.3	4496.3
0.5	2.4	4497.0

Mutation value	**Avg. required iterations**	**Avg. Max. fitness**
5	3.7	4494.7
10	4.1	4494.6

Population size	**Avg. required iterations**	**Avg. Max. fitness**
6	8.5	4489.4
10	3.8	4495.8
14	2.2	4496.6
20	1.2	4497.0

When looking at the mutation probability, it can be seen that an increasing mutation probability results in an increasing maximum fitness and a decreasing average number of required iterations. So the highest mutation probability of 0.5 results in the highest maximum fitness and the least required iterations to reach this.

The mutation value results show a different trend in comparison to the mutation probability results. Here, the maximum fitness is slightly lower for the highest mutation value of 10 compared to 5, while the average number of required iterations to reach this maximum fitness is slightly higher for the mutation value of 10.

The final parameter is the population size, where 4 different options were compared: 6, 10, 14 and 20. The trend is that the performance of the GA increases with increasing population sizes. So with the largest population size of 20, the maximum fitness is the highest and the required iterations to reach this maximum fitness is the lowest.

Based on the previously discussed results, the parameters for the genetic algorithm can be selected. The mutation probability has been set to 0.5, the mutation value has been set to 5 and the population size has been set to 20. Tables 4.6 and 4.7 confirm that these are the ideal parameters based on this GA calibration experiment, since the maximum fitness is the highest with 4497 and the average required iterations is the lowest with 0.67.

Besides the quality of the solution, the computation time it takes to reach the optimal solution is important as well. The maximum number of iterations has a large impact on this. Decreasing this number would lead to lower computation times. Based on the previously discussed results, it is possible to lower the number. However, it is chosen not to do this since it could negatively impact the quality of the results in certain cases. Instead, an end condition has been implemented, which stops the iteration process of the algorithm if a certain threshold has been reached. This end condition has been clarified in section 3.5.4.

4.3. Expectations

As stated in chapter 2.3, vehicle platooning can significantly improve the capacity of an intersection (Lioris et al., 2017; Kockelman et al., 2016). This study focuses improving the total delay, average travel time and average number of stops under identical traffic intensities. Still it is expected that truck and vehicle platooning can improve the total delay and average travel time due to the lower headways and lower reaction times when accelerating. The expectation is that the CACC-equipped vehicles benefit more than the non-equipped vehicles. However, long platoons could also cause disturbances near bottlenecks where the platooning vehicles might have different routes (Martinez-Diaz et al., 2021). This could result in more acceleration/deceleration maneuvers, which could affect the average number of stops negatively.

The DTM system uses vehicle connectivity and platooning capabilities to estimate the intersection throughput and adjust the green split and cycle time accordingly to maximize this throughput. The system is based on the proposed systems by Liu et al. (2019) and Liang et al. (2018). Both systems bring an improvement to the traffic flow at an intersection, even with low penetration rates of connected vehicles. Therefore, it is expected that the DTM system will outperform the vehicle-actuated signal controller at all penetration rates.

5

Simulation Results

This section will discuss the results that are obtained from the microsimulation in the PTV Vissim model. First the used key performance indicators will be discussed. Then the relevant obtained results are discussed and finally a brief summary and conclusion regarding these results are given.

5.1. Key Performance Indicators

The performance of the different scenarios will be compared to each other by the key performance indicators (KPI's). In order to provide an answer to the main research question, the following KPI's have been chosen:

- Total delay
- Average travel time
- Number of stops

The total delay is the product of the average delay and the number of vehicles. This will be calculated for each direction of the intersection and for each vehicle type separately. The average delay is directly obtained from the Vissim model. This is calculated as the actual travel time in the measurement zone minus the theoretical travel time within this zone. This zone starts a few hundred metres prior to the intersection and ends 300 metres after the intersection. As a result, both waiting and acceleration losses are incorporated into these measurements.

Similarly to the average delay, the average travel time is directly obtained from the Vissim simulation results. Again, it is given for each intersection direction and vehicle type separately.

The number of stops is obtained from the Vissim simulation results as well, which has also been given per intersection direction and vehicle type separately.

5.2. Result Analysis

The obtained results will be analysed per key performance indicator in this section, starting with the total delay results in section 5.2.1. The average travel time results will be discussed in section 5.2.2 and finally the average number of stops results will be discussed in section 5.2.3.

5.2.1. Total Delay

This section will provide and analyse the total delay results of each scenario. The results will be compared to the base scenario for all vehicles combined and per vehicle type. Another comparison that will be made is between the results of the Platoon and DTM scenarios, which will be done for all vehicles combined and per vehicle type as well.

Figures 5.1 and 5.2 show a comparison of the aggregate delay of all vehicle types combined for the two considered simulation hours between respectively the Platoon and base scenarios and the DTM and base scenarios. This total delay is for all directions of the intersection combined. Figures 5.3 and 5.4 show the percentage difference of the total delay on the main and other directions between the base scenario and respectively the Platoon and DTM scenarios. The main direction implies the two ongoing directions of the logistic corridor, which are directions 2 and 8 on the intersection (see chapter 4.2 for the directions on the intersection).

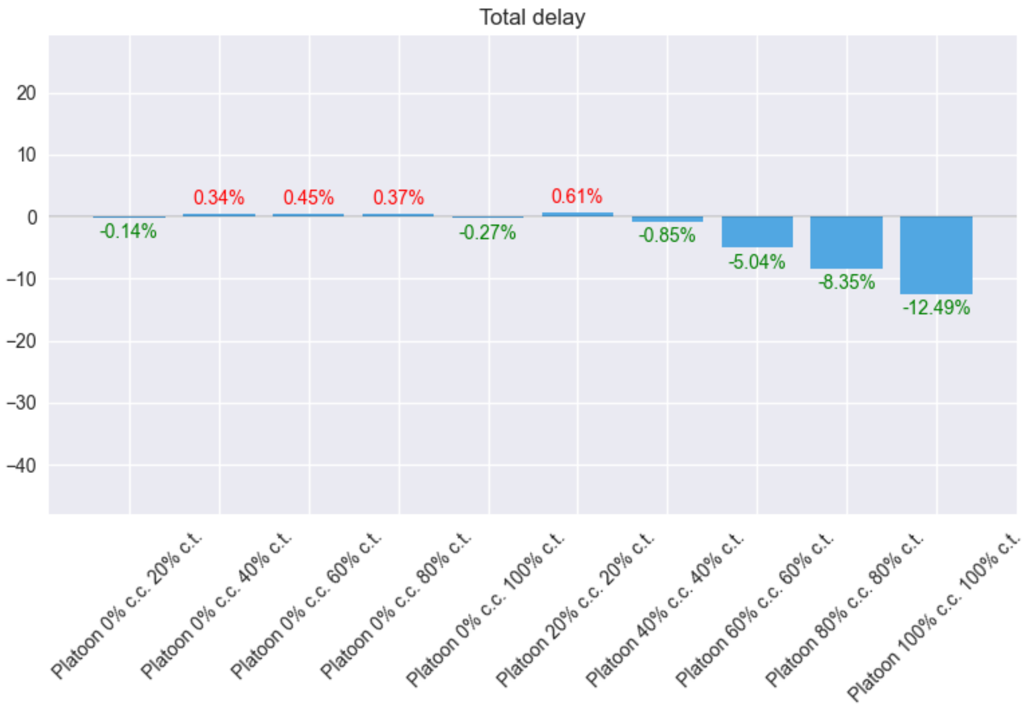


Figure 5.1: The percentage difference of the Platoon scenario total delay results compared to the base scenario for all directions on the intersection.

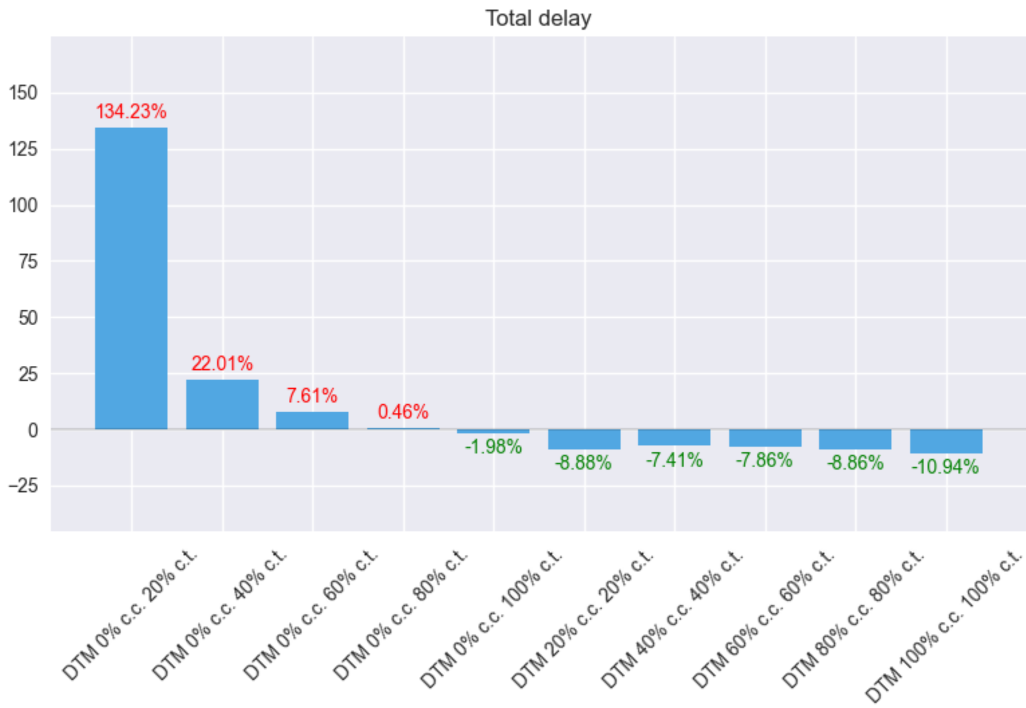


Figure 5.2: The percentage difference of the DTM scenario total delay results compared to the base scenario for all directions on the intersection.

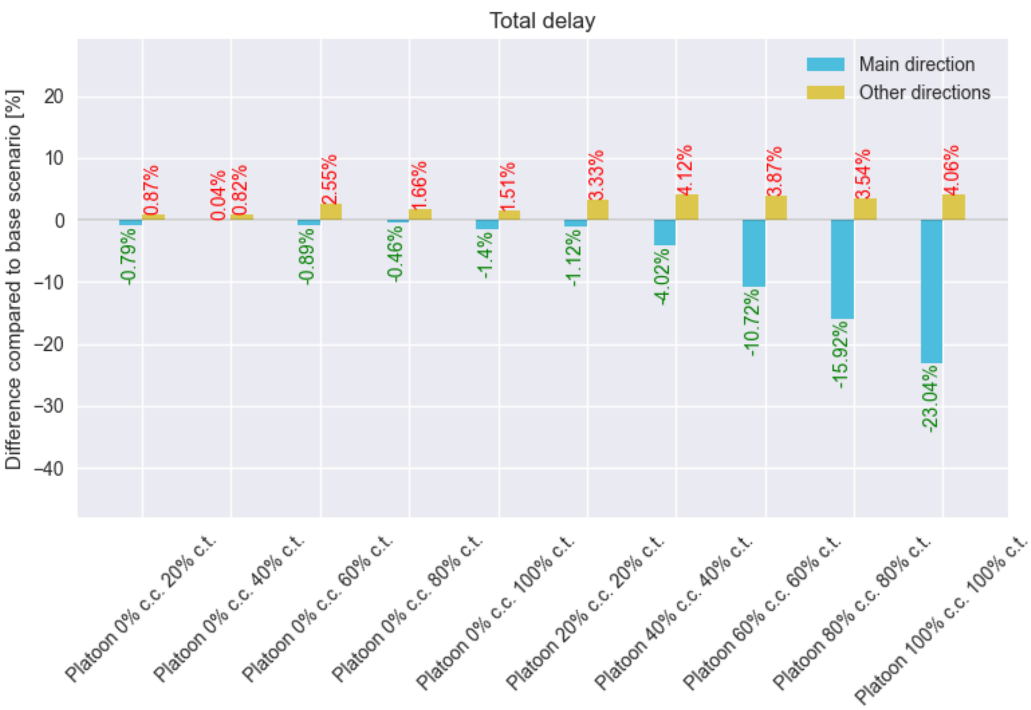


Figure 5.3: The percentage difference of the Platoon scenario total delay results compared to the base scenario for the main and other directions on the intersection.

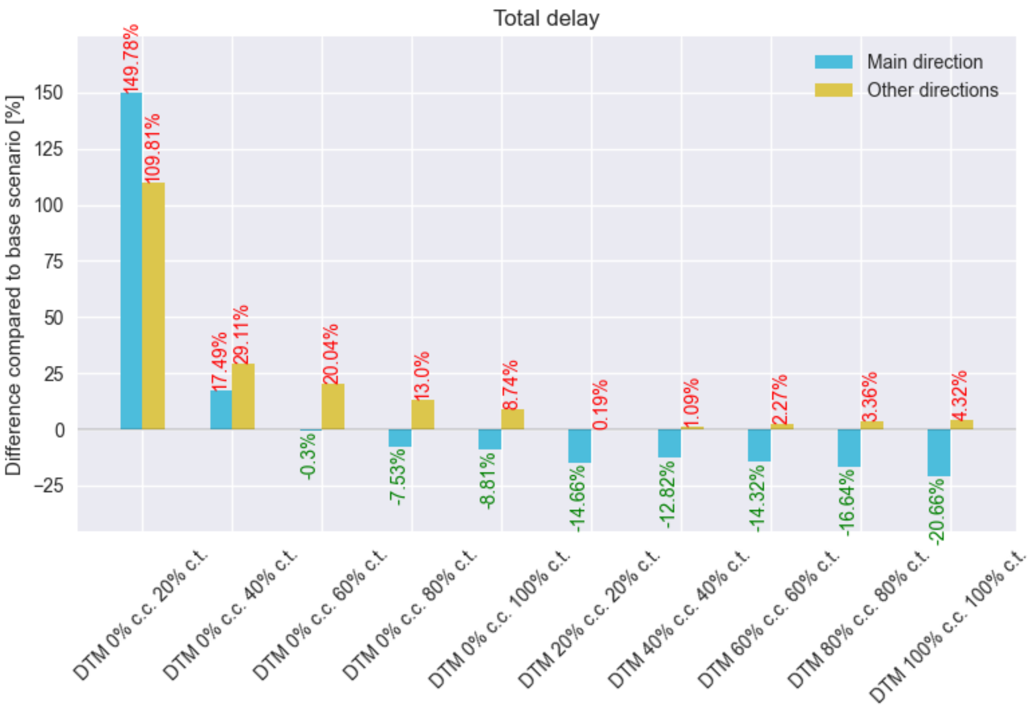


Figure 5.4: The percentage difference of the DTM scenario total delay results compared to the base scenario for the main and other directions on the intersection.

When looking at the total delay for all directions for the Platoon scenarios, it can be seen that there are no significant improvements at lower penetration rates of CACC-equipped vehicles compared to the base scenario. The 0% CACC-equipped cars (c.c.) and 20% CACC-equipped trucks (c.t.), 0% c.c. and 100% c.t. and 40% c.c. and 40% c.t. Platoon scenarios show a slight decrease in total delay compared to the base scenario. However, this decrease is marginal since it is lower than one percent as can be seen in figure 5.1. The 0% c.c. and 40 - 80% c.t. and 20% c.c. and 20% c.t. Platoon scenarios have a slightly increased total delay compared to the base scenario. From the 60% c.c. and 60% c.t. Platoon scenarios onwards, the decrease in total delay increases up to 12.5%.

The DTM scenario with a penetration rate of 0% c.c. and 20% c.t. shows an significant increase in total delay of 134.2% compared to the base scenario. Moving up a tier in the truck penetration rate (0% c.c. and 40% c.t.), the total delay is still significantly higher than in the base scenario with 22%. The 0% c.c. and 60% c.t. DTM scenario shows an increase in total delay of 7.6%. The increase in delay compared to the base scenario is negligible for the DTM scenario with a penetration rate of 0% c.c. and 80% c.t. (0.5%). The DTM scenarios with penetration rates of 0% c.c. and 100% c.t. and 20 - 100% c.c. and 20-100% c.t. show an decrease in total delay compared to the base scenario that reaches -10.9%.

An observation that can be made from figures 5.3 and 5.4 is that for both the Platoon and DTM scenarios the total delay only decreases on the main direction. Again no significant decrease in total delay on the main direction can be observed in the Platoon scenarios with lower penetration rates of CACC-equipped trucks and no CACC-equipped cars. The Platoon scenarios with penetration rates of 0% c.c. and 100% c.t. and 0 - 100% c.c. and 0 - 100% c.c. clearly show a decrease in total delay on the main direction compared to the base scenario. This ranges from -1.6% up to -25.8%.

A similar pattern regarding the total delay on the main direction is visible for the DTM scenarios. However, for the lower penetration rates of 0% c.c. and 0 - 40% c.t. an increase in total delay compared to the base scenario in visible (149.8 - 17.5%). The DTM scenarios with the higher penetration rates of 0% c.c. and 80 - 100% c.t. and 20 - 100% c.c. and 20 - 100% c.t. show a decrease in total delay compared to the base scenario, which ranges from -7.5 to -20.7%.

The delay on the other directions does not decrease for both the Platoon and the DTM scenarios in comparison to the base scenario. An observation that can be made from figure 5.3 regarding the Platoon scenarios is that with higher penetration rates of CACC-equipped vehicles the total delay on the other directions increases. Regarding the DTM scenarios, a similar pattern is visible for the penetration rates of 20 - 100% c.c. and 20 - 100% c.t.. However, for the scenarios with only CACC-equipped trucks, there is a much higher increase in total delay for the DTM scenarios compared to the base scenario. This difference in total delay on the other directions between the DTM and base scenarios decreases with increasing penetration rates of CACC-equipped trucks.

Comparison between DTM and Platoon scenarios

Figure 5.5 is a bar chart that portrays the percentage difference in total delay for all directions and vehicle types between the DTM and Platoon scenarios. Positive percentages mean that the specific Platoon scenario has a lower total delay than the equivalent DTM scenario. This figure will be used for making a comparison between both scenarios in this section.

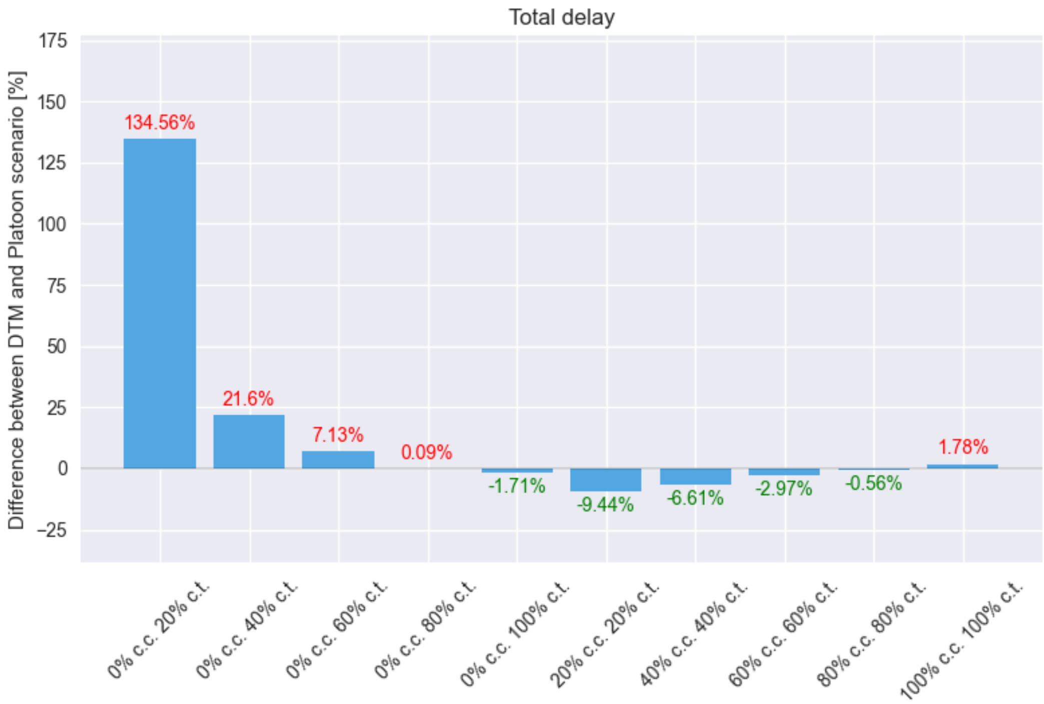


Figure 5.5: The percentage difference between the DTM and Platoon scenario total delay results for all directions on the intersection.

The results from figure 5.5 show that the Platoon scenarios with no CACC-equipped cars and 20 - 60% c.t. have a lower total delay than the equivalent DTM scenarios. The trend that can be observed is that with increasing penetration rates of CACC-equipped trucks the difference in total delay shifts from an advantage for the Platoon scenarios towards and advantage for the DTM scenarios. An opposite trend is visible for the scenarios that have CACC-equipped cars included as well, where the DTM scenarios mostly perform better than the Platoon scenarios. The difference is the largest for the scenario with a 20% penetration rate of CACC-equipped cars, which then reduces with increasing penetration rates. The Platoon scenario with 100% c.c. and c.t. performs 1.76% better than the equivalent DTM scenario.

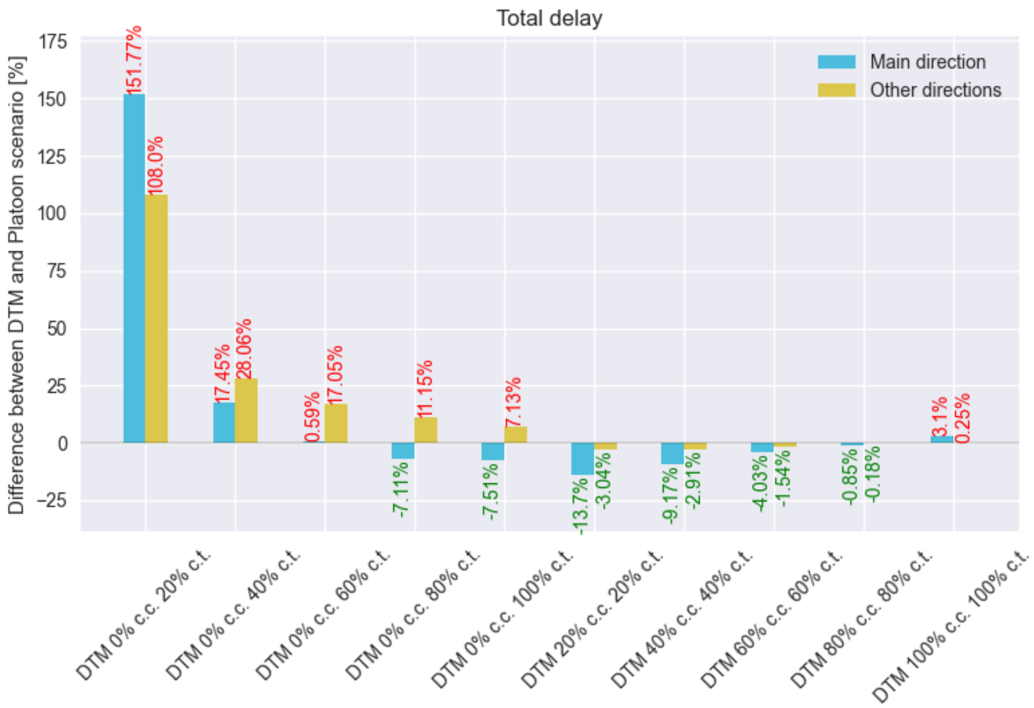


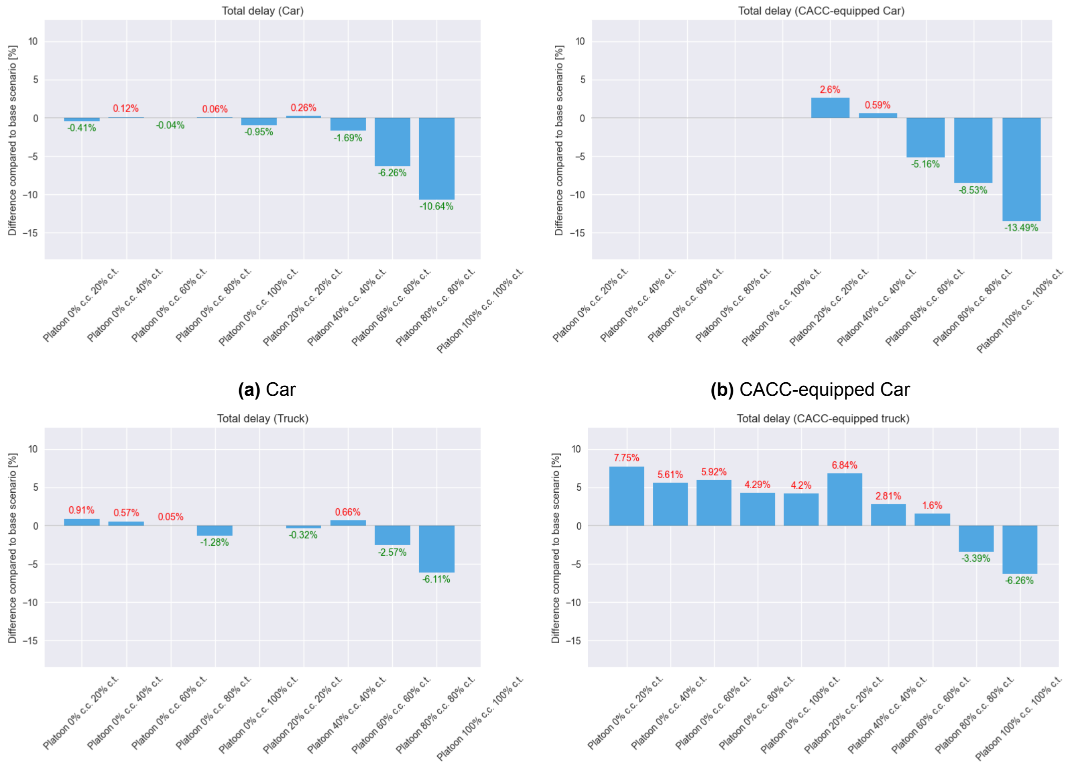
Figure 5.6: The percentage difference between the DTM and Platoon scenario total delay results for the main and other directions on the intersection.

The percentage difference between the DTM and Platoon scenarios, with respect to the total delay on the main and other directions, is displayed in figure 5.6. The pattern of the difference in total delay on the main direction between the DTM and Platoon scenarios is similar to that of all directions. Thus, the difference is the largest in favour of the Platoon scenarios with no CACC-equipped cars and 20% of the trucks equipped with CACC. This difference decreases with increasing penetration rates for the CACC-equipped trucks. Within the scenarios with 0% c.c. and 80 - 100% c.t., the DTM scenarios have a lower total delay on the main direction in comparison to the equivalent Platoon scenarios. When both CACC-equipped cars and trucks are considered, the DTM scenarios perform better than the Platoon scenarios for penetration rates between 20 and 60%. With penetration rates of 80 and 100%, the difference between the DTM and Platoon scenarios is negligible.

All Platoon scenarios have a lower total delay than the equivalent DTM scenarios on the other directions when there are no CACC-equipped cars considered. Again, the difference is the largest for the scenario with 0% c.c. and 20% c.t., which then decreases with an increasing penetration rate of CACC-equipped trucks. The pattern for the scenarios with both CACC-equipped cars and trucks is exactly the same as that for the main direction. So with a penetration rate of 20%, the total delay is lower for the DTM scenario. This difference then decreases with increasing penetration rates of CACC-equipped vehicles. At a 100% penetration rate the total delay on the other directions is marginally lower for the Platoon scenario compared to the equivalent DTM scenario.

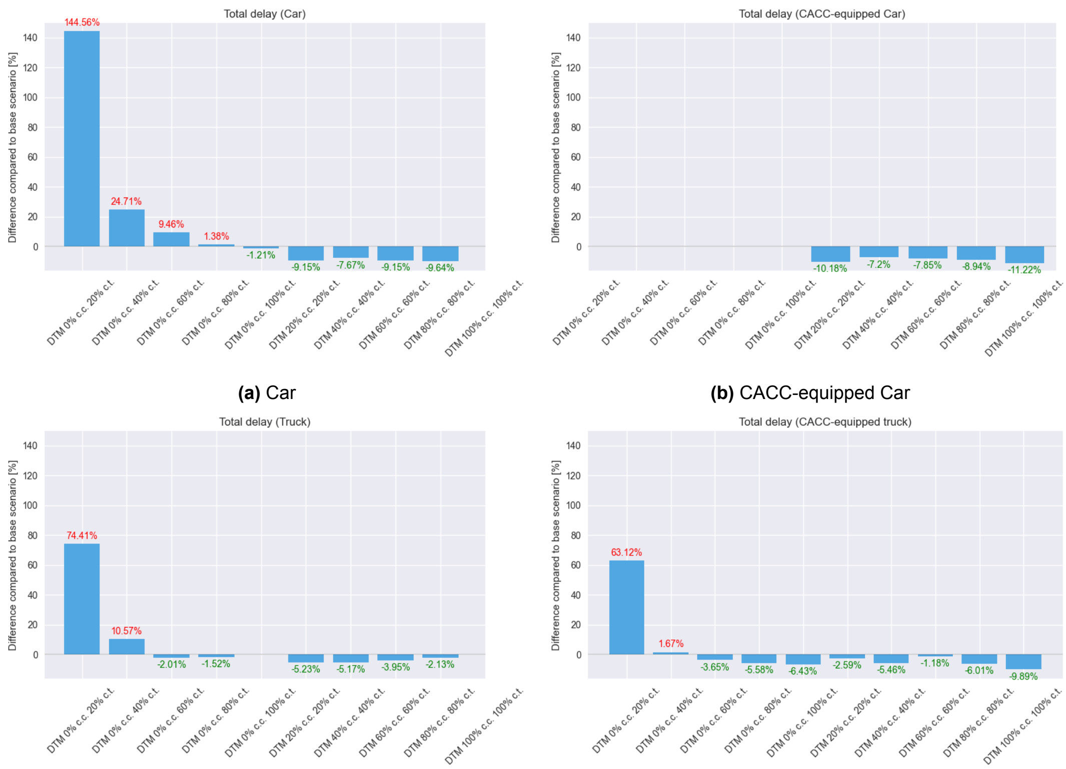
Per Vehicle Type

The next step in the result analysis is to have a closer look into the total delay results. However, this time the results per vehicle type will be analysed. As is stated before, the Vissim microsimulation model uses four vehicle types, which are cars, trucks and their CACC-equipped counterparts. Figures 5.7 and 5.8 present the percentage difference between respectively the Platoon and base scenarios and the DTM and base scenarios regarding the total delay for each vehicle type. The total delay of CACC-equipped cars and trucks are compared to the total delay of manually driven cars and trucks in the base scenario.



(c) Truck **(d)** CACC-equipped Truck

Figure 5.7: The percentage difference of the Platoon scenario total delay results compared to the base scenario per vehicle type.



(a) Car

(b) CACC-equipped Car

(c) Truck

(d) CACC-equipped Truck

Figure 5.8: The percentage difference of the DTM scenario total delay results compared to the base scenario per vehicle type.

When looking at the total delay for manually driven cars and trucks within the Platoon scenarios, the same pattern is observed. This pattern is that for the scenarios with no CACC-equipped cars and with CACC-equipped trucks under different penetration rates, the total delay is somewhat lower or higher than it is in the base scenario for the specific vehicle type. The same conclusion can be drawn for the Platoon scenario with a penetration rate of 20% of CACC-equipped cars and trucks. The Platoon scenario with a 40% penetration rate of CACC-equipped cars and trucks results in a slight decrease of 1.7% in total delay for the cars, while the total delay of the trucks increases marginally with 0.7% compared to the base scenario. The Platoon scenarios with a 60 and 80% penetration rate of CACC-equipped cars and trucks result in a decrease is total delay for the manually driven cars and trucks compared to the base scenario.

With lower penetration rates of 20 and 40%, connected cars have a slightly higher total delay within the Platoon scenarios than manually driven cars have in the base scenario. From a penetration rate of 60% and higher, CACC-equipped cars have a lower total delay than manually driven cars have in the base scenario. So with increasing penetration rates, the total delay of CACC-equipped cars decrease within the Platoon scenarios compared to manually driven cars in the base scenario. CACC-equipped trucks seem to have less benefit from platooning than cars have. All Platoon scenarios with no connected cars and only connected trucks result in a higher total delay for the connected trucks compared to manually driven trucks in the base scenario. Only the scenarios with penetration rates of 80 - 100% for both CACC-equipped cars and trucks result in a lower total delay for the connected trucks compared to the base scenario.

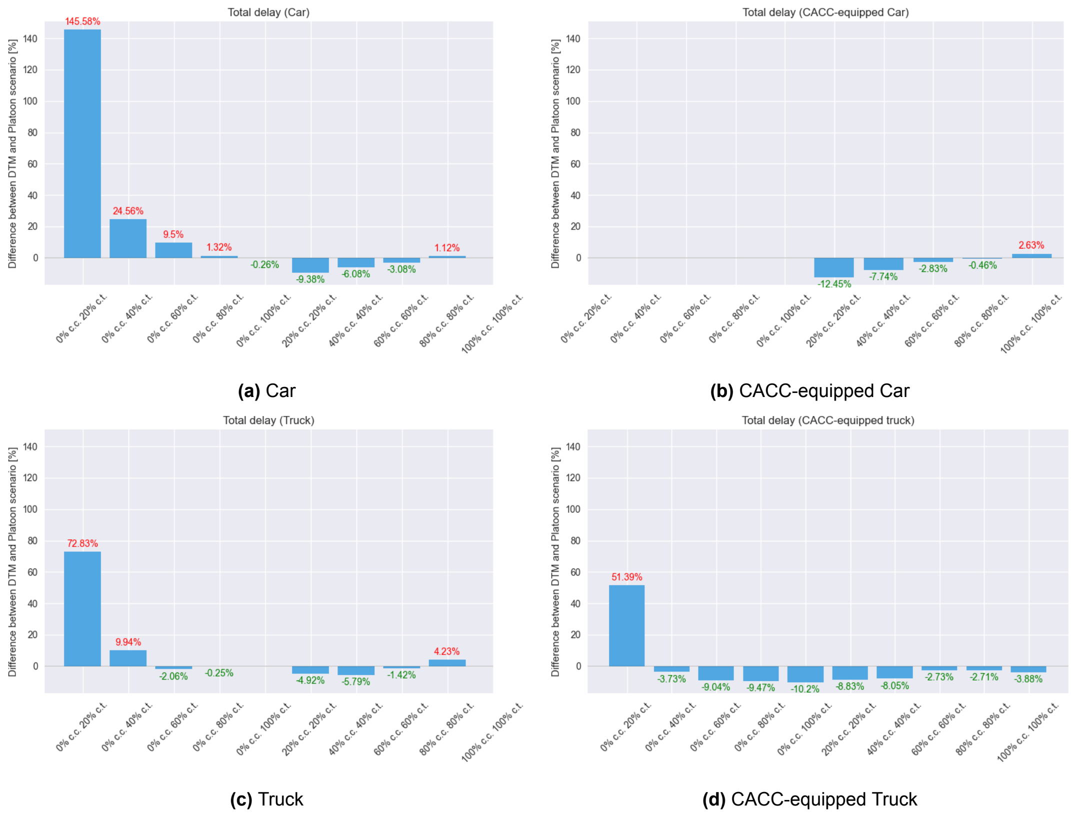
When looking at the total delay results per vehicle type for the DTM scenarios compared to the base scenario in figure 5.8, slightly different results are observed. The DTM scenarios with no CACC-equipped cars and 0 - 80% CACC-equipped trucks result in an increase in total delay for manually driven cars compared to the base scenario. Only when 100% of the trucks are connected, the manually driven cars have a slightly lower total delay compared to the base scenario. Manually driven trucks have a higher total delay compared to the base scenario within the DTM scenarios with no CACC-equipped cars and

20 - 40% CACC-equipped trucks. All other DTM scenarios result in a lower total delay for manually driven trucks relatively to the base scenario. So for both the manually driven cars and trucks, it can be concluded that the total delay within the DTM scenarios decreases with increasing penetration rates of CACC-equipped trucks. Within the DTM scenario with both CACC-equipped cars and trucks, the total delay for all manually driven cars and trucks is lower compared to the base scenario. This percentage difference for the non-connected cars is stable for different penetration rates. However, for the non-connected trucks this difference decreases with increasing penetration rates of CACC-equipped cars and trucks.

All DTM scenarios containing CACC-equipped cars result in a lower total delay for these connected cars in comparison to the manually driven cars in the base scenario. The same statement can be made for the CACC-equipped trucks in a majority of DTM scenarios that contain these connected trucks. However, the 0% c.c. and 20 - 40% c.t. DTM scenarios are excepted since those result in a higher total delay for the CACC-equipped trucks relatively to the manually driven trucks in the base scenario.

Comparison between DTM and Platoon scenarios per vehicle type

Figure 5.9 shows the percentage difference of the total delay per vehicle type between the DTM and Platoon scenarios. This section will elaborate these results.



(a) Car **(b)** CACC-equipped Car

(c) Truck **(d)** CACC-equipped Truck

Figure 5.9: The percentage difference between the DTM and Platoon scenario total delay results per vehicle type.

The patterns for the manually driven cars and trucks are similar for the scenarios without CACC-equipped cars and with CACC-equipped trucks under various penetration rates. With a penetration rate of 20% CACC-equipped trucks, the total delay is much higher for the DTM scenario compared to the equivalent Platoon scenario. This difference decreases with increasing penetration rates of the CACC-equipped trucks. The total delay for manually driven cars is lower for the DTM scenarios than the equivalent Platoon scenario at a 100% penetration rate of the connected trucks. The total delay for manually driven cars is lower for the DTM scenarios with penetration rates of 0% c.c. and 60 - 80% c.t. in comparison to the equivalent Platoon scenarios. An opposite trend is visible for the scenarios with both CACC-equipped cars and trucks. Here, the non-connected cars and trucks have a lower total delay within the DTM scenario at a penetration rate of 20% for the CACC-equipped cars and trucks. An increasing penetration rate results in the fact that the difference in total delay for the manually driven cars and trucks between the DTM and Platoon scenarios becomes less. At 80% penetration, the non-connected cars and trucks have a lower total delay within the Platoon scenario.

The total delay of CACC-equipped trucks is generally lower Within the DTM scenarios compared to the Platoon scenarios. The only exception is the scenario with 0% c.c. and 20% c.t.. The trend for the scenarios with no CACC-equipped cars and 40 - 100% CACC equipped trucks is that a higher penetration rate results in a greater difference in favour of the DTM scenarios. When both CACC-equipped cars and trucks are considered, the trend is different. At a 20% penetration rate the total delay for CACC-equipped trucks is lower for the DTM scenario. Increasing penetration rates results in a decreasing difference in total delay for CACC-equipped trucks between the DTM ans Platoon scenarios. However, the total delay remains lower within the DTM scenarios. The same trend is visible for CACC-equipped cars. However, at a 100% penetration rate, the CACC-equipped cars have a lower total delay for the Platoon scenario compared to the DTM scenario.

5.2.2. Average Travel Time

The second KPI is the average travel time. These results will be analysed in this section, where the same comparisons will be made as for the total delay.

Figure 5.10 displays the percentage difference in average travel time for all directions and vehicles combined between the Platoon scenarios and the base scenario. Figure 5.11 does the same but between the DTM scenarios and base scenario. Figures 5.12 and 5.13 compare the Platoon and base scenarios and the DTM scenarios to the base scenario regarding the average travel time on the main and other directions.

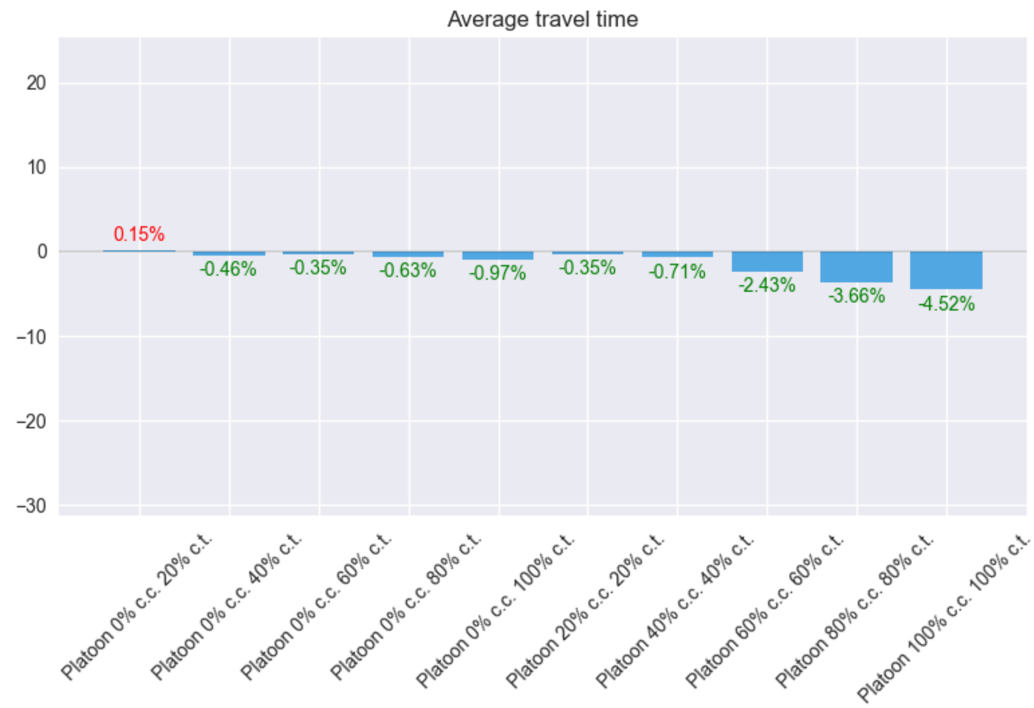


Figure 5.10: The percentage difference of the Platoon scenario average travel time results compared to the base scenario for all directions on the intersection.

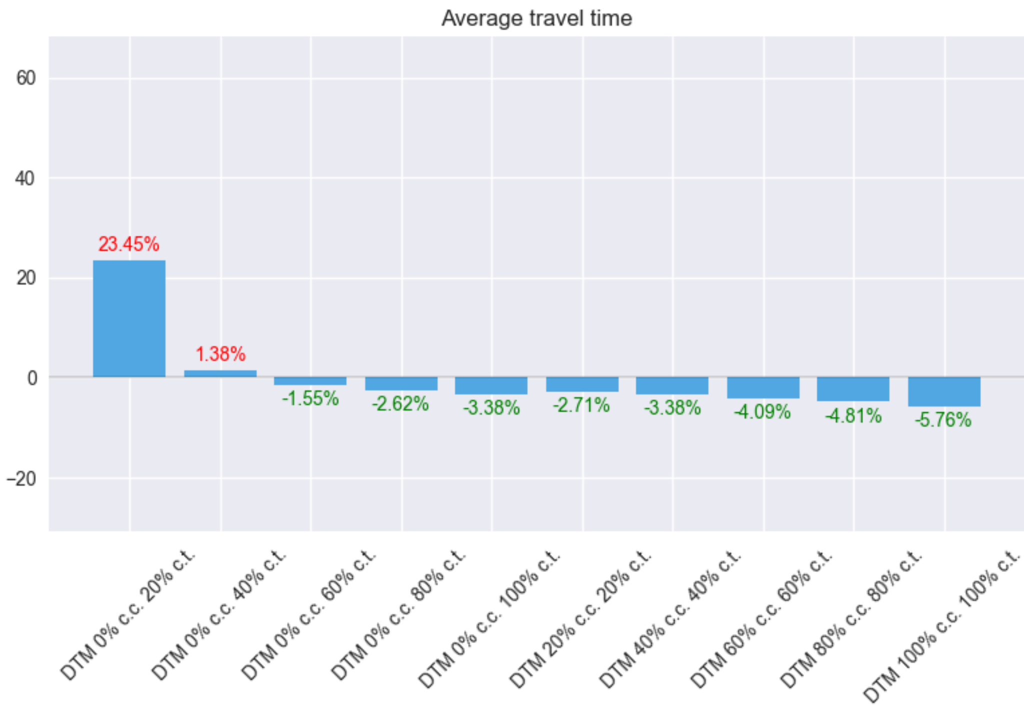


Figure 5.11: The percentage difference of the DTM scenario average travel time results compared to the base scenario for all directions on the intersection.

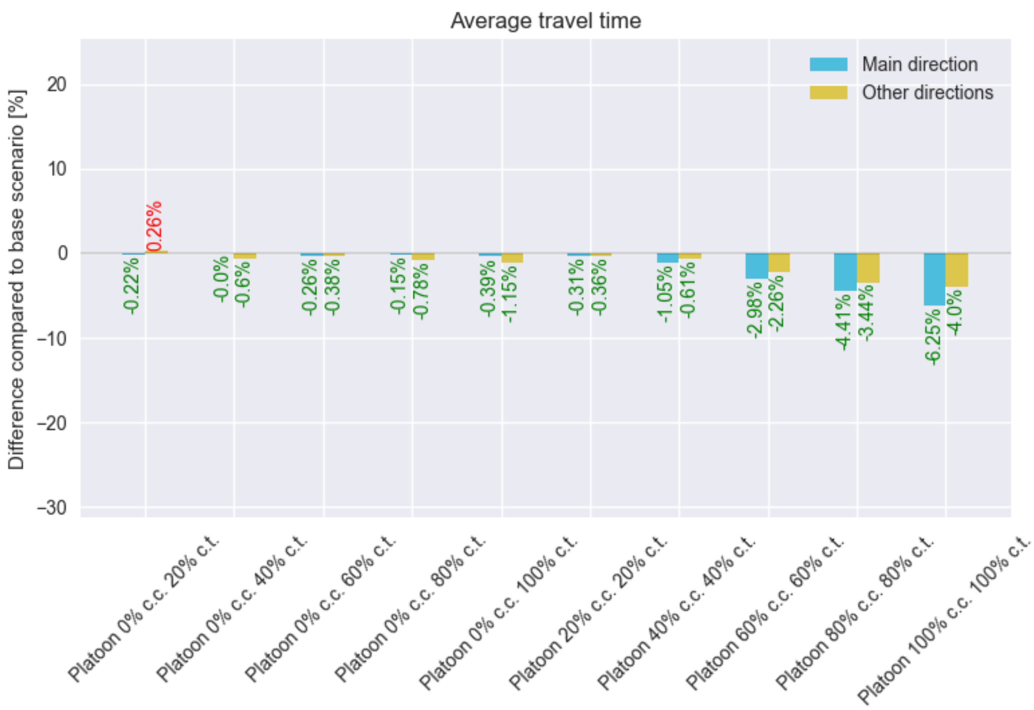


Figure 5.12: The percentage difference of the Platoon scenario average travel time results compared to the base scenario for the main and other directions on the intersection.

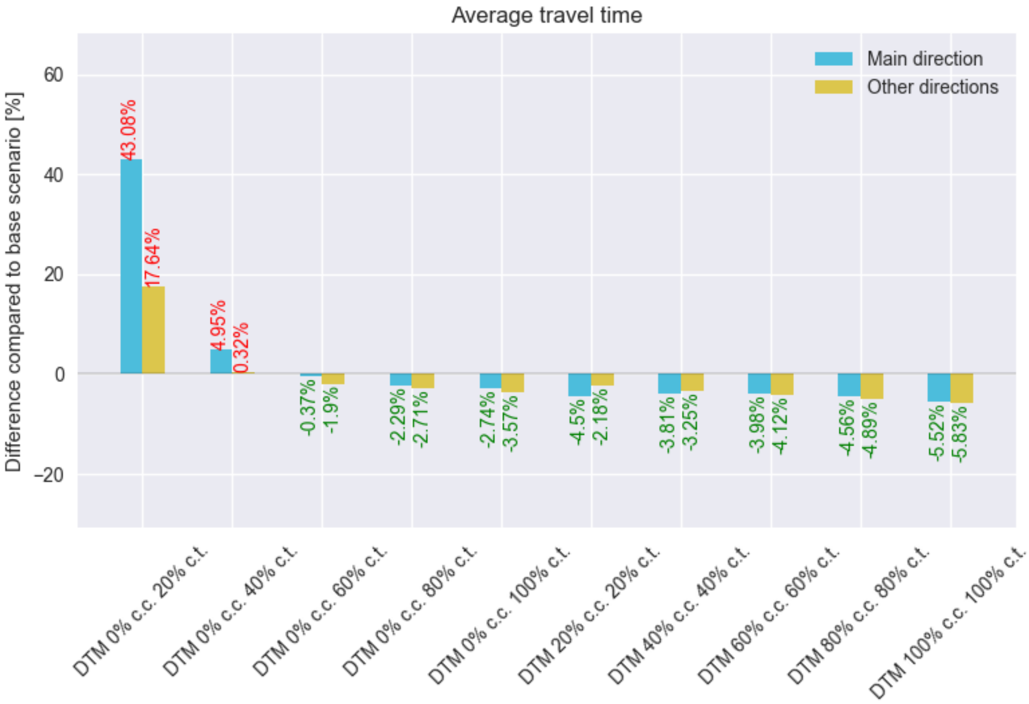


Figure 5.13: The percentage difference of the DTM scenario average travel time results compared to the base scenario for the main and other directions on the intersection.

Looking at the Platoon scenario results for all directions, an decrease in the average travel time is observed for most penetration rates. The only exception is the Platoon scenario with no CACC-equipped cars and 20% of the trucks is equipped with CACC. Another observation that can be made is that the average travel time decreases with increasing penetration rates of CACC-equipped trucks and both CACC-equipped cars and trucks. A similar pattern is visible in figure 5.12 regarding the main and other directions for the Platoon scenarios. Again there is a slight decrease in average travel time on the main direction and other directions within the scenarios with no CACC-equipped cars and 20 - 100% CACC-equipped trucks. Within the Platoon scenarios with 20-100% CACC-equipped cars and trucks the average travel time starts decreasing more when the penetration rate increases.

The DTM scenarios regarding all, main and other directions show similar results as for the Platoon scenarios. However, the DTM scenarios with penetration rates of 0% c.c. and 20 - 40% c.t. have a higher average travel time compared to the base scenario. This difference is the highest for the 0% c.c. and 20% c.t. DTM scenario. Again, the DTM scenarios have a decreasing average travel time when the penetration rate of CACC-equipped vehicles rises.

Comparison between DTM and Platoon scenarios

Figure 5.14 displays the percentage difference of the average travel time over all directions of the intersection between the DTM and Platoon scenarios. The negative percentages mean that the Platoon scenario performs better and the postive values mean the the DTM scenario performs better than the Platoon scenario. What can be concluded from this figure is that the Platoon scenarios perform better with no CACC-equipped cars and a penetration rate of 20 - 40% of CACC-equipped trucks regarding the average travel time. With higher penetration rates of CACC-equipped trucks (0% c.c. and 60 - 100% c.t.) the average travel time is lower for the DTM scenarios. So the observed trend is that the advantage shifts from the Platoon scenarios towards the DTM scenarios with increasing penetration rates of CACC-equipped trucks.

All DTM scenarios with both CACC-equipped cars and trucks have a lower average travel time for all directions than the equivalent Platoon scenarios. This difference decreases with increasing penetration rates of the CACC-equipped vehicles.

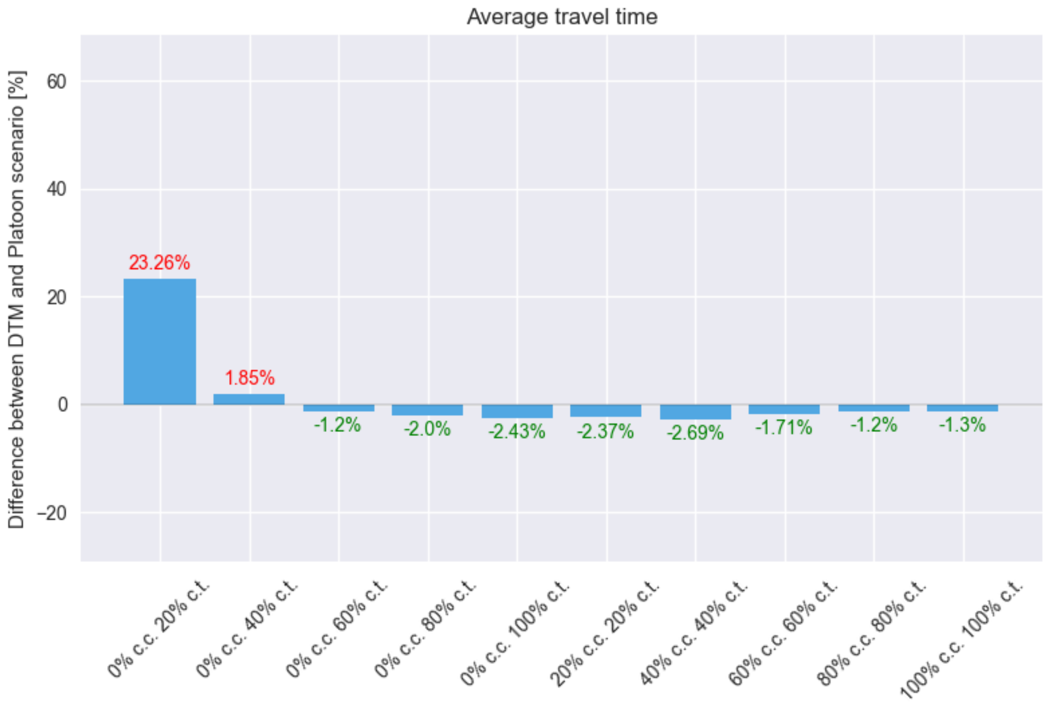


Figure 5.14: The percentage difference between the DTM and Platoon scenario average travel time results for all directions on the intersection.

The percentage difference between the DTM and Platoon scenarios, with respect to the average travel time on the main and other directions, is displayed in figure 5.15.

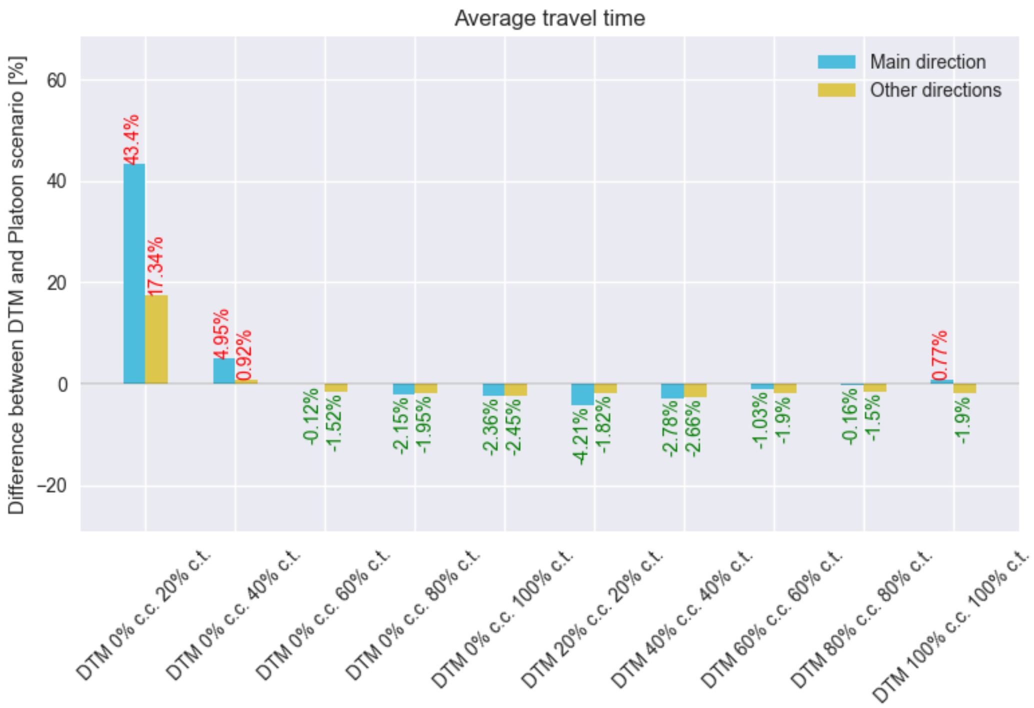


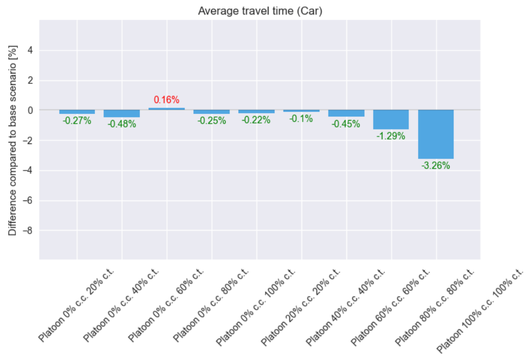
Figure 5.15: The percentage difference between the DTM and Platoon scenario average travel time results for the main and other directions on the intersection.

The pattern of the difference in average travel time on the main direction between the DTM and Platoon scenarios is similar to that of all directions. Thus, the difference is the largest in favour of the Platoon scenarios with no CACC-equipped cars and 20% of the trucks equipped with CACC. This difference decreases with increasing penetration rates for the CACC-equipped trucks. For the scenarios with 0% c.c. and 60 - 100% c.t. the DTM scenarios have a lower average travel time in comparison to the equivalent Platoon scenarios on the main direction. When both CACC-equipped cars and trucks are considered, the DTM scenarios perform better than the Platoon scenarios for penetration rates between 20 and 60%. With penetration rates of 80 and 100%, the difference between the DTM and Platoon scenarios is negligible.

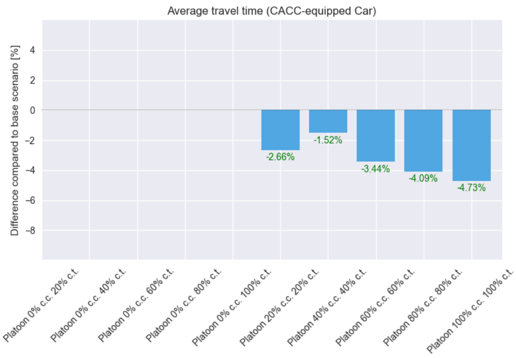
The difference between the DTM and Platoon scenarios have a similar pattern for the other directions as that for the main direction. However, this difference is lower for the scenarios with no CACC-equipped cars and 20 - 40% CACC-equipped trucks, where the Platoon scenarios have a lower average travel time than the equivalent DTM scenarios. The average travel time on the other directions is lower for the DTM scenarios with no CACC-equipped cars and a 60 - 100% penetration rate of CACC-equipped trucks. All DTM scenarios have a lower average travel time compared to the Platoon scenarios when both CACC-equipped cars and trucks are considered. However, this difference decreases with an increasing penetration rate of these CACC-equipped vehicles.

Per Vehicle Type

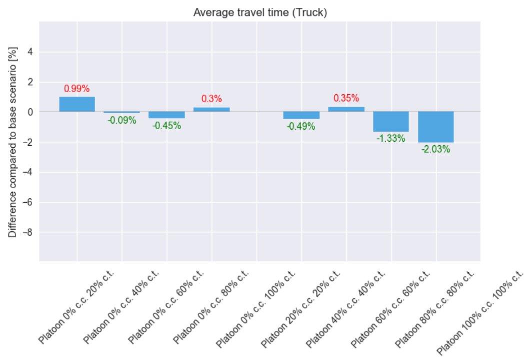
Similar to section 5.2.1, the results will be analysed per vehicle type as well. Figures 5.16 and 5.17 provide bar charts that compare the total delay per vehicle type between respectively the Platoon and base scenarios and the DTM and base scenarios.



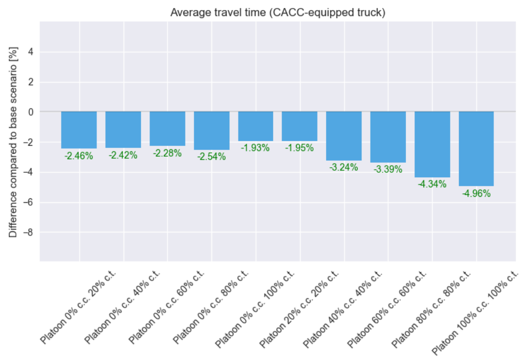
(a) Car



(b) CACC-equipped Car



(c) Truck



(d) CACC-equipped Truck

Figure 5.16: The percentage difference of the Platoon scenario average travel time results compared to the base scenario per vehicle type.

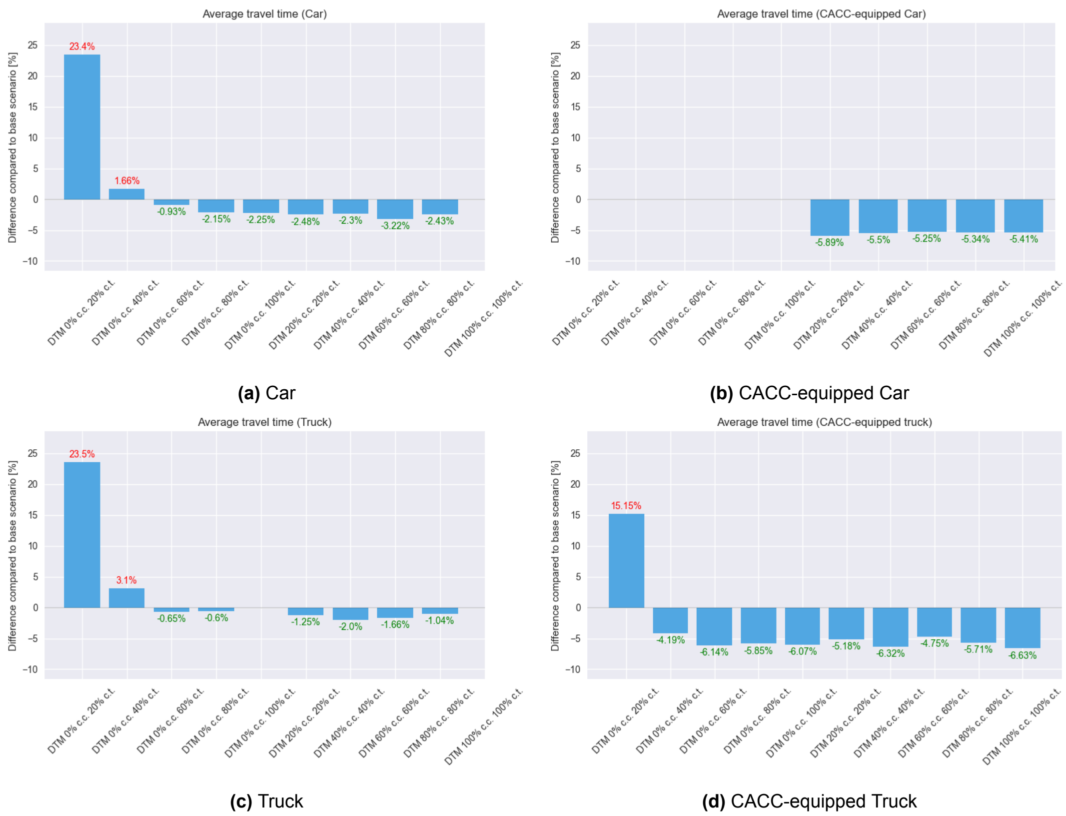


Figure 5.17: The percentage difference of the DTM scenario average travel time results compared to the base scenario per vehicle type.

A similar pattern can be observed when looking at the average travel time for manually driven cars and trucks within the Platoon scenarios. The scenarios with no CACC-equipped cars and 20 - 100% CACC-equipped trucks have a quite similar average travel time as for the base scenario. The average travel time of the manually driven cars and trucks within Platoon scenarios with penetration rates 20 and 40% CACC-equipped cars and trucks are quite similar to the base scenario as well. Only the Platoon scenarios with a penetration rate of 60 and 80% result in a lower average travel time for the manually driven cars and trucks in comparison to the base scenario.

All Platoon scenarios that have CACC-equipped cars included result in a lower average travel time for those connected cars compared to the manually driven cars in the base scenario. This difference in favour of the Platoon scenarios decreases with increasing penetration rates of CACC-equipped vehicles. The only exception is the Platoon scenario with a 40% penetration rate of CACC-equipped cars and trucks. Within, this scenario the average travel time of CACC-equipped cars is lower than for the other Platoon scenarios.

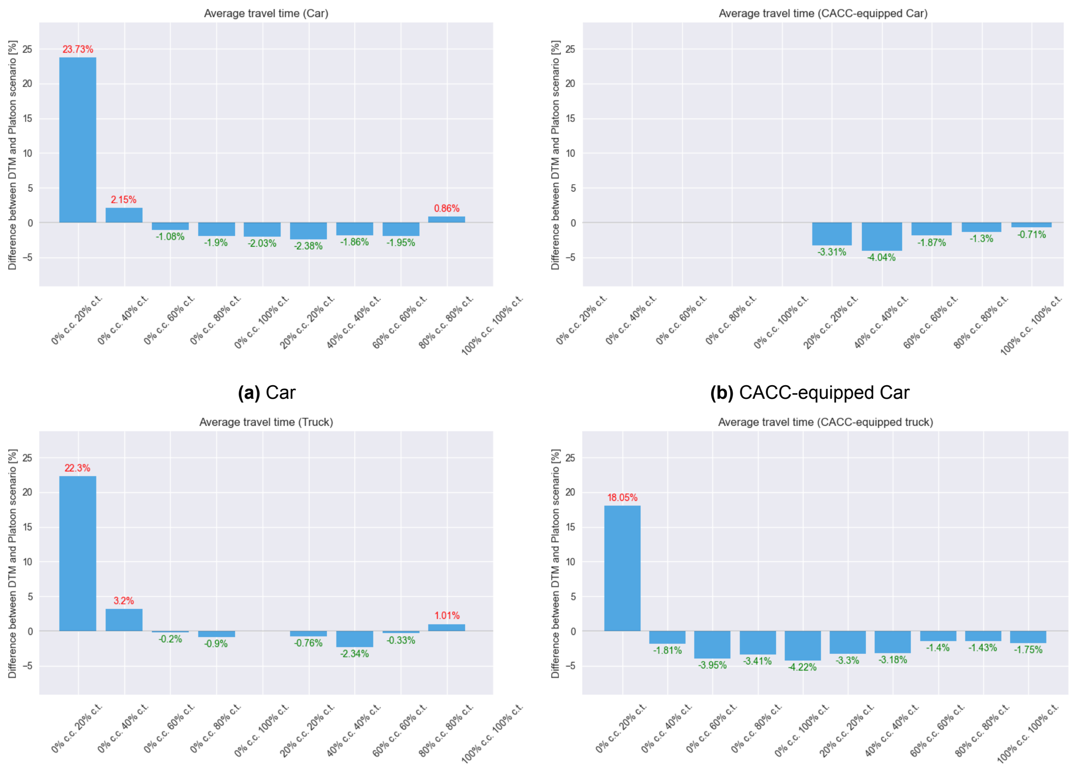
The average travel time results for the CACC-equipped trucks are similar as for the CACC-equipped cars. So the average travel time for this vehicle type is lower than for the manually driven trucks within the base scenario. The average travel time results for the CACC-equipped trucks are quite similar to the base scenario for the Platoon scenario with no CACC-equipped cars. Within the Platoon scenarios with both CACC-equipped cars and trucks, the average travel time of the CACC-equipped trucks compared to the base scenario decreases with increasing penetration rates.

When looking at the DTM scenario results per vehicle type in figure 5.17, it can be seen that the manually driven cars and trucks generally have a lower average travel time in within the DTM scenarios compared to the base scenario. The only exceptions are the DTM scenarios with no CACC-equipped cars and 20 and 40% CACC-equipped trucks, where manually driven cars and trucks have a significantly higher average travel time than within the base scenario.

Similar to the Platoon scenarios, all DTM scenario with CACC-equipped cars result in lower lower average travel time for those vehicles in comparison to the manually driven cars in the base scenario. The results for the CACC-equipped trucks within the DTM scenarios are similar as well. However, the DTM scenario with no CACC-equipped cars and 20% CACC-equipped trucks results in a higher average travel time for the connected trucks in comparison to the base scenario.

Comparison between DTM and Platoon scenarios per vehicle type

Figure 5.18 shows the percentage difference of the average travel time per vehicle type between the DTM and Platoon scenarios. An elaboration of these results will be given in this section.



(a) Car

(b) CACC-equipped Car

(c) Truck

(d) CACC-equipped Truck

Figure 5.18: The percentage difference between the DTM and Platoon scenario average travel time results per vehicle type.

When looking at the manually driven cars and trucks in figure 5.18 it can be seen that those have a similar pattern. For the scenarios with no CACC-equipped cars and 20% CACC equipped trucks, the Platoon scenario has a significantly lower average travel time than the DTM scenario. This difference is lower with a penetration rate of 40% for the CACC-equipped trucks. 60 and 80% penetration for the CACC-equipped trucks leads to a slightly lower average travel time in favour of the DTM scenarios. For the scenarios with both CACC-equipped cars and trucks, the average travel time for manually driven cars and trucks is generally lower within the DTM scenarios. The only exception is the scenario with an 80% penetration rate.

Similar to all other vehicle types, CACC-equipped trucks have a significantly higher average travel time within the DTM scenario compared to the Platoon scenario with 0% c.c. and 20% c.t.. The average travel time for these CACC-equipped trucks is lower within the DTM scenarios for all other penetration rates. Additionally, the average travel time for CACC-equipped cars is lower within all DTM scenarios compared to the Platoon scenarios where those vehicle types are present.

5.2.3. Number of Stops

The number of stops is the last KPI that will be discussed, which will be done in this section. Figures 5.19 and 5.20 are bar charts that show the percentage difference between the Platoon and base scenario and DTM and base scenario regarding the average number of stops for all directions of the intersection. Figures 5.21 and 5.22 compare respectively the Platoon and DTM scenarios to the base scenario, with respect to the average number of stops on the main and other directions.

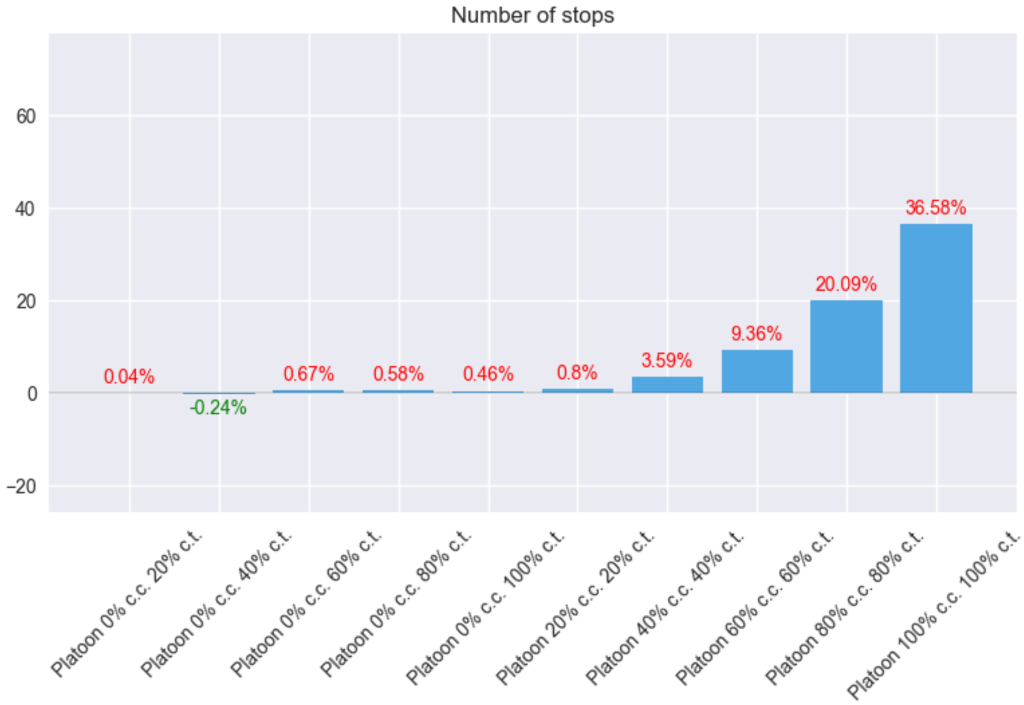


Figure 5.19: The percentage difference of the Platoon scenario average number of stops results compared to the base scenario.

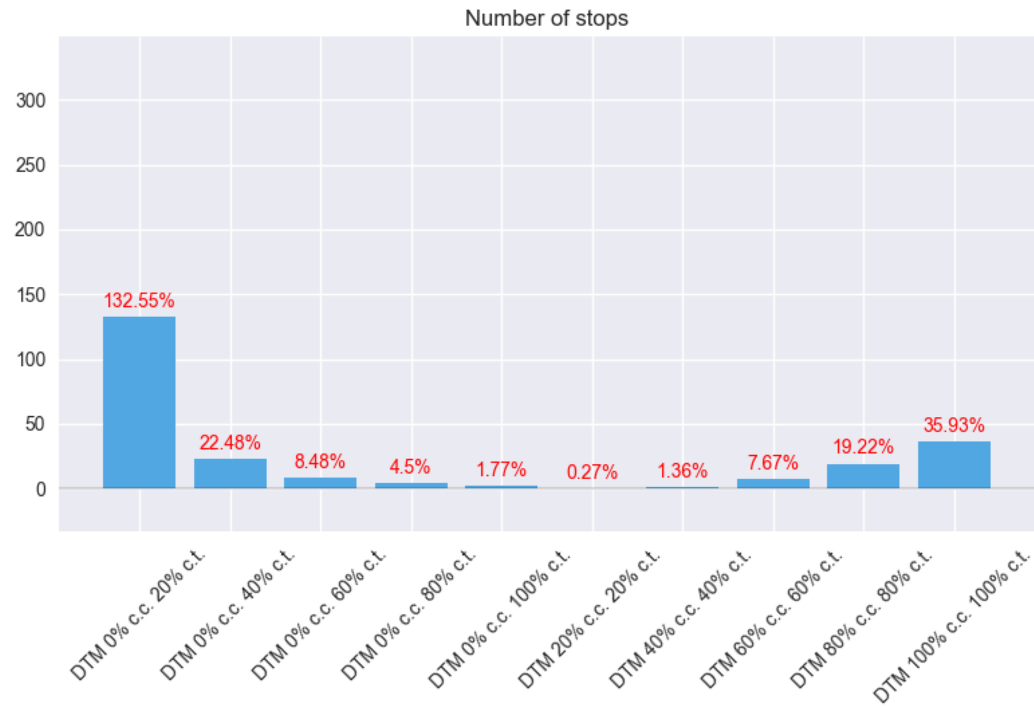


Figure 5.20: The percentage difference of the DTM scenario average number of stops results compared to the base scenario.

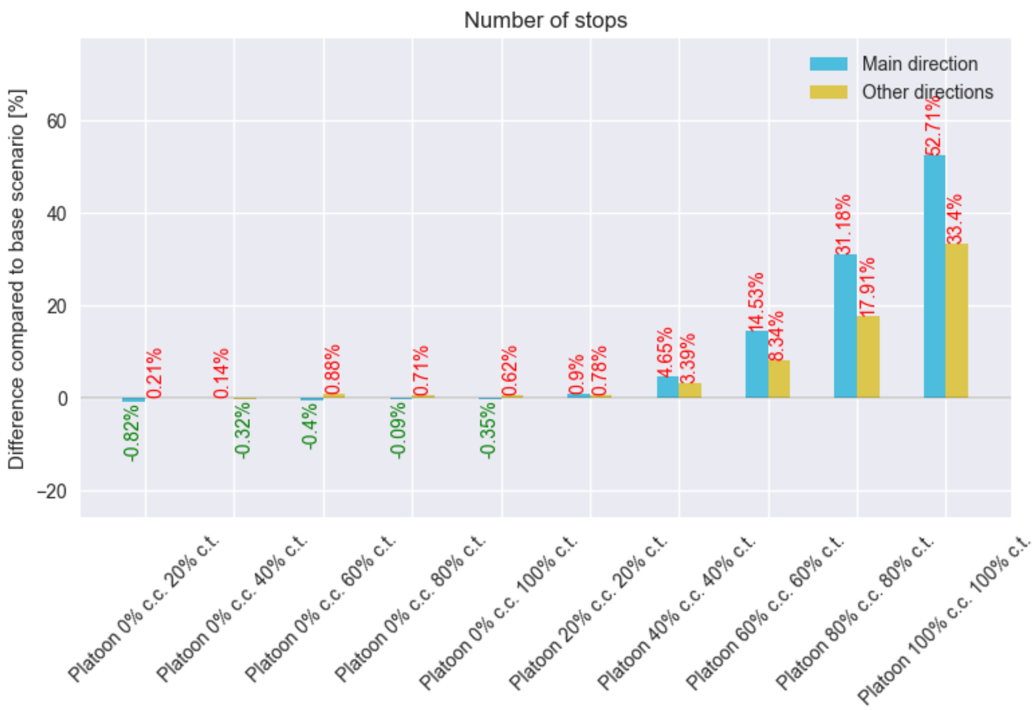


Figure 5.21: The percentage difference of the Platoon scenario average number of stops results compared to the base scenario for the main and other directions on the intersection.

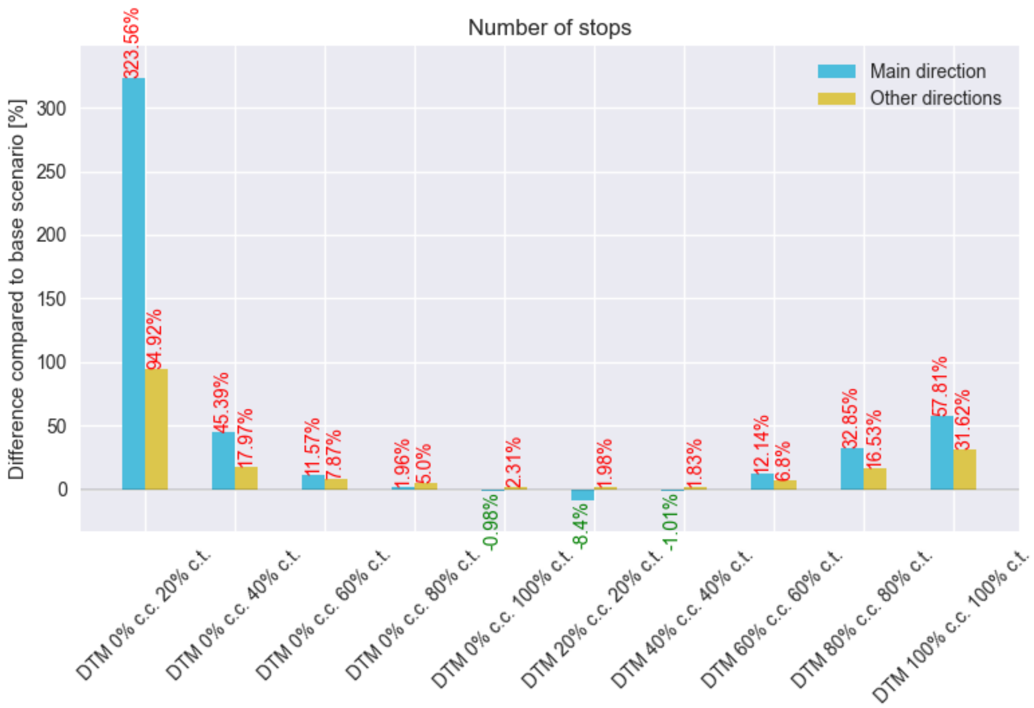


Figure 5.22: The percentage difference of the DTM scenario average number of stops results compared to the base scenario for the main and other directions on the intersection.

The results regarding the average number of stops are different in comparison to the total delay and average travel time results. For both the Platoon and DTM scenarios the average number of stops are mostly higher than it is in the base scenario. The average number of stops are similar to the base scenario for the Platoon scenarios with no CACC-equipped cars and 20 - 100% of the trucks equipped with CACC. A different trend is observed for the Platoon scenarios with both CACC-equipped cars and trucks. The Platoon scenario with a 20% penetration rate of CACC-equipped cars and trucks has a marginal difference in the average number of stops compared to the base scenario. However, an increase in penetration rate of the CACC-equipped vehicles leads to an increase in the average number of stops compared to the base scenario. This increases to up to 36.6%.

Figure 5.20 shows a similar pattern for the DTM scenarios with no CACC-equipped cars and 20 - 100% CACC-equipped trucks as figures 5.2 and 5.11, for respectively the total delay and average travel time. The average number of stops are much higher than it is in the base scenario with low penetration rates and it decreases with an increasing penetration rate of CACC-equipped trucks. The DTM scenarios with both connected cars and trucks show a similar pattern as the Platoon scenarios regarding the average number of stops compared to the base scenario. All these DTM scenarios have a higher average number of stops and this increases with an increasing penetration rate of CACC-equipped cars and trucks.

When looking at the comparison between the Platoon and base scenario, with respect to the average number of stops on the main and other directions (figure 5.21), a similar pattern can be seen as for all directions combined. Again the difference between the Platoon and base scenarios is marginal with no CACC-equipped cars and a penetration rate of 20 - 100% of CACC-equipped trucks. For the Platoon scenarios with a 20% penetration rate of both connected cars and trucks it is evident that the difference is marginal as well. However, with an increasing penetration rate of CACC-equipped cars and trucks, the difference in number of stops between the Platoon and base scenario increase as well. This difference is the larger for the main direction than for the other directions.

The comparison between the DTM and base scenario regarding the average number of stops on the main and other directions shows similar results as for all directions. So the average number of stops are higher for the DTM scenarios with no CACC-equipped cars and CACC-equipped trucks under different penetration rates compared to the base scenario. However, this difference decreases when the penetration rate of CACC-equipped trucks increase. An opposite trend is visible for the DTM scenarios with both CACC-equipped cars and trucks, where the difference in the average number of stops between the DTM and base scenario is the smallest for the scenario with a penetration rate of 20% of CACC-equipped cars and trucks. The average number of stops for the main and other directions will then increase with an increasing penetration rate of CACC-equipped vehicles for the DTM scenarios compared to the base scenario. However, the average number of stops on the main direction is lower for the DTM scenarios with 20 and 40% penetration rates of CACC-equipped vehicles in comparison to the base scenario.

Figure 5.23 compares the DTM to the Platoon scenarios, with respect to the average number of stops on all directions of the intersection. It is evident from this figure that the Platoon scenarios result in a smaller average number of stops than the DTM scenarios when that are no CACC-equipped cars and the penetration rate of CACC-equipped trucks ranges between 20 and 100%. A larger number of connected trucks result in a smaller difference between the DTM and Platoon scenarios. The average number of stops is marginally lower for the DTM scenarios compared to the Platoon scenarios with penetration rates of 20 - 100% of CACC-equipped cars and trucks. However, the difference is more pronounced for the scenarios without connected cars.

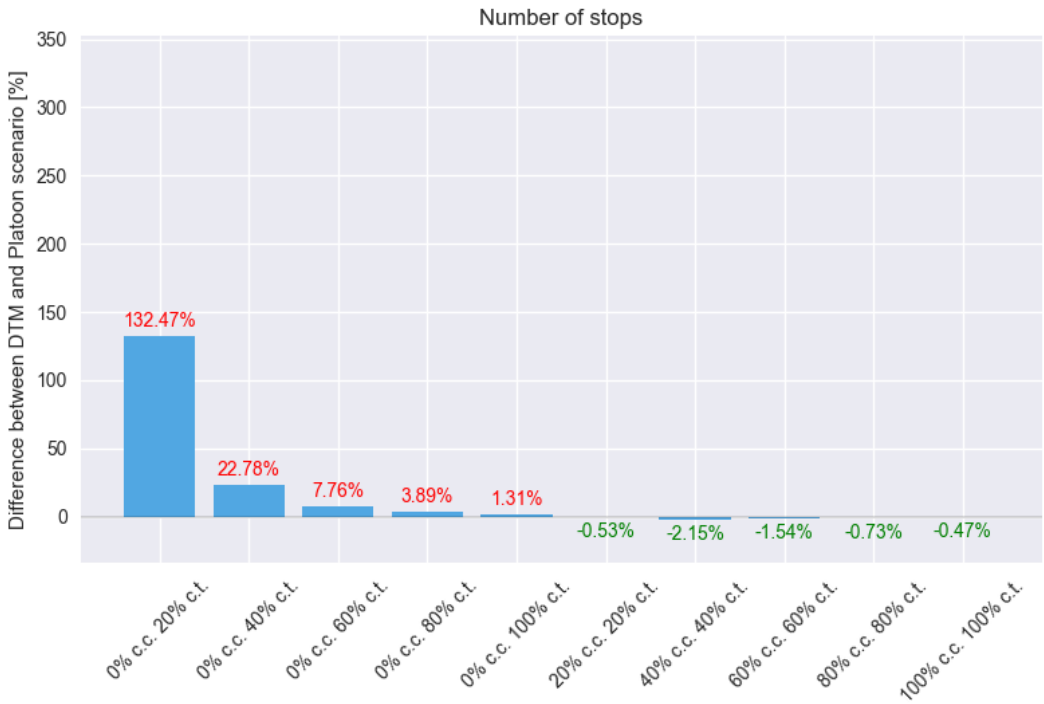


Figure 5.23: The percentage difference between the DTM and Platoon scenario average number of stops results for all directions on the intersection.

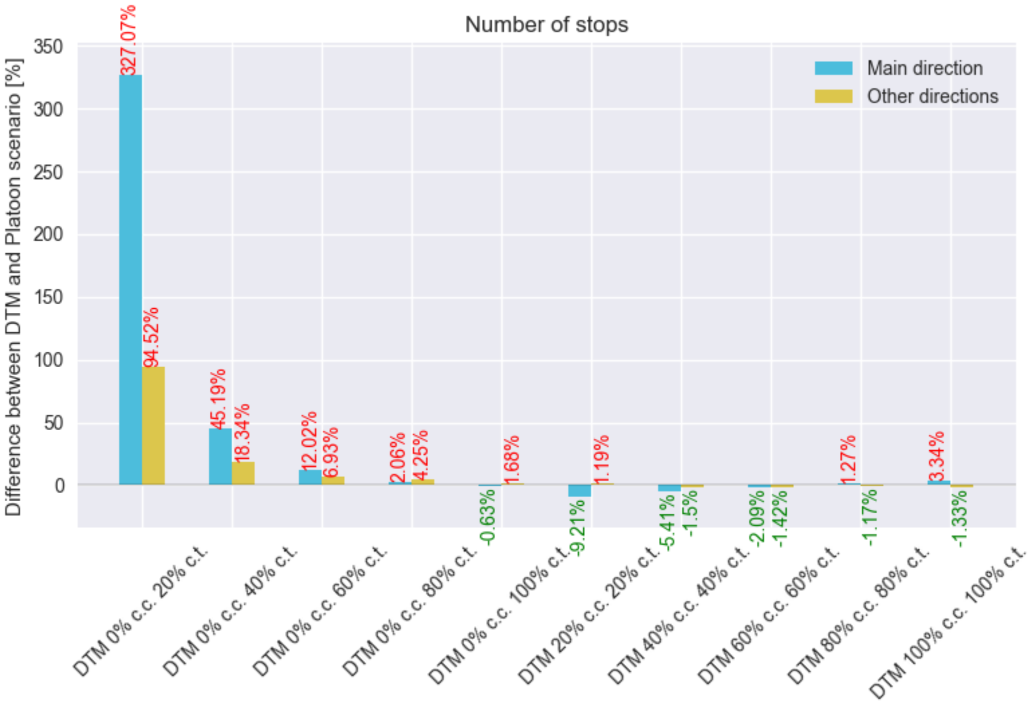
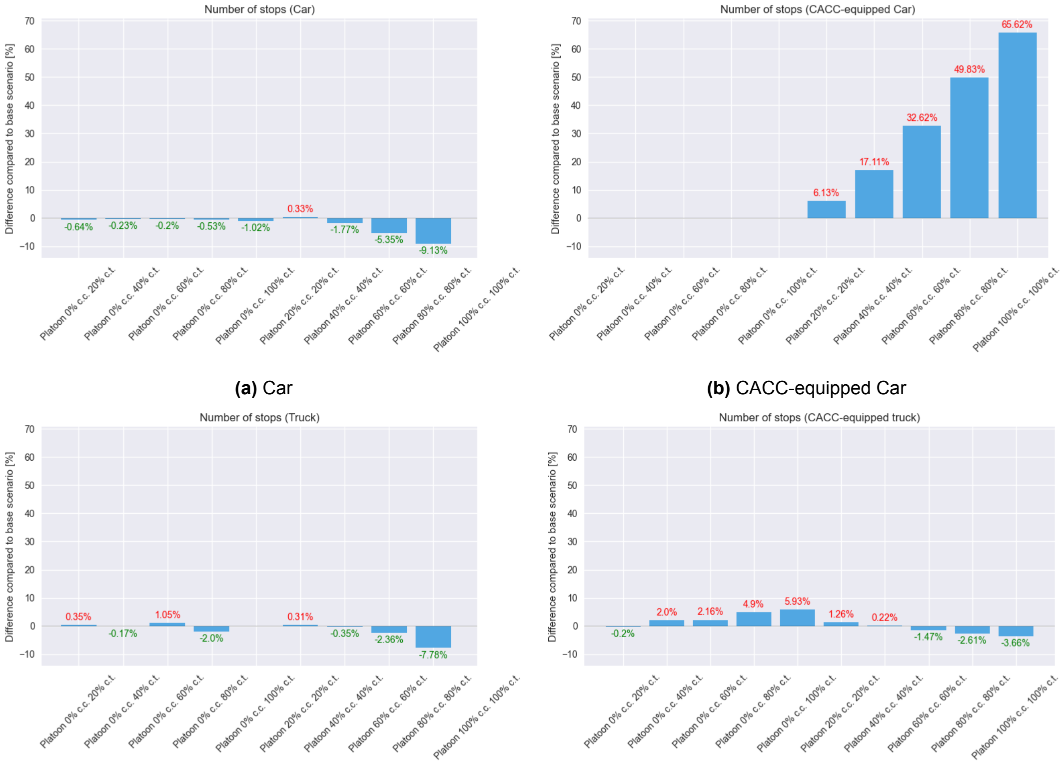


Figure 5.24: The percentage difference between the DTM and Platoon scenario average number of stops results for the main and other directions on the intersection.

Per Vehicle Type



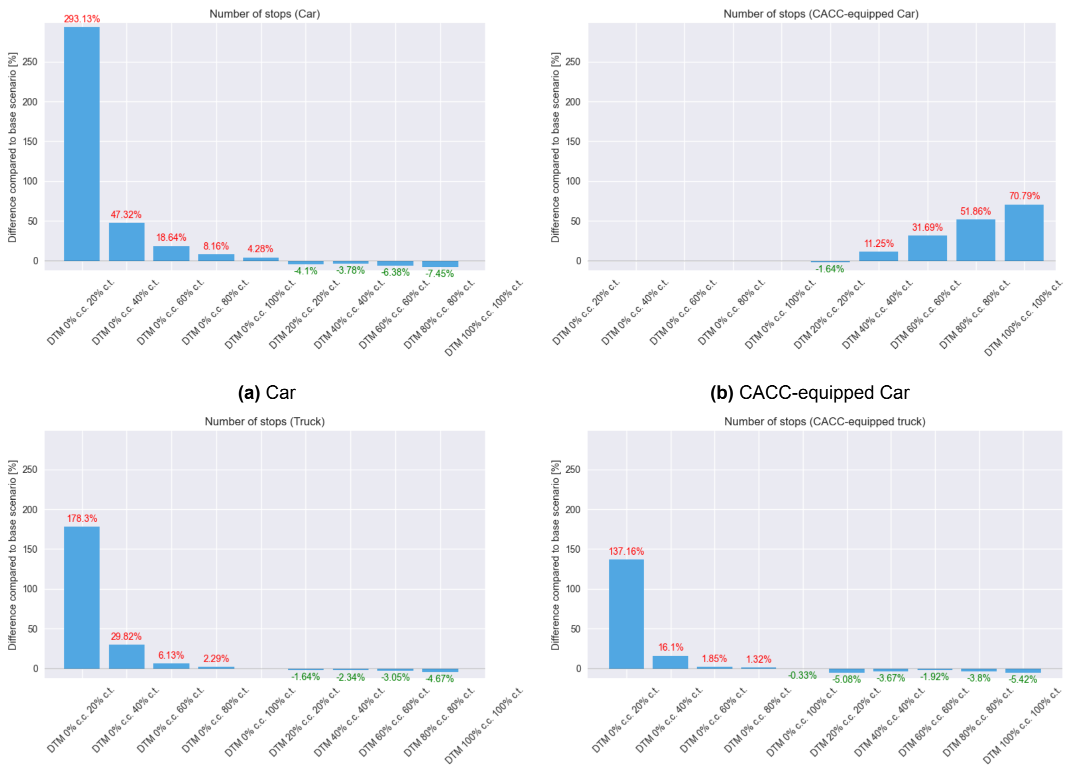
(a) Car

(b) CACC-equipped Car

(c) Truck

(d) CACC-equipped Truck

Figure 5.25: The percentage difference of the Platoon scenario number of stops results compared to the base scenario per vehicle type.



(a) Car

(b) CACC-equipped Car

(c) Truck

(d) CACC-equipped Truck

Figure 5.26: The percentage difference of the DTM scenario number of stops results compared to the base scenario per vehicle type.

The Platoon scenarios with 0% CACC-equipped cars and 20 - 100% CACC-equipped trucks result in a marginal decrease in the number of stops for manually driven cars in comparison to the base scenario. The Platoon scenarios with both CACC-equipped cars and trucks result in a decreasing number of stops for these manually driven cars in comparison to the base scenario with increasing penetration rates. The pattern regarding the manually driven trucks within the Platoon scenarios is somewhat similar as for the manually driven cars. However, for the Platoon scenarios with no CACC-equipped cars the average number of stops for the manually driven trucks is slightly higher or lower depending on the exact scenario. When looking at the Platoon scenarios with both CACC-equipped cars and trucks, it can be seen that the average number of stops for the manually driven trucks decreases with increasing penetration rates of the CACC-equipped vehicles.

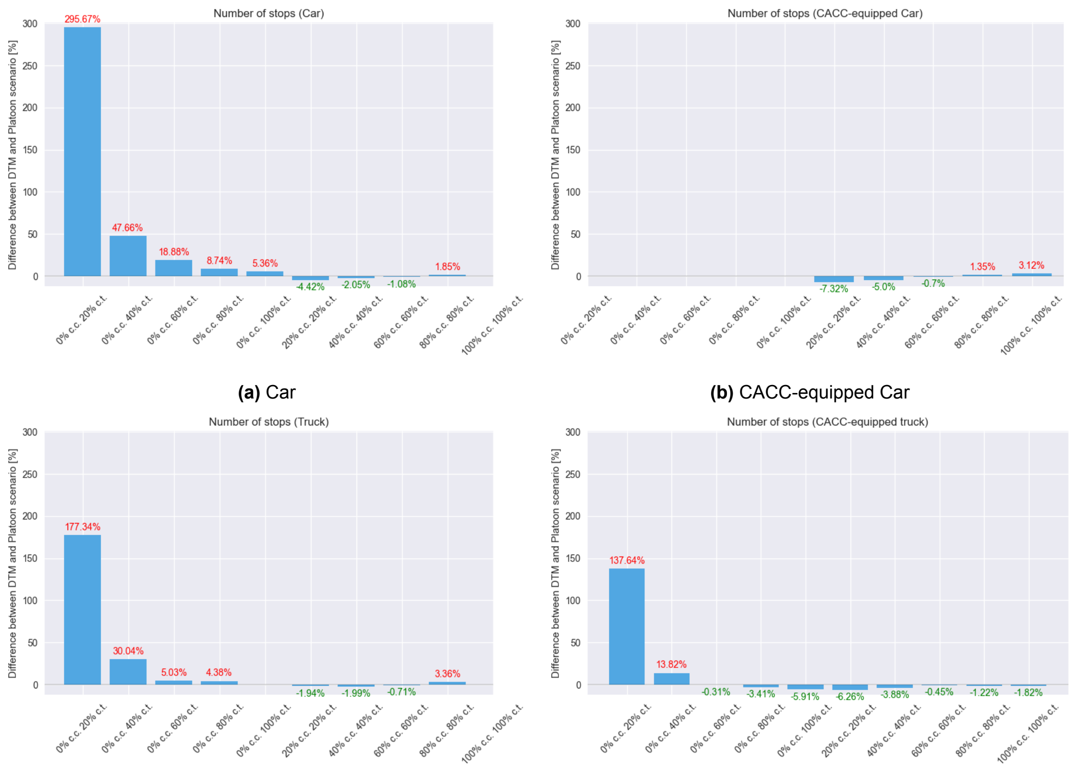
All CACC-equipped cars have an increased average number of stops within the Platoon scenarios. Increasing penetration rates result in an increasing average number of stops. CACC-equipped trucks show a completely different pattern in the Platoon scenarios. The scenarios with only CACC-equipped trucks result in an increasing average number of stops with increasing penetration rates of these vehicles. However, with both CACC-equipped cars and trucks, an increasing penetration rate of both vehicles results in a decreasing average number of stops for CACC-equipped trucks.

When looking at the DTM scenarios, the same pattern can be observed for manually driven cars and trucks and CACC-equipped trucks within the scenarios without CACC-equipped cars and with CACC-equipped trucks under various penetration rates. This pattern is that the average number of stops is significantly higher than it is for the base scenario with low penetration rates. With increasing penetration rates of CACC-equipped trucks, the average number of stop decreases for manually driven cars and trucks and CACC-equipped trucks. These three vehicle types have the same pattern for the DTM scenario with both CACC-equipped truck and cars as well. Here, the average number of stops is lower in comparison to each vehicle type within the base scenario. This difference increases with increasing penetration rates of both CACC-equipped vehicles.

CACC-equipped cars show a completely different pattern in the DTM scenarios than the manually driven cars and trucks and CACC-equipped trucks. Here, the average number of stops in comparison to the manually driven cars in the base scenario increases with higher penetration rates of CACC-equipped vehicles to up to 70.8%.

Comparison between DTM and Platoon scenarios per vehicle type

Figure 5.27 shows the percentage difference of the average travel time per vehicle type between the DTM and Platoon scenarios. An elaboration of these results will be given in this section.



(a) Car **(b)** CACC-equipped Car

(c) Truck **(d)** CACC-equipped Truck

Figure 5.27: The percentage difference between the DTM and Platoon scenario average number of stops results per vehicle type.

When looking at the scenario with no CACC-equipped cars and with CACC-equipped trucks under various penetration rates, it can be seen that the average number of stops for the manually driven cars and trucks is higher within the DTM scenarios in comparison to the Platoon scenarios. This difference is the largest at the lowest penetration rate of CACC-equipped trucks and it decreases with increasing penetration rates. The average number of stops for these manually driven vehicles is lower within the DTM scenario with a penetration rate of 20% for CACC-equipped cars and trucks compared to the equivalent Platoon scenario. This difference then decreases with increasing penetration rates of both CACC-equipped vehicles. At an 80% penetration rate, the average number of stops for both manually driven vehicle types are lower within the Platoons scenario.

CACC-equipped cars have a lower average number of stops within the DTM scenarios for a penetration rate of 20 to 60%. At 80 and 100% penetration, the average number of stops for these vehicles is lower within the Platoon scenarios.

The CACC-equipped trucks have a significantly higher average number of stops within the 0% c.c. and 20% c.t. DTM scenario compared to the equivalent Platoon scenario. This difference decreases with increasing penetration rates of CACC-equipped trucks. The average number of stops for these CACC-equipped trucks is lower within the DTM scenario compared to the Platoon scenarios for penetration rates of 0% for CACC-equipped cars and 60 - 100% for CACC-equipped trucks. All scenario with both CACC-equipped cars and trucks results in a lower average number of stops for the CACC-equipped trucks. However, this difference decreases as the penetration rate increases.

5.3. Conclusions

After discussing all findings in section 5.2, the conclusions can be drawn, which will be presented in this section. Firstly, the effects of truck and vehicle platooning on the traffic flow KPI's at the intersection will be discussed. Then, the effects that applying truck and vehicle platooning in combination with the DTM system have on the traffic flow KPI's will be discussed. Finally, the difference that the DTM system makes compared to just vehicle platooning will be discussed.

5.3.1. Platooning

Firstly the conclusions regarding the effects that platooning have on an signalized intersection will be drawn.

The results show that when only the trucks are able to form platoons the total delay, average travel time and average number of stops are not effected massively in comparison to the base scenario. These effects are visible on all directions, the main direction and the other directions.

The results are different when both cars and trucks are able to form platoons. The effects are positive for the total delay and average travel time, which both decrease with an increasing penetration rate of vehicles that are able to form platoons. This effect is mainly visible on the main direction. However, platooning does lead to an increase in total delay on the other directions, while the average travel time decreases for those directions.

The average number of stops increases when more vehicles are able to form platoons, which is for both the main and other directions. Several reasons for this have been identified by observing what happens during these simulation runs. Firstly, due to the fact that (big) platoons could cause disturbances near bottlenecks where the vehicles within a platoon might have different routes (Martinez-Diaz et al., 2021). Consequently, the number of acceleration and deceleration maneuvers increases, resulting in a higher number of stops. Furthermore, it has been observed that late lane changes of manually driven vehicles can force trailing vehicles into having to brake. If a platoon is behind this when such a late lane changing maneuver happens, the whole platoon has to brake due to the close following distances. In certain scenarios, this causes the whole platoon to stop, which is a cause for the increased number of stops. Another maneuver that has been observed is a long platoon that stops for a red traffic light with one or more vehicles behind that are not part of a platoon. In some cases, these vehicles are not able to switch lanes in time and end up having to stop together with the platoon, only to change lanes and stop again further down the lane for the red traffic light. This adds up to the number of stops as well.

Each key performance indicator provides a slightly different perspective when looking at the individual vehicle types. These findings have been described in section 5.2. A conclusion that can be drawn from these findings is that the total delay is lower for each vehicle type in comparison to the base scenario when 80% or more of the cars and trucks are equipped with CACC. These connected vehicles benefit more than their non-connected counterparts. However, each CACC-equipped vehicle has a lower average travel time than their non-equipped counterpart in the base scenario for all penetration rates. The manually driven vehicles do only significantly benefit in terms of the average travel time if the penetration rate of CACC-equipped vehicles is 60 % or higher. The situation is completely different regarding the average number of stops, where CACC-equipped vehicles have a higher average number of stops than the manually driven vehicles at higher penetration rates.

So platooning does only give an advantage, with respect to the total delay and average travel time, when the penetration rate is high enough of both cars and trucks that are able to form a platoon. However, the CACC-equipped vehicles do notice a decreased average travel time for all penetration rates. Truck platooning on its own is not enough to bring these advantages. The main reason for this is that trucks are only 10 - 15% of the total traffic flow in this simulation network. Even at a 100% penetration rate of CACC-equipped trucks, the possibility is small that trucks are able to form a platoon. Therefore, the effects are not noticeable. The same holds for the Platoon scenarios with lower penetration rates of CACC-equipped cars and trucks. However, platooning does increase the number of stops at an intersection for the vehicles that are able to form platoons.

So from these results it can be concluded that platooning brings benefits to the traffic flows near an intersection, since the total delay and average travel time decreases if the penetration rate is high enough. However, this comes at a cost of an increased average number of stops before the intersection.

5.3.2. Dedicated Traffic Management System

This section will look into the effects that truck and vehicle platooning in combination with the DTM system have on the traffic flow KPI's.

The first aspect that can be observed from the DTM results is that the system performs poorly in comparison to the base scenario with a 0% penetration rate for CACC-equipped cars and 20% for CACC-equipped trucks. All KPI's are negatively effected by the DTM system under this penetration rate. The reason for this is that there are not enough connected vehicles to make good enough estimations for the speed and location of all manually driven vehicles around the intersection, which are used by the signal controller to determine the green split. Trucks are only 10 - 15% of the total traffic in the network. So a 20% penetration rate means that only 2 - 3% of all vehicles are connected, which is clearly not enough for the system to perform equal or better than a vehicle actuated signal controller. This statement is backed up by the fact that higher penetration rates result in a much better performance of the DTM system, regarding the total delay and average travel time.

When looking at the simulation itself, it was observed that green times were not assigned properly to each signal phase. Some phases with a lot of traffic on the approaches that wanted to cross the intersection were cut short in green time, while other phases with no traffic demand were assigned too much green time. From these observations, it can be concluded that the vehicle speed and location estimation method in combination with the throughput estimation using the genetic algorithm does not work well under low penetration rates. As a result, inefficient green times were assigned to the different phases.

The DTM system has a negative impact on the average number of stops for all penetration rates. This is especially the case for low and higher penetration rates. The reason why this is for low penetration rates has already been discussed in the previous paragraph. With higher penetration rates of both CACC-equipped cars and trucks, the average number of stops is significantly higher than for the base scenario as well. These are similar results as for the Platoon scenarios. Therefore it can be concluded that the DTM system does not have a huge impact on the average number of stops, but vehicle platooning does have a negative impact.

Based on the results per direction that are discussed in appendix D, it can be concluded that the DTM system performs worse than the base scenario on directions 3 and 9 in terms of all KPI's. Additionally the average number of stops is higher on a majority of other directions as well. Directions 3 and 9 are the right turning directions on the N201 - Rijkerdreef. However, for the other directions the DTM system does bring an improvement compared to the base scenario in terms of the total delay and average travel time.

When looking at the results per vehicle type, it can be concluded that the DTM system benefits all vehicle types in terms of total delay and average travel time. However, the benefits are higher and already visible at lower penetration rates for the CACC-equipped vehicles.

Within the DTM scenarios with only truck platooning, the number of stops is higher for each vehicle type. However, the CACC-equipped cars are the only vehicle type with a higher average number of stops compared to the base scenario within the DTM scenarios with both CACC-equipped cars and trucks. So with low overall penetration rate of connected vehicles the number of stops is higher for all vehicles. However, with higher overall penetration rates, the higher average number of stops is solely caused by the CACC-equipped cars.

5.3.3. Platooning compared to Dedicated Traffic Management System

Finally, the Platoon and DTM scenarios are compared to each other. This comparison will be used to determine if the positive effects that the DTM system brings, which are described in the previous section, are caused by the system itself or that vehicle platooning is the main reason for this.

Based on the comparison between the DTM and Platoon scenarios in terms of total delay and average travel time, it can be concluded that platooning performs better in combination with a vehicle actuated signal controller than the DTM system under low penetration rates when only truck platooning is considered. However, with higher penetration rates of the CACC-equipped trucks and with both CACC-equipped cars and trucks, platooning performs better in combination with the dedicated traffic management system. However, this advantage for the DTM system is less or even gone at the highest penetration rates of CACC-equipped cars and trucks.

When looking at the average number of stops, the same conclusion can be drawn for the scenarios with no CACC-equipped cars and lower penetration rates of CACC-equipped trucks. Within these scenarios, the vehicle actuated signal controller performs better than the DTM system. However, there is barely any difference between the DTM system and the vehicle actuated signal controller within the scenarios with both CACC-equipped cars and trucks.

The comparison between the DTM and Platoon scenarios per vehicle type is similar as for all vehicles combined. So at the scenarios with a low overall penetration rate of CACC-equipped vehicles, the platoon scenario results are better than the DTM scenario results. This advantage shifts towards the DTM scenarios when the overall penetration rate increases. However, when the penetration rate gets closer towards 100%, the advantage shifts back towards the Platoon scenarios.

The comparison between the DTM and platoon scenarios per direction in appendix D gives a similar result for all KPI's. This is the the DTM scenarios perform better than the Platoon scenarios on approach 2 and 4 (directions 4, 5, 6, 10, 11, 12). The platoon scenarios perform better on the right turning directions of the N201 - Rijkerdreef (directions 3 and 9). Directions 1, 2, 7 and 8 show similar results as the overall results. So the platoon scenarios perform better at the lowest and highest penetration rates.

6
Conclusion and Recommendations

This chapter provides the conclusion to the main research question and the main limitations of the study. Furthermore, it answers all sub-research questions and it gives the practical and scientific recommendations.

6.1. Conclusion

The objective of this study is to propose a dedicated traffic management (DTM) system that uses truck and vehicle connectivity and platooning capabilities to improve the traffic flow on an intersection that is part of a real logistic corridor. As a result, the following main research question was formulated:

What dedicated traffic management system can potentially improve the traffic flows on a logistic corridor where truck platoons drive in mixed traffic (consisting of regular and connected vehicles) and what are the traffic flow effects on this corridor when the system is implemented?

6.1.1. Findings

This study has proposed a DTM system that uses vehicle connectivity and platooning capabilities to estimate the intersection throughput. The green split and cycle time are adjusted in order to maximize this throughput. The system is tested with identical traffic intensities under different penetration rates of CACC-equipped trucks and both CACC-equipped cars and trucks. The results of this DTM system are compared with a vehicle actuated signal controller with identical traffic intensities but without CACC-equipped vehicles, as well as with CACC-equipped vehicles. The expectations were that vehicle platooning would bring an improvement to the total delay and average travel time. However, the number of stops could be negatively effected near the intersection due to the fact that large platoons make it more difficult for vehicles to change lanes. The DTM system is expected to improve the KPI's even further than vehicle platooning on its own under all penetration rates.

The results show that truck platooning does not have a significant impact on the traffic flow KPI's, which is not as expected. A possible reason for this is the fact that trucks are only a small part of the total traffic composition (10 - 15%). The used platoon forming strategy struggles to form enough platoons in this case to see any results. However, when looking at solely the CACC-equipped trucks, the average travel time is lower. When both cars and trucks are able to form platoons, the total delay for all vehicles combined is lower as well. So in this case the expectations are met. The number of stops do increase with higher penetration rates, which is also as expected. However, this is mainly the case for the CACC-equipped vehicles. The reason for this might be the fact the number of acceleration and deceleration maneuvers near a bottleneck increase with longer platoons (Martinez-Diaz et al., 2021), and weaving maneuvers become harder with long platoons, which also result in more stops.

The results of the DTM system are not completely as expected. Under low overall penetration rates, the DTM system does have a negative impact on the traffic flows of the intersection. This is because there not not enough connected vehicles to make an accurate enough estimation of the intersection throughput to base the green split on. Higher overall penetration rates do result in an improvement in terms of the total delay and average travel time in comparison to the base and Platoon scenarios. However, this advantage over the Platoon scenarios reduces at the highest overall penetration rates. The average number of stops results are similar to those of the Platoon scenarios, except for the low overall penetration rates.

So it can be concluded that the DTM scenario does not bring an improvement to the total delay, average travel time and average number of stops if only trucks are able to form platoons and the penetration rate is lower than 80%. If both cars and trucks are equipped with CACC, the DTM system does bring an advantage over the vehicle actuated signal controller. However, at the highest penetration rate (80% and higher), this advantage is mainly caused by vehicle platooning, since the Platoon scenarios perform slightly better than the DTM scenarios in that case. Yet, at the medium overall penetration rates (20 - 60% CACC-equipped cars and trucks), the DTM system performs better than the vehicle actuated signal controller.

6.1.2. Limitations

The results of the DTM system are somewhat promising. However, there are still some limitations to this study which could potentially have an impact on these conclusions. These limitations are about the way that the DTM system is designed, how the DTM system handles low penetration rates and the used calibration process. These limitation were discussed in this section.

DTM System

There are some limitations to the DTM model that has been used for this thesis. These will be discussed in this section.

First of all, the method that has been applied to account for lane changes of either the CACC-equipped vehicles or the non CACC-equipped vehicles. This method cannot notice real-time lane changes of the manually driven vehicles. The vehicles are measured by the fixed traffic sensors when they enter the zone of interest and this count data is stored at the first CACC-equipped vehicle that passes the sensor, after which the count for the specific lane is reset to zero. This count data stored at the CACC-equipped vehicle is updated at induction loop detector, which is located the farthest away from the intersection stop line. However, lane changes by manually driven vehicles that occur after this induction loop are not accounted for. This influences the throughput estimations made by the algorithm on which the green split and cycle time is based. So lane changes have a negative effect on the performance of the algorithm. These negative effects are even stronger when connected vehicles change lane, since the count data of the manually driven vehicles between two CACC-equipped vehicles is stored at the trailing CACC-equipped vehicle. If this trailing CACC-equipped vehicle changes lane, the algorithm assumes that all its leading manually driven vehicles up to the next CACC-equipped vehicle change lane as well, which is not the case. For these reasons, overtaking vehicles do also have a negative effect on the algorithm.

The signal controller uses four phases, which have been predetermined based on preferred phase order of the real vehicle actuated signal controller. Flexibility in the signal groups that belong to a phase or the order of the phases is not applied to the DTM system. Therefore, the impact of it is unknown, but it could be assumed that the lack of this has a negative impact on the performance of the DTM system.

Another limitation of this study is the number of simulation runs for certain scenarios is too low to get statistical significant results, as can be seen in appendix E.2. This is mainly the case for the DTM scenario with 0% CACC-equipped cars and 20% CACC-equipped trucks, where 268 simulation runs are required for the average number of stops. However, each simulation run requires a large amount of computation time and doing 268 simulation runs is therefore not feasible due to time constraints.

The effectiveness of the DTM system has only been tested by performing a microsimulation on one existing intersection. However, this effectiveness could be completely different on another intersection with different properties, for instance the the length of the approaches, the place in a traffic network, the number of lanes.

Furthermore, the effectiveness of the DTM system has only been tested using the same traffic volume. Consequently, not a lot is known about the performance of the DTM system under different traffic volumes, such as a low demand or congested traffic.

Poor Performance of DTM System Under Low Penetration Rates
As discussed before in this chapter, the DTM system results for the scenarios with only truck platooning under low penetration rates are significantly worse in comparison to all other scenarios. This means that the system does not work as intended under low penetration rates. However, the two systems by Liu et al. (2019) and Liang et al. (2018) on which this DTM system is based show completely different results under low penetration rates, even at 0%. This section discusses some of the limitations of the proposed DTM system that have a influence on the poor performance under low penetration rates.

The main reason for the poor performance of the DTM system under low penetration rates is the used method for the speed and location estimation. This method relies on two CACC-equipped vehicles driving in the same lane to estimate the speed and location of the manually driven vehicles in between. However, this is not always the case under low penetration rates, especially since the only CACC-equipped vehicles are trucks, which mainly drive on the right lane. As a result, the speed and location of a substantial number of manually driven vehicles is not estimated. These vehicles are therefore not considered in the throughput estimation on which the cycle time and green split is based. This results then in an inefficient green split.

Another reason for the differences in results between the DTM system and the two systems proposed by Liu et al. (2019) and Liang et al. (2018) under low penetrations rates is the way that the data measured by the fixed traffic sensors is used in the speed and location estimation of manually driven vehicles. As stated before, the used method for this depends on CACC-equipped vehicles. However, the method proposed by Liu et al. (2019), which the speed and location estimation method of the DTM system is based on, uses the speed measurements and the known location of the fixed traffic sensors to estimate the speed and location of the first and last vehicle in the zone of interest if these vehicles are not CACC-equipped, as explained in section 3.2.3. Incorporating this into the DTM system would lead to more manually driven vehicles being included in the speed and location estimation and therefore in the objective function, where the intersection throughput is calculated based on the speed and location estimation.

GA Calibration
In order to make sure that the genetic algorithm (GA) has an as optimal performance as possible, a calibration has been performed. The used method for this has been explained in section 4.2.3. However, there are some limitations to the used method, which could have an impact on the overall performance of the DTM system.

First of all, the performance measures that have been used to evaluate the performance of the different parameters. The maximum fitness was one of the performance measures, which is good for comparing different scenarios. However, this does not tell if the GA has reached the global optimum. In order to know this for certain, a naive algorithm should have been run each simulation second to determine the global optimum. The second performance measure that has been used in the average number of iterations that are required to reach the maximum fitness. However, this performance measure is limited if a scenario does not reach the maximum fitness within the 100 iterations. Some scenarios do not reach the global optimum for certain since those have a lower maximum fitness than the maximum that has been observed.

Another limitation of the used calibration method is that it has only been done during a single microsimulation run. However, PTV Vissim is a stochastic model and multiple runs should therefore have been performed to account for this stochasticity. The reason that this has not been done is that performing a GA calibration required a lot of computational effort and doing more runs was not feasible.

The next limitation of the GA calibration method is that it has only been done for one penetration rate of CACC-equipped vehicles, which was a rate of 40% CACC-equipped cars and trucks. It could be possible that the penetration rate has an influence on the outcome of the GA calibration.

6.1.3. Answers Sub-Research Questions

The sub-research question have been answered throughout this report. A brief summary to all answers were given in this section.

1. *What are possible intersection traffic control types that can be used for partially connected traffic?*

There are multiple criteria to categorize intersection control. Firstly, the type of intersection control, which can be signalized intersection management (SIM) or autonomous intersection management (AIM). Intersection control can then be categorized based on the hierarchical layer it belongs to, which is either the corridor coordination layer, the intersection management (trajectory planning) layer or the vehicle control layer.

The intersection management (trajectory planning) layer can be differentiated further into three categories. These are advanced driver guidance based on CAV's, advanced traffic signal control with CAV's and signal vehicle coupled control (SVCC). The advanced traffic signal control can be split up into three categories. These categories are the actuated (adaptive) traffic signal control, the platoon-based signal control method and the planning-based signal control method.

2. *What is the state-of-the-art of truck-platooning in arterial and urban traffic?*

Vehicle platooning is a topic that has been researched since the 1970s. Vehicle and/or truck platooning has some (expected) benefits, which are improved traffic flows, lower emissions and fuel consumption, improved safety and lower labour costs.

Most research on the topic has been performed on freeway traffic, while the effects on intersections within an arterial or urban network still require more research.

3. *What are the requirements for a dedicated intersection control system that controls mixed traffic which partially consists of truck platoons?*

The dedicated traffic management system will have to work in traffic conditions where less than 100% of the vehicles are connected and partially autonomous. This will require it to be a signalized intersection management (SIM) system. The hierarchical layer will be the intersection management layer. Both of these requirements mean that the system will be a 'advanced traffic signal control based on CAV's'. This can then be further specified into platoon-based signal control method, since this research also focuses on truck platooning.

4. *Which of the researched advanced intersection control systems are the most suitable for the logistic corridor?*

Based on the requirements that have been specified in the previous sub-research question, two articles about intelligent intersection control were chosen to serve as the main inspiration of the dedicated traffic management system. The first article uses the data provided by CACC-equipped vehicles and traditional fixed traffic sensors to predict the future traffic state. This is then used to optimize the green split.

The second article uses the data of connected vehicles that arrive at an intersection to identify naturally occurring vehicle platoons. This is then used to determine the optimal departure sequence of these naturally occurring platoons to minimize the total delay.

5. *What are the properties of the dedicated traffic management system that will be used on the intersection on the logistic corridor?*

The dedicated traffic management will check in a certain interval if a trigger event has happened. If this is the case, the algorithm will continue and if not, the algorithm will remain idle until the next trigger event check. There are three trigger events, which are if a CACC-equipped vehicle has entered the zone of interest, if a CACC-equipped vehicle comes to a complete stop and if a CACC-equipped vehicle comes to a complete stop.

So if one of these trigger events has happened, the algorithm continues. First, it will sort all connected and non-connected vehicles that are within the zone of interest per lane based on their position. Then the speed and location of all non-connected vehicles are estimated by the algorithm.

The speed and location of each vehicle is used to determine the intersection throughput for a given green split. The green split with the highest throughput is determined using a genetic algorithm. This green split will then be applied by the intersection controller until it is updated.

6. *What micro-simulation software can be used for simulating the effectiveness of the dedicated traffic management system on the logistic corridor?*

Multiple microscopic simulation software packages for traffic flows have been compared with each other. From this comparison it became clear that PTV Vissim has scored the best on the criteria that were used.

7. *What is the effectiveness of the current traffic control strategy on the intersection on the logistic corridor?*

The effectiveness of the current traffic control system is tested within the base scenario, where normal traffic flows of non-connected vehicles were used in combination with the vehicle actuated signal controller. This will serve as the baseline measurement to which the other scenarios will be compared.

8. *What is the effectiveness of platooning on an intersection on the logistic corridor?*

Platooning does only bring an advantage to intersections if the overall penetration rate is high enough. The scenarios with only truck platooning do not bring a significant (dis)advantage to any of the KPI's. A reason for this is that trucks are only a small part (10-15%) of the total traffic in the network. This seems to be not enough to form platoons and give advantages under the currently used platooning strategy.

Within the scenarios with both CACC-equipped cars and trucks, the effects are much better visible. The total delay and average travel time are both lower in comparison to the base scenario. Higher penetration rates show better results in terms of the total delay and average travel time.

The total number of stops are negatively effected within the scenarios where both cars and trucks are able to form platoons. This effect is mainly caused by the CACC-equipped vehicles that are able to form platoons, since those have an increased average number of stops.

9. *What is the effectiveness of the proposed dedicated traffic management system when it is implemented to an intersection on the logistic corridor?*

The DTM system does not perform well under low overall penetration rates. The system relies on the data of connected vehicles to estimate the speed and location of all vehicles in range of the intersection. This cannot be done accurately if there are not enough connected vehicles.

When the overall penetration rate reaches a certain threshold, the advantages of the DTM system over to the base scenario become evident in terms of the total delay and average travel time. The total delay and average travel time decrease with increasing penetration rates of CACC-equipped vehicles. Conversely, the average number of stops are higher for all penetration rates when the DTM system is applied.

When the DTM system is compared to the vehicle actuated signal controller in combination with vehicle platooning, it becomes evident that the vehicle actuated signal controller has an advantage over the

DTM system under the lowest penetration rates. This advantage in terms of total delay and average travel time shifts towards the DTM system after a certain penetration rate threshold. With increasing penetration rates, the advantage shifts back to the vehicle actuated controller again. So when looking at the total delay and average travel time, the DTM system performs better than a vehicle actuated signal controller at medium overall penetration rates.

However, this is not the case for the average number of stops. These are generally equal for both the DTM system and vehicle actuated signal controller after a certain penetration rate.

6.2. Recommendations

This section discusses the practical and scientific recommendation that follow from this thesis.

6.2.1. Practical Recommendations

The intersection between the N201 and Koolhovenlaan at which the DTM system has been implemented within the microsimulation model is maintained by the Province of Noord-Holland. This practical recommendation is therefore mainly aimed at the Province of Noord-Holland.

This study has shown the effects that truck and vehicle platooning have at the intersection between the N201 and Koolhovenlaan with a vehicle actuated signal controller and with the DTM system. It has shown that the combination of CACC-equipped cars and trucks can improve the overall total delay and average travel times. The DTM system can enhance these improvements even further with penetration rates of 20 - 60% of both CACC-equipped cars and trucks. However, this comes at the cost of an increased number of stops on the approaches of the intersection, which could lead to an increase in fuel consumption and emissions.

So the recommendation to the Province of Noord-Holland is to keep using the vehicle-actuated signal controller once CACC-equipped vehicles start to become mainstream. Once the overall penetration rate start to exceed 20%, the use of the DTM system should be considered, since it will reduce the total delay and average travel times around the intersection. At 80 - 100% penetration, the vehicle actuated signal controller is recommended, since the overall total delay and average travel time is lower then. Therefore, a flexible signal controller would be recommended that serves as a vehicle actuated signal controller at low penetration rates and is able to switch to the DTM system if the penetration rate allows.

These recommendations apply for the current state of the DTM system. The next section gives some scientific recommendations that are partially aimed to improve the DTM system. The effectiveness of the DTM system is expected to increase when more research into this system has been conducted. This could then lead to different practical recommendations than that have been given in this section.

6.2.2. Scientific Recommendations

This study showed that the DTM system can potentially decrease the total delay and average travel time around the intersection under certain CACC penetration rates in mixed and heterogeneous traffic. However, the systems that the DTM system is based on (Liu et al., 2019; Liang et al., 2018) also show positive results under low penetration rates. Therefore further research in improving the DTM system in low penetration rates is required to solve this problem. A possible research direction for this is by implementing the speed and location data of the manually driven vehicles measured by the fixed traffic sensors into the algorithm.

There are more limitations to the DTM system that has been used in this study. Despite these limitations, the system has showed some solid results for the medium penetration rates of both CACC-equipped cars and trucks. This indicates that the positive results could be increased further. In order to do this more research is required in the following directions:

- Develop a better method to account for lane changes.
- Apply flexibility to the signal groups that belong to a phase and the order of the phases.
- Test the effectiveness of the DTM system on more intersections with different properties.

- Test the effectiveness of the DTM system using more traffic volumes.

There are multiple parameters that can be calibrated in the DTM system. For instance, the length of the zone of interest, the maximum platoon size, the maximum cycle length, etc. A future research direction is to apply a sensitivity analysis to all these parameters, in order to determine the right properties for the DTM system so that the results can be improved further. Furthermore, the calibration of the genetic algorithm can be extended. As stated before, there are some limitations to the used method in this study. So within further research it recommended to calibrate the genetic algorithm using multiple simulation runs and using more different penetration rates of CACC-equipped vehicles. Furthermore, the naive algorithm, where all possible solutions are considered, should be applied each run as well. This will make sure that the maximum fitness is known.

As described in section 2.3, there are various properties to vehicle platooning. This study did not dive deep into the effects of the different platooning strategies at intersections. So another direction for future research is to investigate what platooning strategies are most suitable for urban/arterial traffic.

The results of this study have shown that the used truck/vehicle platooning properties result in an increased number of stops. However, the exact reasons why this happens have not been found out during this study. Only some of the reasons have been clarified based on observations made during the simulations. Therefore, it is recommended for further research to dive deeper into the impact that platooning has on the number of stops near intersections.

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A

Genetic Algorithm

A genetic algorithm is an optimization technique that can drastically improve computation times compared to a naïve optimization technique. A wide range of problems, such as optimization and search problems, can be solved with a genetic algorithm. This chapter will discuss the fundamentals of genetic algorithms, including the advantages and limitations.

Genetic algorithms belong to the larger set of evolutionary algorithms (Melanie, 1999). These algorithms are inspired by the principles of natural evolution, such as reproduction, genetic mutations and natural selection. Each possible solution represents an individual in nature. The individuals that are best adapted to the outside circumstances have the highest fitness and are selected for reproduction. Possible genetic mutations might slightly adapt their descendants, which introduces a diversity into the population and adapts the next generation for the changing environment. The process is repeated for the next generations.

This concept has been translated to computer science, eventually resulting in the genetic algorithm. For this thesis, the genetic algorithm will be applied on an optimization problem. This algorithm consist out of multiple aspects inspired from the evolutionary theory (Mirjalili, 2019), which are listed below. Then the use of these aspects are clarified for an optimization problem.

- Genetic representation of a solution
- Population
- Fitness function
- Selection
- Crossover
- Mutation

The objective of the optimization problem is to find the best fitting solution out of all feasible solutions. A candidate solution will get a genetic representation in a genetic algorithm. In biological terms this means that a set of candidate solutions will represent a population of individuals that each have their own genome. A genome contains all genetic information of that individual (Roth, 2019). Therefore, each candidate solution is represented by a genome that consists of the different properties that are relevant to the specific optimization problem. Several encoding schemes could be used for representing the genome (Katoch et al., 2021). A binary encoding scheme is commonly used, where the genome is represented as a string that consists of only 1 and 0. Other examples of encoding schemes are octal, hexadecimal, permutation, value-based, and tree.

As stated before, a set of candidate solutions is represented as the population, which should be generated by the algorithm. There are two important aspects for generating the population. Firstly, the method of this generation. A widely used method to perform this generation is to use a Gaussian random distribution (Mirjalili, 2019). The most important aspect of this initial population generation is to create uniformly spread solutions. This will assure a high diversity and increases the probability of finding a near optimal fitting solution. The second important aspect is the size of the population. If a population is too small it is not diverse enough and it could happen that only a local optimum will be reached. However, a population that is too large will result in a much higher computational complexity (Hassanat et al., 2019).

The different candidate solutions will be compared to each other based on the fitness. This is done with the use of a fitness function, which evaluates the genome of the candidate solution and calculates the according fitness value.

The next step in the algorithm is to select the individuals that will reproduce the next generation. This process is the main component of the genetic algorithm and it is inspired by natural selection. This means that the main selection condition is the fitness of the candidate solution. Likewise, in nature the most fitted individuals have a higher probability of reproducing. Within the genetic algorithm a selection function will perform this task. A commonly used method is using a roulette wheel for selecting the parents of the next generation. The probability of selecting an individual is based on their fitness. So the individual with the highest fitness score has the largest probability of being selected. Therefore, an individual with a low fitness score might still be selected for reproduction. If an individual with a low fitness score is discarded immediately, the diversity of the model is highly reduced and should therefore be avoided. The 'roulette wheel method' is not the only variant for the selection function. Other examples that are used in literature are rank selection, tournament selection, Boltzmann selection, etc. (Katoch et al., 2021).

The individuals that come out of the selection function serve as the parents and will reproduce. In a genetic algorithm, the child solution is a combination of both parent solutions, similar to how the genome of the child will consist of a combination of the genes from the father and mother in nature. This process is called crossover and a variety of techniques can be used for this. The simplest version is the single-point crossover, where the chromosomes of two parent solutions are swapped at a random single point. A slightly more advanced method is the double-point crossover where the chromosomes between two point of the parent solutions are swapped. Both methods are visualized in figure A.1. Other examples of crossover methods that are used in literature are reduced surrogate crossover, uniform crossover, etc. (Katoch et al., 2021).

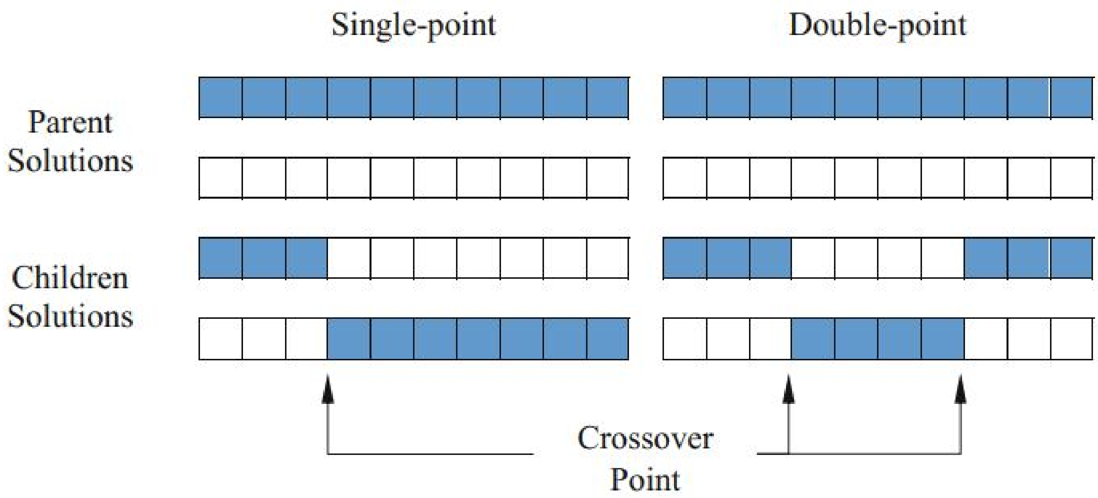

Figure A.1: Single- and double-point crossover (Mirjalili, 2019).

The final evolutionary concept applied in a genetic algorithm is the mutation of the child solution. The probability of the occurrence of a mutation will be low. A high number of mutations will alter the genetic algorithm to a primitive random search, which is undesired. A low number of mutations is necessary, since it will assure the diversity of the population, which adds another factor of randomness to the algorithm. In fact, it prevents similar solutions among the different generations. This also avoids the probability of only finding a local solution to the optimization problem. Figure A.2 visualizes a single-point mutation, which is the simplest mutation technique that can be applied. Examples of other mutation techniques that are described in literature are displacement mutation, simple-inversion mutation and scramble mutation (Katoch et al., 2021).

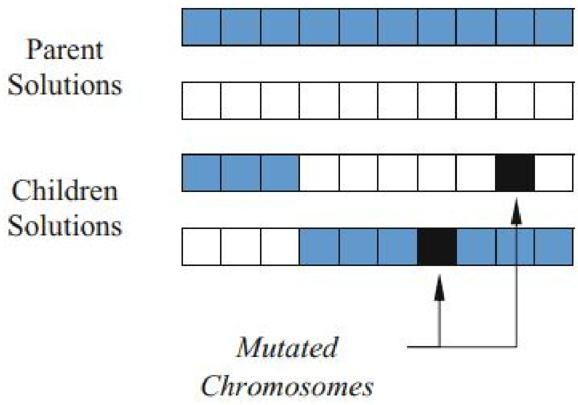

Figure A.2: An example of single-point mutation (Mirjalili, 2019).

Most genetic algorithms consist of three evolutionary operators, which were discussed above. Namely, selection, crossover and mutation (Melanie, 1999). These operators are applied to each generation to improve it from its predecessor. Some genetic algorithms apply another operator, which is elitism (Mirjalili, 2019). Within elitism, the best solution from the latest generation will be maintained and transferred to the next generation without any modification. The idea behind this concept is the prevention of a solution being downgraded by crossover and mutation.

The genetic algorithm will iterate through the previously discussed steps until it has reached the maximum number of iterations or the end criterion has been met. It starts out with a randomly selected population and ends with the best solution from the last generation.

B
Genetic Algorithm Calibration Results

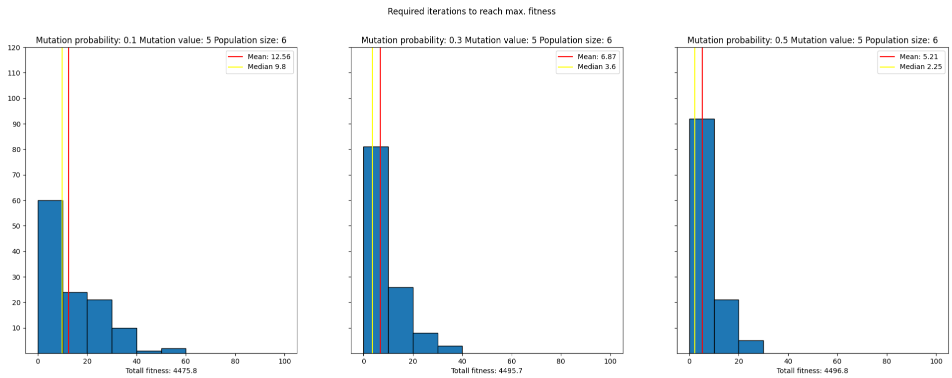

Figure B.1: Results scenario 1, 2, 3

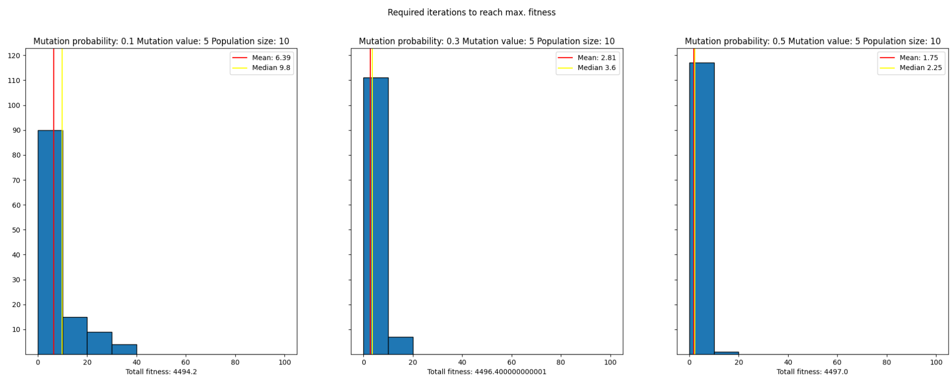

Figure B.2: Results scenario 4, 5, 6

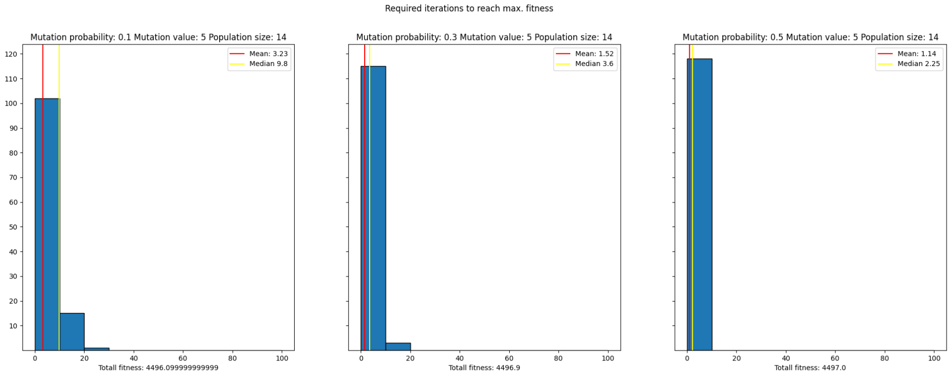

Figure B.3: Results scenario 7, 8, 9

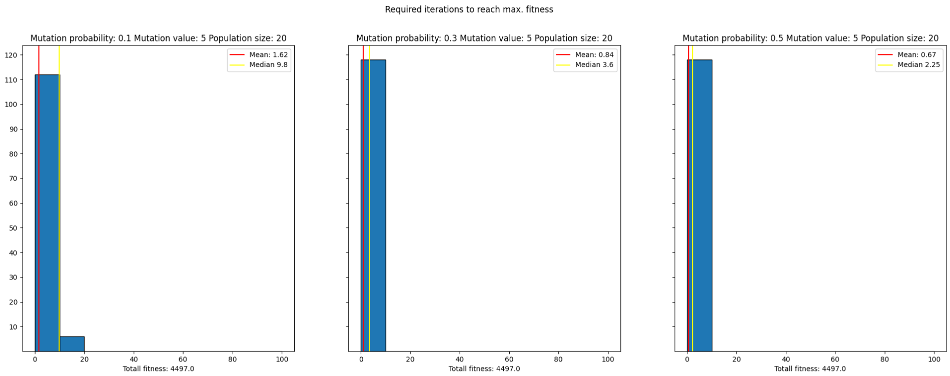

Figure B.4: Results scenario 10, 11, 12

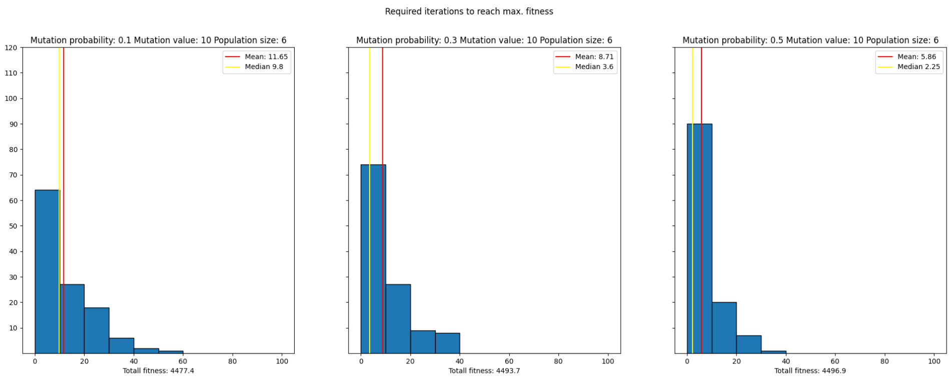

Figure B.5: Results scenario 13, 14, 15

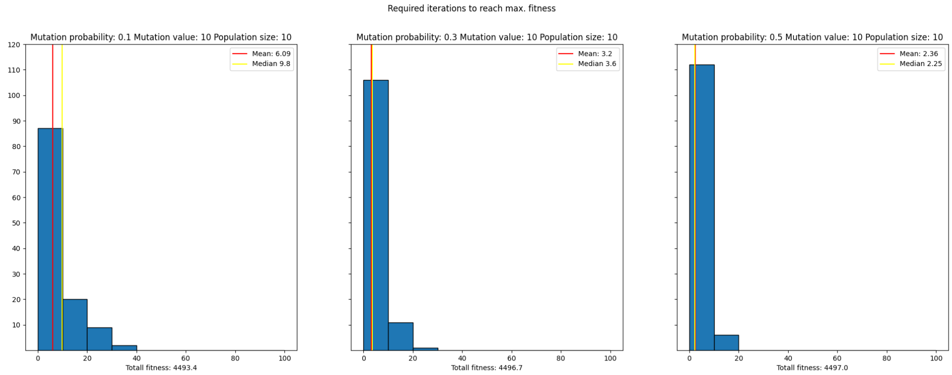

Figure B.6: Results scenario 16, 17, 18

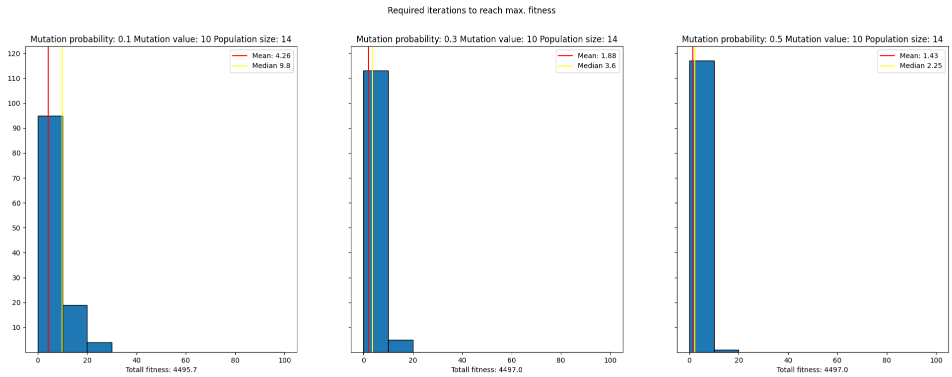

Figure B.7: Results scenario 19, 20, 21

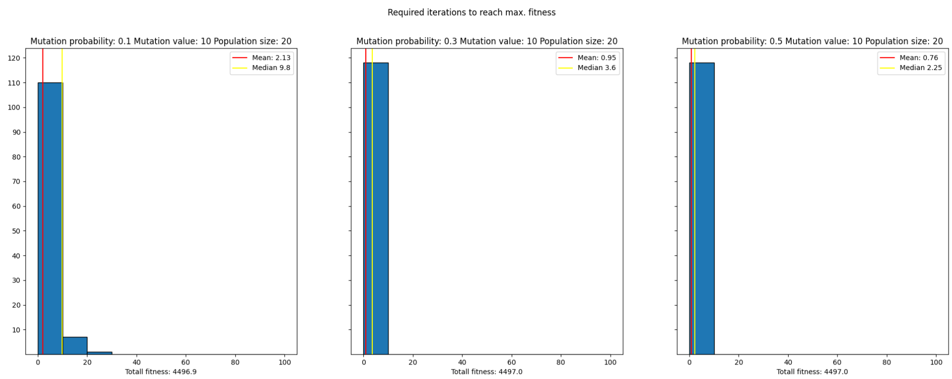

Figure B.8: Results scenario 22, 23, 24

C
OD Matrices

The OD-matrices that have been used for the microsimulation are presented in this appendix.

Table C.1: The OD-matrix for cars between 07:00 and 08:00.

	1	2	3	4	5	6	7	8	9	10
1	0	653	0	119	0	152	0	266	409	0
2	332	0	0	30	0	39	0	68	105	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	46	0	10	15	0
5	44	0	29	0	0	0	0	0	0	0
6	12	0	8	18	0	0	0	15	23	0
7	0	0	0	0	0	0	0	150	231	0
8	0	0	0	0	0	0	0	0	0	0
9	322	0	214	94	0	120	287	0	0	0
10	335	0	223	98	0	125	299	0	678	0

Table C.2: The OD-matrix for cars between 08:00 and 09:00.

	1	2	3	4	5	6	7	8	9	10
1	0	821	0	180	0	197	0	291	522	0
2	331	0	0	59	0	65	0	96	172	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	74	0	10	17	0
5	70	0	47	0	0	0	0	0	0	0
6	9	0	6	27	0	0	0	12	22	0
7	0	0	0	0	0	0	0	135	242	0
8	0	0	0	0	0	0	0	0	0	0
9	411	0	274	137	0	240	430	0	0	0
10	391	0	260	130	0	228	409	0	989	0

Table C.3: The OD-matrix for cars between 09:00 and 10:00.

	1	2	3	4	5	6	7	8	9	10
1	0	388	0	79	0	92	0	182	286	0
2	308	0	0	33	0	38	0	76	120	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	58	0	7	11	0
5	47	0	31	0	0	0	0	0	0	0
6	15	0	10	24	0	0	0	14	22	0
7	0	0	0	0	0	0	0	123	194	0
8	0	0	0	0	0	0	0	0	0	0
9	266	0	177	82	0	188	204	0	0	0
10	248	0	165	77	0	175	189	0	668	0

Table C.4: The OD-matrix for trucks between 07:00 and 08:00.

	1	2	3	4	5	6	7	8	9	10
1	0	69	0	13	0	17	0	30	46	0
2	28	0	0	8	0	10	0	17	27	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	34	0	8	13	0
5	12	0	8	0	0	0	0	0	0	0
6	29	0	19	24	0	0	0	14	21	0
7	0	0	0	0	0	0	0	16	24	0
8	0	0	0	0	0	0	0	0	0	0
9	11	0	7	3	0	4	11	0	0	0
10	41	0	27	12	0	15	38	0	25	0

Table C.5: The OD-matrix for trucks between 08:00 and 09:00

	1	2	3	4	5	6	7	8	9	10
1	0	87	0	20	0	22	0	33	60	0
2	38	0	0	7	0	8	0	12	21	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	35	0	6	11	0
5	26	0	17	0	0	0	0	0	0	0
6	20	0	13	30	0	0	0	14	26	0
7	0	0	0	0	0	0	0	15	27	0
8	0	0	0	0	0	0	0	0	0	0
9	13	0	8	4	0	7	15	0	0	0
10	32	0	21	10	0	18	34	0	9	0

Table C.6: The OD-matrix for trucks between 09:00 and 10:00.

	1	2	3	4	5	6	7	8	9	10
1	0	58	0	16	0	19	0	37	59	0
2	42	0	0	6	0	7	0	13	21	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	26	0	7	11	0
5	20	0	13	0	0	0	0	0	0	0
6	22	0	15	31	0	0	0	8	13	0
7	0	0	0	0	0	0	0	6	9	0
8	0	0	0	0	0	0	0	0	0	0
9	19	0	12	6	0	13	16	0	0	0
10	40	0	26	12	0	28	32	0	27	0

D

Results per direction

An analysis of the total delay, average travel time and average number of stops per direction have been given. For each KPI, the Platoon and DTM scenarios have been compared to the base scenario and the DTM and Platoon scenarios have been compared to each other.

D.1. Total Delay

D.1.1. Platoon and DTM scenarios vs Base scenario

Tables D.1 and D.2 provide a better insight into the total delay for the main direction and the other directions since those give the percentage difference of total delay per direction between the Platoon and DTM scenarios in comparison to the base scenario for all vehicles combined. The cells that are coloured green have a lower total delay than the total delay for the base scenario on the specific direction.

Table D.1: Percentage difference of the total delay per direction between respectively the Platoon and DTM scenarios with the base scenario.

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Platoon	0	20	0.19%	-0.69%	-1.14%	1.02%	2.43%	4.06%
Platoon	0	40	0.64%	0.30%	0.18%	2.70%	1.96%	-4.05%
Platoon	0	60	1.05%	-2.11%	-1.93%	6.20%	1.82%	3.81%
Platoon	0	80	4.33%	-0.64%	-0.04%	4.25%	-2.51%	3.02%
Platoon	0	100	1.04%	-2.10%	1.60%	5.10%	0.35%	5.11%
Platoon	20	20	1.22%	-1.87%	1.86%	3.39%	-0.23%	-0.13%
Platoon	40	40	4.12%	-3.68%	1.73%	6.70%	-1.25%	4.25%
Platoon	60	60	2.32%	-9.71%	6.48%	7.74%	-5.37%	1.50%
Platoon	80	80	2.72%	-14.12%	7.57%	8.49%	-4.88%	0.88%
Platoon	100	100	-1.21%	-20.40%	9.18%	10.46%	-6.17%	10.71%
DTM	0	20	67.63%	81.06%	37.78%	-3.30%	6.60%	-18.23%
DTM	0	40	1.67%	9.37%	17.90%	-14.95%	-9.19%	-17.20%
DTM	0	60	-6.32%	-5.18%	15.01%	-13.56%	-10.90%	-12.83%
DTM	0	80	-7.50%	-10.35%	13.13%	-9.50%	-13.01%	-7.71%
DTM	0	100	-9.43%	-10.05%	12.11%	-8.15%	-12.69%	-8.84%
DTM	20	20	-11.41%	-15.84%	0.36%	-0.16%	-1.95%	-5.88%
DTM	40	40	-3.86%	-12.39%	2.99%	-2.91%	-6.47%	-4.84%
DTM	60	60	-0.92%	-13.74%	6.92%	-1.83%	-8.77%	-3.07%
DTM	80	80	-0.36%	-14.40%	10.50%	-3.19%	-10.12%	0.02%
DTM	100	100	-0.71%	-17.59%	14.01%	0.08%	-9.51%	-0.82%

Table D.2: Percentage difference of the total delay per direction between respectively the Platoon and DTM scenarios with the base scenario.

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Platoon	0	20	0.9%	-0.9%	0.9%	4.0%	-3.3%	4.7%
Platoon	0	40	0.5%	-0.2%	1.0%	5.6%	-4.8%	1.8%
Platoon	0	60	3.0%	0.1%	3.2%	6.5%	-0.2%	6.4%
Platoon	0	80	0.7%	-0.3%	1.3%	7.8%	-3.7%	4.8%
Platoon	0	100	0.5%	-0.8%	0.3%	8.3%	-6.6%	7.7%
Platoon	20	20	4.7%	-0.5%	6.2%	0.9%	-1.2%	3.3%
Platoon	40	40	5.8%	-4.3%	4.9%	9.7%	-0.5%	3.6%
Platoon	60	60	1.5%	-11.5%	5.6%	10.0%	-7.3%	7.1%
Platoon	80	80	-3.3%	-17.4%	5.6%	11.9%	-9.8%	7.1%
Platoon	100	100	-4.8%	-25.1%	6.5%	16.8%	-7.4%	5.6%
DTM	0	20	184.9%	204.7%	240.2%	-3.6%	-6.0%	-25.2%
DTM	0	40	6.5%	24.0%	94.3%	-12.9%	-15.0%	-20.3%
DTM	0	60	-3.1%	3.6%	73.2%	-9.3%	-20.8%	-18.3%
DTM	0	80	-7.1%	-5.3%	51.1%	-3.8%	-17.4%	-14.6%
DTM	0	100	-7.9%	-7.8%	38.3%	-5.7%	-14.2%	-10.8%
DTM	20	20	-12.4%	-13.7%	10.7%	2.1%	-0.4%	-5.3%
DTM	40	40	-1.8%	-13.2%	8.6%	1.2%	-8.0%	-6.2%
DTM	60	60	-0.9%	-14.8%	9.5%	-1.0%	-9.7%	-4.8%
DTM	80	80	-1.4%	-18.4%	11.3%	3.0%	-9.4%	-6.4%
DTM	100	100	-3.6%	-23.1%	13.4%	2.7%	-15.6%	-3.9%

When looking at the Platoon scenarios it can be seen that the total delay is lower on directions 2, 8 and 11 in comparison to the base scenario. Direction 5 only shows an improvement in total delay for the Platoon scenarios with both CACC-equipped cars and trucks. With a few exceptions, the total delay on the directions 1, 3, 4, 5, 6, 9, 10 and 12 is higher than it is in the base scenario.

The results for the DTM scenarios regarding the total delay per direction in caparison to the base scenario show a different pattern than the Platoon scenario results do. Similarly, the directions 2, 8 and 11 have less total delay compared to the base scenario. However, directions 4, 5, 6, 7 and 12 also have a decreased total delay in comparison to the base scenario. Another observation that can be made from tables D.1 and D.2 is that direction 10 has a lower total delay in the DTM scenarios with only CACC-equipped trucks in comparison to the base scenario, which is not the case for the DTM scenarios with both CACC-equipped cars and trucks.

D.1.2. Platoon vs DTM scenarios

After comparing the Platoon and DTM scenarios to the base scenario, both scenarios will be compared to each other. Tables D.3 and D.4 show the percentage difference of the total delay per direction between the DTM and DTM scenarios. A cell is coloured in red if for that specific direction and penetration rate the Platoon scenario has a lower total delay than the DTM scenario and green if otherwise. The findings from both tables will be discussed in this section.

Table D.3: Percentage difference of the total delay per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	1	2	3	4	5	6
0	20	67.3%	82.3%	39.4%	-4.3%	4.1%	-21.4%
0	40	1.0%	9.0%	17.7%	-17.2%	-10.9%	-13.7%
0	60	-7.3%	-3.1%	17.3%	-18.6%	-12.5%	-16.0%
0	80	-11.3%	-9.8%	13.2%	-13.2%	-10.8%	-10.4%
0	100	-10.4%	-8.1%	10.4%	-12.6%	-13.0%	-13.3%
20	20	-12.5%	-14.2%	-1.5%	-3.4%	-1.7%	-5.8%
40	40	-7.7%	-9.0%	1.2%	-9.0%	-5.3%	-8.7%
60	60	-3.2%	-4.5%	0.4%	-8.9%	-3.6%	-4.5%
80	80	-3.0%	-0.3%	2.7%	-10.8%	-5.5%	-0.8%
100	100	0.5%	3.5%	4.4%	-9.4%	-3.6%	-10.4%

Table D.4: Percentage difference of the total delay per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	7	8	9	10	11	12
0	20	182.4%	207.3%	237.3%	-7.3%	-2.8%	-28.5%
0	40	6.0%	24.2%	92.3%	-17.5%	-10.7%	-21.7%
0	60	-5.9%	3.5%	67.8%	-14.8%	-20.6%	-23.2%
0	80	-7.8%	-5.0%	49.2%	-10.8%	-14.2%	-18.5%
0	100	-8.4%	-7.0%	38.0%	-13.0%	-8.1%	-17.2%
20	20	-16.4%	-13.3%	4.3%	1.2%	0.9%	-8.3%
40	40	-7.2%	-9.3%	3.5%	-7.8%	-7.6%	-9.4%
60	60	-2.4%	-3.7%	3.7%	-10.0%	-2.6%	-11.2%
80	80	1.9%	-1.3%	5.4%	-7.9%	0.5%	-12.7%
100	100	1.2%	2.7%	6.5%	-12.1%	-8.8%	-9.0%

An important observation that can be made from tables D.1 and D.2 is that the total delay is lower for the DTM scenarios on approach 2 and 4 (directions 4, 5, 6, 10, 11, 12) in comparison to the Platoon scenarios. Another major observation is that the Platoon scenarios have a lower total delay on directions 3 and 9 in comparison to the DTM scenarios. These are the left turning directions on both approaches on the N201 - Rijkerdreef.

The total delay on directions 1, 2, 7 and 8 are lower for the Platoon scenarios with no CACC-equipped cars and 20 - 40% CACC-equipped trucks in comparison to the DTM scenarios. The same counts for a 100% penetration rate of CACC-equipped cars and trucks.

D.2. Average Travel Time

D.2.1. Platoon and DTM scenarios vs Base scenario

Tables D.5 and D.6 provide the percentage difference of the average travel time between the Platoon and DTM scenarios and the base scenario for all vehicle types. A green cells indicates if the average travel time of the specific scenario and direction is lower than it is for the base scenario. This section will describe the findings from both tables.

Table D.5: Percentage difference of the average travel time per direction between respectively the Platoon and DTM scenarios with the base scenario.

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Platoon	0	20	0.14%	-0.18%	-0.56%	-0.13%	2.14%	1.35%
Platoon	0	40	-0.04%	0.12%	0.10%	-0.45%	1.17%	-3.12%
Platoon	0	60	0.10%	-0.59%	-1.02%	0.07%	1.83%	-2.10%
Platoon	0	80	0.71%	-0.18%	-0.53%	-1.37%	-1.17%	-2.83%
Platoon	0	100	-0.38%	-0.61%	-0.22%	-1.92%	0.17%	-1.80%
Platoon	20	20	-0.48%	-0.57%	0.47%	-0.50%	0.34%	-0.53%
Platoon	40	40	-1.05%	-1.06%	-0.31%	-1.54%	0.04%	-0.21%
Platoon	60	60	-3.49%	-3.10%	0.31%	-3.85%	-3.44%	-3.27%
Platoon	80	80	-4.74%	-4.60%	0.25%	-5.88%	-2.93%	-4.72%
Platoon	100	100	-7.04%	-6.38%	-0.34%	-7.36%	-3.28%	-1.98%
DTM	0	20	19.57%	27.85%	14.17%	-1.83%	6.02%	-10.97%
DTM	0	40	-0.29%	2.99%	6.29%	-8.89%	-6.03%	-11.92%
DTM	0	60	-2.31%	-1.88%	4.64%	-8.71%	-6.92%	-11.08%
DTM	0	80	-3.16%	-3.43%	4.53%	-8.52%	-8.48%	-9.58%
DTM	0	100	-3.50%	-3.44%	3.57%	-8.26%	-9.25%	-9.66%
DTM	20	20	-4.56%	-5.41%	-0.04%	-2.06%	-0.85%	-5.58%
DTM	40	40	-3.88%	-4.11%	0.03%	-6.45%	-4.10%	-4.79%
DTM	60	60	-4.20%	-4.35%	1.00%	-7.96%	-5.52%	-5.95%
DTM	80	80	-5.71%	-4.58%	1.42%	-11.43%	-6.36%	-6.10%
DTM	100	100	-7.00%	-5.41%	1.50%	-12.15%	-6.72%	-6.98%

Table D.6: Percentage difference of the average travel time per direction between respectively the Platoon and DTM scenarios with the base scenario.

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Platoon	0	20	-0.2%	-0.3%	0.2%	0.8%	-2.8%	1.8%
Platoon	0	40	0.0%	-0.1%	0.2%	0.4%	-4.0%	-1.6%
Platoon	0	60	0.3%	0.0%	0.7%	-1.1%	-2.0%	-1.5%
Platoon	0	80	-0.2%	-0.1%	0.1%	-1.0%	-3.2%	-0.5%
Platoon	0	100	-0.3%	-0.2%	-0.2%	-2.2%	-4.9%	-2.1%
Platoon	20	20	-0.1%	-0.1%	1.3%	-2.3%	-2.3%	-1.5%
Platoon	40	40	-1.1%	-1.0%	0.5%	-0.4%	-0.8%	-1.7%
Platoon	60	60	-3.0%	-2.9%	0.1%	-2.4%	-5.9%	-0.9%
Platoon	80	80	-5.0%	-4.3%	-0.2%	-4.1%	-8.4%	-2.4%
Platoon	100	100	-6.2%	-6.1%	-0.5%	-4.4%	-5.5%	-5.8%
DTM	0	20	38.9%	54.9%	72.9%	-3.9%	-6.5%	-15.2%
DTM	0	40	1.2%	6.5%	28.4%	-9.2%	-10.9%	-13.5%
DTM	0	60	-1.2%	0.8%	21.3%	-9.1%	-16.2%	-14.4%
DTM	0	80	-2.0%	-1.4%	14.8%	-7.5%	-12.7%	-14.4%
DTM	0	100	-2.3%	-2.2%	11.1%	-10.3%	-11.2%	-13.6%
DTM	20	20	-4.0%	-3.8%	2.7%	-1.9%	-1.5%	-5.5%
DTM	40	40	-2.9%	-3.6%	1.4%	-4.5%	-6.6%	-6.7%
DTM	60	60	-3.3%	-3.7%	1.4%	-8.4%	-8.2%	-8.0%
DTM	80	80	-4.4%	-4.5%	1.5%	-8.5%	-7.2%	-10.5%
DTM	100	100	-5.9%	-5.6%	1.6%	-10.4%	-12.5%	-10.0%

Tables D.5 and D.6 show that the majority of Platoon scenarios result in a lower average travel time on directions 1, 2, 4, 6, 7, 8, 10, 11 and 12 in comparison to the base scenario. This is particularly the case for the Platoon scenarios with both CACC-equipped cars and trucks with penetration rates of 40% or higher. However, Platoon scenarios with lower penetration rates and with solely connected trucks at different penetration rates do not differ significantly from the base scenario for these directions. Directions 3, 5 and 9 do not show significant improvements in the Platoon scenarios compared to the base scenario.

When looking at the DTM scenarios it can be seen that the majority of those result in a lower average travel time on directions 1, 2, 4, 5, 6, 7, 8, 10, 11, 12 compared to the base scenario. This is similar to the Platoon scenarios, but the difference is that direction 5 does show a better performance within the DTM scenarios. The DTM scenarios for directions 3 and 9 do not show an improvement in average travel time in comparison to the base scenario.

D.2.2. Platoon vs DTM scenarios

Tables D.7 and D.8 show the percentage difference of the average travel time between the DTM and Platoon scenarios. The red coloured cells indicate that the Platoon scenario has a lower average travel time in comparison to the DTM scenario for a specific direction and penetration rate and green if otherwise. This section will discuss the observation made from both tables.

Table D.7: Percentage difference of the average travel time per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	1	2	3	4	5	6
0	20	19.40%	28.08%	14.82%	-1.70%	3.80%	-12.15%
0	40	-0.25%	2.86%	6.18%	-8.48%	-7.12%	-9.08%
0	60	-2.41%	-1.29%	5.72%	-8.78%	-8.59%	-9.17%
0	80	-3.85%	-3.26%	5.09%	-7.25%	-7.40%	-6.95%
0	100	-3.13%	-2.86%	3.79%	-6.46%	-9.40%	-8.01%
20	20	-4.10%	-4.86%	-0.50%	-1.57%	-1.18%	-5.08%
40	40	-2.86%	-3.08%	0.34%	-4.98%	-4.14%	-4.60%
60	60	-0.74%	-1.29%	0.69%	-4.28%	-2.15%	-2.78%
80	80	-1.01%	0.02%	1.18%	-5.90%	-3.53%	-1.46%
100	100	0.05%	1.05%	1.84%	-5.17%	-3.56%	-5.10%

Table D.8: Percentage difference of the average travel time per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	1	2	3	4	5	6
0	20	39.1%	55.3%	72.6%	-4.7%	-3.8%	-16.7%
0	40	1.2%	6.6%	28.2%	-9.6%	-7.2%	-12.1%
0	60	-1.5%	0.8%	20.4%	-8.1%	-14.5%	-13.1%
0	80	-1.8%	-1.3%	14.7%	-6.6%	-9.8%	-14.0%
0	100	-2.1%	-2.0%	11.3%	-8.2%	-6.6%	-11.7%
20	20	-3.9%	-3.7%	1.4%	0.4%	0.7%	-4.1%
40	40	-1.8%	-2.6%	1.0%	-4.2%	-5.8%	-5.1%
60	60	-0.4%	-0.8%	1.3%	-6.1%	-2.4%	-7.2%
80	80	0.6%	-0.3%	1.6%	-4.6%	1.3%	-8.3%
100	100	0.3%	0.6%	2.1%	-6.2%	-7.4%	-4.5%

The results from tables D.7 and D.8 are quite similar to the results from tables D.3 and D.4, which compare the total delay between the DTM and Platoon scenarios per direction. The average travel time is lower for the DTM scenarios on approach 2 and 4 of the intersection (directions 4, 5, 6, 10, 11, 12). The Platoon scenarios have a lower average travel time compared to the DTM scenarios on direction 3 and 9.

The average travel time on directions 1, 2, 7 and 8 is lower for the majority of the DTM scenario in comparison to the Platoon scenarios. However, the Platoon scenarios perform better in scenarios with no CACC-equipped cars and 20 - 40% CACC-equipped trucks, as well as with a 100% penetration rate of both CACC-equipped cars and trucks for these directions.

D.3. Number of Stops

D.3.1. Platoon and DTM scenarios vs Base scenario

Tables D.9 and D.10 compare the Platoon and DTM scenarios to the base scenario. The green coloured cells indicate the direction and penetration rate for which the Platoon or DTM scenario has a lower average number of stops. This section will review the results that are portrayed in both tables.

Table D.9: Percentage difference of the average number of stops per direction between respectively the Platoon and DTM scenarios with the base scenario

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Platoon	0	20	-0.1%	-0.7%	-1.3%	-1.0%	2.8%	2.8%
Platoon	0	40	1.1%	1.2%	0.0%	-1.0%	3.8%	-1.4%
Platoon	0	60	0.6%	-0.1%	-1.2%	1.9%	4.7%	0.2%
Platoon	0	80	2.2%	0.9%	-0.6%	-2.5%	2.3%	1.2%
Platoon	0	100	-0.9%	0.5%	0.5%	0.7%	2.9%	-0.7%
Platoon	20	20	1.6%	0.5%	2.2%	-0.2%	2.6%	-0.6%
Platoon	40	40	3.0%	5.7%	5.1%	3.2%	4.4%	1.2%
Platoon	60	60	3.3%	15.9%	16.7%	9.0%	4.2%	0.8%
Platoon	80	80	17.7%	30.7%	39.6%	13.0%	6.3%	3.1%
Platoon	100	100	36.9%	52.9%	63.4%	23.7%	19.2%	6.7%
DTM	0	20	137.8%	188.0%	62.7%	4.8%	30.5%	-2.7%
DTM	0	40	20.7%	33.4%	25.7%	-0.3%	11.3%	-0.9%
DTM	0	60	6.3%	6.6%	15.7%	-2.3%	2.1%	-1.6%
DTM	0	80	0.8%	-0.3%	15.9%	-3.1%	2.3%	0.0%
DTM	0	100	-2.2%	-2.3%	11.1%	-0.8%	-0.2%	-1.1%
DTM	20	20	-3.6%	-9.2%	5.2%	0.7%	4.7%	1.4%
DTM	40	40	-1.0%	-1.3%	8.3%	-3.0%	2.6%	1.1%
DTM	60	60	3.2%	12.4%	19.9%	1.4%	3.0%	1.4%
DTM	80	80	15.5%	32.7%	44.3%	4.0%	5.8%	3.8%
DTM	100	100	34.3%	59.1%	68.7%	15.0%	10.9%	5.1%

Table D.10: Percentage difference of the average number of stops per direction between respectively the Platoon and DTM scenarios with the base scenario

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Platoon	0	20	-1.3%	-0.9%	-0.2%	2.4%	-4.6%	2.0%
Platoon	0	40	-1.0%	-0.8%	-0.5%	-0.4%	-3.3%	-0.3%
Platoon	0	60	-0.7%	-0.6%	1.4%	0.6%	-1.6%	2.6%
Platoon	0	80	-1.2%	-1.1%	1.4%	1.9%	-2.0%	4.1%
Platoon	0	100	0.2%	-1.2%	1.3%	1.2%	-4.3%	5.1%
Platoon	20	20	1.2%	1.3%	5.1%	-1.5%	-1.3%	-0.9%
Platoon	40	40	1.3%	3.6%	14.3%	1.5%	-0.3%	-0.1%
Platoon	60	60	4.5%	13.3%	39.2%	1.9%	-2.6%	5.0%
Platoon	80	80	16.1%	31.6%	80.1%	2.0%	-2.7%	3.6%
Platoon	100	100	50.1%	52.5%	129.8%	5.1%	-1.7%	3.7%
DTM	0	20	355.1%	451.9%	394.3%	6.6%	3.4%	-6.7%
DTM	0	40	25.3%	56.7%	104.9%	-0.5%	-2.6%	-3.6%
DTM	0	60	8.9%	16.3%	66.9%	-2.2%	-7.9%	-8.0%
DTM	0	80	0.6%	4.1%	43.8%	-1.1%	-4.1%	-6.5%
DTM	0	100	-2.2%	0.3%	33.8%	-5.4%	-3.1%	-8.2%
DTM	20	20	-8.8%	-7.6%	13.5%	4.4%	1.4%	-1.3%
DTM	40	40	0.6%	-0.8%	17.5%	-2.7%	-4.0%	-1.8%
DTM	60	60	4.4%	11.9%	45.7%	-3.9%	-5.0%	-3.3%
DTM	80	80	19.3%	33.0%	87.0%	-4.0%	-2.9%	-7.4%
DTM	100	100	45.6%	56.6%	146.4%	-2.6%	-7.7%	2.3%

The average number of stops per direction is different than the results for the total delay and average travel time per direction. The main difference lies in the fact that for most Platoon and DTM scenarios the number of stops results do not improve as much.

Looking at the Platoon scenarios in tables D.9 and D.10, it can be seen that the number of stops is lower compared to the base scenario only for direction 11, for all penetration rates. Directions 3, 7 and 8 have a lower average number of stops for the Platoon scenarios without CACC-equipped cars and with 20 - 80% CACC-equipped trucks. However, the average number of stops on these directions is higher in comparison to the base scenario for the Platoon scenarios with higher penetration rates of CACC-equipped trucks and with both CACC-equipped cars and trucks. The majority of the Platoon scenarios do not have a decreased number of stops on the other directions compared to the base scenario.

The majority of DTM scenarios have a lower average number of stops on approach 4 (directions 10, 11, 12). However, unlike the total delay and average travel time results, the DTM scenarios do not improve the average number of stops on most of the other directions. All DTM scenarios have a significantly increased average number of stops on directions 3 and 9.

D.3.2. Platoon vs DTM scenarios

Tables D.11 and D.12 compare the DTM to the platoon scenarios, with respect to the average number of stops per directions. A cell is coloured red if the Platoon scenario has a lower average number of stops for the specific direction and penetration rate in comparison to the DTM scenario and green if otherwise. The findings from both tables will be discussed in this section.

Table D.11: Percentage difference of the average number of stops per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	1	2	3	4	5	6
0	20	138.2%	190.1%	64.8%	5.9%	27.0%	-5.4%
0	40	19.4%	31.9%	25.7%	0.7%	7.2%	0.5%
0	60	5.7%	6.7%	17.0%	-4.1%	-2.5%	-1.8%
0	80	-1.4%	-1.3%	16.6%	-0.6%	0.0%	-1.2%
0	100	-1.3%	-2.8%	10.6%	-1.5%	-3.1%	-0.4%
20	20	-5.0%	-9.6%	2.9%	0.9%	2.0%	2.1%
40	40	-3.9%	-6.6%	3.0%	-6.0%	-1.7%	-0.1%
60	60	0.0%	-3.0%	2.8%	-6.9%	-1.1%	0.6%
80	80	-1.8%	1.5%	3.4%	-7.9%	-0.5%	0.7%
100	100	-1.9%	4.0%	3.2%	-7.0%	-7.0%	-1.4%

Table D.12: Percentage difference of the average number of stops per direction between the Platoon and DTM scenarios for all vehicles combined.

Penetration rate		Direction					
% C.C.	% C.T.	7	8	9	10	11	12
0	20	361.0%	457.1%	395.3%	4.1%	8.4%	-8.5%
0	40	26.6%	58.1%	105.9%	-0.1%	0.7%	-3.2%
0	60	9.7%	17.1%	64.6%	-2.8%	-6.4%	-10.3%
0	80	1.8%	5.3%	41.8%	-3.0%	-2.2%	-10.2%
0	100	-2.4%	1.5%	32.1%	-6.5%	1.3%	-12.6%
20	20	-9.9%	-8.8%	8.0%	6.0%	2.8%	-0.3%
40	40	-0.7%	-4.2%	2.8%	-4.1%	-3.7%	-1.7%
60	60	-0.1%	-1.2%	4.7%	-5.7%	-2.4%	-7.9%
80	80	2.7%	1.1%	3.8%	-5.8%	-0.1%	-10.6%
100	100	-3.0%	2.7%	7.2%	-7.3%	-6.1%	-1.4%

Similar to the total delay and average travel time results, the average number of stops results show that the DTM scenarios generally perform better than the Platoon scenarios on approach 2 and 4 (directions 4, 5, 6, 10, 11 and 12). All platoon scenarios perform better on directions 3 and 9 compared to the equivalent DTM scenarios.

Tables D.11 and D.12 show less clear results for directions 1, 2, 7 and 8. One of two things the results for these directions have in common is that the Platoon scenarios have a lower number of stops with a penetration rate of 0% for CACC-equipped cars and 20 - 60% for CACC equipped trucks. Secondly, the DTM scenarios perform better on these directions for a penetration rate of 20 - 60% for CACC-equipped cars and trucks.

E
Validation

This chapter will discuss some of the validation steps that have been taken for the microsimulation model. Validation is the process where it is checked whether the model is an accurate representation of the real system.

Most parameters within the Vissim model were unchanged, which means that the default values are used. A face-validity check has been performed to check whether the model seems to work as intended. From this is it is concluded that a part of the vehicles had very late lane changes in front of the intersection, which resulted in unusual disruptions in front of the intersection stop lines. How this has been solved will be explained in the next section. Another validation step is to check whether enough simulation runs have been done to account for the stochasticity. This is done in section E.2.

E.1. Late Lane Changes

As stated before, a part of the vehicles changed there lane at the last possible moment just before the intersection stop line. This could lead to the fact that the vehicle did have to come to a complete stop in order to be able to merge to the right lane. If the vehicle remains idle for longer than 60 seconds, it will be removed from the simulation. Moreover, this negatively impacted the traffic flow KPI's of the model.

A few measures were taken to fix this problem. First of all, the lane change distance of the intersection connectors were increased, which had a small impact. Another fix that mostly solved the problem was to increase the emergency stop distance, which is the distance at which the vehicle will stop if it has not merged to the right lane yet. Increasing this distance resulted in the fact that vehicles will change to the right lane earlier. This made it easier to merge, so the vehicles did not have to stop as much anymore. The number of vehicles that were removed from the simulation drastically decreased as a result of this increased emergency stop distance.

E.2. Number of Simulation Runs

The PTV Vissim model is a stochastic model, which is caused by a variance in desired speed, spacing, route/lane choice, traffic volume and more (Fries and Qi, 2017). To account for this stochasticity, multiple simulation runs are required. The exact amount of required runs for statistically relevant results per scenario will be determined in this section.

The required number of runs will be calculated per scenario and per key performance indicator (KPI). 10 simulation runs have been performed per scenario. For each scenario the average and standard deviation will be calculated per KPI. These will then be used to calculate the minimum number of iterations that are required using the following formula (Fries and Qi, 2017):

$$n = (\frac{s * z}{\mu * \epsilon})^2$$

Where:

- s: the standard deviation of the KPI.
- z: z-score, this is 1.96 for a 95% confidence level.
- μ: the mean of the KPI.
- ϵ: the accepted error. 3% has been chosen as an acceptable margin of error.

Table E.1 shows the required number of runs per scenario and KPI. From this it is evident that most scenarios do not need a lot of runs. However, the DTM 20% c.c. and 0% c.t. and DTM 40% c.c. and 0% c.t. require more than 10 simulation runs. This has not been possible to due to the computation times that are too long. This means that the number of conducted simulation runs have been insufficient to meet this confidence interval for both scenarios.

Table E.1: The minimum required number of simulation runs for each scenario and KPI.

Scenario			KPI		
Name	% C.C.	% C.T.	Total delay	Average travel time	Number of stops
Base	0	0	0.73	0.45	1.36
Platoon	0	20	1.32	0.16	0.17
Platoon	0	40	0.52	0.15	0.48
Platoon	0	60	0.94	0.15	0.94
Platoon	0	80	0.79	0.21	0.37
Platoon	0	100	1.02	0.11	0.59
Platoon	20	20	0.89	0.21	0.62
Platoon	40	40	0.79	0.17	0.60
Platoon	60	60	1.40	0.15	0.55
Platoon	80	80	0.52	0.12	0.73
Platoon	100	100	1.66	0.40	0.71
DTM	0	20	225.64	44.25	267.74
DTM	0	40	23.44	1.54	11.49
DTM	0	60	4.37	0.43	3.72
DTM	0	80	3.39	0.39	1.87
DTM	0	100	2.26	0.43	1.05
DTM	20	20	1.39	0.17	0.67
DTM	40	40	1.09	0.15	0.62
DTM	60	60	1.65	0.12	0.23
DTM	80	80	0.67	0.10	1.20
DTM	100	100	0.41	0.23	0.89

F

All Simulation Results

All result tables will be given in this section.

F.1. Total Delay

Table F.1: Total delay for all vehicles and direction combined

Scenario			All directions		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2
Base	0	0	282455	173767	108689
Plt	0	20	282052	174213	107839
Plt	0	40	283427	173390	110037
Plt	0	60	283722	173043	110678
Plt	0	80	283493	174332	109162
Plt	0	100	281686	172527	109159
Plt	20	20	284188	173211	110977
Plt	40	40	280053	170682	109371
Plt	60	60	268208	162751	105457
Plt	80	80	258880	157086	101795
Plt	100	100	247163	148247	98916
DTM	0	20	661589	423413	238176
DTM	0	40	344633	213459	131174
DTM	0	60	303954	191703	112251
DTM	0	80	283749	175159	108590
DTM	0	100	276861	171808	105053
DTM	20	20	257360	156578	100782
DTM	40	40	261538	160123	101414
DTM	60	60	260247	155909	104338
DTM	80	80	257440	155263	102178
DTM	100	100	251569	150874	100695

Table F.2: Total delay for all vehicles combined on the main direction and other directions.

Scenario			Main direction			Other directions		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	172544	109128	63416	109912	64639	45273
Plt	0	20	171180	108696	62485	110872	65517	45355
Plt	0	40	172613	108642	63971	110814	64748	46066
Plt	0	60	171006	107672	63334	112716	65371	47345
Plt	0	80	171758	108687	63071	111736	65645	46091
Plt	0	100	170120	107344	62776	111566	65183	46383
Plt	20	20	170616	107076	63540	113572	66135	47437
Plt	40	40	165615	104048	61567	114438	66635	47804
Plt	60	60	154042	95671	58371	114166	67081	47086
Plt	80	80	145077	90547	54530	113803	66539	47265
Plt	100	100	132788	80961	51827	114375	67286	47089
DTM	0	20	430979	283305	147674	230610	140108	90502
DTM	0	40	202729	130108	72621	141904	83351	58553
DTM	0	60	172021	111318	60703	131933	80385	51548
DTM	0	80	159552	100495	59057	124198	74665	49533
DTM	0	100	157338	100126	57212	119523	71682	47841
DTM	20	20	147244	92480	54764	110115	64098	46017
DTM	40	40	150427	94886	55541	111111	65237	45874
DTM	60	60	147840	91027	56813	112407	64883	47524
DTM	80	80	143840	89226	54613	113601	66036	47564
DTM	100	100	136904	83998	52906	114664	66876	47788

Table F.3: Total delay for cars and CACC-equipped cars.

Scenario			Car			C Car		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	241990	152733	89257			
Plt	0	20	240992	153017	87975			
Plt	0	40	242281	152243	90038			
Plt	0	60	241901	151614	90287			
Plt	0	80	242137	152936	89201			
Plt	0	100	239701	150776	88924			
Plt	20	20	194092	121314	72778	49654	30906	18748
Plt	40	40	142738	89332	53406	97365	60856	36509
Plt	60	60	90735	56226	34509	137699	86047	51652
Plt	80	80	43249	26794	16455	177087	110214	66873
Plt	100	100				209340	128823	80517
DTM	0	20	591822	387067	204755			
DTM	0	40	301779	191305	110474			
DTM	0	60	264875	170994	93881			
DTM	0	80	245327	155295	90032			
DTM	0	100	239068	151876	87192			
DTM	20	20	175886	109751	66135	43473	27194	16279
DTM	40	40	134061	84326	49735	89830	56330	33500
DTM	60	60	87938	54157	33781	133797	82606	51191
DTM	80	80	43732	26847	16885	176276	108995	67281
DTM	100	100				214840	132103	82737

Table F.4: Total delay for trucks and CACC-equipped trucks.

Scenario			Truck			C Truck		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	40609	21243	19366			
Plt	0	20	32785	16916	15868	8751	4461	4290
Plt	0	40	24505	12574	11931	17155	8831	8325
Plt	0	60	16251	8164	8087	25808	13123	12686
Plt	0	80	8018	4257	3761	33882	17520	16362
Plt	0	100				42316	22083	20233
Plt	20	20	32384	16713	15671	8677	4397	4280
Plt	40	40	24527	12493	12033	16701	8512	8188
Plt	60	60	15827	8390	7437	24755	12667	12088
Plt	80	80	7626	4024	3602	31387	16098	15289
Plt	100	100				38068	19361	18707
DTM	0	20	56661	29914	26747	13248	7323	5925
DTM	0	40	26940	13855	13086	16516	8512	8004
DTM	0	60	15917	8320	7597	23476	12403	11074
DTM	0	80	7998	4346	3653	30675	15750	14924
DTM	0	100				37998	19948	18050
DTM	20	20	30789	15751	15039	7911	4177	3734
DTM	40	40	23107	11715	11391	15357	7932	7425
DTM	60	60	15603	7903	7700	24078	12054	12024
DTM	80	80	7949	4318	3630	30536	15852	14683
DTM	100	100				36592	18485	18106

F.1.1. Total Delay Per Direction

All Vehicles

Table F.5: Total delay for all vehicles (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	12845	76608	14835	9054	7469	3753
Platoon	0	20	12870	76076	14665	9146	7651	3906
Platoon	0	40	12927	76841	14862	9299	7616	3602
Platoon	0	60	12980	74990	14549	9615	7606	3896
Platoon	0	80	13401	76118	14828	9439	7282	3867
Platoon	0	100	12979	74999	15071	9516	7496	3945
Platoon	20	20	13002	75174	15110	9361	7452	3749
Platoon	40	40	13374	73788	15092	9660	7376	3913
Platoon	60	60	13143	69168	15795	9755	7068	3810
Platoon	80	80	13195	65787	15958	9823	7105	3786
Platoon	100	100	12689	60976	16196	10001	7008	4155
DTM	0	20	21532	138705	20440	8755	7963	3069
DTM	0	40	13059	83785	17490	7700	6783	3108
DTM	0	60	12033	72642	17061	7826	6655	3272
DTM	0	80	11882	68682	16783	8194	6497	3464
DTM	0	100	11633	68910	16632	8316	6521	3422
DTM	20	20	11380	64472	14888	9039	7324	3533
DTM	40	40	12350	67113	15279	8790	6986	3572
DTM	60	60	12726	66082	15861	8888	6815	3638
DTM	80	80	12799	65573	16393	8765	6714	3754
DTM	100	100	12754	63134	16913	9061	6759	3723

Table F.6: Total delay for all vehicles (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	12977	95936	35183	4601	4499	4696
Platoon	0	20	13094	95105	35488	4785	4352	4914
Platoon	0	40	13041	95772	35548	4858	4283	4779
Platoon	0	60	13368	96016	36316	4898	4492	4996
Platoon	0	80	13074	95639	35630	4961	4332	4922
Platoon	0	100	13042	95121	35273	4983	4202	5059
Platoon	20	20	13588	95442	37372	4644	4444	4851
Platoon	40	40	13732	91827	36904	5047	4478	4863
Platoon	60	60	13170	84874	37167	5059	4170	5029
Platoon	80	80	12552	79290	37152	5147	4056	5030
Platoon	100	100	12352	71812	37480	5372	4164	4957
DTM	0	20	36974	292274	119698	4435	4231	3515
DTM	0	40	13819	118944	68372	4008	3825	3740
DTM	0	60	12578	99379	60933	4173	3565	3836
DTM	0	80	12050	90870	53175	4427	3716	4010
DTM	0	100	11951	88428	48660	4337	3861	4191
DTM	20	20	11362	82772	38961	4698	4483	4448
DTM	40	40	12743	83314	38193	4655	4139	4405
DTM	60	60	12853	81758	38541	4554	4062	4468
DTM	80	80	12794	78266	39172	4741	4075	4393
DTM	100	100	12505	73770	39913	4724	3799	4513

Cars

Table F.7: Total delay for cars (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	10984	65545	12766	6465	4961	2123
Platoon	0	20	10989	65198	12540	6510	5165	2024
Platoon	0	40	10861	65936	12779	6564	5028	2069
Platoon	0	60	10989	64356	12436	6702	5068	2094
Platoon	0	80	11323	65442	12668	6467	4997	2002
Platoon	0	100	10883	64530	12727	6524	4944	2102
Platoon	20	20	8719	51700	10214	5341	4035	1600
Platoon	40	40	6554	38249	7444	3979	2984	1247
Platoon	60	60	4294	23746	5195	2669	1959	667
Platoon	80	80	2015	11122	2538	1194	978	505
Platoon	100	100	0	0	0	0	0	0
DTM	0	20	18606	119963	17588	6172	5371	1598
DTM	0	40	11282	72306	14859	5374	4629	1640
DTM	0	60	10296	62693	14664	5460	4643	1636
DTM	0	80	10075	59171	14373	5598	4424	1800
DTM	0	100	9766	59629	14259	5600	4509	1834
DTM	20	20	7606	44425	10161	4971	4044	1564
DTM	40	40	5975	35041	7679	3818	2897	1209
DTM	60	60	4088	22566	5125	2398	1955	780
DTM	80	80	2004	11087	2711	1087	1024	512
DTM	100	100	0	0	0	0	0	0

Table F.8: Total delay for cars (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	12061	88532	32398	2451	1989	1715
Platoon	0	20	12049	87783	32763	2480	1907	1585
Platoon	0	40	12067	88438	32671	2466	1867	1535
Platoon	0	60	12328	88714	33085	2439	1975	1715
Platoon	0	80	12044	88516	32551	2498	1935	1694
Platoon	0	100	11940	88045	32007	2471	1838	1690
Platoon	20	20	9882	70972	26889	1913	1589	1239
Platoon	40	40	7333	51672	19589	1490	1156	1042
Platoon	60	60	4737	32101	12928	999	767	673
Platoon	80	80	2145	15026	6467	444	396	419
Platoon	100	100	0	0	0	0	0	0
DTM	0	20	34621	271727	110915	2294	1792	1174
DTM	0	40	12742	110648	63302	2090	1606	1301
DTM	0	60	11676	92365	56577	2039	1532	1294
DTM	0	80	11131	84253	49337	2210	1657	1297
DTM	0	100	10907	82329	45042	2041	1752	1400
DTM	20	20	8195	61896	28236	1987	1594	1207
DTM	40	40	6758	46927	20271	1351	1149	986
DTM	60	60	4449	31138	13289	851	732	568
DTM	80	80	2161	15099	6694	465	490	399
DTM	100	100	0	0	0	0	0	0

CACC-equipped cars

Table F.9: Total delay for CACC-equipped cars (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0						
Platoon	0	20						
Platoon	0	40						
Platoon	0	60						
Platoon	0	80						
Platoon	0	100						
Platoon	20	20	2428	12674	2828	1406	1026	455
Platoon	40	40	4924	25079	5519	2981	2027	909
Platoon	60	60	7104	35465	8304	4334	2777	1312
Platoon	80	80	9167	45315	11300	5480	3756	1646
Platoon	100	100	10719	52479	13863	6900	4770	2182
DTM	0	20						
DTM	0	40						
DTM	0	60						
DTM	0	80						
DTM	0	100						
DTM	20	20	2131	10596	2591	1339	837	400
DTM	40	40	4586	22555	5499	2492	1853	735
DTM	60	60	6857	33903	8508	3936	2624	1217
DTM	80	80	9021	45001	11455	4971	3617	1629
DTM	100	100	10777	54412	14509	6245	4628	2018

Table F.10: Total delay for CACC-equipped cars (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0						
Platoon	0	20						
Platoon	0	40						
Platoon	0	60						
Platoon	0	80						
Platoon	0	100						
Platoon	20	20	2756	17053	7616	546	400	466
Platoon	40	40	5397	33251	14562	1174	770	771
Platoon	60	60	7443	46102	21248	1542	1037	1031
Platoon	80	80	9493	58115	27904	2040	1426	1445
Platoon	100	100	11504	66481	34365	2604	1935	1538
DTM	0	20						
DTM	0	40						
DTM	0	60						
DTM	0	80						
DTM	0	100						
DTM	20	20	2374	14401	7482	459	418	445
DTM	40	40	5099	29824	14827	1056	766	539
DTM	60	60	7362	44132	21953	1412	1013	881
DTM	80	80	9578	57123	29398	1924	1410	1149
DTM	100	100	11517	68386	36784	2272	1723	1570

Trucks

Table F.11: Total delay for trucks (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	1807	11052	2004	2596	2506	1681
Platoon	0	20	1416	8690	1623	2042	2016	1412
Platoon	0	40	1209	6699	1298	1406	1525	1043
Platoon	0	60	775	4327	739	1163	976	551
Platoon	0	80	380	2064	428	496	557	325
Platoon	0	100						
Platoon	20	20	1468	8616	1632	2005	1969	1371
Platoon	40	40	1138	6341	1275	1637	1538	1158
Platoon	60	60	711	4090	807	1133	984	633
Platoon	80	80	331	1928	487	491	466	404
Platoon	100	100						
DTM	0	20	2312	15207	2196	2135	2135	1176
DTM	0	40	1029	7279	1599	1327	1428	921
DTM	0	60	738	4170	938	878	863	503
DTM	0	80	338	1952	597	419	503	402
DTM	0	100						
DTM	20	20	1243	7663	1619	2181	1936	1328
DTM	40	40	1040	5867	1151	1445	1377	1051
DTM	60	60	718	3991	849	1013	1000	499
DTM	80	80	363	2087	579	458	501	329
DTM	100	100						

Table F.12: Total delay for trucks (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	941	7275	2826	2228	2618	3076
Platoon	0	20	861	5943	2208	1781	2096	2696
Platoon	0	40	505	4527	1647	1319	1489	1837
Platoon	0	60	415	2964	1120	894	1074	1253
Platoon	0	80	206	1369	662	495	474	562
Platoon	0	100						
Platoon	20	20	759	6122	2269	1626	2077	2469
Platoon	40	40	548	4440	1645	1437	1580	1792
Platoon	60	60	420	2853	1112	866	983	1235
Platoon	80	80	170	1263	537	500	519	532
Platoon	100	100						
DTM	0	20	1967	17087	6925	1532	2037	1953
DTM	0	40	621	5314	3242	1137	1510	1533
DTM	0	60	358	2936	1778	828	844	1084
DTM	0	80	178	1266	855	439	550	500
DTM	0	100						
DTM	20	20	756	5234	2464	1884	2019	2463
DTM	40	40	472	4200	1879	1343	1514	1767
DTM	60	60	357	2817	1293	873	956	1238
DTM	80	80	159	1295	623	529	505	523
DTM	100	100						

CACC-equipped trucks

Table F.13: Total delay for CACC-equipped trucks (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0						
Platoon	0	20	461	2241	512	610	511	474
Platoon	0	40	794	4365	801	1314	1041	617
Platoon	0	60	1284	6359	1467	1820	1510	1372
Platoon	0	80	1748	8589	1855	2495	1795	1520
Platoon	0	100	2128	10576	2296	3021	2471	1999
Platoon	20	20	422	2156	532	597	505	403
Platoon	40	40	826	4117	806	1239	1063	604
Platoon	60	60	1245	5906	1523	1818	1409	1293
Platoon	80	80	1621	7562	1885	2412	1718	1434
Platoon	100	100	2016	8559	2363	3188	2314	1907
DTM	0	20	578	3491	588	500	539	334
DTM	0	40	737	4189	968	1013	815	548
DTM	0	60	1084	5781	1506	1588	1223	1042
DTM	0	80	1429	7634	1915	2140	1662	1347
DTM	0	100	1859	9263	2421	2796	2052	1580
DTM	20	20	391	1933	547	529	486	335
DTM	40	40	789	3712	783	1116	931	693
DTM	60	60	1194	5686	1492	1725	1305	1237
DTM	80	80	1491	7546	1898	2340	1648	1484
DTM	100	100	1878	8689	2293	2840	2077	1759

Table F.14: Total delay for CACC-equipped trucks (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0						
Platoon	0	20	205	1470	660	655	407	546
Platoon	0	40	509	2906	1267	1116	1046	1379
Platoon	0	60	612	4309	1979	1556	1433	2109
Platoon	0	80	857	5746	2372	2139	1917	2848
Platoon	0	100	1202	7140	3122	2582	2368	3412
Platoon	20	20	202	1457	758	657	409	580
Platoon	40	40	501	2773	1309	1077	1035	1351
Platoon	60	60	635	3891	1999	1606	1343	2084
Platoon	80	80	855	4903	2324	2075	1771	2826
Platoon	100	100	893	5376	3128	2664	2336	3322
DTM	0	20	632	3673	1502	598	396	416
DTM	0	40	492	3101	1832	862	913	1043
DTM	0	60	610	3934	2534	1403	1161	1609
DTM	0	80	822	5245	2898	1867	1531	2186
DTM	0	100	985	6024	3839	2332	2097	2750
DTM	20	20	203	1208	748	598	446	487
DTM	40	40	494	2532	1210	976	890	1231
DTM	60	60	658	3855	2044	1504	1448	1930
DTM	80	80	932	4722	2522	1864	1752	2337
DTM	100	100	1012	5385	3164	2456	2057	2982

F.2. Average Travel Time

Table F.15: Average travel time for all vehicles combined. (All direction, main direction, other directions)

Scenario			All directions			Main direction			Other directions		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	91.6	93.0	90.2	125.3	129.1	121.6	84.9	85.8	83.9
Plt	0	20	91.7	93.1	90.4	125.1	128.7	121.4	85.1	86.0	84.2
Plt	0	40	91.2	92.3	90.1	125.3	129.0	121.7	84.4	84.9	83.8
Plt	0	60	91.3	92.1	90.5	125.0	128.4	121.6	84.5	84.8	84.2
Plt	0	80	91.0	92.5	89.5	125.2	128.9	121.4	84.2	85.2	83.1
Plt	0	100	90.7	92.1	89.3	124.9	128.5	121.3	83.9	84.9	82.9
Plt	20	20	91.3	92.6	90.0	125.0	128.1	121.8	84.6	85.4	83.7
Plt	40	40	91.0	92.1	89.8	124.0	127.1	120.9	84.3	85.0	83.6
Plt	60	60	89.4	90.6	88.1	121.6	124.0	119.2	82.9	83.9	81.9
Plt	80	80	88.3	89.4	87.2	119.8	122.2	117.4	81.9	82.8	81.1
Plt	100	100	87.5	88.5	86.5	117.5	118.8	116.2	81.5	82.4	80.5
DTM	0	20	113.1	118.8	107.3	179.3	194.2	164.5	99.8	103.8	95.9
DTM	0	40	92.9	94.9	90.8	131.5	137.3	125.8	85.1	86.5	83.8
DTM	0	60	90.2	92.6	87.8	124.9	129.7	120.1	83.2	85.1	81.3
DTM	0	80	89.2	91.0	87.4	122.5	125.7	119.2	82.6	84.1	81.0
DTM	0	100	88.5	90.2	86.8	121.9	125.6	118.2	81.8	83.2	80.5
DTM	20	20	89.1	90.4	87.8	119.7	122.6	116.8	83.0	84.0	82.0
DTM	40	40	88.5	89.8	87.3	120.6	123.6	117.6	82.1	83.0	81.2
DTM	60	60	87.9	88.3	87.4	120.4	122.2	118.5	81.4	81.5	81.2
DTM	80	80	87.2	88.0	86.4	119.6	121.7	117.5	80.7	81.3	80.1
DTM	100	100	86.3	86.8	85.9	118.4	120.0	116.8	79.9	80.2	79.7

Table F.16: Average travel time for cars and CACC-equipped cars.

Scenario			Car			C Car		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	90.4	91.8	89.0			
Plt	0	20	90.1	91.9	88.3			
Plt	0	40	89.9	91.0	88.9			
Plt	0	60	90.5	91.5	89.5			
Plt	0	80	90.1	91.9	88.4			
Plt	0	100	90.2	91.4	88.9			
Plt	20	20	90.3	91.5	89.0	88.0	89.7	86.3
Plt	40	40	90.0	91.4	88.5	89.0	89.9	88.0
Plt	60	60	89.2	90.1	88.2	87.3	88.8	85.7
Plt	80	80	87.4	88.0	86.8	86.7	87.7	85.6
Plt	100	100				86.1	86.9	85.3
DTM	0	20	111.5	116.9	106.1			
DTM	0	40	91.9	94.0	89.7			
DTM	0	60	89.5	91.7	87.3			
DTM	0	80	88.4	90.1	86.7			
DTM	0	100	88.3	89.9	86.7			
DTM	20	20	88.1	89.5	86.7	85.0	85.9	84.2
DTM	40	40	88.3	89.7	86.9	85.4	87.0	83.8
DTM	60	60	87.5	87.8	87.1	85.6	86.8	84.4
DTM	80	80	88.2	89.1	87.3	85.5	86.2	84.9
DTM	100	100				85.5	86.0	84.9

Table F.17: Average travel time for trucks and CACC-equipped trucks.

Scenario			Truck			C Truck		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	95.4	97.2	93.6			
Plt	0	20	96.3	97.5	95.2	93.1	94.0	92.1
Plt	0	40	95.3	96.8	93.8	93.1	93.9	92.3
Plt	0	60	95.0	95.6	94.3	93.2	94.2	92.2
Plt	0	80	95.7	97.0	94.4	93.0	94.1	91.9
Plt	0	100				93.6	95.4	91.7
Plt	20	20	94.9	96.6	93.3	93.5	95.0	92.1
Plt	40	40	95.7	96.8	94.7	92.3	93.6	91.0
Plt	60	60	94.1	96.5	91.7	92.2	93.3	91.0
Plt	80	80	93.5	95.2	91.7	91.3	92.6	89.9
Plt	100	100				90.7	91.6	89.8
DTM	0	20	117.8	124.8	110.8	109.9	116.5	103.2
DTM	0	40	98.4	100.7	96.0	91.4	93.4	89.4
DTM	0	60	94.8	96.6	92.9	89.5	92.5	86.6
DTM	0	80	94.8	97.2	92.5	89.8	91.5	88.1
DTM	0	100				89.6	91.6	87.7
DTM	20	20	94.2	95.1	93.3	90.5	92.7	88.2
DTM	40	40	93.5	93.8	93.2	89.4	91.1	87.6
DTM	60	60	93.8	93.8	93.9	90.9	91.1	90.7
DTM	80	80	94.4	95.9	92.9	90.0	91.1	88.8
DTM	100	100				89.1	89.8	88.4

F.2.1. Total Delay Per Direction

All Vehicles

Table F.18: Average travel time for all vehicles (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	91.6	109.6	99.2	69.6	53.5	81.3
Platoon	0	20	91.8	109.4	98.7	69.5	54.7	82.4
Platoon	0	40	91.6	109.7	99.3	69.3	54.2	78.7
Platoon	0	60	91.7	108.9	98.2	69.7	54.5	79.6
Platoon	0	80	92.3	109.4	98.7	68.7	52.9	79.0
Platoon	0	100	91.3	108.9	99.0	68.3	53.6	79.8
Platoon	20	20	91.2	109.0	99.7	69.3	53.7	80.8
Platoon	40	40	90.7	108.4	98.9	68.6	53.6	81.1
Platoon	60	60	88.5	106.2	99.5	67.0	51.7	78.6
Platoon	80	80	87.3	104.6	99.5	65.5	52.0	77.4
Platoon	100	100	85.2	102.6	98.9	64.5	51.8	79.7
DTM	0	20	109.6	140.1	113.3	68.4	56.8	72.4
DTM	0	40	91.4	112.9	105.5	63.4	50.3	71.6
DTM	0	60	89.5	107.5	103.9	63.6	49.8	72.3
DTM	0	80	88.8	105.8	103.7	63.7	49.0	73.5
DTM	0	100	88.4	105.8	102.8	63.9	48.6	73.4
DTM	20	20	87.5	103.7	99.2	68.2	53.1	76.7
DTM	40	40	88.1	105.1	99.3	65.1	51.3	77.4
DTM	60	60	87.8	104.8	100.2	64.1	50.6	76.4
DTM	80	80	86.4	104.6	100.7	61.7	50.1	76.3
DTM	100	100	85.2	103.7	100.7	61.2	49.9	75.6

Table F.19: Average travel time for all vehicles (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	121.8	141.1	130.6	69.3	55.0	76.6
Platoon	0	20	121.6	140.7	130.9	69.9	53.4	77.9
Platoon	0	40	121.8	140.9	130.9	69.6	52.7	75.3
Platoon	0	60	122.2	141.1	131.5	68.6	53.9	75.4
Platoon	0	80	121.5	140.9	130.8	68.7	53.2	76.2
Platoon	0	100	121.5	140.8	130.3	67.8	52.2	75.0
Platoon	20	20	121.6	140.9	132.3	67.7	53.7	75.4
Platoon	40	40	120.5	139.6	131.2	69.1	54.5	75.3
Platoon	60	60	118.2	137.0	130.7	67.6	51.7	75.9
Platoon	80	80	115.7	135.1	130.4	66.5	50.4	74.7
Platoon	100	100	114.2	132.4	130.0	66.3	52.0	72.2
DTM	0	20	169.2	218.6	225.8	66.6	51.4	64.9
DTM	0	40	123.2	150.2	167.8	62.9	49.0	66.2
DTM	0	60	120.3	142.2	158.4	63.0	46.1	65.6
DTM	0	80	119.3	139.1	150.0	64.1	48.0	65.5
DTM	0	100	118.9	138.0	145.1	62.2	48.8	66.2
DTM	20	20	116.9	135.7	134.1	68.0	54.1	72.4
DTM	40	40	118.3	136.0	132.5	66.2	51.4	71.5
DTM	60	60	117.7	135.9	132.4	63.5	50.5	70.4
DTM	80	80	116.4	134.7	132.5	63.4	51.0	68.5
DTM	100	100	114.6	133.2	132.7	62.1	48.1	69.0

Cars

Table F.20: Average travel time for cars (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	90.9	108.7	97.9	68.4	52.7	77.8
Platoon	0	20	91.0	108.6	97.3	69.0	53.8	77.9
Platoon	0	40	90.8	108.9	98.2	68.7	53.8	76.9
Platoon	0	60	91.2	108.1	97.3	69.6	53.8	77.3
Platoon	0	80	91.9	108.7	97.9	68.3	52.8	74.9
Platoon	0	100	90.9	108.2	97.9	68.7	52.9	78.4
Platoon	20	20	91.1	108.3	98.6	69.2	53.5	77.1
Platoon	40	40	91.2	107.8	97.7	69.1	52.1	75.6
Platoon	60	60	90.0	105.7	98.7	68.8	52.5	74.8
Platoon	80	80	89.1	103.4	98.2	67.3	51.7	74.9
Platoon	100	100						
DTM	0	20	109.1	139.2	112.0	66.8	56.4	67.7
DTM	0	40	91.2	112.2	103.9	62.6	50.2	69.3
DTM	0	60	89.4	107.0	103.2	63.2	50.6	69.7
DTM	0	80	88.4	105.2	102.7	63.8	48.7	70.9
DTM	0	100	88.1	105.3	102.1	64.1	49.1	72.3
DTM	20	20	87.5	103.1	98.5	67.5	53.3	72.8
DTM	40	40	88.2	104.7	98.6	67.3	52.1	74.0
DTM	60	60	89.1	103.9	98.6	66.0	52.1	73.6
DTM	80	80	87.8	103.6	98.8	63.4	53.1	75.4
DTM	100	100						

Table F.21: Average travel time for cars (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	121.6	140.8	130.1	67.3	53.4	74.8
Platoon	0	20	121.3	140.4	130.5	67.8	51.8	72.1
Platoon	0	40	121.7	140.6	130.5	68.2	51.1	69.8
Platoon	0	60	122.2	140.8	130.9	67.4	54.1	73.4
Platoon	0	80	121.4	140.7	130.2	67.5	53.5	73.9
Platoon	0	100	121.3	140.5	129.8	67.8	51.6	74.0
Platoon	20	20	122.2	140.9	131.6	66.9	51.9	72.0
Platoon	40	40	122.1	139.9	130.4	67.6	53.5	72.6
Platoon	60	60	120.9	137.3	129.9	66.4	51.4	73.9
Platoon	80	80	118.9	134.7	130.2	67.2	47.5	66.0
Platoon	100	100						
DTM	0	20	168.9	218.1	225.6	65.3	49.0	59.9
DTM	0	40	123.1	150.2	167.3	62.9	46.6	63.0
DTM	0	60	120.4	142.1	158.4	62.0	44.7	63.7
DTM	0	80	119.3	139.0	149.9	63.8	47.1	62.3
DTM	0	100	118.9	137.9	144.9	61.5	49.0	66.7
DTM	20	20	117.1	135.9	133.7	67.1	53.3	67.7
DTM	40	40	119.8	136.2	131.8	66.0	51.6	69.1
DTM	60	60	119.7	136.2	131.3	61.6	50.4	66.9
DTM	80	80	119.3	134.9	131.4	69.1	55.3	65.7
DTM	100	100						

CACC-equipped cars

Table F.22: Average travel time for CACC-equipped cars (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0						
Platoon	0	20						
Platoon	0	40						
Platoon	0	60						
Platoon	0	80						
Platoon	0	100						
Platoon	20	20	88.5	107.7	97.9	63.8	51.8	73.2
Platoon	40	40	88.2	107.5	97.9	65.1	53.9	80.3
Platoon	60	60	86.5	105.4	98.3	64.2	49.5	76.2
Platoon	80	80	85.7	104.0	99.0	62.8	51.3	73.2
Platoon	100	100	84.1	102.1	97.7	62.9	51.4	76.1
DTM	0	20						
DTM	0	40						
DTM	0	60						
DTM	0	80						
DTM	0	100						
DTM	20	20	83.8	101.8	96.0	61.8	47.2	70.9
DTM	40	40	85.8	103.9	97.7	58.9	49.7	71.8
DTM	60	60	85.9	104.1	99.5	60.7	48.6	72.1
DTM	80	80	85.1	103.9	99.8	59.2	49.5	73.7
DTM	100	100	84.4	103.3	100.0	59.7	50.1	74.2

Table F.23: Average travel time for CACC-equipped cars (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0						
Platoon	0	20						
Platoon	0	40						
Platoon	0	60						
Platoon	0	80						
Platoon	0	100						
Platoon	20	20	118.9	139.5	132.7	63.8	47.9	69.6
Platoon	40	40	117.8	138.6	131.4	64.0	50.6	72.6
Platoon	60	60	115.7	136.3	130.6	63.2	48.9	72.1
Platoon	80	80	114.7	134.9	130.2	62.2	49.2	72.8
Platoon	100	100	114.1	132.3	129.5	63.8	53.2	65.7
DTM	0	20						
DTM	0	40						
DTM	0	60						
DTM	0	80						
DTM	0	100						
DTM	20	20	114.5	133.5	132.2	60.3	49.4	69.2
DTM	40	40	115.9	134.9	132.3	61.2	50.1	62.7
DTM	60	60	115.8	135.0	132.1	60.2	47.4	65.9
DTM	80	80	115.2	134.4	132.3	59.4	49.7	64.4
DTM	100	100	114.2	133.1	132.4	59.4	48.3	66.7

Trucks

Table F.24: Average travel time for trucks (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0	95.9	115.5	106.4	72.9	55.5	86.0
Platoon	0	20	96.6	114.7	107.3	72.7	56.2	86.5
Platoon	0	40	99.0	115.4	109.8	69.7	55.0	85.5
Platoon	0	60	94.8	114.8	102.8	74.2	56.7	80.5
Platoon	0	80	96.1	112.0	102.3	75.2	54.4	87.8
Platoon	0	100						
Platoon	20	20	96.9	114.1	106.6	71.5	53.7	86.7
Platoon	40	40	97.1	113.3	109.0	74.2	55.5	89.0
Platoon	60	60	93.9	112.6	104.7	74.3	53.5	86.0
Platoon	80	80	92.6	109.7	108.8	73.8	51.7	88.3
Platoon	100	100						
DTM	0	20	113.2	147.1	122.1	74.0	58.8	78.2
DTM	0	40	94.9	119.6	120.3	67.2	52.6	74.8
DTM	0	60	95.0	113.7	111.6	66.9	49.4	76.3
DTM	0	80	92.5	110.5	116.2	69.1	50.9	84.1
DTM	0	100						
DTM	20	20	92.6	109.1	107.2	73.9	55.1	80.9
DTM	40	40	94.4	110.3	108.1	70.3	51.5	83.5
DTM	60	60	92.7	111.1	109.6	72.0	54.9	80.0
DTM	80	80	95.3	112.1	113.2	71.8	51.7	78.2
DTM	100	100						

Table F.25: Average travel time for trucks (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0	125.5	144.7	136.4	71.6	56.7	77.8
Platoon	0	20	128.9	144.4	136.9	72.6	56.6	82.9
Platoon	0	40	123.4	145.8	135.5	70.7	53.5	80.4
Platoon	0	60	126.7	145.2	139.3	72.4	55.7	76.6
Platoon	0	80	129.7	143.5	140.2	71.4	57.4	78.4
Platoon	0	100						
Platoon	20	20	124.6	146.4	136.6	69.3	55.8	77.0
Platoon	40	40	122.5	143.8	134.7	75.7	55.9	78.1
Platoon	60	60	124.9	142.6	135.6	70.2	53.4	77.8
Platoon	80	80	121.7	138.8	132.8	71.7	55.7	76.0
Platoon	100	100						
DTM	0	20	168.8	224.9	236.4	66.0	54.4	70.0
DTM	0	40	128.0	153.7	179.1	65.8	53.1	71.2
DTM	0	60	123.0	145.4	165.6	69.7	48.5	72.3
DTM	0	80	123.4	140.6	156.5	65.8	55.6	72.9
DTM	0	100						
DTM	20	20	122.8	140.4	141.9	73.1	55.6	77.9
DTM	40	40	120.3	141.9	138.5	72.2	54.4	76.6
DTM	60	60	119.6	142.0	141.9	71.4	52.9	77.7
DTM	80	80	124.7	139.9	139.9	72.3	58.2	75.6
DTM	100	100						

CACC-equipped trucks

Table F.26: Average travel time for CACC-equipped trucks (direction 1 - 6).

Scenario			Direction					
Name	% C.C.	% C.T.	1	2	3	4	5	6
Base	0	0						
Platoon	0	20	95.8	116.0	104.1	66.3	58.0	86.9
Platoon	0	40	93.0	114.2	102.3	71.5	55.5	77.8
Platoon	0	60	95.0	113.9	106.7	68.2	56.8	84.3
Platoon	0	80	95.0	114.5	104.6	68.6	52.3	81.5
Platoon	0	100	94.9	114.1	105.9	67.1	55.4	83.2
Platoon	20	20	92.8	114.4	104.9	70.6	57.5	80.3
Platoon	40	40	92.3	113.3	103.8	69.2	55.4	75.7
Platoon	60	60	92.5	110.3	107.3	68.0	53.3	82.8
Platoon	80	80	93.6	109.0	104.2	68.6	53.1	81.3
Platoon	100	100	92.2	105.5	107.6	68.9	51.9	81.9
DTM	0	20	105.6	140.8	110.6	60.6	60.3	74.1
DTM	0	40	90.6	114.2	110.2	62.1	46.8	72.0
DTM	0	60	89.4	110.0	106.4	61.6	48.6	73.8
DTM	0	80	89.5	109.7	108.3	62.7	50.4	74.4
DTM	0	100	90.0	108.9	107.6	64.0	48.0	74.3
DTM	20	20	90.2	109.3	109.6	65.9	55.9	76.9
DTM	40	40	91.4	108.9	99.9	63.6	51.4	78.6
DTM	60	60	91.3	109.3	107.8	65.4	49.8	80.1
DTM	80	80	90.8	109.1	106.5	65.2	49.4	80.0
DTM	100	100	90.9	106.2	106.1	64.9	48.8	77.5

Table F.27: Average travel time for CACC-equipped trucks (direction 7 - 12).

Scenario			Direction					
Name	% C.C.	% C.T.	7	8	9	10	11	12
Base	0	0						
Platoon	0	20	119.4	144.6	131.9	72.7	48.4	72.6
Platoon	0	40	123.4	142.9	136.5	70.8	53.1	76.0
Platoon	0	60	118.1	143.5	136.3	68.1	52.5	75.3
Platoon	0	80	120.5	143.9	135.4	69.1	53.7	76.7
Platoon	0	100	124.1	143.9	137.0	68.6	53.1	75.4
Platoon	20	20	125.7	143.3	138.5	69.9	48.8	75.8
Platoon	40	40	123.1	141.8	136.2	68.4	54.3	74.4
Platoon	60	60	119.5	139.2	136.4	69.1	51.4	76.1
Platoon	80	80	117.7	137.5	133.4	69.3	50.5	76.9
Platoon	100	100	115.1	133.3	135.9	68.6	52.7	74.4
DTM	0	20	173.6	217.1	203.4	67.4	45.4	59.3
DTM	0	40	120.5	146.5	161.6	59.9	47.9	64.6
DTM	0	60	120.7	140.5	152.5	61.2	45.7	64.0
DTM	0	80	118.6	140.6	145.8	65.0	47.3	65.6
DTM	0	100	118.6	138.3	148.4	63.5	47.9	66.0
DTM	20	20	116.1	135.9	141.0	64.8	51.8	68.1
DTM	40	40	119.5	139.1	136.4	64.8	49.0	69.8
DTM	60	60	122.3	138.7	137.8	64.1	53.0	71.0
DTM	80	80	121.9	136.5	136.5	64.7	50.3	68.5
DTM	100	100	118.8	133.6	136.6	66.2	49.0	70.4

F.3. Average Number of Stops

Table F.28: Average number of stops for all vehicles combined. (All direction, main direction, other directions)

Scenario			All directions			Main direction			Other directions		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	0.75	0.77	0.73	0.74	0.79	0.69	0.75	0.76	0.74
Plt	0	20	0.75	0.77	0.74	0.74	0.78	0.69	0.75	0.76	0.75
Plt	0	40	0.75	0.76	0.74	0.74	0.79	0.69	0.75	0.75	0.75
Plt	0	60	0.76	0.76	0.75	0.74	0.79	0.69	0.76	0.76	0.76
Plt	0	80	0.75	0.77	0.74	0.74	0.79	0.69	0.76	0.76	0.75
Plt	0	100	0.75	0.77	0.73	0.74	0.78	0.69	0.76	0.77	0.74
Plt	20	20	0.76	0.76	0.75	0.75	0.79	0.71	0.76	0.76	0.76
Plt	40	40	0.78	0.79	0.76	0.78	0.83	0.72	0.78	0.79	0.77
Plt	60	60	0.82	0.85	0.79	0.85	0.90	0.80	0.82	0.84	0.79
Plt	80	80	0.90	0.95	0.86	0.97	1.04	0.90	0.89	0.93	0.85
Plt	100	100	1.03	1.10	0.95	1.13	1.20	1.06	1.00	1.08	0.93
DTM	0	20	1.75	2.14	1.35	3.14	3.97	2.31	1.47	1.78	1.16
DTM	0	40	0.92	0.96	0.88	1.08	1.20	0.96	0.89	0.91	0.87
DTM	0	60	0.81	0.86	0.77	0.83	0.92	0.73	0.81	0.84	0.78
DTM	0	80	0.78	0.81	0.76	0.76	0.80	0.71	0.79	0.81	0.77
DTM	0	100	0.76	0.79	0.74	0.73	0.79	0.68	0.77	0.79	0.75
DTM	20	20	0.75	0.77	0.74	0.68	0.72	0.64	0.77	0.78	0.76
DTM	40	40	0.76	0.78	0.74	0.73	0.79	0.68	0.77	0.78	0.75
DTM	60	60	0.81	0.83	0.78	0.83	0.88	0.78	0.80	0.82	0.79
DTM	80	80	0.89	0.94	0.85	0.98	1.04	0.93	0.88	0.92	0.83
DTM	100	100	1.02	1.09	0.96	1.17	1.26	1.08	0.99	1.05	0.93

Table F.29: Average number of stops for cars and CACC-equipped cars.

Scenario			Car			C Car		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	0.75	0.78	0.72			
Plt	0	20	0.74	0.78	0.71			
Plt	0	40	0.75	0.78	0.72			
Plt	0	60	0.75	0.78	0.72			
Plt	0	80	0.74	0.78	0.71			
Plt	0	100	0.74	0.77	0.71			
Plt	20	20	0.75	0.77	0.73	0.79	0.82	0.77
Plt	40	40	0.73	0.76	0.71	0.88	0.93	0.82
Plt	60	60	0.71	0.72	0.69	0.99	1.05	0.93
Plt	80	80	0.68	0.70	0.66	1.12	1.20	1.05
Plt	100	100				1.24	1.32	1.17
DTM	0	20	2.94	3.69	2.18			
DTM	0	40	1.10	1.18	1.03			
DTM	0	60	0.89	0.96	0.81			
DTM	0	80	0.81	0.85	0.77			
DTM	0	100	0.78	0.82	0.74			
DTM	20	20	0.72	0.74	0.70	0.74	0.77	0.71
DTM	40	40	0.72	0.75	0.69	0.83	0.88	0.79
DTM	60	60	0.70	0.72	0.68	0.98	1.05	0.92
DTM	80	80	0.69	0.70	0.68	1.14	1.20	1.07
DTM	100	100				1.28	1.36	1.20

Table F.30: Average number of stops for trucks and CACC-equipped trucks.

Scenario			Truck			C Truck		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	0.71	0.75	0.68			
Plt	0	20	0.71	0.74	0.68	0.71	0.74	0.68
Plt	0	40	0.71	0.74	0.68	0.73	0.74	0.71
Plt	0	60	0.72	0.73	0.70	0.73	0.75	0.70
Plt	0	80	0.70	0.73	0.67	0.75	0.76	0.73
Plt	0	100				0.75	0.79	0.72
Plt	20	20	0.71	0.73	0.69	0.72	0.74	0.70
Plt	40	40	0.71	0.73	0.69	0.71	0.73	0.69
Plt	60	60	0.70	0.73	0.66	0.70	0.72	0.69
Plt	80	80	0.66	0.67	0.64	0.69	0.70	0.68
Plt	100	100				0.69	0.69	0.69
DTM	0	20	1.98	2.23	1.65	1.69	2.04	1.30
DTM	0	40	0.92	0.97	0.86	0.83	0.82	0.83
DTM	0	60	0.76	0.78	0.73	0.73	0.78	0.67
DTM	0	80	0.73	0.78	0.68	0.72	0.73	0.71
DTM	0	100				0.71	0.73	0.68
DTM	20	20	0.70	0.72	0.67	0.68	0.70	0.65
DTM	40	40	0.70	0.71	0.68	0.69	0.70	0.66
DTM	60	60	0.69	0.70	0.68	0.70	0.70	0.70
DTM	80	80	0.68	0.71	0.64	0.69	0.70	0.68
DTM	100	100				0.67	0.69	0.66

F.4. Throughput

Table F.31: Throughput for all vehicles combined (All directions, main direction, other directions).

Scenario			All directions			Main direction			Other directions		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	7503	4376	3127	4392	2580	1812	3111	1796	1315
Plt	0	20	7497	4386	3111	4392	2592	1800	3105	1794	1311
Plt	0	40	7508	4374	3134	4397	2579	1818	3111	1795	1316
Plt	0	60	7506	4381	3125	4389	2583	1806	3117	1798	1319
Plt	0	80	7501	4374	3127	4398	2583	1815	3103	1791	1312
Plt	0	100	7500	4371	3129	4390	2577	1813	3110	1794	1316
Plt	20	20	7502	4374	3128	4393	2584	1809	3109	1790	1319
Plt	40	40	7492	4369	3123	4388	2582	1806	3104	1787	1317
Plt	60	60	7508	4382	3126	4397	2587	1810	3111	1795	1316
Plt	80	80	7499	4384	3115	4396	2590	1806	3103	1794	1309
Plt	100	100	7497	4390	3107	4388	2584	1804	3109	1806	1303
DTM	0	20	7521	4354	3167	4420	2579	1841	3101	1775	1326
DTM	0	40	7487	4339	3148	4389	2564	1825	3098	1775	1323
DTM	0	60	7493	4375	3118	4392	2585	1807	3101	1790	1311
DTM	0	80	7501	4375	3126	4395	2582	1813	3106	1793	1313
DTM	0	100	7501	4380	3121	4391	2582	1809	3110	1798	1312
DTM	20	20	7497	4364	3133	4395	2580	1815	3102	1784	1318
DTM	40	40	7506	4383	3123	4393	2585	1808	3113	1798	1315
DTM	60	60	7492	4380	3112	4388	2590	1798	3104	1790	1314
DTM	80	80	7498	4385	3113	4393	2588	1805	3105	1797	1308
DTM	100	100	7495	4384	3111	4388	2581	1807	3107	1803	1304

Table F.32: Throughput for cars and CACC-equipped cars.

Scenario			Car			C Car		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	6508	3887	2621	0	0	0
Plt	0	20	6504	3895	2609	0	0	0
Plt	0	40	6514	3884	2630	0	0	0
Plt	0	60	6503	3883	2620	0	0	0
Plt	0	80	6515	3888	2627	0	0	0
Plt	0	100	6504	3881	2623	0	0	0
Plt	20	20	5206	3105	2101	1310	777	533
Plt	40	40	3902	2330	1572	2610	1555	1055
Plt	60	60	2607	1556	1051	3904	2337	1567
Plt	80	80	1308	779	529	5203	3114	2089
Plt	100	100	0	0	0	6500	3892	2608
DTM	0	20	6520	3863	2657	0	0	0
DTM	0	40	6497	3852	2645	0	0	0
DTM	0	60	6495	3877	2618	0	0	0
DTM	0	80	6510	3884	2626	0	0	0
DTM	0	100	6506	3883	2623	0	0	0
DTM	20	20	5209	3103	2106	1304	775	529
DTM	40	40	3911	2335	1576	2613	1560	1053
DTM	60	60	2605	1557	1048	3896	2333	1563
DTM	80	80	1313	782	531	5204	3116	2088
DTM	100	100	0	0	0	6493	3884	2609

Table F.33: Throughput for trucks and CACC-equipped trucks.

Scenario			Truck			C Truck		
Name	% C.C.	% C.T.	Total	Hour 1	Hour 2	Total	Hour 1	Hour 2
Base	0	0	998	493	505	0	0	0
Plt	0	20	800	397	403	203	98	105
Plt	0	40	604	296	308	403	199	204
Plt	0	60	405	199	206	609	298	311
Plt	0	80	202	101	101	800	397	403
Plt	0	100	0	0	0	1001	496	505
Plt	20	20	805	398	407	203	98	105
Plt	40	40	608	298	310	402	198	204
Plt	60	60	407	203	204	612	301	311
Plt	80	80	202	101	101	798	393	405
Plt	100	100	0	0	0	1005	499	506
DTM	0	20	809	400	409	200	99	101
DTM	0	40	610	297	313	399	197	202
DTM	0	60	400	201	199	610	301	309
DTM	0	80	204	103	101	794	392	402
DTM	0	100	0	0	0	999	497	502
DTM	20	20	802	396	406	203	100	103
DTM	40	40	606	300	306	404	198	206
DTM	60	60	405	204	201	613	303	310
DTM	80	80	206	105	101	801	401	400
DTM	100	100	0	0	0	996	491	505