A decentralized traffic control strategy for various levels of vehicle technology in an urban network

Master thesis

M. H. van Rest

27 November 2017

Delft University of Technology

TU Delft Delft University of Technology

A decentralized traffic control strategy for various levels of vehicle technology in an urban network

by

M.H. van Rest (Max)

to obtain the degree of Master of Science
at the Delft University of Technology,
Faculty of Civil Engineering and Geosciences
to be defended publicly on Monday, 4 December 2017 at 10:00 AM.

Student number:	4159624	
Project duration:	1 January 2017 – 4 December 2017	
Graduation committee:	Prof. dr. ir. S. P. Hoogendoorn,	TU Delft, chairman
	Dr. M. Menéndez,	ETH Zurich, supervisor
	MSc. K. Yang,	ETH Zurich, daily supervisor
	Dr. V. L. Knoop,	TU Delft, daily supervisor
	Prof. dr. ir. B. De Schutter,	TU Delft, external supervisor
Thesis coordinator:	Dr. ir. R. van Nes,	Transport & Planning, TU Delft

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Preface

This report is the final product of my master graduation project and therefore the very last work of my master studies at Delft University of Technology. I had the opportunity to partly conduct this research at the ETH Zurich in Switzerland, where I became part of the SVT (traffic engineering) research team. It was a great opportunity to work together with some excellent researchers in the field of traffic engineering at a top ranked university. Even though I found the cultures both at the ETH Zurich as well as in Switzerland in general more different than I expected, thanks to my colleagues at the ETH I felt welcome at the university from the very beginning and I enjoyed my stay in Zurich.

I'm very thankful to the Delft university for giving me the opportunity to follow my dreams when it comes to the choice of study topics and projects abroad. In my personal experiences, I was free to choose the courses and projects based on my interests and as part of my studies, I was able to do research in Myanmar, Sri Lanka, Chile and Switzerland. Working and studying in such different countries taught me a lot about people and cultures and changed my view towards The Netherlands and towards the rest of the world significantly.

I would like to thank the members of my committee for the supervision during this master thesis project. I would like to thank the members of the SVT research team for welcoming me at the ETH and for helping me in all kinds of ways during my time in Switzerland. I would like to express my special thanks to:

Dr. Victor L. Knoop, for the supervision in a very motivating and energetic way, for introducing me to other professors and researchers at the TU Delft and at the ETH Zurich which was valuable for this report, for the practical help obtaining the IDEA League Research Grant and for being attainable for questions at any time,

Prof. Mónica Menéndez, for welcoming me in the SVT research group at the ETH Zurich, for the supervision and for being attainable for questions at any time,

MSc. Kaidi Yang, for the supervision during my time in Zurich, for the valuable advices regarding my research, for the necessary practical help especially regarding the traffic simulation software and the programming language, and for being attainable for questions at any time.

Max van Rest
Delft, 27-11-2017

Abstract

There is a high probability that communication between vehicles in a traffic network and between vehicles and traffic controllers will be the next major wave of technological innovation in traffic. The collection of data of communicating vehicles in traffic offers live information about the traffic conditions, which can be used to control traffic optimally. It is expected that in the coming years a new vehicle type will take part in traffic that is able to navigate through traffic without driver and communicates with traffic controllers to share its information and receive its optimal trajectory: the automated vehicle. The automated vehicle is different from the autonomous vehicle, which does not communicate with traffic controllers or other traffic.

The traffic mixture consisting of conventional, connected and automated vehicles will change gradually over time. Designing a traffic control strategy that performs well for traffic consisting of different shares of these three types of vehicles and requires only a limited amount of computational power will be a main challenge in traffic control the coming years.

This report proposes a traffic control strategy and assesses the influences of this strategy on the network wide traffic conditions using a traffic simulation. In this way, the research will provide insight in the effects of vehicle connectivity and automation on the network wide traffic conditions.

Based on the live traffic information from the communicating vehicles in a network, traffic can be controlled from two sides: the traffic signal control and the automated vehicle trajectory control. The traffic control method proposed in this report works as follows: first, the traffic controller collects all the information of connected and automated vehicles in the network to update the vehicle set. Locations and speeds of connected and automated vehicles can be obtained directly. Automated vehicles also provide the traffic controller of information of the non-communicating vehicles in their surroundings, detected by their sensors. Then, the virtual departure time of each vehicle will be determined, which is the time at which the vehicle would depart not hindered by other traffic or traffic signal and can be calculated using the kinematic laws. Also the corresponding virtual departure speed is determined for each vehicle. Then, starting from the first vehicle on the link, the expected departure time will be calculated, based on the virtual departure time and the traffic signal state. The expected departure times and speeds of the other vehicles on the link will be based on their virtual departure time, the expected departure time of the vehicles in front of the vehicle and the signal state. The virtual and expected departure times and speeds are used for both the signal control and the trajectory control.

This report presents a decentralized signal control to limit the computational power required in large traffic networks. This signal control is based on the original back-pressure algorithm, which compares the downstream traffic conditions with the upstream traffic conditions around an intersection and makes decisions for the signal control based on the difference in back-pressure of different movements on an intersection. The proposed signal control strategy takes the approaching and exiting vehicles within a certain range from the intersection into account. At the start of each time slot, a prediction is made for the pressure of a link on the intersection at the start of the next time slot, based on the current number of approaching and exiting vehicles on a link, their expected departure time from the intersection and the expected traffic demand. Based on the predicted pressures at every link that is connected with the intersection, the traffic controller decides whether it should switch the traffic signal at the start of the next time slot.

The proposed method for the trajectory control of the automated vehicles is based on the decisions of the traffic controller regarding the traffic signal and the expected departure times and speeds of the vehicles in the network. The main goal of the trajectory control is to use the green phases in an optimal way, i.e. maximizing the amount of departing vehicles per unit of green time. The trajectory control should limit accelerations and decelerations in the network as much as possible to limit emissions and traveller discomfort. Therefore, a third type of departure time and speed, the smooth departure time and speed, is introduced and compared with the expected time and speed of an automated vehicle to optimize its trajectory. The smooth departure time is the moment in time at which the vehicle would depart from the intersection if it would accelerate constantly to the expected departure speed over the total distance to the intersection. If the expected departure time is later in time than the smooth departure time, the vehicle will slow down and vice versa. If the smooth departure time is equal to the expected departure time, the vehicle will accelerate constantly towards the intersection.

The proposed control method is tested in a traffic simulation to obtain the effects of the method on the traffic conditions for different traffic scenarios. For each scenario the average traffic time delay, average green time, average and maximum queue length and average acceleration and acceleration time is retrieved from the simulation to assess the effects of the proposed methods on the traffic conditions. The simulated network consists of a two-directional main road with five signalized intersections with side roads. The traffic consists of only cars and other modes of transportation are neglected for simplicity. Different shares of connected and automated vehicles and different vehicle flows in the network are tested.

The simulation results show that the proposed signal control strategy leads to relatively short green times, which decrease the intersection throughput and the ability of adjusting the green time ratio between the two crossing roads to the traffic demand. Traffic on the main road encounters relatively longer green times and shorter queue lengths than traffic on the side roads. The throughput of the intersections does not satisfy the traffic demand and therefore, the first intersection will function as a bottleneck and lowers the traffic flow at the next intersections. Therefore, queues especially occur at the first intersection that vehicles encounter. The results show that the higher the penetration rate of communicating vehicles is, the better the traffic controller is able to adapt the signal sequence to the current traffic situation. The signal control requires several improvements in order to function optimally, but has the potency to be a suitable decentralized control method in a partly connected and automated environment.

Results regarding the proposed trajectory control show that a higher share of automated vehicles in the network results in a higher average acceleration in a relatively shorter total acceleration time, which is a result of the fluctuations in the vehicle speed due to the trajectory control. However, automated vehicles increase the average number of departing vehicles per unit of green time, which leads to shorter queues and less average travel time delay in the network.

Next to the proposed signal control strategy, an existing coordinated signal control strategy is implemented and tested in the simulation without connected or automated vehicles to compare the results with the proposed methods. Simulations of this green wave control result in larger average travel time delays and larger queue lengths due to relatively shorter green phases. The average acceleration, however, is relatively low, since the green wave strategy avoids vehicles to decelerate to complete standstill after they cross the first intersection of the traffic corridor.

This research shows that vehicle connectivity and automation offer the ability to improve network wide traffic conditions applying a decentralized traffic control method to control signalized intersections and automated vehicles. Although the proposed traffic control method is not optimized yet, it shows that low shares of connected and automated vehicles in traffic already make a significant difference in the network wide traffic conditions and that the signal sequences and automated vehicle trajectories can be even optimized if these shares get higher. Since the control strategy is decentralized, the required amount of computational power of a traffic controller is limited to the amount that the control of one single intersection requires and is not depending on the network size.

This research provides several recommendations for further research to improve the proposed strategy. Instead of taking only vehicles into account within a certain range from the intersection, which all have the same contribution to the back-pressure, an interesting alternative is to take all vehicles around an intersection into account for the back-pressure and add a certain weight to each vehicle based on the distance to the intersection. This weight can be used to determine the contribution of each vehicle to the back-pressure. Next, a threshold for switching and a dynamic slot time instead of a fixed one could be improvements to the proposed method and should be tested in further research.

The trajectory can be optimized especially regarding the vehicle accelerations and decelerations. It is recommended to avoid the occurring speed fluctuations in the proposed method by optimizing the acceleration rate that is used for automated vehicles to reach the desired trajectory.

It is recommended to test the proposed method in more realistic traffic simulations in further research to get more insight in the effects to real traffic. In that way the control method can be adapted to real traffic. The simulation of this research uses many assumptions regarding several parameters which require further research to optimize the performance of the control method. Last, before implementing the proposed method or a similar method in traffic, further research is required regarding the traffic safety. Especially the fact that automated vehicles are able to depart from intersections exactly at the moment the traffic signal switches to green could lead to unsafe situations, since other traffic users are not yet used to this behaviour of automated vehicles.

Contents

1
Introduction

Over the last years, the automation of vehicles has become a trending research topic. On-going studies are focused on the possibilities for the users, the possibilities and safety of the vehicle itself and the implementation in traffic streams. Automated vehicles are controlled by an external traffic controller. Together with the information from other connected vehicles that send their locations and speeds, the traffic controller can optimize the sequences of signalized intersections and the trajectories of the automated vehicle in the network. More connected and automated vehicles could lead to better traffic performances, higher traffic safety and a reduction of emissions. Therefore, there is a high probability that this would be the next major wave of technological innovation in traffic [28][32].

It is hard to predict the impact of the different levels of vehicle technology and the growing presence of communication between vehicles and infrastructure on the network wide traffic conditions. Many researches have been conducted towards the possible effects on traffic and towards methods to optimally control intersections and automated vehicles in a connected environment. Many of these researches cover fully automated or connected traffic network situations. However, the composition of traffic regarding vehicle technology will change gradually over time and controlling traffic consisting of different vehicle types in this transition phase for network optimization will be a complex challenge. Although studies that are focused on a mixture of different levels of vehicle technology already exist, these studies describe situations at a microscopic level only and leave space for further research into the network wide effects. Existing research points out that limiting the computational power behind the control strategy is one of the main challenges in connected traffic.

The main objective of this research is to find a strategy to control traffic consisting of vehicles with different levels of technology that leads to better traffic network performances. Three levels of vehicle technology will be considered: conventional vehicles, connected vehicles and automated vehicles. This traffic control consists of two parts: the trajectory control of the automated vehicles and the traffic signal control of the intersections. The goal of the trajectory control is to maximize the amount of vehicles crossing the intersections per unit of green time and to limit accelerations and decelerations in the network as much as possible. The goal of the traffic signal control is to minimize the total travel time delay while crossing a network. Furthermore, to limit the required computational power of the traffic control method, the goal is to create a decentralized traffic control solution, in which the required computational power is divided over the intersections in the network. The main research question is:

M: How could the traffic signal and automated vehicles in a traffic network be controlled in a decentralized way in order to optimize the network wide traffic conditions?

This research question is divided into the following sub questions:

S1 What are the possibilities and challenges of connected and automated vehicles in traffic?

S2 Is there already an existing traffic signal control strategy that is suitable for a partly connected and automated environment?

S3 In what way could the back-pressure approach be a solution for the traffic signal control in a partly connected and automated traffic network?

S4 In what way should the automated vehicles be controlled in order to optimize traffic conditions given the proposed traffic signal control system?

S5 How could a traffic simulation be used to assess the proposed control method?

S6 What network wide traffic conditions should be measured to assess the proposed control method?

S7 What effects does the proposed control method have for the network wide traffic conditions?

S8 What are the effects of the proposed method regarding environment?

S9 What are the effects of the proposed method regarding driver comfort?

S10 To what extent could the simulation results be used to make conclusions about the effects of connectivity and automation in traffic networks in general?

Table 1.1 presents the outline of this report. In order to answer sub questions S1 and S2, chapter 2 includes a literature study with the most relevant findings of earlier studies concerning vehicle automation and the possibilities of different levels of vehicle technology. Furthermore, several traffic signal control strategies will be discussed in order to find the most appropriate one for this study. This control strategy will be adapted to traffic consisting of different levels of vehicle technology. The overview of the proposed control strategy will be presented in chapter 3. Two parts of the control strategy, the signal control and the trajectory control, will be described into more detail in the two chapters afterwards. Chapter 4 gives the description of the back-pressure based signal control strategy and answers sub question S3. A description of the proposed control of the trajectories of the automated vehicles can be found in chapter 5, which answers the sub question S4. The combination of the traffic signal control and trajectory control is tested in a simulated traffic corridor consisting of a two-directional main road with five intersections with one-directional side roads. The simulation objectives, the tested scenarios, the analysis setup and the expected simulation results are described in the test setup in chapter 6, which will answer sub questions S5 and S6. The simulation setup in chapter 7 presents the network configuration, vehicle generation, traffic characteristics and other assumptions used in the simulation. The simulation results and the answers on sub questions S7, S8 and S9 can be found in chapter 8. The assumptions and results of this research are discussed in detail in chapter 9 to find the answer to sub question S10. Finally, chapter 10 gives the conclusions and recommendations that can be made based on this research.

Ch.	Titel	Objectives	Research question
1	**Introduction**	- Introduce the subject - Define the problem - Set research objectives - Present the report outline	
2	**Literature review**	Obtain insight about: - Vehicle automation - Traffic control strategies	S1, S2
Proposed traffic control method			
3	**Modelling framework**	Present proposed control method	
4	**Traffic signal control**	Describe proposed signal control method in detail	S3
5	**Trajectory control**	Describe proposed trajectory control method in detail	S4
Test and assessment of the traffic control method			
6	**Test setup**	Present methodology of testing: - Simulation objectives - Simulation network - Scenarios - Base case - Analysis setup - Expected results	S5, S6
7	**Simulation setup**	Present the technical details of the simulation: - Network dimensions - Vehicle generation - Used parameters - Vehicle characteristics	
8	**Simulation results**	Present the results: - Average travel time delay - Average green times - Average and maximum queue length - Average acceleration and acceleration time	S7, S8, S9
9	**Discussion**	Discuss the assumptions and limitations of the proposed control method and the test methodology	S10
10	**Conclusions & recommendations**	Present: - Findings - Conclusions - Recommendations for science - Recommendations practice	M

Table 1.1: Report outline

2
Literature review

This chapter provides an overview of relevant literature used in this report. The main objectives of this review are to gain insight into the possibilities and challenges of vehicle automation and into different ways to control traffic in a connected or automated environment. Section 2.1 provides the terminology regarding different vehicle technologies. Then, an overview of earlier research regarding the possibilities and challenges of vehicle automation on traffic will be given. Section 2.3 presents an overview of existing and earlier proposed traffic control algorithms for connected or automated traffic. Different traffic control methods and their performance in a partly connected and automated environment will be discussed. The most appropriate signal control strategy will be chosen and will be adapted and optimized for an urban traffic network consisting of vehicles with different levels of technology in the next chapters.

2.1. Terminology: conventional, connected, automated and autonomous vehicles

Different terms for vehicle types have showed up in earlier research and have been used interchangeably. Therefore, this section gives a clear definition of different vehicles types. In this report the terms used to indicate the different vehicle types are: conventional, connected and automated vehicles. Conventional vehicles are vehicles that are humanly controlled and have no connection with any traffic controller. Connected vehicles are vehicles that are humanly controlled and that send their position and speed information to the traffic controller. Finally, automated vehicles can navigate through traffic without driver, send their position and speed information to the traffic controller and receive their trajectories of the traffic controller. The traffic controller in this report is the agent that controls both the traffic light system of one intersection and the trajectories of the automated vehicles around one intersection.

This report only considers the three types of vehicles named above. Direct communication only exists in both ways between an automated vehicle and the traffic controller and between the intersection control system and the traffic controller. Additionally, the locations and speeds of connected vehicles are also sent to the traffic controller. There is no direct communication between vehicles or between the intersection control systems of different intersections. However, automated vehicles are equipped with sensors to scan the environment and other vehicles to be able to navigate safely in traffic. This can be seen as a passive form of communication and is also included in this report.

In this report autonomous vehicles, which differ significantly from automated vehicles, are not taken into consideration. Autonomous vehicles are vehicles that are able to navigate through traffic without driver nor communication with the traffic controller. Since autonomous vehicles do not have any communication with other traffic or traffic controllers, they can be considered as conventional vehicles, but with different driving characteristics. For these reasons they have not been taken into account in further chapters of this report.

Researches regarding connectivity or automation of vehicles often refer the SEA international's levels of driving automation for on-road vehicles, see figure **??** [37]. The automated vehicles that are taken into consideration in this research belong to SAE level 5, full automation. The conventional and connected vehicles do not have any automation at all and therefore belong to SAE level 0.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
Human driver **monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
Automated driving system **("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.1: SEA international's levels of driving automation for on-road vehicles [37].

2.2. Possibilities and challenges regarding vehicle automation

The expected effects of vehicle automation on traffic can be divided in three different groups of implications, according the ripple effect of automated driving [31]. The first-order implications are the direct effects on traffic, such as travel cost, road capacity and travel choices. The second-order implications describe the effects regarding vehicle ownership, location choices and land use, and transport infrastructure. Last, the third-order implications describe the energy consumption, air pollution, safety, social equity, economy, and public health. In this section, the most important effects of each group regarding this research are pointed out: travel costs, road capacity, energy consumption, air pollution and safety. Effects of vehicle automation on the other factors can be found in the literature review by Milakis et al. [32].

2.2.1. Travel costs

Travel costs consists of the fixed costs of automated vehicles, the travel comfort, the travel time and the value of time. Currently, fixed costs of automated vehicles are a multiple times higher than the fixed costs of conventional vehicles. However, the expectation regarding the fixed costs of automated vehicles is that prices can be reduced significantly with mass production [16]. Travel comfort is very depend on several aspects of the trajectory control and path planning of automated vehicles, such as the time headway between vehicles, motion sickness, apparent safety and included natural human-like paths [32]. Automated vehicles can reduce travel time by limiting delays on highways and intersections [1][15][17][50]. The value of time could be reduced by vehicle automation. Mainly the possibility to relax while travelling appeared to be benefit regarding the time use, where the possibility to work while travelling is not perceived as a major benefit [12].

2.2.2. Road capacity

By increasing the average speed and flow rate, vehicle automation increases road capacity of a highway significantly at a penetration level of 40% or higher [1][2]. Vehicle automation can improve string stability and prevent shock wave formation [40]. Literature shows that also traffic operations at highways on ramps can be improved regarding safety and mobility [49], and travel time and traffic oscillations [53]. Capacity of intersections can be increased by more than 150% compared to today's road system and could even be increased more with reductions in jam spacing [9][22]. Again, the higher the penetration rate is, the higher the positive impact is on the intersection capacity [50].

2.2.3. Energy consumption and air pollution

Different researches show that vehicle automation can increase fuel efficiency and reduce emissions at intersections [18][22][54], on highways [24] and at on-ramps on highways [36]. In different ways and for different situations, trajectories of automated vehicles can be optimize to limit accelerations and decelerations for automated vehicles and their followers. Vehicle sharing makes a further emission reduction possible [16].

2.2.4. Traffic safety

Especially advanced driver assistance systems could have beneficial effects regarding traffic safety. Fully automated vehicles might only be able to guarantee higher traffic safety levels at high penetration rates [32]. However, Waymo recently claimed to guarantee enough safety with its self-driving cars to introduce them, starting from the end of November 2017, to the public roads in the city of Phoenix (USA) without a person on the driver seat to take over in case of emergency. However, the company does not say whether the vehicles will operate in any traffic, weather and road condition, or that it will avoid challenging traffic situations or conditions [44]. Most of the companies that are developing self-driving vehicles aim to guarantee enough safety to get their vehicle on the market by 2020 [4].

2.3. Control strategies for connected and automated traffic

This section provides the general description, the abilities, the benefits and disadvantages of traffic control strategies that have been proposed in earlier research regarding connected and automated vehicles. These strategies use the information of communicating vehicles to optimize only the signal sequence on intersections, or to both the signal sequence and the trajectories of automated vehicles.

2.3.1. The optimal solution

It is an interesting question what the optimal traffic control method would be when live data of connected vehicles is available. To find the optimal solution, first an objective has to be set, such as minimizing travel time delay, maximizing network throughput or minimizing queue lengths. Then, an algorithm has to be set up to determine the optimal signal sequence and the trajectories of automated vehicles. In case traffic would only consist of automated vehicles, traffic signals would not be needed and the traffic controller only has to determine the optimal trajectories of the automated vehicles [48]. However, in a partly conventional environment, traffic signals are necessary to avoid collisions at the intersections.

Priemer et al. [35] proposed a method to minimize both the total queue length and the travel time delay by determining the optimal signal sequence using information of connected vehicles. Every 5 seconds a prediction of the queue lengths in the network is made for the next 20 seconds. Then, the optimal signal sequence is determined using dynamic programming and complete enumeration. The proposed method is tested in a traffic simulation with different penetration rates of connected vehicles. Results show that the method is able to reduce travel time delay and total queue length, but that the performance of the method is dependent on the penetration rate. Penetration rates higher than 20% result in a reduction of delay and queue lengths in comparison to the reference case in the research.

K. Yang et al [50]. presented an algorithm which finds the minimal total traffic delay on an isolated intersection, controlling both the traffic light system as the trajectories of automated vehicles. In his paper, Yang considers three categories of vehicles: conventional vehicles, connected vehicles and automated vehicles. The goal of the algorithm is the real-time determination of the optimal departure sequence of all vehicles and of the optimized trajectory of the automated vehicles. To find the optimal solution a branch and bound procedure is proposed.

Cassandras et al. [10][11] proposed a decentralized solution in which every intersection controller determines the optimal order in which the approaching vehicles within a certain range from the intersection should cross the intersection. The objective is to maximize the throughput of an intersection, to minimize fuel consumption and to minimize passenger discomfort. However, downstream conditions of each intersection are not taken into account and therefore, this solution will not react to network effects such as spillback from one intersection to a successive intersection.

One major problem with finding an optimal solution is the required computational power, especially when it comes to expending the network from one single intersection to a larger network consisting of more intersections. Using the same approaches as the ones described in this section for a larger or more complex network will be very challenging regarding the computational requirement.

2.3.2. Multi-agent control system

In 2008, Dresner and Stone [15] proposed a multi-agent system to coordinate the movements of automated vehicles through intersections, with driver agents (the vehicle controllers) and the intersection manager (the intersection controller). Driver agents send a reservation request, including the important parameters of its arrival at the intersection, and the vehicle characteristics to the intersection manager. The intersection manager uses the intersection control policy to confirm or reject the request of the driver agent and is able to respond with a counter-offer after rejection. The driver agent may only enter the intersection with a reservation. Figure 2.2 shows this reservation process.

Later, a planning-based motion controller is proposed to improve this method regarding the number of vehicle stops [3]. By reducing the number of stops before intersections the efficiency of the intersection control mechanism and the throughput of an intersection can be increased.

Dresner and Stone show that intersection-associated delays can be reduced dramatically if traffic would fully exist out of autonomous vehicles. They also proposed different signal control policies to combine the multi-agent system with traditional signal control systems as a solution for the transition phase of conventional traffic into autonomous traffic. However, simulation results show that the control method adapted to human drivers only performs well for penetration rates higher than 90% automated vehicles.

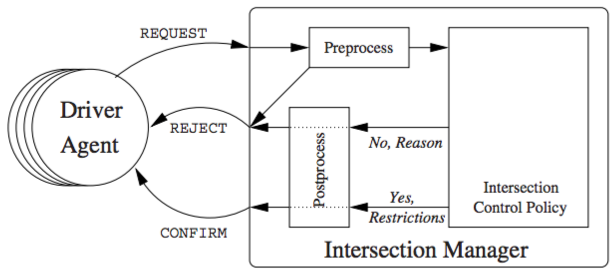

Figure 2.2: One of the driver agents attempts to make a reservation. The intersection manager responds based on the decision of an intersection control policy [15].

2.3.3. Back-pressure algorithm

As Wongpiromsarn et al. [47] introduced, a back-pressure algorithm can be used as a decentralized approach to optimize the traffic control sequence on intersections in an urban road network. Although the original back-pressure algorithm was proposed for controlling conventional traffic, detected by loop detectors in the road, one may expect that this method will perform even better in a partly connected environment when the exact speeds and locations of the connected vehicles in the network are known.

In case of a back-pressure traffic control approach, the corresponding controller determines for each intersection the optimal phase sequence by comparing the back-pressure of the different phases in real-time. The back-pressure of a phase describes the sum of the traffic load of each movement in that phase, where the traffic load of a movement is the difference in queue lengths on a link leading into the intersection and a link leading out of the intersection. The traffic signal controller will take actions to limit or lower the phase with the largest back-pressure [39]. This can be done by optimizing the time lengths of the slots in which the phases will be activated and/or by optimizing the order of the phases. Different strategies have been proposed and tested to determine the optimal slot times and phase order.

The strategy can be either periodic or aperiodic. The periodic control strategy is based on a fixed cycle time, in which every phase is activated once. In an aperiodic control strategy there is no fixed cycle time and the next activated phase can be any phase and fully depends on the highest back-pressure. The second strategy is the most demand responsive strategy, however it decreases the robustness when loop detectors are used to obtain the pressures. A failed loop detector could affect the network performance significantly [51].

The slot time can be either static or dynamic. In a static slot time approach, the duration of the slot is fixed over the whole control period and the controller only decides what phase will get green in the next slot. The total duration of one single phase can be a sum of multiple slot times. In a dynamic slot time approach the duration of the slots is dependent on the local traffic conditions. Additionally, the slot time can be either global or local. With a global slot time, every intersection in the network has the same slot time, where with a local slot time approach every intersection controller chooses its optimal slot time independent of the other intersection [51].

Literature shows that the back-pressure algorithm maximizes the throughput for each intersection as well as for the network as whole. Choosing the right slot time approach leads to a significantly better network performance [39][51].

3

Modelling framework

The literature review in chapter 2 shows that earlier research regarding control strategies for connected and automated traffic mainly focusses on solutions for single intersections and on fully automated and/or connected traffic. This report proposes a decentralized traffic control method to control traffic with different penetration rates of automated and connected vehicles and to optimize the performances of the traffic network.

This chapter presents the modelling framework of the proposed traffic control method. First, the flow chart of the algorithm is presented and a general description of the model will be given in section 3.1. Before the traffic controller makes its decision for the traffic signal control and the automated vehicle trajectory control, the vehicles in the network have to be detected (section 3.2) and the virtual (section 3.3) and expected (section 3.4) departure times and speeds have to be determined.

Based on the vehicle set and the virtual and expected departure times and speeds, the traffic controller will control the traffic signals and the automated vehicles. These two control parts of the modelling framework are described in detail in chapters 4 and 5. The algorithms presented in this chapter will be used and tested in the simulations (chapters 7 and 8).

3.1. General description

Figure 3.1 presents the flow diagram of the proposed algorithm. For each time step, the traffic controller carries out this process starting with the detection of vehicles to update the vehicle set, at the top of the diagram, until the signal control and trajectory control, at the bottom of the diagram. Note that in one time step, there is not a loop within or a certain hierarchy between the signal control and the trajectory control. Both the controls will react to the current traffic conditions, the traffic signal state and the moment of switching of the traffic signal, planned in the previous time steps. As can be seen in the flow chart, the traffic controller first takes several steps before controlling the signal and trajectories of automated vehicles. These steps will be explained in this chapter.

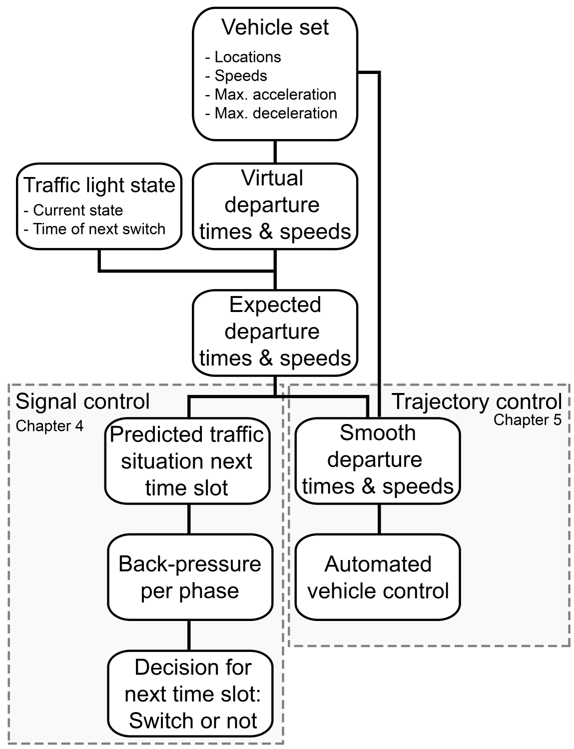

Figure 3.1: Flow diagram of the proposed model

First, the traffic controller updates the vehicle set using the information provided by connected and automated vehicles, as will be described in section 3.2 of this chapter. The locations, speeds and maximum acceleration of the vehicles will be used to determine the virtual departure times and the corresponding virtual departure speeds. The virtual departure time is the moment in time at which a vehicle would depart from the intersection if it would not be hindered by other traffic or a red or yellow traffic signal. The virtual departure speed is the corresponding speed at which the vehicle would drive at the moment of virtual departure. Section 3.3 describes in detail how the virtual departure time and speed for each vehicle is determined.

The next step is to determine the expected departure times and speeds of vehicles. The expected departure time and speed are a more realistic prediction of the moment in time and the corresponding speed at which a vehicle will depart. Other traffic and the traffic signal state is taken into account for this determination. The calculation of the expected departure time and speed depends on the position of the vehicle in the queue and the type of the vehicle, e.i. conventional, connected or automated. Section 3.4 explains this process in detail.

The proposed signal control is based on the original back-pressure approach, presented in the literature review (section 2.3.3). Using the information provided by the connected and automated vehicles in the network a prediction will be made for the back-pressures at the next time slot. The time slot that is used in this report has a length of 5 seconds. Where the trajectories of the automated vehicles will be updated every time step, there will be only one decision moment for the traffic signals each time slot, unless the maximum phase time is already reached before the start of a new time slot. The decisions for the traffic signal are based on the predicted back-pressures. The back-pressure of a movement on an intersection is the difference between the numbers of vehicles on the upstream and downstream links of the intersection corresponding to this movement. A movement on the intersections is a possible combination of an entering (or upstream) link with an exiting (or downstream) link on that intersection. For example, in case vehicles would only be able to travel from east to west and from north to south on the intersection, there are two different movements: 'east-west' and 'north-south'. The back-pressure of the movement 'north-south' is determined out of the difference in number of vehicles on the upstream link (north) and the number of vehicles on the downstream link (south). Chapter 4 describes the proposed back-pressure algorithm in more detail.

3.2. Vehicle detection

The appearance of automated vehicles in traffic has two benefits when it comes to determining locations and speeds of the vehicles in the network. First of all, the position and speed of each automated vehicle can be directly obtained by the intersection traffic controller and can be used to optimize the traffic control. The second benefit is the ability of automated vehicles to detect conventional vehicles around them. In order to navigate safely through the traffic, automated vehicles use sensors to scan their surroundings. Different technologies are used, for example LiDAR, RADAR and optical sensors [41][46]. An optical sensor should be able to scan surroundings within the same range as the human eye and the quality of its detection depends on weather conditions. Since RADAR uses radio waves which also can be transmitted through rain, snow and fog, bad weather conditions will not have significant influences on the result of scanning. Currently tested autonomous vehicles are equipped with a combination of these scanning technologies to maximize the radius and precision, and minimize the chance of errors [26]. The LiDAR sensor Google used to equip its autonomous vehicle with, the 64 Channel sensor of Velodyne, has a range up to 120 metre with a accuracy of 2 cm [26][43]. Tesla says its hardware can scan the surroundings with a radius of up to 250 metre in front of the vehicle and 100 metresbehind the vehicle. Mercedes-Benz even claims an environment recognition of 500 metresin front of the vehicle [30].

With the ability to scan surrounding vehicles, automated vehicles are able to detect the location and relative speed of their leaders and followers in a distance of at least 100 metres. This means that leading or following conventional vehicles within this range can be included in the vehicle set as well. Conventional vehicles can also be detected in queues: if a connected or automated vehicle has to stop at a larger distance from the intersection as expected, assumed is that the space in front of this vehicle is used by conventional vehicles.

The connected vehicles in the network also send their locations and speeds directly to the traffic controller, but are not able to scan their surroundings to collect information about surrounding vehicles.

3.3. Virtual departure time and speed

The virtual departure time is the moment in time at which a vehicle can depart from the intersection, i.e. can depart from the stopping line, if the vehicle would not be hindered by any other vehicle or traffic light, see figure 3.2. In this report the virtual departure time and the virtual departure speed are calculated using the current speed, the distance to the intersection, the vehicle acceleration and the speed limit of the road. The virtual departure time $T_{\text{dep},v,i}(t)$ of vehicle i at time step t is calculated in different ways depending on the current speed v_{current} and the distance to the intersection L_{int}. The formulas follow out of the kinematic laws.

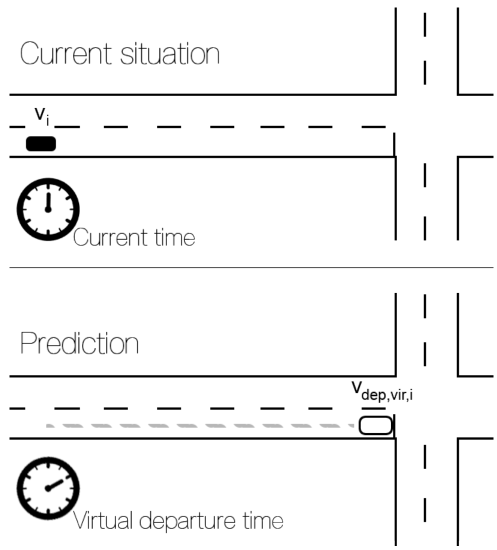

Figure 3.2: The virtual departure time and speed of a vehicle at t = current time

If the vehicle has a speed equal to the speed limit:

$$T_{\text{dep,vir},i}(t) = t + \frac{L_{\text{int},i}(t)}{v_{\max}} \tag{3.1}$$

$$v_{\text{dep,vir},i}(t) = v_{\max} \tag{3.2}$$

If the vehicle has a lower speed than the speed limit and is able to accelerate to the maximum speed regarding the speed limit before reaching the intersection:

$$T_{\text{dep,vir},i}(t) = t + t_{\text{vmax},i}(t) + \frac{L_{\text{int},i}(t) - L_{\text{vmax},i}(t)}{v_{\max}} \tag{3.3}$$

$$v_{\text{dep,vir},i}(t) = v_{\max} \tag{3.4}$$

If the vehicle has lower speed than the speed limit and is not able to accelerate to the maximum speed regarding the speed limit before reaching the intersection:

$$T_{\text{dep},v,i}(t) = t + t_{\text{vmax},i}(t) + \frac{v_{\text{dep},v,i}(t) - v_{\text{current},i}(t)}{2} \tag{3.5}$$

$$t_{\text{vmax},i}(t) = \frac{v_{\max} - v_{\text{current},i}(t)}{a_i} \tag{3.6}$$

$$L_{\text{vmax},i}(t) = t_{\text{vmax},i}(t) \cdot \frac{v_{\text{current},i}(t) + v_{\max}}{2} \tag{3.7}$$

$$v_{\text{dep,vir},i}(t) = \sqrt{2 \cdot a_i \cdot L_{\text{int},i}(t) + v_{\text{current},i}(t)^2} \tag{3.8}$$

where:

$T_{\text{dep},v,i}(t)$ = Virtual departure time of vehicle i at time t [-]

$L_{\text{int},i}(t)$ = Distance to intersection of vehicle i at time t [m]

$t_{\text{vmax},i}(t)$ = Time required for acceleration to maximum speed of vehicle i at time t [s]

$L_{\text{vmax},i}(t)$ = Distance required for acceleration to maximum speed of vehicle i at time t [m]

$v_{\text{current},i}(t)$ = Current speed of vehicle i at time t [m/s]

$v_{\text{dep},v,i}(t)$ = Virtual departure speed of vehicle i at time t [m/s]

$v_{\max}$ = Maximum speed [m/s]

a_i = Acceleration of vehicle i [m/s^2]

3.4. Expected departure time and speed

The expected departure time $T_{\text{dep,exp},i}(t)$ of vehicle i at time step t is the predicted moment at which a vehicle will depart from the intersection and is not only depending on its own characteristics such as current speed and acceleration, but also on the traffic light control system and the position of the vehicle on the road and in the queue. First of all, the traffic light decides during which time intervals vehicles can depart (green light). The position in the queue or on the road also defines the real departure time of the vehicle. If a vehicle is automated and is not hindered by any vehicles in front, the expected departure time is exactly the time the traffic light will switch to green or is equal to the virtual departure time when the vehicle approaches the intersection too late to depart exactly at the moment of switching. Conventional and connected vehicles will have a human reaction delay.

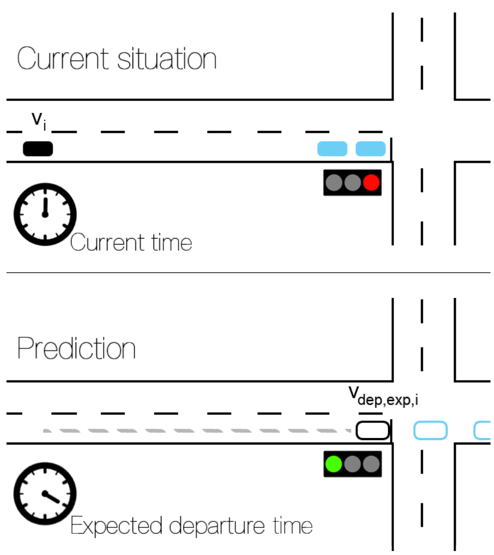

Figure 3.3: The expected departure time and speed of a vehicle at t = current time

3.4.1. Expected departure time of the first vehicle on an approaching link

For the first vehicle on an approaching link, there are four options to define its expected departure time, depending on the state of the traffic light, whether the vehicle can get the current green time when the traffic light is green or the next green time when the traffic light is not green, and whether the vehicle is automated or not. Figure 3.4 shows when and which of the following four options are chosen:

1. **Expected departure time = Virtual Departure Time**
   The earliest moment of the vehicle to arrive at the intersection is during the current green phase.
2. **Expected departure time = Switch-to-Green time**
   The vehicle is automated and is able to adjust its speed such that it arrives (and departs from) the intersection exactly when the traffic light switches to green.
3. **Expected departure time = Switch-to-Green time + acceleration delay**
   The vehicle is not automated and has to decelerate because of the traffic light. The expected departure time is the time of switching to green plus the time the vehicle needs to depart from the intersection at the speed it will have at the moment of switching.
4. **Expected departure time is unknown**
   When a vehicle cannot get the current green time anymore, the expected departure time is unknown since the duration of the upcoming red phase is unknown.

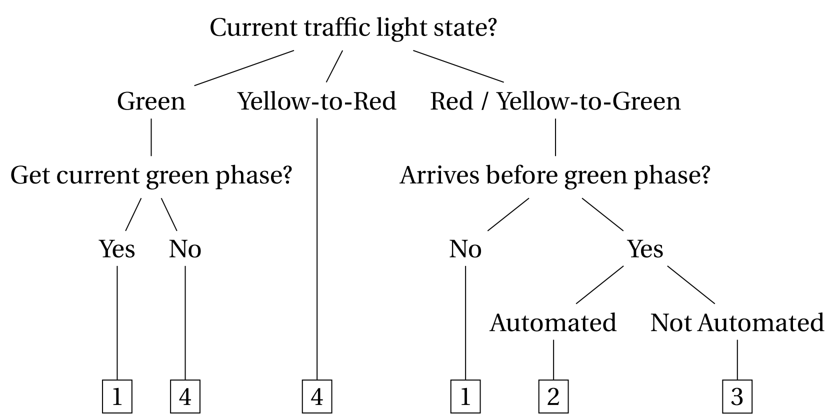

Figure 3.4: Determination of the expected departure time

Note that it depends on the traffic light control approach at what moment the expected departure time is known. If a classic back-pressure approach with a fixed slot time is chosen, which means that the traffic controller decides after each time slot whether it should switch the traffic light, it is not possible to predict when this is going to happen. Automated vehicles will adapt their speed in a less efficient way as they would do for an approach in which future switches are (earlier) known, e.g. the predicted back-pressure approach introduced in section 4.3.

3.4.2. Expected departure speed of the first vehicle on an approaching link

For the determination of the expected departure times of the rest of the vehicles on the link, also the expected departure speed $v_{\text{dep,exp},i}$ of a vehicle i has to be determined.

- If the expected departure time of a vehicle is equal to the virtual departure time, the expected departure speed will be equal to the virtual departure speed (see 3.3).
- If the vehicle cannot get the current green time, the expected departure speed is close to 0 m/s, since the vehicle will have to break, wait at the stop line and will not have any space until the stopping line to accelerate.

If these statements do not apply for a vehicle i, the expected departure speed can be calculated with help of the kinematic laws.

$$t_{\text{acc,tot}} = \frac{v_{\text{max}} - v_{\text{queuing}}}{a_i} \tag{3.9}$$

$$L_{\text{acc,tot}} = t_{\text{acc,tot}} \cdot \frac{v_{\text{max}} + v_{\text{queuing}}}{2} \tag{3.10}$$

$$T_{\text{acc,start}} = T_{StG} - t_{\text{acc,tot}} \tag{3.11}$$

$$L_{\text{acc,start}}(t) = (T_{\text{acc,start}} - t) \cdot v_{\text{queuing}} \tag{3.12}$$

$$L_{\text{req,tot,min}}(t) = L_{\text{acc,start}} + L_{\text{acc,tot}} \tag{3.13}$$

where:

$t_{\text{acc,tot}}$	= Time needed for acceleration from queuing speed to the maximum speed regarding the speed limit [s]
$L_{\text{acc,tot}}$	= Distance needed for acceleration from queuing speed to the maximum speed regarding the speed limit [m]
v_{max}	= Maximum speed (speed limit on road) [m/s]
v_{queuing}	= Queuing speed [m/s]
a_i	= Acceleration rate of vehicle i [m/s^2]
t	= Current time step [-]
$T_{\text{acc,start}}(t)$	= Moment in time at which a vehicle has to accelerate to cross the intersection at maximum speed at time t [-]
$L_{\text{acc,start}}(t)$	= Minimal distance from the intersection at which a vehicle has to accelerate to cross the intersection at the maximum speed regarding the speed limit at time t [m]
T_{StG}	= Moment in time at which the traffic light switches to green [-]
$L_{\text{req,tot,min}}(t)$	= The minimal required distance to the intersection that a vehicle needs to cross the intersection at the maximum speed regarding the speed limit at time t [m]

If the minimum required distance to cross the intersection at maximum allowed speed is smaller than the actual distance to the intersection, the expected departure speed of the vehicle equals the speed limit on the road. If the vehicle cannot accelerate to the speed limit, there are three options:

- The vehicle would arrive exactly at switching to green, while driving only on queuing speed. In that case the expected departure speed is equal to the queuing speed.
- The vehicle would still arrive too early while driving only on queuing speed. The expected departure time is lower than the queuing speed. If the vehicle has to stop completely the expected departure speed will be very low since the vehicle almost has no space to accelerate until it crosses the stopping line.
- The vehicle has little space and time left to accelerate to a departure speed higher than the queuing speed. In that case, the expected departure speed will be:

$$v_{\text{dep,exp},i}(t) = v_{\text{queuing}} + t_{\text{acc}^*} \cdot a_i \tag{3.14}$$

$$t^*_{\text{acc}} = \sqrt{\frac{2 \cdot L_{\text{int},i}(t) - t_{\text{green,average}}(t) \cdot v_{\text{queuing}}}{a_i}} \tag{3.15}$$

where:

$v_{\text{dep,exp},i}(t)$	= Expected departure speed of vehicle i at time t [m/s]
v_{queuing}	= Queuing speed [m/s]
t^*_{acc}	= Time left for acceleration [s]
a_i	= Acceleration rate of vehicle i [m/s^2]
$L_{\text{int},i}(t)$	= Distance to the intersection for vehicle i on time t [m]
$t_{\text{green,average}}(t)$	= Time left until switch to green [s]

3.4.3. Expected departure times and speeds of the other vehicles on an approaching link

After the expected departure time and speed of the first vehicle on the link is determined, the expected departure time of the other vehicles on the link are determined in order of departure. Considering a triangular shape of the fundamental diagram (FD) the density and flow corresponding to a certain speed can be determined. Considering the expected departure speed of the vehicle $i-1$ in front of the considered vehicle i, with the FD an expected space headway and time headway can be calculated. Using these headways, the expected departure time and departure speed of the vehicle i can be determined.

Note that the triangular shape is a simplified representation of the FD. In chapter 9 gives an extinsive discussion about the use of this simplified shape.

The road capacity q_{cap} and the speed limit on the road $v_{\max}$ give the density k_{cap} on the road when the flow is equal to the road capacity:

$$k_{\text{cap}} = \frac{q_{\text{cap}}}{v_{\max}} \tag{3.16}$$

With the FD, the density can be calculated that is corresponding to the expected departure speed of the vehicle in front, $v_{\text{dep,exp},i-1}(t)$.

$$k_{\text{dep},i-1}(t) = \frac{q_{\text{cap}} + k_{\text{cap}} \cdot \frac{q_{\text{cap}}}{k_{\text{jam}}-k_{\text{cap}}}}{v_{\text{dep,exp},i-1}(t) + \frac{q_{\text{cap}}}{k_{\text{jam}}-k_{\text{cap}}}} \tag{3.17}$$

where:

$k_{\text{dep},i-1}(t)$	= Local road density based on the speed of vehicle $i-1$ at time t [veh/km]
q_{cap}	= Road capacity flow [veh/h]
k_{cap}	= Road capacity density [veh/km]
k_{jam}	= Jam density [veh/km]
$v_{\text{dep,exp},i-1}(t)$	= Expected departure speed of vehicle $i-1$ at time t [km/h]
v_{max}	= Maximum speed (speed limit on road) [km/h]

The space headway $h_{x,dep,i-1}(t)$ of vehicle $i-1$ at the moment it departs from the intersection (see figure 3.5), determined at time t can be calculated according:

$$h_{x,dep,i-1}(t) = \frac{1}{k_{\text{dep},i-1}(t)} \tag{3.18}$$

This means, if vehicle i would be following vehicle $i-1$, at the time vehicle $i-1$ departs from the intersection the gap between those two vehicles will be $h_{x,dep,i-1}$. Assumed is that vehicle i has the same speed at this moment, but will accelerate until it reaches the intersection if the current speed is lower than the speed limit.

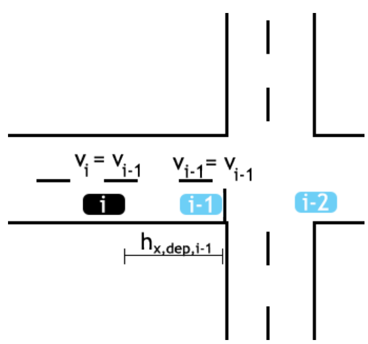

Figure 3.5: Expected space headway for speed $v_{\text{dep,exp},i-1(t)}$

The time that is left for this last acceleration of vehicle i:

$$t_{\text{acc}**,i}(t) = \frac{h_{x,dep,i-1}(t) - \frac{v_{\text{dep,exp},i-1(t)}}{2}}{v_{\text{dep,exp},i-1}(t) + \frac{a_i}{2}} \tag{3.19}$$

The earliest possible departure time of vehicle i will be:

$$T_{\text{dep,min},i} = T_{\text{dep,exp},i-1}(t) + t_{\text{acc}^{**},i}(t) \tag{3.20}$$

where:

$t_{\text{acc}^{**},i}(t)$	= Time left for acceleration for vehicle i at the moment that vehicle $i-1$ crosses the intersection [s]
$h_{x,dep,i-1}(t)$	= Space headway of vehicle $i-1$ at moment of departure, determined at time t [m]
$v_{\text{dep,exp},i-1}(t)$	= Expected departure speed of vehicle $i-1$ at time t [m/s]
$T_{\text{dep,exp},i-1}(t)$	= Expected departure time of vehicle $i-1$ at time t [-]
a_i	= Acceleration rate of vehicle i [m/s^2]
$T_{\text{dep,min},i}$	= Earliest possible departure time of vehicle i

Note that it is not sure yet whether vehicle i is actually able to depart at this earliest possible departure time. The earliest possible departure time is the first moment in time at which there is space for vehicle i after its leader to depart from the intersection. If the vehicle is too far from the intersection and/or its leader, it might not be able to depart at the earliest possible departure time, but will depart later. Now, for every vehicle i the expected departure time $T_{\text{dep,exp},i}(t)$ and expected departure speed $v_{\text{dep,exp},i}(t)$ can be determined, according the next algorithm:

Note that this algorithm can only be applied when the expected departure time of the vehicle in front ($T_{\text{dep,exp},i-1}(t)$) is known. If not, the expected departure time $T_{\text{dep,exp},i}(t)$ and the expected departure speed $v_{\text{dep,exp},i}(t)$ of the considered vehicle i are unknown.

Algorithm 1 Determination of the expected departure time and speed

if traffic signal is green **then**
if $T_{\text{dep,min},i}(t)$ < end of green time **then**
if $T_{\text{dep,exp},i}(t) = T_{\text{dep,vir},i}(t)$ **then** ▷ If vehicle is following its leader
$T_{\text{dep,exp},i}(t) = T_{\text{dep,min},i}(t)$
$v_{\text{dep,exp},i}(t) = min \begin{cases} v_{\text{dep,exp},i-1}(t) + a \cdot t_{\text{acc}^{**},i}(t) \\ v_{\max} \end{cases}$
else ▷ If vehicle is not following its leader
if $T_{\text{dep,vir},i}(t)$ < end of green time: **then**
$T_{\text{dep,exp},i}(t) = T_{\text{dep,vir},i}(t)$
$v_{\text{dep,exp},i}(t) = v_{\text{dep,vir},i}(t)$
else
$T_{\text{dep,exp},i}(t)$ = unknown
$v_{\text{dep,exp},i}(t)$ = unknown
end if
end if
else ▷ If vehicle cannot get current green phase
$T_{\text{dep,exp},i}(t)$ = unknown
$v_{\text{dep,exp},i}(t)$ = unknown
end if
else ▷ If traffic signal is not green
$T_{\text{dep,exp},i}(t) = T_{\text{dep,min},i}$
$v_{\text{dep,exp},i}(t) = min \begin{cases} v_{\text{dep,exp},i-1}(t) + a \cdot t_{\text{acc}^{**},i}(t) \\ v_{\max} \end{cases}$
end if

3.5. Conclusions

This chapter presented the modelling framework of the proposed traffic control method and described the determination of the virtual and expected departure times and speeds. The model works as follows.

First, the traffic controller determines the vehicle set. Locations and speeds of automated and connected vehicles can be obtained directly and locations and speeds of some of the conventional vehicles can be obtain indirectly when scanned by automated vehicles or when detected in the queue.

The next step is to determine the virtual departure time and the corresponding virtual departure speed of each vehicle. The virtual departure time is the earliest moment in time at which a vehicle can depart from the intersection without any interruption caused by other traffic or a red traffic signal. The virtual departure speed is the speed at which the vehicle would depart at this virtual departure time. Both the virtual departure time and speed of a vehicle can be determined using the location and speed of the vehicle, the distance to the intersection and the basic kinematic laws.

Next, the expected departure times and speeds are determined. The expected departure time is realistic prediction of the moment in time at which a vehicle would depart from the intersection. Other traffic and the traffic signal state are taken into account. The expected departure time is equal to the virtual departure time in case the vehicle is not hindered by any traffic and the traffic signal it will encounter is green. In case a vehicle would arrive before the signal is green, the expected departure time of an automated vehicle will be equal to the planned moment of switching to green, since the traffic controller will control the vehicle in such a way that it will depart as soon as possible. For conventional and connected vehicles the expected departure time in this case is the moment of switching to green plus a certain acceleration delay, since they will only start accelerating after the signal switches to green.

The expected departure times and speeds of the rest of the vehicles on the link are based on their virtual departure times, the expected departure time of the vehicle in front and the expected headway it will use between the vehicle and the vehicle in front at the moment of departure. This headway is determined using a triangular shaped fundamental diagram.

The traffic controller is able to control both the signals and the trajectories of automated vehicles using the determined vehicle set and virtual and expected departure times and speeds. The signal will be controlled based on the back-pressure approach. Every time slot, a prediction is made of the back-pressures at the intersection for the next time slot. The back-pressure of a movement on the intersection depends on the difference in number of vehicles downstream and upstream of the intersection. Chapter 4 describes the proposed signal control proposal in detail.

The traffic controller controls the automated vehicles is such a way that the green time is used optimally. When an automated vehicle is the first vehicle to approach the intersection and currently has a red signal, the traffic controller will decrease its speed to a certain queuing speed and will let the vehicle accelerate to the highest possible departure speed, such that the vehicle will depart from the intersection exactly when the traffic signal switches to green. Also in other cases, the automated vehicles will be controller in an optimal way. A detailed description of the trajectory control will be given in chapter 5.

4

Traffic signal control

The literature review in chapter 2 showed that many different traffic signal control strategies for connected and automated traffic have been proposed in earlier research. These strategies are mainly focussed on optimizing the performances of one intersection, while network wide conditions are neglected in many of these researches. A large share of the proposed methods seem to require too much computational power if applied to a larger network. Therefore, this report proposes a decentralized signal control method that focusses on improving the network conditions.

The back-pressure approach, already introduced in the literature review of this report, is an effective way to optimize the throughput of a network compared to other traffic control approaches. This real-time traffic demand responsive solution takes upstream and downstream traffic conditions around an intersection into account. Furthermore, the back-pressure approach is suitable for a partly automated and connected environment. For these reasons, an adapted back-pressure approach is proposed in this report. The steps taken by the traffic controller to control the traffic signal are presented in figure 4.1.

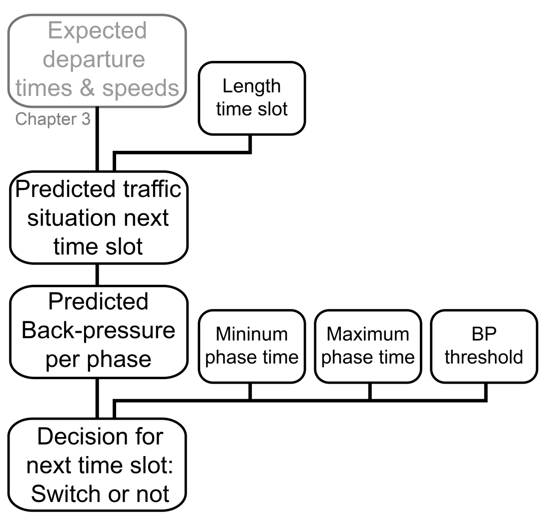

Figure 4.1: Flow chart of the traffic signal control

The first section of this chapter presents the objectives and requirements of the proposed traffic signal control. The flow chart (figure 4.1), shows that the first step after the determination of the expected departure times and speeds (chapter 3), is the prediction of the traffic situation at the next time slot. Section 4.2 of this chapter presents the proposed method to make this prediction, based on the prediction of the number of entering and exiting vehicles. The next step is the determination of the back-pressures, which is described in detail in section 4.3. Section 4.4 describes the algorithm that is used by the traffic controller to control the traffic signal based on the predicted back-pressures.

The conclusions of this chapter are presented in section 4.5. The performances of the proposed traffic control method, including the signal control and the trajectory control, to be introduced in chapter 5, will be tested in a traffic simulation. The simulation setup and results will be presented in chapters 7 and 8.

4.1. Objectives

The main objective of the traffic signal control is to find a method for controlling the traffic signal of one intersection in such a way that it improves the network wide traffic conditions in case the other intersections in the network are controlled in the same way. The only input that the traffic controller will have is the information received from connected and automated vehicles. The method has to be predictable in such a way that trajectories of automated vehicles can be adapted to the traffic signal. The method has to be robust and should not cause a total disruption in the traffic flow when there is no information of vehicles obtained, either due to failure of the communication system or simply because there are only conventional vehicles in the network.

4.2. Prediction of the number of approaching and exiting vehicles around the intersection

As mentioned in the literature review (section 2.3.3), the back-pressure of a phase follows out of the sum of the traffic loads of the set of movements in that phase. Where in original back-pressure algorithm the traffic load is related to the queue length, in a partly automated environment queues will be created differently or will be even avoided by adapting the trajectories of automated vehicles that are approaching an intersection. Therefore, the number of known vehicles (either automated, connected or detected conventional vehicles) within a certain range from the intersection will be considered as the queue length on a link, see figure 4.2. From now on, we call this the back-pressure range of the intersection.

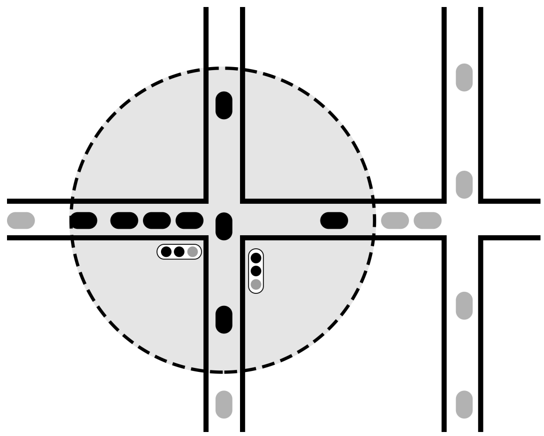

Figure 4.2: Only vehicles within the back-pressure range of the intersection are taken into account for the back-pressure determination

If the traffic controller would switch directly based on the current back-pressures, the automated vehicles will not have any time to anticipate on this switch. Therefore, instead of using the current back-pressures, a prediction is made for the back-pressures at the next slot time. Based on the predicted back-pressures, the traffic controller decides if it should switch at the start of the next time slot.

The number of vehicles on each link at the next time slot is predicted as follows. If the link is located at the edge of the back-pressure controlled network area and no other information about the inflow is known except for the average inflow at a certain time of the day, the predicted inflow $\hat{Q}_{in,T_{\text{slot}}}$ is the average inflow during one time slot, which is equal to the the average flow [veh/s] times the time length of a slot [s]. For the other links, between two successive intersections of which we easily can predict their outflow during the next time slot, the predicted inflow $\hat{Q}_{in,T_{\text{slot}}}$ during one slot time is equal the predicted outflow of the upstream intersection during one time slot. The predicted outflow of an intersection in one time slot is the number of vehicles that are able to depart from the intersection within one time slot. This predicted number of departing vehicles is equal to the number of vehicles with an expected departure time earlier than the current time t plus the slot time T_{slot}. Note that there will be a delay between the outflow and the inflow of two successive intersection in case the distance between the intersections is large. In this case, the time that vehicles need to reach the downstream intersection can be calculated first. The predicted inflow of the downstream intersection at a certain time of interest will be equal to the number of vehicles that departed from the upstream intersection at the time of interest minus the time needed for vehicles drive from the upstream intersection towards the downstream intersection.

4.3. Back-pressure determination

The previous section explains how the number of vehicles on each link at the start of the next time slot are predicted. The next step that the traffic controller has to take is determining the back-pressures. This section describes in detail how the back-pressures will be determined.

4.3.1. Back-pressure basics

Literature shows that an aperiodic control (see section 2.3.3) is able to react better to the traffic conditions than the periodic control since slot times in the periodic approach are less flexible due to the fixed cycle time [50]. The robustness problem of the aperiodic control that could appear, i.e. when there are only conventional vehicles on a link, can be solved by disabling the same phase in two successive slots, together with a minimum and maximum slot time.

The back-pressure of a phase is calculated according equations 4.1, 4.2 and 4.3.

$$B_p(t+T_{\text{slot}}) = \sum_{\phi_p} w_{ab}(t+T_{\text{slot}})\ \xi_{ab}(t+T_{\text{slot}}) \tag{4.1}$$

$$w_{ab}(t+T_{\text{slot}}) = Q_a(t+T_{\text{slot}}) - Q_b(t+T_{\text{slot}}) \tag{4.2}$$

$$Q(t+T_{\text{slot}}) = Q(t) + \hat{Q}_{\text{in},T_{\text{slot}}}(t) - \hat{Q}_{\text{out},T_{\text{slot}}}(t) \tag{4.3}$$

where:

$B_p(t+T_{\text{slot}})$	= Back-pressure of phase p at time $t+T_{\text{slot}}$ [veh^2/s]
ϕ_p	= Set of movements in phase p [-]
$w_{ab}(t+T_{\text{slot}})$	= Traffic load of the movement from link a to link b [veh]
$\xi_{ab}(t+T_{\text{slot}})$	= The rate (i.e., the number of vehicles per unit time) at which vehicles can go from link a to link b through the intersection if phase p is activated at time $t+T_{\text{slot}}$ [veh/s]
$Q_a(t+T_{\text{slot}})$	= Number of approaching vehicles on link a at time $t+T_{\text{slot}}$ [veh]
$Q_b(t+T_{\text{slot}})$	= Number of approaching vehicles on link b at time $t+T_{\text{slot}}$ [veh]
$\hat{Q}_{\text{in},T_{\text{slot}}}(t)$	= Prediction of the inflow of vehicles that will join the approaching vehicles on a link in time interval T_{slot} at time t [veh]
$\hat{Q}_{\text{out},T_{\text{slot}}}(t)$	= Prediction of the outflow of vehicles that will leave the approaching vehicles on a link by departing from the intersection in time interval T_{slot} at time t [veh]

4.3.2. Time slot length

A traffic signal control system based on back-pressure is able to respond very fast on the traffic demand if the time slot is set to a relative short time interval. After every time slot, the predicted back-pressures of the different phases are checked and green will be given to the phase with the highest back-pressure. However, a smaller slot time gives the automated vehicles less time to react to the decision of the controller for after the time slot. Setting the slot time too small could also result in more acceleration and deceleration of vehicles which could lead to a larger travel time delay and higher emissions. There are several options to avoid this from happening: choosing a slot time that is not too small, setting a threshold value when the back-pressures are compared or choosing a minimum phase duration.

In this report, a slot time of 5 second is proposed. This time length will be used by automated vehicles to adapt their speed (see chapter 5). A shorter slot time will decrease their time span and ability to adapt their speed. At the other side, a longer slot time will result in a less adaptive control method, since only once every slot the traffic conditions are checked. To avoid the traffic controller switching the traffic light too often, a minimum phase duration is set on 10 seconds. In that way, acceleration, deceleration and loss of green time due to the yellow phases will be limited.

4.3.3. Threshold for switching

The threshold for switching is the value the back-pressure of the non-active phase has to be higher than the back-pressure of the active phase to switch phases. This can be a fixed number of vehicles, a fixed ratio between the two back-pressures or it can be related to the current traffic situation such as the amount of vehicles that will be stopped if the traffic light switches. In that way, also the traffic demand will play a role like it does in the dynamic slot time approach (section **??**).

Even though a threshold might be beneficial towards the traffic conditions, the threshold is set to 0 in this report. To find the optimal threshold in, simulations could be run with different threshold values to see for what value the results are best. Expected is that a fixed ratio would be the most suitable threshold. However, the study to the optimal threshold value is not included in this research.

4.4. Proposed algorithm

For the approach proposed in this report a fixed slot time is implemented and a minimum and maximum phase duration are set. The earliest possible departure times of connected, automated and detected conventional vehicles at the intersection are known and the moment of switching can be delayed until the first vehicle on the to be activated link can cross the intersection. An overview of the proposed algorithm:

Algorithm 2 Signal control algorithm

At the start of every time slot:

if $(T_{\text{phase,current}} + T_{slot}) < T_{\text{phase,min}}$ **then**

    Do nothing

else if $T_{\text{dep,vir,non-act,1}} \geq (T_{\text{phase,current,start}} + T_{\text{phase,max}})$ **then**

    Switch directly

else

    Determine predicted back-pressures (section 4.3)

    if $B_{\text{non}}(t_{current} + T_{slot}) > B_{\text{act}}(t_{current} + T_{slot}) + \phi_{BP}$ **then**

        if first vehicle on the to-be-activated road is not automated **then**

            Switch at $t = t_{current} + T_{slot}$

        else

            Set time of switching $\rightarrow T_{\text{dep,vir,non,1}}$

        end if

    end if

end if

where:

$T_{\text{phase,current}}$	= Current phase duration [s]
$T_{\text{phase,min}}$	= minimum phase time [s]
$T_{\text{phase,min}}$	= maximum phase time [s]
$T_{\text{dep,vir,act,1}}$	= virtual departure time of the first approaching vehicle on the active road [-]
$T_{\text{dep,vir,non,1}}$	= virtual departure time of the first approaching vehicle on the non-active road [-]
$T_{\text{phase,current,start}}$	= starting time of current phase [-]
$B_{\text{non}}(t_{current} + T_{slot})$	= predicted back-pressure of active phase at time $t_{current} + T_{slot}$ [veh]
$B_{\text{act}}(t_{current} + T_{slot})$	= predicted back-pressure of active phase at time $t_{current} + T_{slot}$ [veh]
ϕ_{BP}	= Back-pressure threshold [veh^2/s]

First it is checked if the current phase does not have a smaller duration than the minimum phase duration (line 2). Then, it is ensured that the phase will not have a longer duration than the maximum phase duration (line 4). Instead of comparing the current phase duration with the maximum phase duration, this statement uses the virtual departure time of the next vehicle that is approaching the intersection. Therefore, the traffic light can already be switched earlier than the exact maximum as the next vehicle will not be able to get the phase anyhow. If the statements of lines 2 and 4 will not be satisfied, the predicted back-pressures on the links will decide if the traffic signal has to switch or not.

4.5. Conclusions

The proposed signal control strategy is based on the original back-pressure approach. The back-pressure approach is proven to be an effective, decentralized control strategy to optimize network performances. It is possible to adapt this approach to function well in partly connected and automated traffic.

The proposed signal control works as follows. First, a prediction for the next time slot is made of the number of approaching and exiting vehicles for each link around the intersection within a certain range of the intersection. Based on the predicted number of vehicles on each link, the predicted back-pressures are determined. As soon as the current phase on the intersection passed the minimum phase time, the traffic controller determines at the start of a time slot the back-pressures at the start of the next time slot. As soon as the back-pressure of the non-active road is higher than the back-pressure on the active road, the traffic controller switches the phase and gives green to the non-active road. There is also a maximum phase time set to avoid very long waiting times in case there are no connected or automated vehicles appearing on a certain link. As soon as the current phase reaches this maximum phase duration, or as soon as the traffic controller notices that the first vehicle on the link will no be able to depart from the intersection, the traffic controller switches the signal.

5 Trajectory control

Chapter 3 presented the modelling framework and explained the first steps the traffic controller has to take before controlling the traffic signal and the trajectories of automated vehicles. In these steps, the vehicle set and the virtual and expected departure times and speeds are determined. Subsequently, chapter 4 presented the proposed signal control method, which is based on the original back-pressure algorithm. At the start of a time slot, a prediction is made for the number of vehicles on each link around an intersection at the start of the next time slot. Based on this prediction, the traffic controller determines the back-pressures at the start of the next time slot and decides to switch the traffic signal at the start of the next time slot or not. The proposed length of the time slot is 5 seconds.

This chapter presents the proposed control for the trajectories of the automated vehicles. Figure 5.1 presents the flow diagram of the trajectory control. Before explaining the steps of this process, the objectives of the trajectory control will be given in section 5.1. The first step of the trajectory control is to determine the smooth departure times and speeds of the automated vehicles, which will be explained in section 5.2. The next step is to control the automated vehicles. The trajectory control is based on the speeds and locations of the known vehicles in the network (section 3.2) and the three different departure times and speeds: the virtual and expected departure times and speeds, introduced in chapter 3 and the smooth departure time.

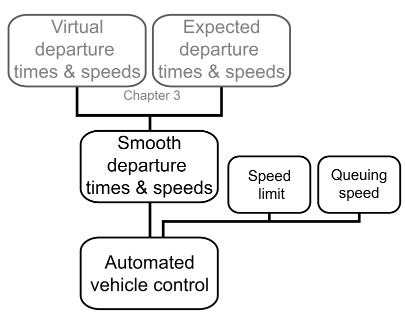

Figure 5.1: Flow diagram of the trajectory control

The performance of the proposed traffic control method including the trajectory control will be tested using a traffic simulation. The simulation setup and results will be presented in chapters 7 and 8.

5.1. Objectives

The main objective of the trajectory control is to maximize the number of vehicles departing from the intersection on average per unit of green time. To accomplish this objective, automated vehicles are not only controlled in such way that they will depart from the intersection as early in time as possible, but also with a speed as high as possible. The second objective is to minimize deceleration and acceleration of automated vehicles in order to limit emissions and passenger discomfort. This second objective is accomplished by introducing the smooth departure time.

5.2. Smooth departure time

The expected departure time, introduced in chapter 3, is equal to the desired departure time: it is the earliest possible departure time the vehicle could depart from the intersection. The same stands for the desired speed of the vehicle, which is equal to the expected departure speed: in case the vehicle is not hindered the speed will be as high as possible considering the vehicle acceleration, distance to the intersection and the road speed limit and in case the vehicle is hindered, the speed will depend on the vehicle in front and/or on the moment the traffic signal switches to green.

The smooth departure time is introduced to let the automated vehicles not only depart from the intersection at the expected departure time and with the expected departure speed, but also to let them accelerate to this time and speed with a minimal constant acceleration. The smooth departure time is the moment in time at which vehicle i would cross the stopping line of the intersection if the vehicle would accelerate constantly from its current speed to the expected departure speed over the distance until intersection. If the calculated smooth departure time of a vehicle is earlier in time than the expected departure time, this means the vehicle would arrive at the stopping line too early if it would accelerate constantly from the current speed to the expected departure speed. In this case, the automated vehicle should not yet start accelerating. If the smooth departure time is equal to the expected departure time, the vehicle can start accelerating with a constant acceleration to its departure. If the smooth departure team is later in time than the expected departure time, this means the vehicle would depart later than the desired moment if it would accelerate constantly to the expected departure speed. In this case, the vehicle should first accelerate with a higher acceleration, which will result into an earlier smooth departure time at the next time step(s). As soon as the smooth departure time is equal to the expected departure time, the vehicle can accelerate constantly to the expected departure speed and will depart from the intersection at the expected departure time.

The smooth departure time is calculated as follows. With a constant acceleration from speed v_1 at position x_1 to speed v_2 at position x_2, the average speed over length $x_2 - x_1$ equals $\hat{v} = \frac{v_1+v_2}{2}$ **(1)**. The total time of the acceleration can be calculated according $T_{acc} = \frac{L_{acc}}{\hat{v}}$ **(2)**, where the total distance covered during the acceleration (L_{acc}) is equal to $x_2 - x_1$. From formulas **(1)** and **(2)** follows: $T_{acc} = \frac{2 \cdot L_{acc}}{v_1+v_2}$. In the same way, the formula for the smooth departure time is derived, see formula 5.1.

$$T_{\text{dep,smooth},i}(t) = T_{current} + \frac{2 \cdot L_{\text{int},i}(t)}{v_{\text{current},i}(t) + v_{\text{dep,exp},i}(t)} \tag{5.1}$$

where:

$T_{\text{dep,smooth},i}(t)$ = Smooth departure time of vehicle i [-]

$T_{current}$ = Current time [-]

$L_{\text{int},i}(t)$ = Distance to intersection of vehicle i at time t [m]

$v_{\text{current},i}(t)$ = Current speed of vehicle i at time t [m/s]

$v_{\text{dep,exp},i}(t)$ = Expected departure speed of vehicle i at time t [m/s]

5.3. Controlling the automated vehicles

All the required inputs of the trajectory control are explained earlier in this report: the virtual and expected departure times and speeds were introduced in chapter 3 and section 5.2 described the smooth departure time. The last step of the traffic controller is to actually control the automated vehicles: setting the speeds and accelerations. The traffic controller has the ability to control the automated vehicles within the communication range of the intersection. The traffic controller has three option to set the speed of an automated vehicle: queuing speed, maximum speed and expected departure speed. The queuing speed is the minimum speed that the traffic controller can set to an automated vehicle. This queuing speed is a fixed value and is set at 10 km/h in the simulation of this research (see chapter 7). The traffic controller sets the queuing speed to the automated vehicles of which the expected departure time is unknown, which are the vehicles that cannot depart in the current green time any more, and to the vehicles of which the smooth departure time is earlier in time than the expected departure time. As soon as the traffic controller sets the speed of an automated vehicle to queuing speed, this means that the vehicle will decelerate with a comfortable deceleration until it reaches queuing speed or until it receives another instruction from the traffic controller. The maximum speed is equal to the road speed limit and is set to the vehicles of which the expected departure speed equals the virtual departure speed and the vehicles of which the smooth departure time is later in time than the expected departure time. As soon as the traffic controller sets the speed of an automated vehicle to maximum speed, this means that the vehicle will decelerate with a comfortable acceleration until it reaches maximum speed or until it receives another instruction from the traffic controller. In case the smooth departure time of a vehicle is equal to the expected departure time, the traffic controller sets the speed to the expected departure speed and sets the desired constant acceleration regarding the smooth departure time (see section 5.2), such that it will accelerate with a constant acceleration until it reaches the intersection at the expected departure time and with the expected departure speed. Algorithm **??** is used by the traffic controller to set the speeds to the automated vehicles.

Algorithm 3 Trajectory control algorithm

At the start of every time slot:
if $T_{\text{dep,exp},i}(t)$ = unknown **then**
    Set v_i to v_{queuing}
else
    if $T_{\text{dep,exp},i}(t) = T_{\text{dep,vir},i}(t)$ **then**
        Set v_i to v_{max}
    else
        Calculate smooth departure time $T_{\text{dep,smooth},i}(t)$ ▷ According formula 5.1
        if $T_{\text{dep,smooth},i}(t) < T_{\text{dep,exp},i}(t)$ **then**
            Set v_i to v_{queuing}
        else if $T_{\text{dep,smooth},i}(t) > T_{\text{dep,exp},i}(t)$ **then**
            Set v_i to v_{max}
        else
            Set v_i to $v_{\text{dep,exp},i}(t)$
        end if
    end if
end if

where:

$T_{\text{dep,exp},i}(t)$	= Expected departure time of vehicle i at time t [-]
v_i	= Speed of vehicle i [m/s]
v_{queuing}	= Queuing speed [m/s]
$T_{\text{dep,vir},i}(t)$	= Virtual departure time of vehicle i at time t [-]
v_{max}	= Maximum speed according the speed limit [m/s]
$T_{\text{dep,smooth},i}(t)$	= Smooth departure time of vehicle i [-]

In some cases, two different intersections are located close to each other, which results into an overlap of their communication ranges. In these cases, the automated vehicle has to decide what controller is the one it is going to follow the instructions from. In almost all cases, this is the controller of the intersection that it is approaching. There is one exception: in case the vehicle has just departed from an intersection, it should not decelerate because it might cause spillback on the intersection it just crossed. As a solution, a clearance space downstream of each intersection is implemented. As long as the vehicle is located within this clearance space of an intersection, it still follows the instructions of the traffic controller of this intersection, even if the vehicle has already entered the communication range of the traffic controller of the next intersection.

5.4. Conclusion

This chapter explained the working of the proposed trajectory control of the automated vehicles, which is part of the total traffic control method introduced in chapter 3. The trajectory control is based on the virtual and expected departure times and speeds of vehicles, also described in chapter 3, and the smooth departure time, introduced in this chapter in section 5.2. The smooth departure time is the moment in time of which a vehicle would depart from the intersection if it would accelerate constantly from its current speed towards its expected departure speed over the total distance to the intersection. By comparing the expected departure time of a vehicle with its smooth departure time, the traffic controller sets a speed to the vehicle. The traffic controller sets the speed of the vehicle to queueing speed when the vehicle is not able to get the current green phase any more, or when the smooth departure time of the vehicle is earlier in time than the expected departure time of the vehicle. The queuing speed is the lowest speed that the traffic controller can set to a vehicle. When the smooth departure time of a vehicle is equal to the expected departure time, the traffic controller instructs the vehicle to accelerate to the expected departure speed with a constant acceleration over the distance to the intersection. When the smooth departure time of a vehicle is larger than the expected departure time, the maximum speed is set to the vehicle, regarding the road speed limit. When the queuing speed or the maximum speed is set, the vehicle decelerates or accelerates to the set speed using a comfortable deceleration and acceleration. In this way, the vehicle will not only depart at the desired time and with the desired speed, but the accelerations of the vehicle will be small and constant when that is possible.

In a traffic network, the traffic controller of an intersection controls the automated vehicles within the communication range of the intersection. In case a vehicle is located within the ranges of two different intersection, it will be controlled by the traffic controller of the intersection it is approaching, unless the vehicle is still located in the clearance space of the upstream intersection. In this case, the controller of the upstream intersection sets maximum speed to the vehicle to avoid spill-back on the intersection.

6
Test setup

The main objective of this research is to find a decentralized traffic control method for traffic consisting of conventional, connected and automated vehicles, which will improve the network wide traffic conditions in an urban network. The previous chapters presented the proposed traffic control method to control the traffic signals and the trajectories of automated vehicles. The next step is to test the performances of this method. A traffic simulation will be used to determine the effects of the traffic control to the traffic conditions of a simplified urban network. The results will not only be used to assess the proposed control method, but will also be used for general conclusions about automated and connected vehicles in traffic and recommendations for further research regarding the future traffic control methods.

This chapter presents the methodology that is used to test the proposed traffic control method. First, the objectives of the simulation will be described in section 6.1. Then, the network and different scenarios that will be simulated are presented in sections 6.2 and 6.3. Next to performances of the traffic control method proposed in this report, the performances of another traffic control method will be tested to compare the proposed control method with. This method, based on a green wave strategy into two directions on the main road will be described in section 6.4. Afterwards, the analysis setup, described in section 6.5, describes the outputs that will be retrieved from the simulation. The expected simulation results for each of these outputs will be described in section 6.7. Finally, section 6.8 provides the conclusions of this chapter.

6.1. Objectives

The simulation has the following objectives:

1. **Assessment of the overall performance of the proposed method**

   Finding the effects of the proposed method on the green times, queue lengths and accelerations in the network. These results will be compared with another, yet existing signal control strategy with traffic without connected and automated vehicles.

2. **Assessment of the influence of the proposed method to the network wide traffic conditions**

   Finding the effects of the proposed traffic light control method, the effects of the proposed trajectory control strategy as well as the effects of the overall proposed method towards the network wide traffic conditions.

   (a) **Assessment of the influence of different shares of connected and automated vehicles**
   Checking the performance of the traffic light control in case of different levels of connectivity in the traffic and finding the effects of different levels of automation to the traffic performance.

   (b) **Assessment of the influence of different flow ratios between the main and the side roads**
   Checking the performance of the proposed control strategy in case of different ratios between the flow on the main road and the flows on the side roads.

6.2. Simulation network

To gain insight in the network wide effects of the proposed traffic control method, a traffic corridor will be simulated consisting of 5 intersections linked to each other in one straight line, see figure 6.1. In this way, it is possible to analyse the way traffic would propagate through several successive intersections, like they would in a larger traffic network, but without the need of simulating a larger network. The effects that one intersection will have on the vehicle stream will propagate downstream to the next intersection and so on. In this way, the second-order effects of the proposed control method on the traffic will become visible.

The road that crosses all the intersection will from now on be called the main road. At 5 locations, the main road crosses the other roads, which will be called side roads. Each intersection will be controlled in the way that is proposed in chapter 4. For simplicity reasons, turning is not allowed, the side roads are one-directional roads and no other traffic modes than cars will be simulated. A more detailed description of the simulated network, vehicle generation and other simulation details will be given in chapter 7.

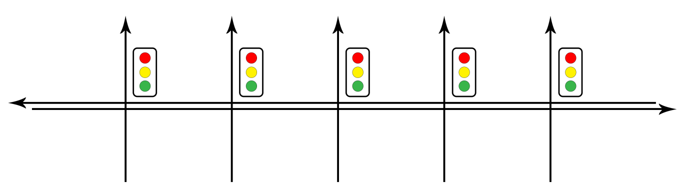

Figure 6.1: Schematic overview of the simulated network

6.3. Scenarios

The different scenarios that will be simulated can be divided into three groups of simulations:

1. **Simulations with various information and automation levels**

   The information level is defined as the share of vehicles that send information out of the total amount of vehicles. This level is calculated according formula 6.1. The automation level is the share of vehicles that are automated among all vehicles that send information, see formula 6.2. All 30 combinations of information levels 0.2, 0.4, ..., 1 and automation levels 0, 0.2 ..., 1 are tested. Note that the information level and automation level is not equal to the share of connected and automated vehicles, for example: an information level of 0.4 and an automation level of 1 means that 40% of the traffic is automated, 60% is conventional and that there are no connected vehicles. Also note that an information level of 0 is not tested since this implies that there are no connected or automated vehicles in the network, the traffic controller of an intersection does not get any input and will always switch as the current active phase reaches the maximum phase time.

$$\text{information level} = \frac{\text{number of automated vehicles} + \text{number of connected vehicles}}{\text{total number of vehicles}} \tag{6.1}$$

$$\text{automation level} = \frac{\text{number of automated vehicles}}{\text{number of automatedvehicles} + \text{number of connected vehicles}} \tag{6.2}$$

   The 30 combinations of information and automation levels are tested for the next flow ratios:

   - 700 veh/h/dir on the main road and 700 veh/h/dir on the side roads
   - 1000 veh/h/dir on the main road and 500 veh/h/dir on the side roads

2. **Simulations with various ratios between the flow on the main roads and the flows on the side roads**

   The following flow ratios will be tested:

   - 250 veh/h/dir on the main road and 1250 veh/h/dir on the side roads
   - 500 veh/h/dir on the main road and 1000 veh/h/dir on the side roads
   - 750 veh/h/dir on the main road and 750 veh/h/dir on the side roads
   - 1000 veh/h/dir on the main road and 500 veh/h/dir on the side roads
   - 1250 veh/h/dir on the main road and 250 veh/h/dir on the side roads

   For this group of simulations the information level and automation level will be fixed at a value of both 0.4 which means that 16% of the traffic is automated, 24% is connected and 60% is conventional.

3. **Simulations without connected and automated traffic and with another, yet existing traffic light control (see section 6.4).**

6.4. Base case

The performance of the proposed traffic control method will be compared with another, yet existing traffic control method. In this base case, there is no connected or automated traffic and another traffic signal control system is implemented. Since the simulated network is a traffic corridor with almost equal distances between the intersections, it is possible to implement a green wave in two directions, as showed in figure 6.2. It is assumed that this traffic control method would be a well performing one in the simulated network and a method that is likely to be chosen in practice for such a situation. Because of time limitations, other signal control methods will not be tested in this research. Chapter 10 presents the recommendations for future research, including other control methods that should be taken into consideration.

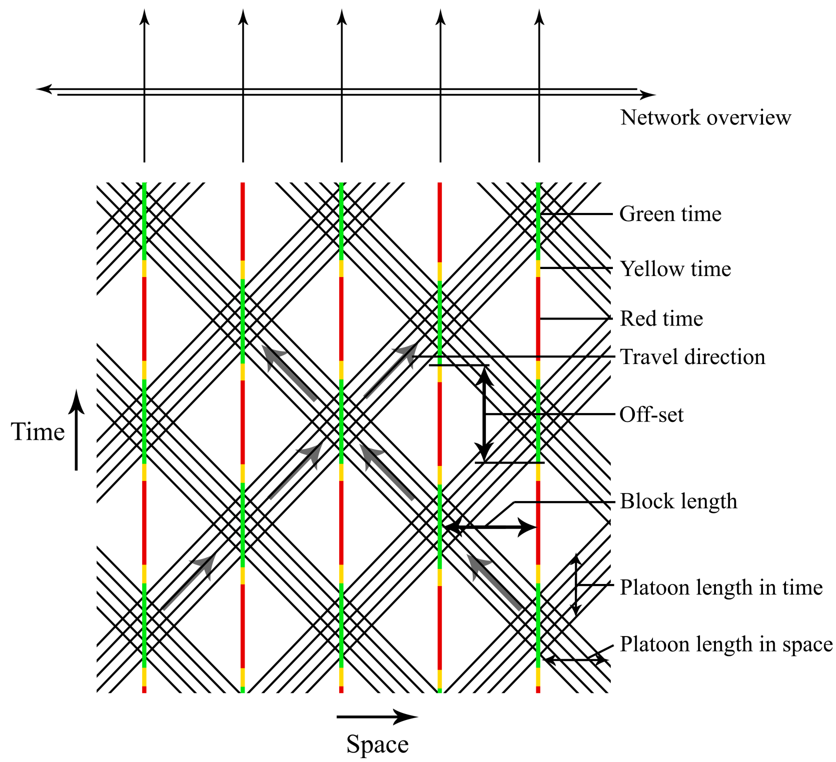

Figure 6.2: Time-space diagram showing the trajectories of the vehicles on the main road in both directions. The green wave signal control avoids decelerations of vehicles in both directions.

The phase durations and the off-set, the time interval of switching between two successive intersections, are calculated according formulas 6.3 - 6.7. The ratio between the green times of the main road and the side roads depends on the flow ratio between the roads (see formulas 6.6 and 6.7).

$$T_{\text{off-set}} = \frac{L_{\text{block}}}{v_{\text{max}}} \tag{6.3}$$

$$T_{\text{cycle}} = 2 \cdot T_{\text{off-set}} \tag{6.4}$$

$$T_{\text{green,average}} = \frac{T_{\text{cycle}}}{2} - T_{yellow} \tag{6.5}$$

$$T_{\text{green,main}} = \frac{2 \cdot q_{main}}{q_{main} + q_{side}} \cdot T_{\text{green,average}} \tag{6.6}$$

$$T_{\text{green,side}} = \frac{2 \cdot q_{side}}{q_{main} + q_{side}} \cdot T_{\text{green,average}} \tag{6.7}$$

where:

$T_{\text{off-set}}$ = Off-set time, to be set between start of green times of two successive intersections [s]

L_{block} = Block length, i.e. the distance between two successive intersections [m]

v_{max} = Speed limit [m/s]

T_{cycle} = Cycle time [s]

$T_{\text{green,average}}$ = Average green time [s]

$T_{\text{green,main}}$ = Green time for main road [s]

$T_{\text{green,side}}$ = Green time for side roads [s]

As will be described in chapter 7, the block lengths are not perfectly equal since that would be an unrealistic situation. However, the green wave off-set is calculated based on the average block length. Therefore, the traffic signal will at some locations switch a bit too early or too late to let the complete platoon of vehicles cross the intersections without any interruptions. Since the block lengths relatively do not differ much in length, this effect is limited. During the simulations it is observed that sometimes the first vehicle of a platoon has to slightly decelerate and that sometimes the last vehicle of the platoon cannot get the green phase any more.

6.5. Analysis setup

Previous sections in this chapter presented the simulation objectives and the network and scenarios that will be simulated. This section explains what types of output will be retrieved from the simulations and in what way these outputs will be analysed and used to reach the objectives of the simulation and to find an answer to the main research question of the report. The expected results for each output will be described in section 6.7.

6.5.1. Average travel time delay

One objective of the simulation is to assess the influence of the proposed method to the network wide traffic conditions. The average travel time delay is one of the measures that describes these conditions. The travel time delay of a vehicle is calculated by subtracting the time that the vehicle would need to cross an intersection at maximum speed without any interruptions, from the time in which the vehicle actually crosses an intersection. The average travel time delay of a simulation is the average of the delays of all the vehicle in the simulation. The influence of different shares of connected and automated vehicles on the traffic conditions will be assessed by calculating the average travel time delay in the network for various information levels and automation levels. Per information level that is tested a graph will be plotted with the automation level on the x-axis and the average travel time delay on the y-axis. In this way, it will be clear if there is a relation between the information level and the average delay, between the automated level and the average delay and between the combination of the automated level and the information level and the average delay. The results with an automation level of 0 show the effect of connected vehicles in the network and the results with an automation level of 1 show the effect of automated vehicles. A graph will be plotted for an equal flow ratio and for an unequal flow ratio to check what information and automation levels the proposed method requires to be able to react on different flow ratios.

To assess the influence of different ratios between the traffic flow on the main road and the traffic flow on the side roads, the average travel time delay per direction (main or side) will be calculated for scenarios with different flow ratios. A histogram will be plotted with the flow ratios on the x-axis and the average delay on the y-axis. For each ratio the average delay at the main road, the average delay at the side road and the total average delay in the network are plotted. In this way, it will be clear if there is any relationship between the flow ratio and the average travel time delay.

6.5.2. Average green time

The average green time provides information about how the traffic signal is controlled in different scenarios. The average green time is the time in seconds for which a traffic signal in the network in average remains green. Both the influence of the share of automated and connected vehicles, and the influence of the flow ratio between the traffic flow on the main road and the traffic flows on the side roads will be tested.

The average green time will be retrieved for the group of simulations with two fixed flow ratios and various shares of automated and connected vehicles. For each information level a graph will be plotted with the automation level on the x-axis and the average green time on the y-axis. Different graphs will be plotted for the average green time per road and per flow ratio. In this way, it will be clear if there is any relationship between the information level and the average green time, between the automation level and the average green time, and the combination of information and automation level and the average green time. These relationships will provide information about the effect of connected and automated vehicles on the traffic signal control.

To assess the influence of different flow ratios, the average green time will be calculated for scenarios with different flow ratios. The average green time is the time in seconds for which a traffic signal in the network in average remains green. Also the average green time per direction will be retrieved to assess the effect of the flow ratio to the length of green times on both directions. A histogram will be plotted with the flow ratios on the x-axis and the average green time on the y-axis. For every ratio the average green time on the main road and the average green time on the side road will be displayed. In this way, it will be clear if there is any relationship between the ratio between the traffic flows on the main and side roads and the average green time. This relationship represents the ability of the traffic signal control to react to different traffic scenarios.

6.5.3. Queue length

Both the average queue length and the maximum queue length of a simulation will be retrieved out of the simulation and will be used to check to what extend the traffic signal control strategy responds to the traffic conditions. Because automated vehicles and their followers in some cases will drive with a low speed when they are waiting for the traffic signal to turn green, the queue length is considered to be the number of vehicles that are approaching an intersection with a speed that is lower than a certain threshold speed. In the simulations this speed is set to 15 km/h.

The average queue length of a road is the queue length in number of vehicles in average over the simulation time. The average queue length of a whole simulation is the average of all the road averages. The maximum queue length is the length of the longest queue length in number of vehicles that occurs in one simulation. Both the average and maximum queue lengths will be calculated separately for the two different directions and for the whole network. The same graphs will be plotted in case the green wave control is applied.

Two graphs will be plotted with different flow ratios on the x-axis and the maximum queue length on the y-axis. For every flow ratio the average queue of the main roads and the average queue length on the side roads will be presented in the first plot. In the second plot the maximum queue length will be displayed instead of the average queue length. In this way not only the effect of the flow ratio on the maximum queue lengths in the network will be visible, but also the effects for the different roads of a certain flow ratio.

To obtain the effects of different information and automation levels on the queue length, the average queue length on each road will also be plotted for different information and automation level. In this way, the effect of automated and connected vehicles on the queue lengths can be obtained.

6.6. Average acceleration and average acceleration time

The average acceleration and the average acceleration time are used to assess the effects of the traffic control method to both emissions and the comfort of the drivers and/or passengers. The average acceleration of one vehicle is the absolute acceleration in average over the total acceleration time of the vehicle. The total average over all the vehicle in the simulation is considered as the average acceleration of the simulation. The acceleration time of one vehicle is the total time that the vehicle is accelerating or decelerating during its trip through the network. The acceleration time will be divided by the total travel time of the vehicle to be able to compare vehicles that have different trip lengths. The average acceleration time in total is the average of the all the vehicle acceleration times. More and/or longer accelerations in the network will have a negative effect on the environment since vehicles will produce more air and sound pollution.

For both an equal and an unequal flow ratio, two graphs will be plotted for traffic consisting of different shares of automated and connected vehicles. For every information level a graph will be plotted with the automation level on the x-axis. For the first graph the average acceleration will be displayed on the y-axis and for the second graph the average of the acceleration time over the total time. Especially the combination of the average acceleration and the acceleration time provides information about the performances of the traffic control method. In case the average acceleration and acceleration time are both rather high, the emissions and the passenger discomfort would be relatively high. This result would indicate that green times are rather short and force vehicles to decelerate and accelerate more often

In case the average acceleration is relatively small and the acceleration time is large, this would indicate that drivers or automated vehicles are able to anticipate well on speed changes. A driver or automated vehicle that can anticipate well, could gently adopt its speed, starting from a large distance from the intersection, to arrive at the intersection when the signal is green. In this way a complete standstill could be avoided and the average acceleration could be limited.

Comparing the results for different shares of automated vehicles provides information about the performances of the automated vehicle trajectory control in comparison with vehicles controlled by human drivers.

6.7. Expected simulation results

This section presents the expectations for each simulation output: the average travel time delay, the average green time, the maximum queue length and the average acceleration and acceleration time.

6.7.1. Expectations regarding the average travel time delay

There will be different factors of the proposed method that will influence the average travel time delay. First of all, the automated vehicles have the possibility to accelerate at exactly the right moment to cross the intersection at the earliest possible moment in time and with the highest possible speed. Considering the triangular shaped fundamental diagram it is expected that the flow on the road is higher for a higher speed of the vehicles. Since not only the automated vehicles will contribute to this higher flow, but the complete platoon that is formed behind an automated vehicle when it approaches an intersection on queuing speed, the flow during green time will be higher in average. That means that in average more vehicles can cross the intersection per second of green, which will result in shorter queues and thus a shorter waiting time per vehicle. Therefore it is expected that the higher the amount of automated vehicles, the lower the average travel time delay will be.

Also the connectivity of both the automated and connected vehicles will effect the average travel time delay. Since the back-pressure based traffic light control reacts to the current traffic situation, it is expected that the more the traffic controller knows about the traffic situation, the more efficient the traffic lights will react to the traffic. Therefore, a higher information level (or share of automated and connected vehicles together) will result in a lower average travel time delay.

6.7.2. Expectations regarding the average green time and queue length

It is expected that the average green time and maximum queue length are both dependent on the information level and the flow ratio between main and side roads. Again, the higher the information level is, the better the traffic light system will react to the traffic conditions. Since the back-pressure approach compares upstream and downstream conditions, it is expected that the difference between queue lengths will be smaller. Therefore, extremes in queue lengths will be avoided and the maximum queue length will be limited. However, since a back-pressure range is introduced in the proposed traffic light control method (see section 4.2), the first part of the queue on the downstream road will not be taken into account for the back-pressure calculations. Therefore, the traffic light controller will be more responsive towards the upstream conditions and equal queue lengths upstream and downstream of the intersection is not the main objective of the signal control any more, but the main objective will be to equal the back-pressure within the back-pressure range only. This means that there are more differences in average queue length and maximum queue length in the simulation is expected. In case the signal control would result in an intersection throughput that is smaller than the traffic demand, long queues are expected at the first intersection that vehicle flows will encounter.

Expected is that the average green time will strongly depend on the flow ratio. The highest flow will have the highest average green time and in case the flows will be equal, also the green times will be equal. The larger the difference in flow, the larger the difference will be in average green time.

The green wave control strategy has fixed green times, depending on the traffic demand given as a simulation input. Since these green times will be rather small (see section 6.4), it is expected that green times will be longer with the proposed back-pressure method. Less vehicles per green time will be passing the intersection using the green wave method, and therefore a larger queue is expected at the first intersection of each route. However, in case of a well functioning green wave, as soon as a vehicle crosses the first intersection, it will only encounter green lights at the next intersections and therefore the queue lengths will be small at these next intersections. Therefore it is expected that the maximum queue length in case of a green wave strategy will be much higher than the average queue length in comparison to the proposed method.

6.7.3. Expectations regarding the average acceleration and average acceleration time

The automated vehicles should be able to adapt their speed in such a way that they do not have to decelerate until standstill when possible and therefore the average acceleration of the automated vehicle and its followers will be lower. However, the trajectory controller checks every time step of the simulation whether a vehicle should accelerate, decelerate or keep the same speed. Expected is that this will result in fluctuations in speed: the vehicle receives the signal that it should accelerate when it drives too slow and vice versa. The vehicle speed will be fluctuating around the desired speed before reaching this desired speed. Expected is that the larger the time step is, the longer the wave length of this fluctuation is and therefore the larger the average acceleration. Since this effect will also influence the speeds of the following vehicles, this might have a big influence on the total average acceleration, as well as the acceleration time.

Regarding the traffic signal control system, it is expected that the proposed back-pressure method will result in a higher average acceleration in comparison to the green wave approach. In case of a well performing green wave strategy, vehicles will have to decelerate because of a red light maximal only one time, at the first intersection they encounter, and will only encounter green lights at the next intersections. The back-pressure based approach is not focused on minimizing the vehicle stops, but is focused on equalling road pressures. Therefore, more vehicle stops will occur that will result in a higher average acceleration and a longer acceleration time.

6.8. Conclusions

In order to assess the performance of the proposed control method and the influence on the network wide traffic conditions, a traffic simulation will be used. The simulated network will be a traffic corridor consisting of 5 signalized intersections. Different traffic scenarios will be tested with different information and automation levels and different flow ratios using both the proposed control method and a green wave control method to compare the results. The outputs that will be retrieved out of the simulations are the average travel time delay, the average green time, the average and maximum queue lengths and the average acceleration and acceleration time. It is expected that these results will provide insight in the performance of the proposed traffic control method and in the influences on the traffic conditions.

7

Simulation setup

The previous chapter presented the methodology that is used to assess the proposed traffic control method, which is based on a traffic simulation. This chapter describes the technical details of the simulation, such as the network dimensions, the vehicle generation and the used parameters and vehicle characteristics. For the simulation, the traffic simulation software of SUMO is used [14]. The Traffic Control Interface (TraCI) of SUMO offers the possibility to control vehicles and traffic signals and retrieve traffic details while the simulation is running, using Python as the interacting programming language.

7.1. Network dimensions

As described in chapter 6, the simulation network will be a traffic corridor consisting of 5 successive intersections. The dimensions of a typical city block will be considered for the distance between the intersections. In U.S. metropolitan areas, urban planners suggest to design city blocks related to the best scale for walking, which is 300 to 600 feet [5], although the average city block size between major cities in the U.S. differ between for example 750 feet in Manhattan [34] to only 200 feet in Oregon [8]). Taking the minimal typical city block size would be an unnecessarily conservative assumption. In this research, a block size of 150 metres(more or less 490 feet) will be used. A simulation network built up out of blocks of exactly 150 metres where each might generate unrealistic results due to perfect symmetry. Therefore, the blocks are randomly shortened or enlarged by a distance between 0 and 15 metres. The lengths of the roads on which vehicles are entering the network are set to 300 metres. Figure 7.1 presents the dimensions of the proposed network.

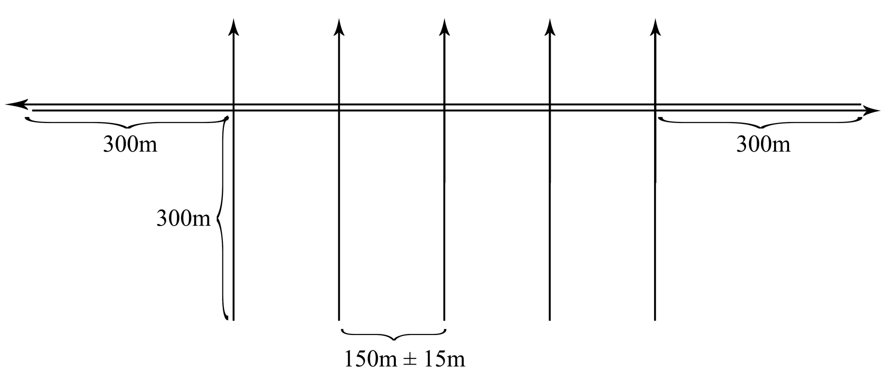

Figure 7.1: Network configuration used in the the simulation

7.2. Vehicle generation

The number of vehicles on average per unit of time is based on the average traffic demand. The average traffic demand on each road is constant over the total length of a simulation and equals the traffic flow that has to be tested, see section 6.3. A list of exponential distributed time headways is created with a rate parameter of $\lambda = \frac{1}{\hat{h}}$, where $\hat{h}$ is the average time headway that equals the inverse of the average traffic demand. The entry moment of each vehicle is equal to the sum of the time headways between earlier entering vehicles.

To decide which vehicle type (conventional, connected or automated) each vehicle gets, a random number is generated between 0 and 1. The share of each vehicle type is chosen on forehand, see section 6.3. If the number is smaller than the share of conventional vehicles, the vehicle will be a conventional vehicle. If the number is larger than 1 minus the share of automated vehicles, the vehicle will be an automated vehicle. In other cases, the vehicle will be connected.

The vehicle characteristics that are used in the simulation will be presented in section 7.3. Discussions regarding the assumed constant average travel demand and the distribution of headways are included in chapter 9 of this report.

7.3. Simulation parameters

This section provides an overview of the chosen parameters in the simulation including a description of each parameter and assumption.

Traffic demand

The traffic demand is the flow in vehicles per hour in which the vehicles will enter the simulation. For the main road a demand of 700 vehicles per hour per direction is set and for the side roads a demand of 700 vehicles per hour. Note that the main road has two directions. Vehicles are entering with a exponential distributed time gap between each other with an average time gap of the flow divided by 3600 seconds.

Road capacity

The road capacity is the maximum flow of vehicles per hour on a road. A higher flow will result in congestion on the road. The road capacity used in the simulation is directly retrieved from SUMO, which is 1600 vehicles per hour.

Minimal gap

The minimal gap is the minimum distance a driver (or automated vehicle controller) chooses to follow its leader. In this simulation the minimal gap is set to 2.5 metres.

Driver imperfection and speed factor

For the humanly controlled vehicles the standard driver imperfection of SUMO is set, which is based on the Krauß car-following model [25]. This imperfection influences the minimal gap, the acceleration and the deceleration of a vehicle. The imperfection of the automated vehicles is set to 10% of the humanly controlled vehicles. A speed factor is set for the humanly controlled vehicles which describes to what extend the actual maximum speed the drivers will take into account relative to the maximum speed on the road.

Vehicle length

The vehicle length is the length of the vehicle from front to rear bumper. In the simulation the vehicle length is set to 5 metres for all vehicles.

Jam density
The jam density is the number of vehicles on a road during a jam, when the vehicles have to break until a complete standstill. The density is the highest density possible and is depending on the lengths of the vehicles and the minimum gap. Since the vehicle length in the simulation is 5 metre-sand the minimum gap is 2.5 metres, the density is $\frac{1000}{5+2.5} = 133.33$ vehicles per kilometre.

Speed limit
The maximum speed limit is the maximum speed on which vehicles are allowed to drive according the traffic regulations for that road. In the simulation a speed limit of 50 kilometres per hour is set for every road.

Queuing speed of automated vehicles
The queuing speed of the automated vehicles is the speed that is set to the automated vehicles when they are approaching an intersection, but cannot cross the intersection yet. In the simulation a queuing speed of 10 kilometers per hour is set.

Maximum vehicle acceleration
The maximum vehicle acceleration is not the maximum possible acceleration of a vehicle but is the maximum acceleration that a driver chooses. In the simulation a value of 2.6 m/s^2 is set to all vehicles [6][7].

Maximum vehicle deceleration
The maximum vehicle deceleration is not the maximum possible deceleration of a vehicle but is the maximum deceleration that a driver chooses. In the simulation a value of 4.0 m/s^2 is set to all vehicles [6][7].

Car-following model
The default car-following model of SUMO is used for the simulations, which is based on the Krauß model [25]. Especially complex scenarios, such as spontaneous jams and behaviour on roads with multiple lanes are still a challenge. However, in the simulations of this report there are no complex traffic simulations as there are only roads with one lane per directions, no turning traffic, only car traffic and no unpredictable events such as car accidents. Therefore, the default car-following model is considered to be appropriate for this research [25].

Yellow time
The yellow time is the length in time of the yellow phases of the traffic signals, after the green phase and before the red phase. In the simulation the yellow time of the traffic signal systems are set to 3 seconds.

Communication range
The communication range between vehicles and infrastructure depends on the used technology. 3G and 4G do not have any limits related to communication range, assuming the zone of interest is not located in a remote environment with no or bad 3G/4G connection. However, Dedicated Short Range Communications (DSRC) will be a more favourable method of communication related to radio interference, extreme weather conditions, high vehicle speeds, latency, and privacy and has a range between 100 and 1000 metres [20] [21] [27]. In the simulation, the maximum distance between a vehicle and the first intersection it will encounter is around 150 meter. We assume the vehicle can communicate with the intersection from the very first moment it enters the simulation. The maximum distance between a vehicle and any other intersection is around 750 metres, which is

the distance from the entry of the main road to the third intersection. This is important for the consideration whether a conventional vehicle which is spotted directly at the entry of the simulation will considered as a spotted vehicle for only the first intersection, or also for the other intersections. In the simulation we assumed that a spotted conventional vehicle is directly included into the vehicle sets of every intersection.

Scan range of automated vehicles
Current technologies offer a scanning range from up to 100 metre behind the vehicle and up to 500 metre in front of the vehicle (see 3.2). In this case a conservative assumption is taken into account for the automated vehicles in the simulation and the scanning range at the front side is set to 150 metre and the scanning range at the rear side is set to 75 meter. It is expected that current technologies will be improved in the coming years and a larger range will be possible. In the simulation automated vehicles are only able to detect the direct leader and follower and not any other vehicles within the scanning range.

Back-pressure range
As presented in section 4.2, only vehicles within a certain range from the intersection will be taken into account to calculate the back-pressures. In the simulation this range is set to 120 metres. This distance is chosen to be smaller than the distance between intersections in order to only take the traffic conditions around one single intersection into account.

Lower boundary for back-pressure
In this report, a lower boundary for the back-pressure of a phase is set to 0 veh^2/s. Since the side roads will never have a negative back-pressure (no queuing vehicles downstream), this only effects the traffic light control in case the main road has currently green and has a negative back-pressure at the same time. In case there would be no vehicles approaching on the side road, the back-pressure would be 0 and would be higher than the back-pressure on the main road. Without this lower boundary, the traffic light controller would switch to green on the side road, even though there are no vehicles approaching on the side road. Since this would give a disadvantage to the main road, the lower boundary is introduced.

Time slot length
The time slot length is the length of the slot time in seconds. The time slot is the interval between the decision moments at which the traffic controller determines and compares the back-pressures and set the traffic signal for the start of the next slot time. In the simulation a fixed slot time of 5 second is chosen, see section 4.3.2.

Maximum phase duration
The maximum phase duration is the maximum time length in seconds that a traffic signal can be on one single phase without interruptions. This influences especially the maximum possible waiting time for road users and makes sure that one phase will not end in case of a defect in the vehicle detection. In the simulation the maximum phase duration is set to 60 seconds.

Minimum phase duration
The minimum phase duration is the minimum time length in seconds that a traffic light cannot switch again after switching. This prevents the vehicles from having to accelerate and decelerate too often and which will, therefore, reduce emissions. In the simulation the minimum phase duration is set to 10 seconds.

Clearance space
To avoid spill back by decelerating automated vehicles directly downstream of an intersection in situations that these vehicles have the option to keep maximum speed as well, the clearance space is introduced. When an automated vehicle just crossed an intersection and is still located in the clearance space of the intersection, the traffic controller cannot instruct the vehicle to decelerate, even though this might be desirable looking at the traffic signal sequence of the upcoming intersection. The length of this clearance space is set to 30 metres in the simulations and will be discussed in chapter 9.

Time step
The time step is the length in time after which the simulation software updates the traffic situation in the simulation. Each time step the traffic controller runs the proposed traffic control algorithm to decide to switch the traffic signals and to set a new speed to the automated vehicles in the network. In the simulations of this report a time step of 0.5 seconds is used. This length will be discussed in chapter 9.

Simulation length
The length of the simulation is the total time length the simulation will run in seconds. In this simulation the simulation length is set to 900 seconds, which is equal to 15 minutes. Results will retrieved after a simulation warm-up time of 2 minutes.

Random seeds
Simulations are ran for 30 different random seeds. The average travel time delay, acceleration and acceleration time are calculated over all vehicles and therefore already have a low standard deviation. The results of the maximum queue length and average green time have a higher deviation. Therefore, more random seeds would provide more precise results, but in this case this was impossible due to limited research time. The precision of the current results however is considered to be adequate in order to answer the research questions of this research.

8

Simulation results

In chapters 3, 4 and 5, the proposed traffic control method was presented. This method is tested in a traffic simulation, described in chapters 6 and 7. This chapter presents the results of the simulation and the implications of these simulation results. The results and implications will be considered when giving the conclusions and recommendations of the research in chapter 10.

In section 8.1, the obtained results of the simulation will be presented regarding the average travel time delay, the average green time, the average and maximum queue length, and the average acceleration and acceleration time. For each of these outputs, the results will be displayed in different graphs for which a short description will be provided. Section 8.2, presents the implications based on the obtained simulation results.

8.1. Obtained simulation results

This section presents the simulation results that are directly obtained from the simulation. The following outputs are considered:

- Average travel time delay
- Average green time
- Queue length
  - Average queue length
  - Maximum queue length
- Acceleration
  - Average acceleration
  - Average acceleration time

The results will be displayed in the graphs as described in the analysis setup in chapter 6. A short description of the findings will be added. Most of the implications of the results will be based on a combination of graphs of different outputs. They will be given in the next section of this chapter.

8.1.1. Average travel time delay

This section provides the following figures of the simulation results regarding the average travel time delay:

Figures 8.1 and 8.2

The average travel time delay for various information and automation levels for an equal flow ratio (fig. 8.1) and for an unequal flow ratio (8.2).

Figures 8.3

The average travel time delay per road direction for various flow ratios and fixed information and automation levels (both 0.4).

Figures 8.1 and 8.2 show the average travel time delay per intersection over all the vehicles in the network for various information and automation levels. For the first graph a flow ratio of 700:700 veh/h/dir (main:side) is used and for the second 1000:500 veh/h/dir. Also the average travel time delay that the vehicles have in case of a green wave signal control is displayed in both figures. The first graph, with equal flows of 700 veh/h/dir, shows that both the information level and the automation level have effect on the average travel time delay. In almost all cases, a higher information level results into a lower average delay. The average delay is reduced by every 20% increase of the information share, however the marginal beneficial effect on the average delay by increasing the information level by 20% decreases when the information level gets higher. For the various automation levels, similar results are obtained. The average delay is significantly reduced especially with an automation level of 0.2, compared to a level of 0. The marginal effect of increasing the automation level decreases when the automation level gets higher.

The second graph, figure 8.2 shows the results in case of a main flow of 1000 veh/h/dir and a side flow of 500 veh/h/dir. It is remarkable that these results show a negative effect of the information level on the average delay for automation levels lower than 0.4: the higher the information level is, the higher is the average delay. Like in the first graph, increasing the automation level has a positive effect on the average delay, especially for high information levels.

As expected (see chapter 6), the green wave control strategy leads to worse results: in all cases the average delay is higher than for the proposed control strategy.

Figure 8.3 presents the average delay of the vehicles on the main road, on the side road and the average delay over all the vehicles in the network for different ratios between the flows on the main and the side roads. There is no clear relationship between the flow ratio and the average delay on each road. It seems that the average delay on the side roads reduces and the average delay on the main road increases in case the main flow increases compared to the side flow. However, this does not stand for the flow ratio of 250:1250 veh/h/dir. In this last case, the side flow is 5 times higher than the main flow, which results into higher back-pressures on the side road. This is not the case for the other flow ratios, since the back-pressure on the main road is a summation of the back-pressure of both lanes of the main road. The side flow has to be at least twice as high to overtake this priority for the main road. The priority for traffic on the main road due to the back-pressure calculations will be discussed in chapter 9.

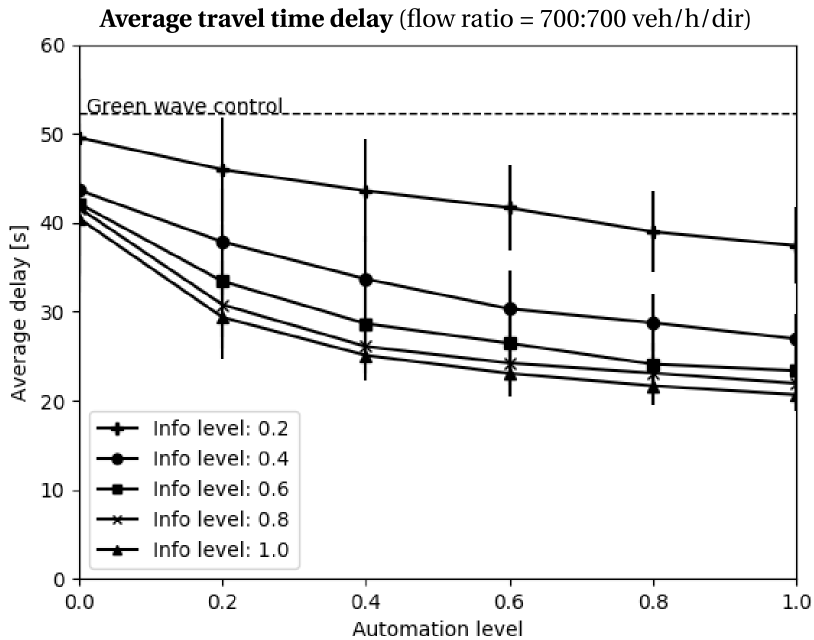

Figure 8.1: Average travel time delay for various information and automation levels (main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

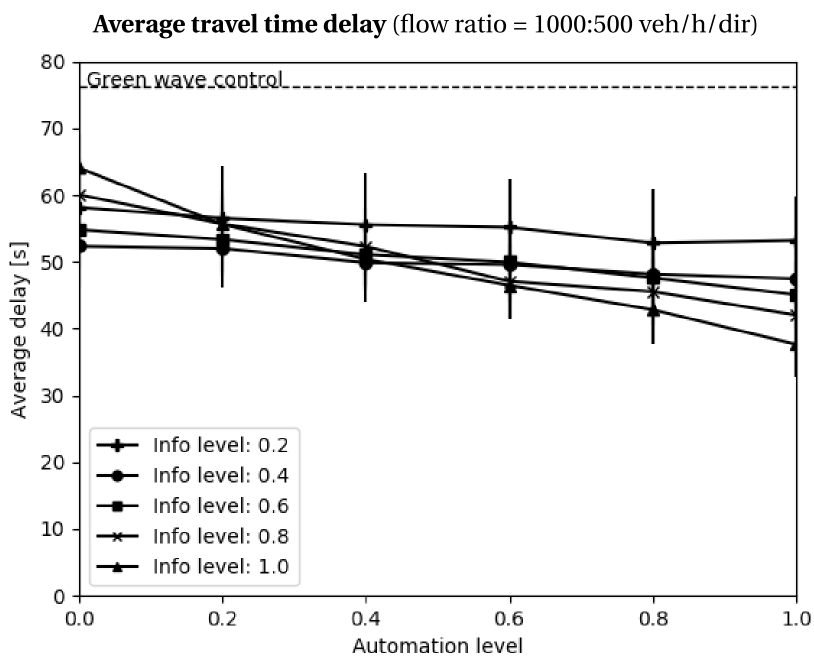

Figure 8.2: Average travel time delay per intersection for various information and automation levels (main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

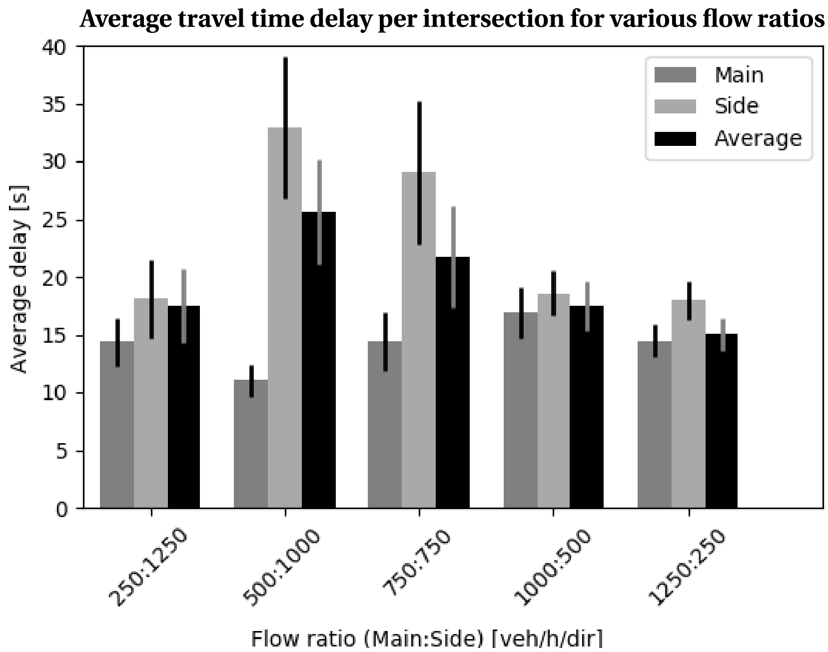

Figure 8.3: Average travel time delay per road direction for various flow ratios (info level = 0.4 and auto level = 0.4).

8.1.2. Average green time

This section provides the following figures of the simulation results regarding the average green time:

Figures 8.4 & 8.5

The average green time for various information and automation levels for flow ratios 700:700 veh/h/dir (fig. 8.4) and 1000:500 veh/h/dir (fig. 8.5).

Figures 8.6 - 8.9

The average green time on the main road and on the side roads for flow ratios 700:700 veh/h/dir (fig. 8.6 & 8.7) and 1000:500 veh/h/dir (fig. 8.8 & 8.9).

Figures 8.10 & 8.11

The average green time on the main and side roads for various flow ratios in case of the proposed control method (fig. 8.10) and in case of the green wave control method (fig. 8.11).

Figures 8.4 and 8.5 present the average green time over the whole network in case of different information and automation levels. Both figures show that the automation level seems to have almost no influence on the average green time in the network at all. However, the information level does have an influence on the average green time. The higher the information level gets, the more the average green time approaches the minimum green time of 10 seconds. The figures show that in case of an unbalanced flow ratio (fig. 8.5), the average green time for each information level is larger compared to the results with an equal flow ratio (8.4).

Figures 8.6 - 8.9 show the differences in the average green time between the main and the side roads for various information and automation levels. Figures 8.6 and 8.7 show that with an equal flow ratio, the average green time on the main road is larger for low information levels than on the side road. On the main road, the average green time becomes around 11 seconds with an information level of 0.6 and higher. On the side road, the average green time becomes around 11 seconds already with an information level of 0.4 and higher.

Figures 8.8 and 8.9 show the differences in the average green time for an unequal flow ratio. The same results can be obtained as for the equal flow ratio, but in this case they are more extreme: the information level seems to have a larger effect on the average green time on the main road, but the green time on the side road approaches the minimum green time quickly.

Figure 8.10 shows that the green times using the proposed traffic signal control are corresponding to the different flow ratios: the larger the difference in flow, the longer the green time is on the road with the highest flow. However, the ratio between the green time on the main and side road is not directly proportional to the traffic flow: when the flow on the main road is 5 times as high as the flow on the side road (ratio 1250:250 veh/h/dir), the green time on the main road is only 3 times as high as the green time on the side roads. The average green time does not get higher than 30 seconds, even though the maximum phase duration is set to 60 seconds. Finally, figure 8.11 shows the green times set in case of the green wave strategy. The ratio between the green times on the main and side road are direct proportional to the traffic flow. The average green time is 7.5 seconds for every flow ratio. Depending on the flow ratio, green times vary between 2.5 and 12.5 seconds.

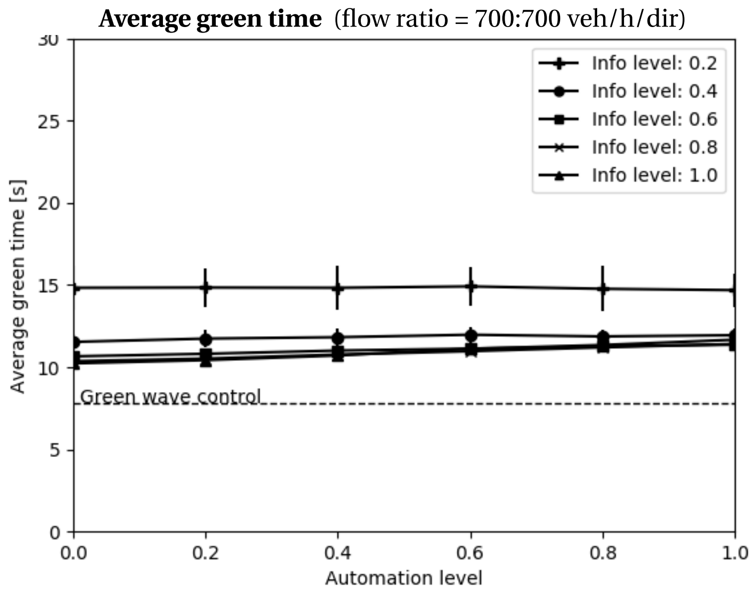

Figure 8.4: Average green time for various information and automation levels (Main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

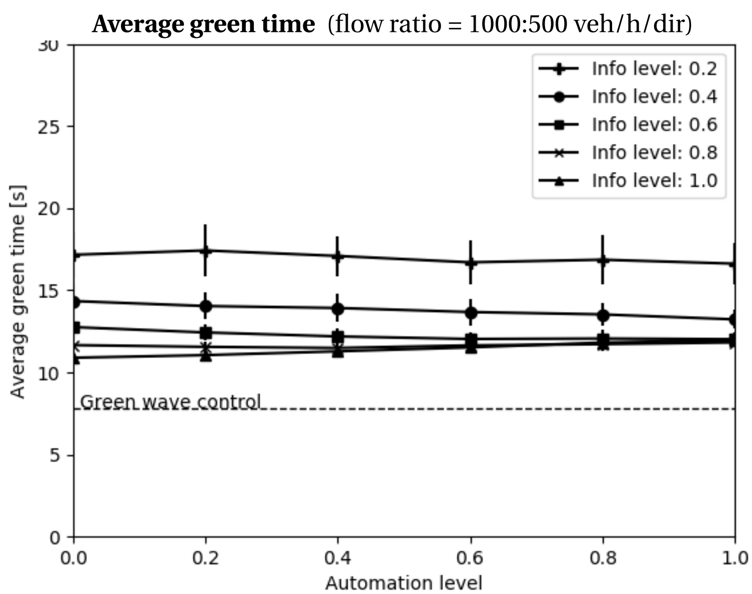

Figure 8.5: Average green time for various information and automation levels (Main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

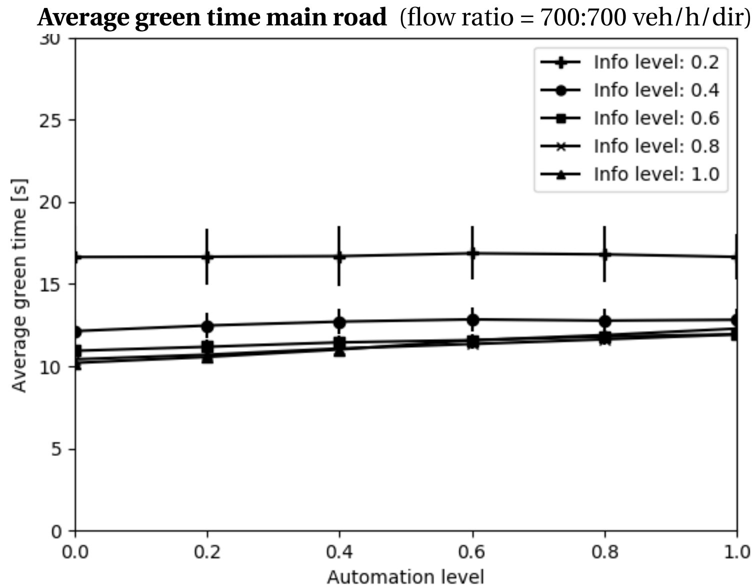

Figure 8.6: Average green time for various information and automation levels (Main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

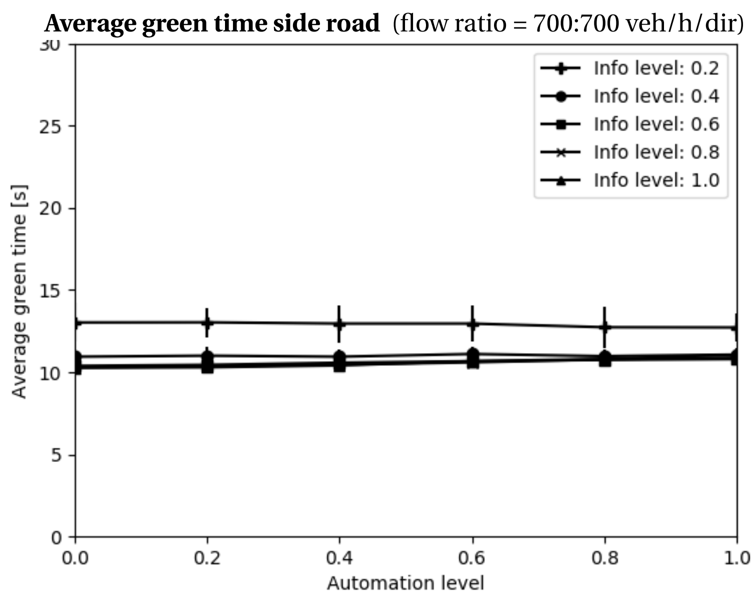

Figure 8.7: Average green time for various information and automation levels (Main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

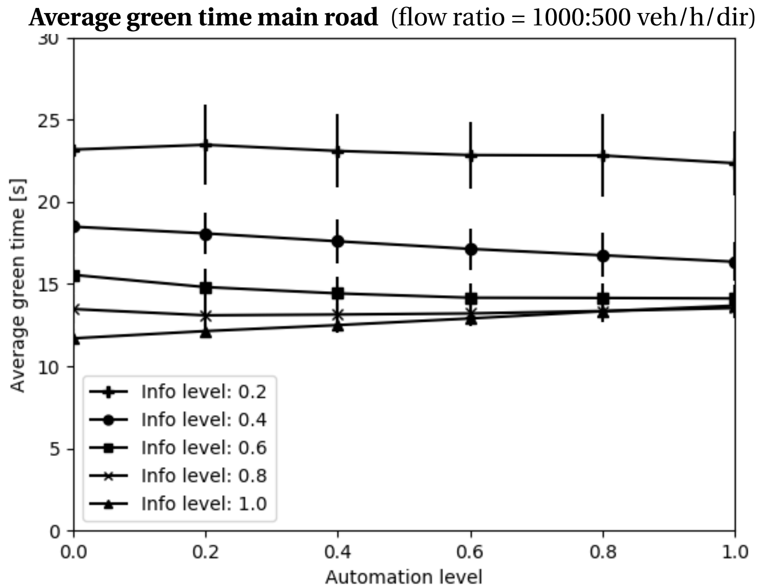

Figure 8.8: Average green time for various information and automation levels (Main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

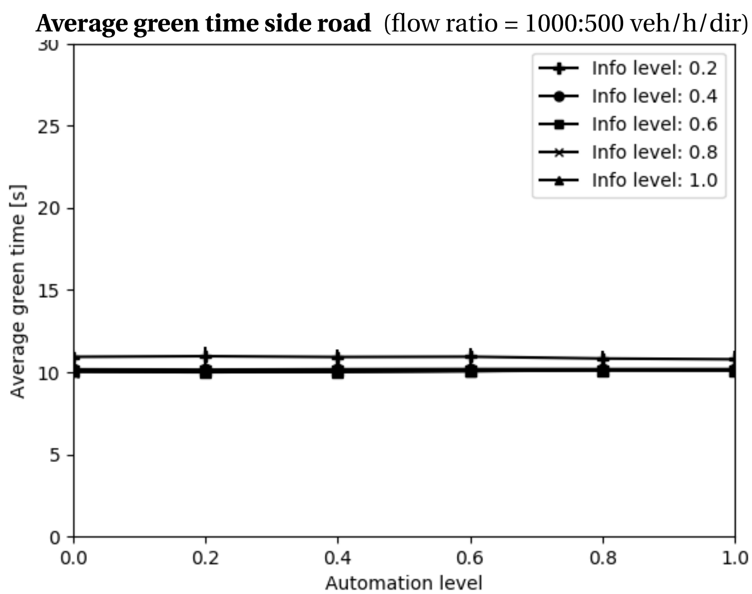

Figure 8.9: Average green time for various information and automation levels (Main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

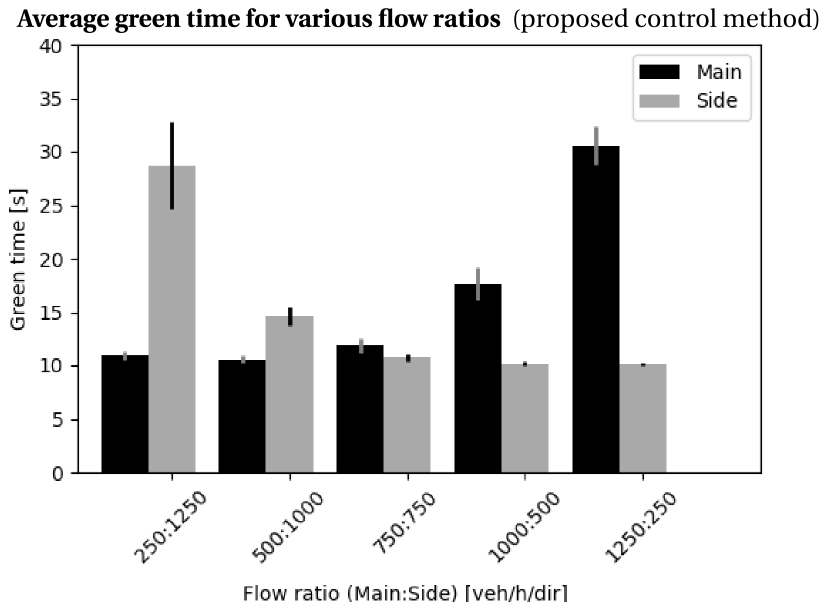

Figure 8.10: Average green time per road direction in case of the **proposed control method** (info level = 0.4 and auto level = 0.4)

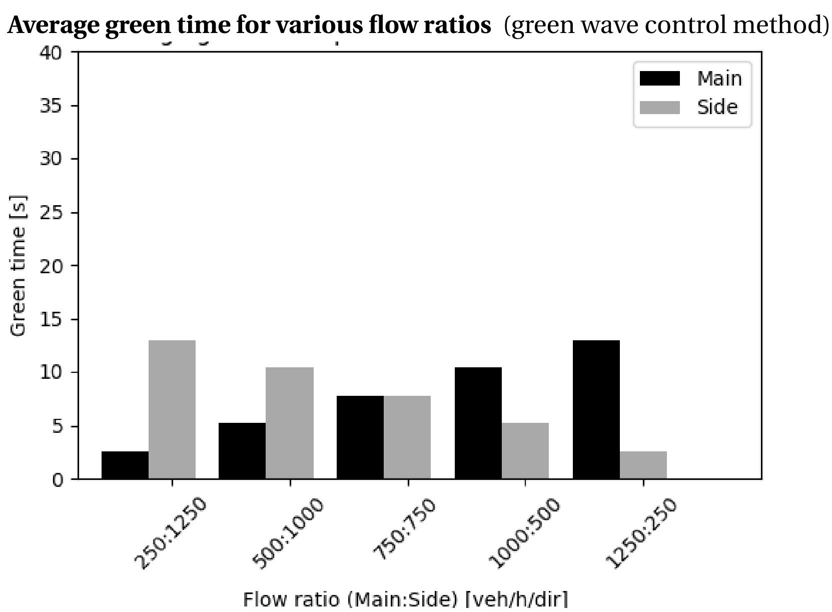

Figure 8.11: Average green time per road direction in case of the **green wave control method**

8.1.3. Queue length

This section provides the following figures of the simulation results regarding the average and maximum queue lengths in the network:

Figures 8.12 & 8.13

The average (fig. 8.12) and maximum (fig. 8.13) queue length on the main and side roads for various flow ratios.

Figures 8.14 - 8.17

The average queue length on the main road and on the side roads for flow ratios 700:700 veh/h/dir (fig. 8.14 & 8.15) and 1000:500 veh/h/dir (fig. 8.16 & 8.17).

Figures 8.18 & 8.19

The average (fig. 8.18) and maximum (fig. 8.19) queue length on the main and side roads for various flow ratios in case of the green wave control method.

Figures 8.12 & 8.13 show the average and maximum queue lengths for various flow ratios with an information and automation level of both 0.4. The first figure shows that the average queue length on the main road increases when the flow on the main road is higher in comparison to the flow on the side flow. However, this does not apply for the ratio with the largest flow on the main road (ratio = 1250:250 veh/h/dir). The same trend can be observed for the queue length on the side road: the larger the side flow gets relatively to the main flow, the larger the queue length on the side road, except for the ratio with the largest flow on the side road (ratio = 250:1250 veh/h/dir). Figure 8.13 shows that the same trend applies for the maximum queue length. The maximum queue lengths vary from 7 up to 27 vehicles.

Figures 8.14 and 8.15 show the average queue length for different information and automation levels in case of an equal flow ratio. The average queue length on the main road seems to be independent of the information level in case of an automation level of 0. As soon as the automation level is 0.2 or higher, increasing the information level seems to have a beneficial effect: the higher the information level, the shorter the average queue length. The average queue length on the side road (see figure 8.15) seems to be dependent on both the information and automation level. For both levels the same applies: increasing the level results into a shorter average queue length on the side road. However, for an information level of 0.8 and higher it seems like the average queue length does not reduce any further for automation levels higher than 0.4.

Figures 8.16 and 8.17 show the average queue length for different information and automation levels in case of an unequal flow ratio (1000:500 veh/h/dir). In this case, both the average queue length on the main road and on the side road seem to be dependent on the information and automation level. The results of the average queue length on the side road show the same trend as the results for a flow ratio of 700:700 veh/h/dir: increasing the information or/and the automation level results into a short queue length. However, the results for the average queue length on the main road differ significantly. In this case, increasing the information level seems to result into longer queues. The queue length seems to be dependent of the automation level especially when the information level is 0.8 or higher.

The results of the average and maximum queue length in case of the green wave control can be seen in figures 8.18 and 8.19. Generally, both the average as the maximum queue lengths are longer compared to the proposed traffic control. The average queue length on the side roads is significantly larger than the average queue length on the main road. This does not apply for the maximum queue length, which is more balanced for each flow ratio. The average queue length varies from 2 to 12 vehicles and the maximum queue length varies from 20 to 37 vehicles.

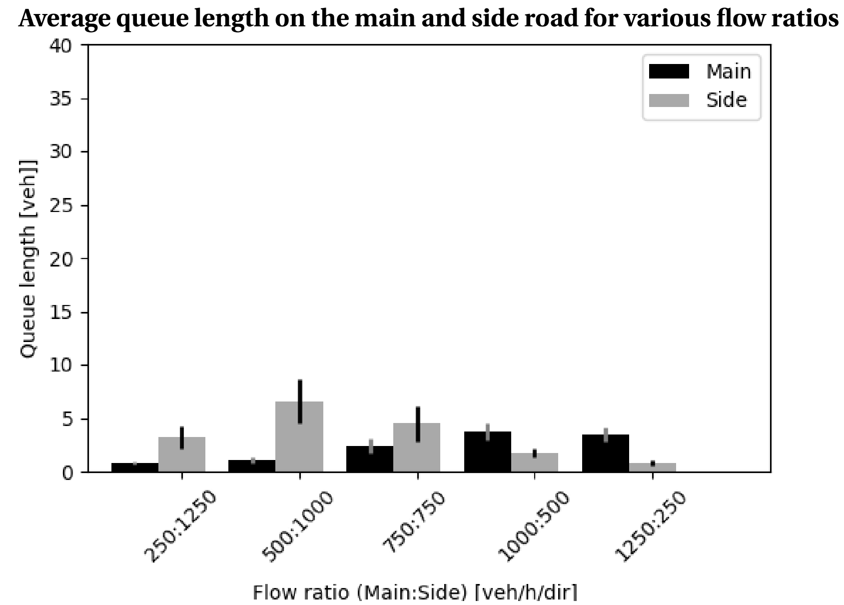

Figure 8.12: Average queue length per road direction for various flow ratios (info level = 0.4 and auto level = 0.4)

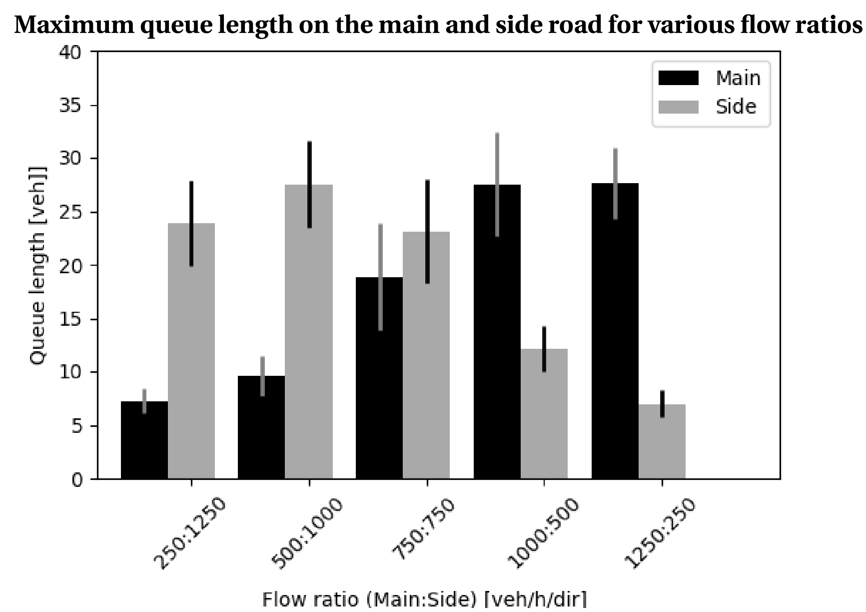

Figure 8.13: Maximum queue length per road direction for various flow ratios (info level = 0.4 and auto level = 0.4)

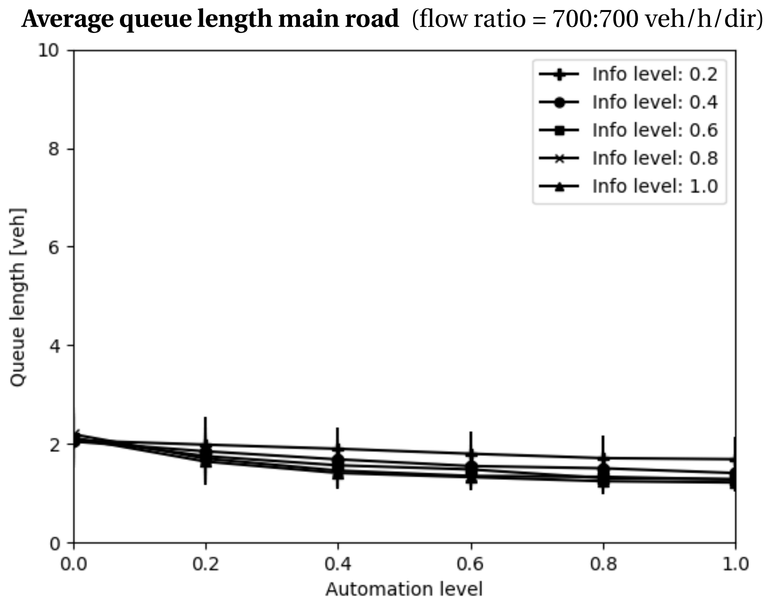

Figure 8.14: Average queue length on the side road for various information and automation levels (Main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

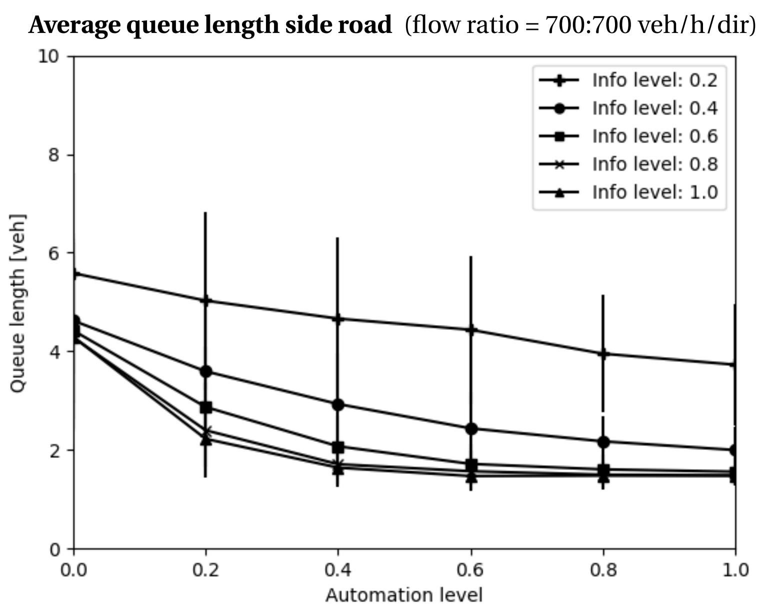

Figure 8.15: Average queue length on the side road for various information and automation levels (Main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

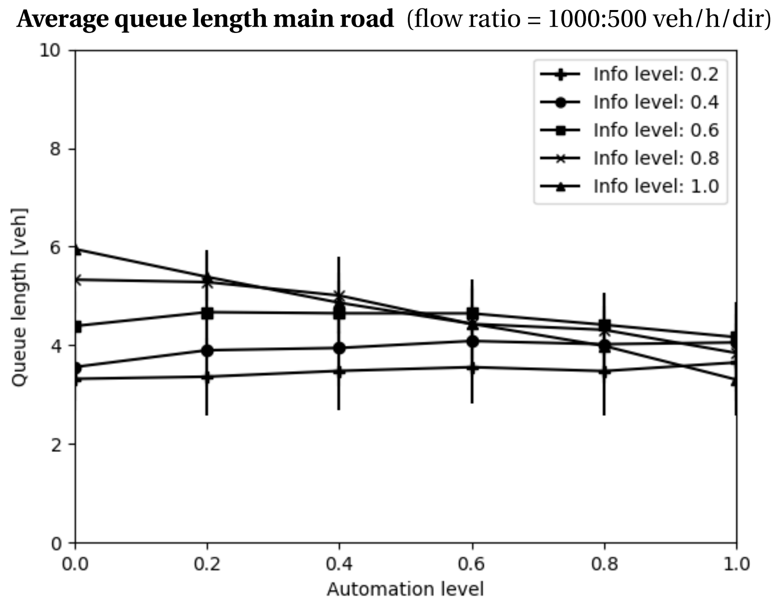

Figure 8.16: Average queue length on the side road for various information and automation levels (Main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

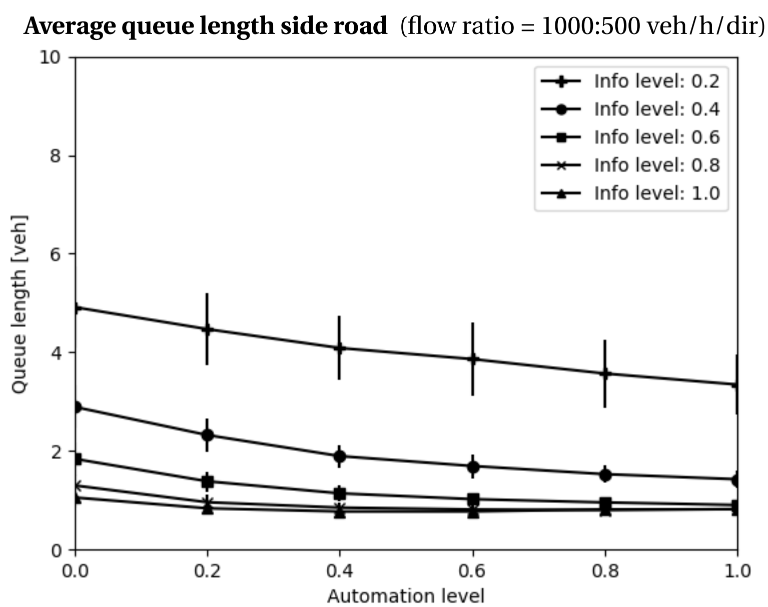

Figure 8.17: Average queue length on the side road for various information and automation levels (Main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

Average queue length on the main and side road for various flow ratios (green wave control)

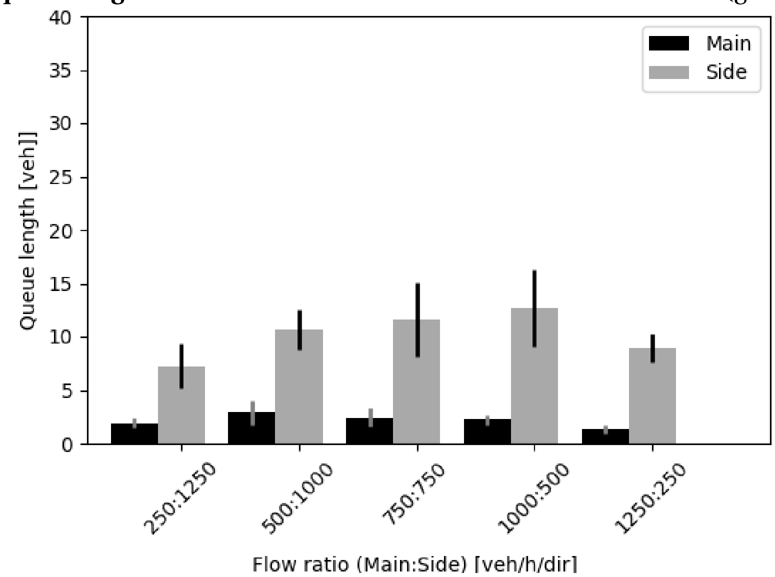

Figure 8.18: Average queue length per road direction in case of **green wave control**

Maximum queue length on the main and side road for various flow ratios (green wave control)

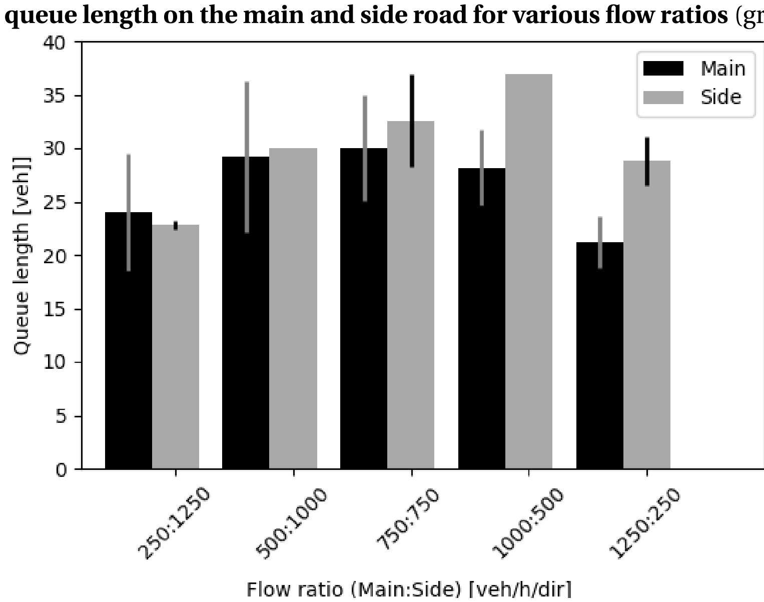

Figure 8.19: Maximum queue length per road direction in case of **green wave control**

8.1.4. Acceleration

This section provides the following figures of the simulation results regarding the average acceleration and average acceleration time of the vehicles in the network:

Figures 8.20 & 8.21

Average acceleration (fig. 8.20) and acceleration time (fig. 8.21) for various information and automation levels in case of a flow ratio of 700:700 veh/h/dir.

Figures 8.22 & 8.23

Average acceleration (fig. 8.22) and acceleration time (fig. 8.23) for various information and automation levels in case of a flow ratio of 1000:500 veh/h/dir.

Figure 8.20 presents the average acceleration over all the vehicles in the network. In order to ignore small speed variations due to driver imperfection, accelerations below a value of 1 m/s^2 are not taken into account. The figure shows that the average acceleration is dependent on both the information level and the automation level. Increasing the information or/and the automation level results into a higher average acceleration. The effect of the information level is very small for an automation level of 0.

Figure 8.21 shows the average share of the acceleration time of the total travel time over all the vehicles in the network for various information and automation level. The results show that the acceleration time is not significantly influenced by the automation rate for information levels 0.2 and 0.4. However, as soon as the information level gets higher, increasing the automation level seems to decrease the average acceleration time. The shortest average acceleration times are obtained for a information level of 0.2, and for a combination of both a high information and automation level.

Figures 8.22 and 8.23 show that the results are similar in case of a flow ratio of 1000:500 veh/h/dir. However, the shortest average acceleration times are in case of a information level of 1. In general, both the average acceleration and the average acceleration time seem to be lower in case of the unequal flow ratio of 1000 veh/h/dir on the main road and 500 veh/h/dir on the side road.

The figures show that the average acceleration and the average acceleration time in all cases is smaller when the green wave control is used.

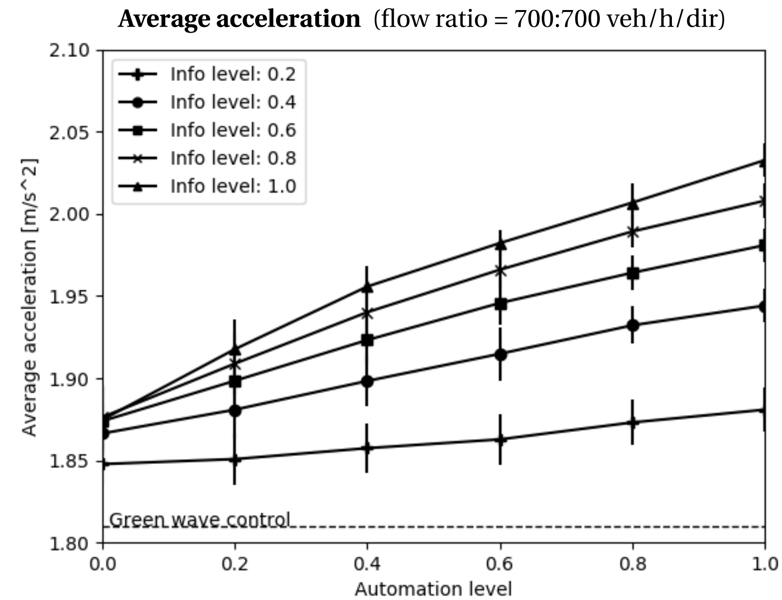

Figure 8.20: Average acceleration for various information and automation levels (main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

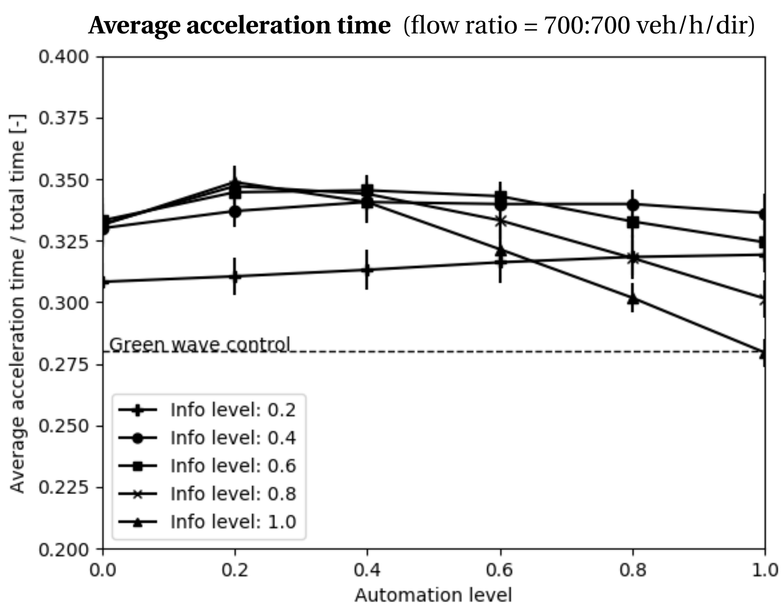

Figure 8.21: Share of the average acceleration time of the average total travel time over all vehicles for various information and automation levels (main flow = 700 veh/h/dir, side flow = 700 veh/h/dir)

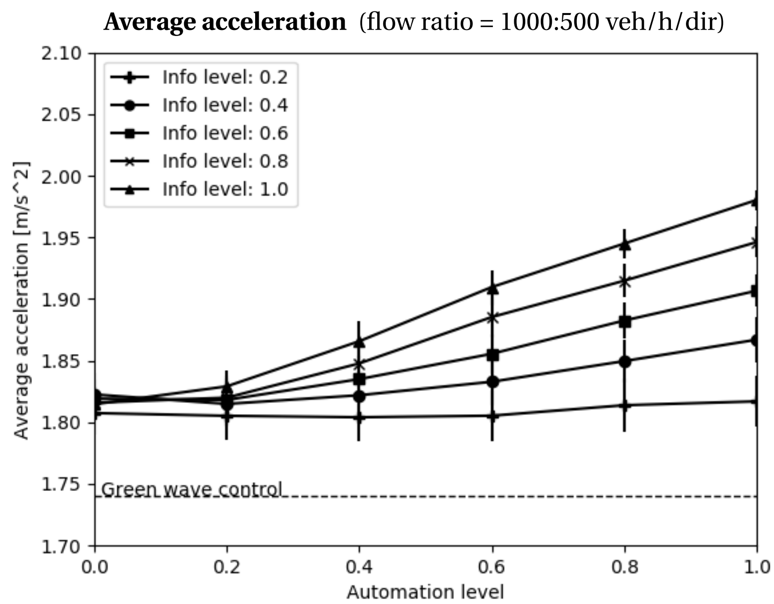

Figure 8.22: Average acceleration for various information and automation levels (main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

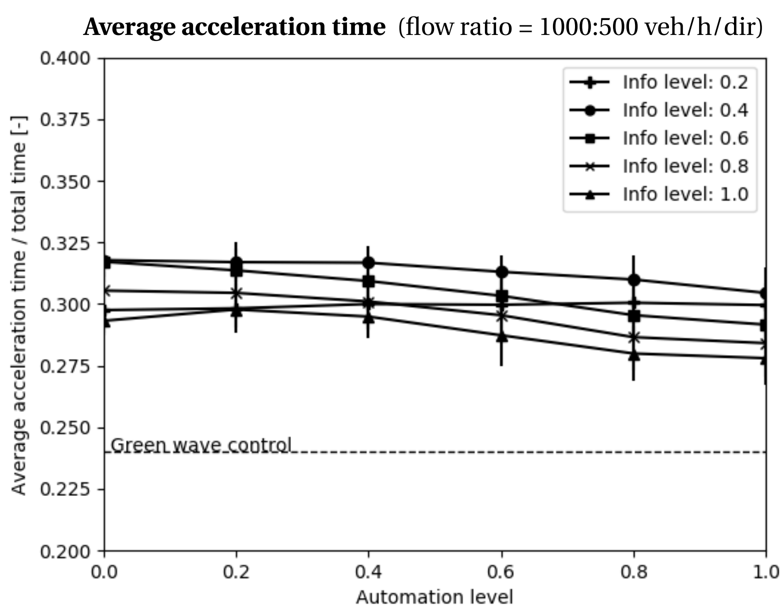

Figure 8.23: Share of the average acceleration time of the average total travel time over all vehicles for various information and automation levels (main flow = 1000 veh/h/dir, side flow = 500 veh/h/dir)

8.2. Implications

The previous section presented the results retrieved from the simulations. This section provides the implications of the obtained results. These implications are mostly based on different graphs from the simulation results. The implications are given regarding the average travel time delay, the green times, queue lengths and accelerations and decelerations.

8.2.1. Average travel time delay

The following implications can be made regarding the average travel time delay:

The proposed trajectory control decreases the average travel time delay

For different flow ratios and levels of information, the automation level seems to have a positive effect on the average travel delay. The higher the information level is, the stronger this effect is (fig. 8.1 & 8.2). It can also be obtained that the queue lengths are reduced in case there are more automated vehicles in the network (fig. 8.14 - 8.17). Together with the fact that the automation level does not affect the average green times (fig. 8.4 - 8.9), this implicates that the trajectory control results in a more efficient use of the green times, such that queues are reduced and the average travel time decreases.

A higher information level reduces the average delay in case the flows on the main and side road are equal

With a flow of 700 veh/h/dir on both the main and side road, a higher information level results in a lower average travel time delay (fig. 8.1). In case there are no automated vehicles (automation level = 0), the average delay for fully connected traffic is almost 20% lower than for traffic where only 20% of the vehicles are connected. However, in case the flows on the main and side road are unequal, vehicles have a higher average delay for high information levels and low automation levels (fig. 8.2). This is caused by the fact that a higher information level leads to shorter green times (fig. 8.4).

8.2.2. Green times

The following implications can be made regarding the green times:

Applying the proposed signal control strategy results in ratios between the average green times on the main and side road that correspond to the ratio in traffic flows, but not in direct proportion

The larger the traffic flow on the main road is in comparison to the traffic flow on the side road, the longer the green time is on the main road relatively to the side road. However, the ratio between the green times on both roads is not direct proportional to the ratio between the traffic flows: a flow ratio of 1:2 results into a green time ratio of 1:1.75 in case of an information level and automation level of both 0.4 (fig. 8.10). Higher information levels lead to an even less proportional ratio since the green time on both roads becomes close to 10 seconds (fig. 8.16 and 8.17). In case the green times are proportional to the traffic flows, the discharge rate and the queue expansion are also proportional to the traffic flows. In case of the proposed traffic control method with an information and automation level of both 0.4, the road with the highest flow gets relatively less green time which results into a faster expanding queue.

The average green time depends on the level of information and on the ratio between the main and side flow

The average green time seems not to be dependent on the automation level, but is dependent on the level of information: the more information the traffic controller receives, the shorter the average green time gets (fig. 8.4 - 8.9). If the level of information is high, the average green time is almost equal to the minimum green time, independent of the flow ratio. For low information levels, the average green time is dependent on the flow ratio. In these cases, the green time ratio corresponds to the flow ratio, however, not in direct proportion.

The fact that the green phases are very short in basically all cases is a logical result of the proposed signal control. As soon as the non-active road has a higher pressure than the active road, it will get green at the start of the next time slot. The pressure is based on the difference in approaching and exiting vehicles within the back-pressure range. The only exiting vehicles on the non-active road are the vehicles from the previous green phase. Therefore, it is very likely that the active road, where vehicles are currently departing from the intersection, has more exiting vehicles within the back-pressure range. Exiting vehicles decrease the back-pressure of a road and therefore, the back-pressure on the non-active road will become larger soon.

A low information level results into a higher average green time since the probability is larger that the traffic controller has a unrepresentative image of the traffic situation and that it decides not to switch while it actually should.

The automation level has no significant effects to the green times. The traffic controller decides to switch the signal based on the number of vehicles within the back-pressure range. In the simulated network, automated vehicles do not significantly stay longer outside this range or arrive earlier in the range, especially because the back-pressure range is almost as large as the block length. However, in networks with longer road lengths and/or a shorter back-pressure range, automated vehicles might decelerate to queuing speed already before they enter the back-pressure range. In this case, this will have an effect on the back-pressure calculated by the traffic controller and, therefore, will also have an effect on the average green time.

Traffic on the main road encounters relatively longer green times due to the signal control compared to traffic on the side roads

In case the flow ratio is equal, the controller gives a longer green time on average to the main road than to the side road. The main road also receives a longer green time for the 250:1250 veh/h/dir and the 500:1000 veh/h/dir ratios than the side road receives for the 1250:250 veh/h/dir and 1000:500 veh/h/dir ratios (fig. 8.10). This results into shorter queues (fig. 8.18) and less travel time delay (fig. 8.3) for traffic on the main road. The cause can be found in the back-pressure calculation per direction: since the main road has two lanes where the side road only has one, the back-pressure on the main road becomes twice as high. Therefore, the controller gives longer green times to the main road, where the discharge rate relatively to the traffic demand is equal for both direction. This results into an advantage for the traffic on the main road. A further discussion regarding this 'unfair' advantage for traffic on the main road will be given in chapter 9. It can be obtained that a flow ratio of 250:1250 veh/h/dir has a flow on the side road which is so much higher than the flow on the main road, that this unfair advantage for traffic on the main road is overruled since in this case the back-pressure of the side roads becomes larger than the back-pressure of the main road and longer green times are given to the side road (fig. 8.3 and 8.10).

8.2.3. Queue lengths

The following implications can be made regarding the queue lengths in the network:

Long queues mostly occur at the first traffic signal traffic encounters

The average queue length in case of an information and automation level of both 0.4 seems to get rarely longer than 5 vehicles (fig. 8.12), but the maximum queue length can get up to 30 vehicles (fig. 8.13). These maximum queues can only occur on the approaching roads of 300 metres in the simulation, which are the only ones that provide enough space for 30 vehicles. Since the average queue length over the whole network is much shorter than the maximum queue length, the queues at the other intersections have to be much shorter.

Queue lengths in different scenarios differ significantly corresponding to the flow ratio
Although the back-pressure algorithm is known for being a control strategy that aims on equalling the queue lengths in a network, the difference in queue length between the main and side roads is significantly depending on the ratio in traffic flows between the main and the side road. For all cases, the road with the highest traffic flow has the longest average and maximum queue length (fig. 8.12 & 8.13). In case the flows are equal, the largest average and maximum queue occurs on the side roads, which is caused by the unbalanced average green time per direction (8.10).

8.2.4. Acceleration and deceleration

The following implications can be made regarding the accelerations and decelerations in the network:

The proposed trajectory control has a negative effect on the amount of accelerations and decelerations in the network
The average acceleration increases up to 9% as the number of automated vehicles in the network increases (fig. 8.20 and 8.21). However, the average acceleration time over the total time in the network of the vehicles decreases for high penetration rates of automated vehicles. This implicates that the automated vehicles accelerate and decelerate faster but over a shorter time than the humanly controlled vehicles in the simulation. This results into more discomfort and emissions.

8.2.5. Comparison with the green wave control

Comparing the proposed traffic control with the green wave control gives the following implications:

The green wave control strategy leads to larger maximum queue lengths than the proposed traffic control method
Long maximum queues occur in case of the green wave control (fig. 8.19). The green times are very short (fig. 8.11), which results into relatively much yellow time. The discharge rate becomes lower than the traffic demand, which creates the long queues at the first intersection the vehicles on each road encounters.

The green times of the green wave control strategy are more in proportion to the flow ratio compared to the green times of the proposed traffic control
The ratio between the green time on the main road and the green time on the side road in case of the green wave controlled is determined based on the ratio of the flows. That is why this ratio between the green times matches perfectly the flow ratio (fig. 8.11). This is not the case if the proposed control method is applied: for a flow ratio of 250:1250 veh/h/dir and both an information and automation level of 0.4, the ratio between the green times is 10:28 seconds (fig. 8.10), which are not in direct proportion.

The green wave control results in lower and shorter accelerations compared to the proposed control method
In all cases, the average acceleration (fig/ 8.20 and 8.22) and the acceleration time (fig. 8.21 and 8.23) are lower in case of the green wave control. Thanks to the green wave, most of the vehicles on the main road only have to decelerate in front of the first intersection, but can continue their trip not hindered by any other traffic signal.

8.3. Conclusions

This chapter presented the obtained simulation results and their implications. The average travel time delay, average green time, average and maximum queue lengths, and average acceleration and acceleration time are retrieved from the simulation to get insight in the performances of the proposed traffic control method. It can be concluded that applying the proposed control method leads to:

- relatively short green times, which get even shorter as the controller receives more information from the traffic;
- green times corresponding to the traffic demand, although not in direct proportion;
- relatively longer green times on the main road than on the side road;
- relatively long queue lengths at the first intersections that traffic encounters and short queues at other intersections;
- longer queues on the roads with the highest traffic demand;
- higher and shorter average accelerations and decelerations.

Compared to the green wave control, the proposed control method results in shorter queues and lower average travel time delays. The higher the information and automation levels, the lower the average delay gets. Especially the trajectory control decreases the average travel time delay significantly. The green wave control performs better than the proposed control method when it comes to the ratio between the green times of both roads and the coordination between the intersections. This coordination results in less accelerations and decelerations and shorter queue lengths at the intersections on the main road, except for the first intersection the vehicles encounter: at this location a long queue will form which becomes longer than the maximum queue in case of the proposed traffic control method due to the shorter green time.

9
Discussion

In previous chapters the proposed traffic control method was introduced and tested. Before the conclusions of the research will be presented in chapter 10, this chapter will first provide a discussion regarding the proposed traffic signal control and the trajectory control, the simulation including the simulation results and the future perspective regarding vehicle automation. The conclusions and recommendations of the report will be based on the simulation results while taking the points of discussion of this chapter into account.

The first sections of this chapter contain the discussions about the proposed traffic control method, divided into the discussions regarding the signal control (section 9.1) and regarding the trajectory control (section 9.2). Section 9.3 presents the discussions regarding the simulation and the simulation results. A discussion about the future perspective of vehicle automation will be given in section 9.4. Finally, section 9.5 provides the conclusions of the chapter.

9.1. Traffic signal control

This report proposes a traffic signal control that is based on the original back-pressure algorithm and is adapted to a partly connected and automated environment. This section give the discussions regarding the assumptions, adaptations, limitations and possible improvements of the proposed strategy.

9.1.1. Queueing vehicles

In the proposed algorithm, the back-pressure of a phase is calculated in a different way than in the original back-pressure algorithm. Where queue lengths are taken into consideration in the original algorithm, in the proposed method the back-pressure is calculated taking the waiting vehicles on a link into account, which are considered to be all the vehicles with a speed that is lower than 15 km/h, located within the back-pressure range (see chapter 4.2). A queue in a traffic network normally appears right in front of the traffic signal, but queuing automated vehicles could be anywhere on the link. In the proposed method, the distance of a vehicle to the intersection is not taken into account to calculate the pressure on a link. However, adding weight to vehicles depending on the distance to the intersection, for both approaching and leaving vehicles, tackles the problem of the (unfair) equal contribution to the back-pressure of vehicles with a different distance to the intersection and might result in a better performance of the signal control method. In that way, vehicles that are further away from the intersection will have less influence on the back-pressure than vehicles that are closer by.

9.1.2. The discharge rate in the back-pressure calculations

In the simulated network, the main road consists of one lane per direction, which makes a total of two lanes. The side road only consists of one lane. The back-pressure of the main road is calculated by the sum of the pressures on both directions, which leads to relatively higher back-pressures on the main road: with the same amount of queuing vehicles per lane on the main and side roads, the green time needed to discharge the vehicles is equal for each lane. The total amount of vehicles on the main road will be twice as high and the discharge rate per lane is equal to the side road. However, the back-pressure of the main road is in this case twice as high as the back-pressure of the side road, which means that the main road is in favour. The simulation results show that the green time is relatively larger at the main road and the queues and average delays are shorter.

In the original back-pressure approach, the back-pressure of one movement is calculated by multiplying the difference in queue length of a road with the discharge rate. This leads to relatively higher back-pressures for roads with a larger discharge rate. This measure to optimize the throughput in a network results in the simulated network of this research in relatively longer green times on the main road. However, the fact that the main road is in favour might always be desired, where for example in this research the main road and side road are considered to have equal importance.

An interesting alternative calculation of the back-pressure of a road is to divide the difference in queue length by the discharge rate of the road. In this way, relatively longer green times will be given to the roads with lower discharge rate which will lead to a lower total throughput of the intersection, but will result into a control sequence that satisfies the traffic demand.

In cases that one of the roads does have more priority, this can also be achieved on a more controlled way by implementing a switching threshold that is used when the back-pressures of the main and side road are compared. In this way, the back-pressure of the road with low priority has to have a back-pressure that is ζ_{priority} times higher than the back-pressure of the road with high priority, where ζ_{priority} is the priority threshold value.

9.1.3. Back-pressure range

Since in a partly automated environment queues will be formed differently and will even be avoided in some cases, the back-pressure range was introduced in section 4.2. Where queueing automated vehicles could be located anywhere on a link, the back-pressure range ensures that vehicles within an equal range from the intersection on both the upstream and the downstream link are taken into account only. The first point of discussion is whether this back-pressure range is indeed a suitable and well-performing solution. The second question is what the optimal radius is of the back-pressure range. Also an alternative solution will be discussed in this section.

The original back-pressure algorithm compares the queue length upstream of an intersection with the queue length downstream. This signal control aims at balancing the queue lengths in a network. The proposed control, including the back-pressure range, does not always include the complete queues upstream and downstream of the intersection and balances only the queueing vehicles within the range. Queueing vehicles more often occur close upstream of the intersection than directly downstream of the intersection, especially in scenarios with a low penetration rate of automated vehicles and in case a clearance space directly after the intersection is implemented (see chapter 5). Queuing vehicles downstream are more often not taken into account, which means that the downstream queue has less influence on the back-pressure. Therefore, the control strategy will not balance all the queueing vehicles on the upstream and downstream links of the intersection. However, the control strategy will still react on spillback as soon as the queue downstream reaches the back-pressure range.

The radius of the range has a significant influence on the back-pressure calculations. Using a short range, the probability that there are queuing vehicles on the downstream link that are taken into account is relatively low, especially when also a clearance space is implemented. In this case, the back-pressure would be more depending on the upstream traffic conditions. Using a large back-pressure range, for example that large that also the neighbour intersections are located within the range, this will result in a totally different traffic signal sequence as the total queues of the neighbour intersections are taken into account as well. Depending on the range and the block length, the downstream intersection might in that case contribute more to the back-pressure than the upstream intersection, especially in case only the upstream link of the downstream intersection and the downstream link of the upstream intersection are located within the back-pressure range. Next, differences in road lengths are not taken into account for the back-pressure range. This might lead to a comparison in back-pressure that is beneficial for a certain direction, e.g. when the back-pressure range is 100 metre and downstream roads of the intersection have different lengths of 150 metre and 100 meter. The queue on the first 50 metre on the downstream road of 150 metre is not taken into account for the back-pressure and therefore this direction will have a lower back-pressure. To avoid these second-order effects, the range should be chosen smaller than both the upstream and downstream link of an intersection. After this research conclusions cannot be made about the optimal back-pressure range. Important is to be aware of this significant influence of the back-pressure range on the traffic control method.

An alternative for the back-pressure range is to take all the queuing vehicles on the upstream and downstream link into account for the back-pressure calculation and give the vehicles a certain weight depending on the distance to the intersection they are approaching. Implementing and testing this alternative is included in the recommendations of this report (see chapter 10).

9.1.4. Intersection throughput

The throughput of the intersections is dependent on the length of the green times and the time loss due to yellow phases. The shorter the green times, the more yellow phases there are on average per unit of time, the larger the relative loss due to the yellow phases is and the smaller the throughput is of an intersection. To determine the minimum average green time needed to satisfy the traffic demand, lets assume that the discharge rate at the intersection is equal to the road capacity of 1600 vehicles per hour. To discharge 1500 vehicles per hour, $\frac{1500}{1600} \cdot 3600 = 3375$ seconds of green time per hour are needed. That means that the total duration of the yellow phases in one hour cannot be larger than 3600-3375 = 225 seconds. Given that the yellow time per cycle is 6 seconds (2 yellow phases of 3 seconds), the maximum number of cycles per hour is 37 cycles ($\frac{225}{6} = 37.5$). 37 cycles are in total $37 \cdot 6 = 222$ seconds, which means the total green time is in this case $3600 - 222 = 3378$ seconds per hour. The minimum average green time therefore is $\frac{3378}{37 \cdot 2} = 45.6$ seconds. The actual minimum average green time will be even larger since the assumption that the discharge rate equals the road capacity is a very optimistic assumption. Since in all the simulations the average green time turns out to be not larger than 28 seconds (fig. 8.10), the total discharge rate of an intersection will not satisfy the traffic demand. Therefore, queue lengths will grow as long as the traffic demand stays on this level, using the proposed traffic control method. It can be concluded that the traffic signal method results into green times that are too short to satisfy the demand. Therefore, queue lengths will grow over time until the traffic demand decreases. The proposed method would cause spillback towards surrounding intersections when the traffic demand stays at high level for a long time (see section 9.1.7).

9.1.5. Coordination between intersections

Because of the fact that limited computational power is often a main challenge when it comes to implementing traffic control solutions that react to live traffic conditions in a network, a decentralized solution is proposed in this report. A decentralized solution however has the downside that there is no coordination between intersections. The simulation results show that the coordination between intersections by implementing a green wave decreases accelerations and decelerations. However, simulation results also show that there is a large space for improvement when it comes to the trajectory control regarding the accelerations and decelerations of automated vehicles. Coordination between intersections might be an interesting way to reduce emissions. Thinking ahead, if the exponential increasing trend of the available computational power over the last years will continue on the same rate, this might not be the limiting factor in the future as it is nowadays and centralized solutions become more favourable.

9.1.6. Transparency and predictability

The transparency of the proposed traffic control method is limited. The transparency of a traffic control method describes the level of predictability of the method and to what extent the decisions made by the traffic controller are explainable. Since the proposed method reacts to the live traffic conditions, the traffic signal state in a further future than a couple of seconds is unknown. Only general conclusions can be made about how the signal control reacts to a certain traffic state. The signal control is based on both the adapted back-pressure algorithm and the algorithm of the predicted departure times of the different types of vehicles. Since both these algorithms are rather complex in comparison to traditional methods, it is more difficult to explain every decision of the controller. The transparency of a signal control strategy is important for different reasons. The road operator is responsible of the functioning of the signal control and therefore demands a transparent solution. In case of malfunctioning of the signal control, transparency gives the opportunity to find and assess the problem and to be able to improve the control strategy.

The predictability of the signal control also affects the performances of the automated vehicles in the network. Automated vehicles are able to adapt their speed in a more efficient way the more predictable the moment of switching of the traffic signal is. The proposed method decides to switch or not at the beginning of the next time slot of 5 seconds later. Therefore, automated vehicles only know the signal state maximal for the next 10 seconds, for example: an automated vehicle knows at t = 0s that the traffic controller decides not to switch at t = 5s, and the earliest possible switch will be at t = 10s. It is not sure if the controller will switch at t = 10s, it is only sure that the controller will not switch any earlier. One solution to improve the increase the time automated vehicles have to adapt their speed may be the implementation of a dynamic slot time, described in section 9.1.8.

9.1.7. Spillback

In the simulations, no queue occurred at any intersection that reached the upstream intersection. Results show that queues between the intersections on the main road are kept very limited because the first intersection that the vehicles encounter functions like a bottleneck and decreases the vehicle flow at the next intersections to a level equal to the throughput of the first intersection and, therefore, also more or less equal to the throughput of the other intersections. The result is that the queue length at the first intersection grows over time. Although there is no spillback obtained in the simulation, the long queues at the first intersections might in real life result into spillback when there is an intersection upstream. Therefore, the proposed control system avoids spillback within the controlled area, but might cause spillback in the intersection around the area if the traffic demand overtakes the discharge rate at the intersection.

9.1.8. Dynamic slot time

Instead of a fixed slot time, a dynamic slot time could be implemented. A dynamic slot time results in a lower total travel delay compared to a fixed slot time [51]. An additional benefit of dynamic slot times is the fact that the length of a green time is determined at the beginning of that green time. This means that the end of green time is known from the start of the same green time. Automated vehicles can adapt their speed in such a way that the green time is used optimally. The downside of dynamic time slots is that it requires a prediction of the maximum queue length in the to be activated phase. Another benefit of a fixed slot time is that it checks the traffic condition every slot time. Where in general the length of fixed slot times are chosen small (i.e. 5 seconds), this solution responds better to changing traffic conditions. In this report an adapted fixed slot time is proposed (see section **??**).

According to the original back-pressure algorithm with a dynamic slot time, the length of the slot time is related to the difference in back-pressure between phases as well as the upstream queue length of the to be activated phase. Note that in case of a dynamic slot time, the phase duration consists of only one time slot where in case of a fixed slot time a phase consists of several time slots. The dynamic slot time is calculated according formulas 9.1 and 9.2.

$$T_{\text{slot}}(t) = \max \left\{ \begin{matrix} \tau_{\text{slot,min}} \\ \min\left\{ \tau_{\text{slot,max}}, \tau_{dyn}(t) \right\} \end{matrix} \right\} \tag{9.1}$$

$$\tau_{\text{dyn}} = a(\ B_{\text{act}}(t) - B_{\text{non}}(t)\ )\ Q^{\text{up}}_{\text{act}}(t) \tag{9.2}$$

where:

$T_{\text{slot}}(t)$ = Slot time at time t [s]

$\tau_{\text{slot,min}}$ = Minimum slot time [s]

$\tau_{\text{slot,max}}$ = Maximum slot time [s]

$\tau_{\text{dyn}}(t)$ = Dynamic part of slot time at time t[s]

$B_{\text{act}}(t)$ = Back-pressure of active phase at time t [veh^2/s]

$B_{\text{non}}(t)$ = Back-pressure of active phase at time t [veh^2/s]

$Q^{\text{up}}_{\text{act}}(t)$ = Maximum number of queuing vehicles in the to be activated phase at time t [veh]

a = Scale factor [s^2/veh^3]

As can be seen in equation 9.2 the maximum number of queuing vehicles in the to be activated phase is used to calculate the dynamic part of the slot time. Since the slot time is calculated at the beginning of the to be activated slot, it is only possible to make a prediction of this number of queuing vehicles. This prediction would need several assumptions such as the arrival and discharge rate of each queue during the next phase. Since the length of this next phase is needed to calculate the back-pressures and the actual required phase length, this solution is more complicated than the fixed slot time approach.

9.2. Trajectory control

The main goal of the trajectory control is to use the green phases optimally while limiting the vehicle accelerations and deceleration as much as possible. The simulation results show that the proposed trajectory control indeed optimizes the use of the green time. However, there is still room for improvement, especially regarding vehicle accelerations. It has to be taken into account that the optimization of the trajectory control might require a more complex and less transparent algorithm. This section discusses the proposed trajectory control, focussing on the simplified fundamental diagram used, the traffic safety, the accelerations and decelerations and the minimal gap between two automated vehicles.

9.2.1. Assumptions regarding the fundamental diagram

Several assumptions have been used in order to simplify the calculations in the proposed algorithm. For the calculation of the expected departure times and speeds, a triangular shaped fundamental diagram (FD) is used (see chapter 3). However, this is a simplified shape of the actual relationship between the traffic density and traffic flow on a road. Measurements in real traffic show that especially the data points in the congested branch of the FD are more spread out instead of being located on one straight line as the triangular shaped FD suggests [23]. Research also shows that congestion causes a considerable drop in the road capacity as drivers maintain a larger headway when they leave congestion than before they enter congested traffic [19]. Next, anticipation of drivers could have large effects on the traffic conditions at the congestion branch of the FD [52]. Drivers can decelerate earlier as soon they see a red signal in the far distance, or accelerate faster when they are queueing and the traffic signal just turned green. In the first case, the congested branch of the FD will be actually lower than as displayed in the triangular shaped FD (arrow 1 in figure 9.1) and will be located higher in the second case (arrow 2 in figure 9.1).

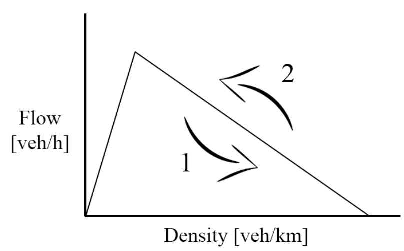

Figure 9.1: Effects of driver anticipation to the congested branch of the fundamental diagram

For these reasons, using the triangular shaped FD will result in densities, flows, headways and expected departure times and speeds which differ from the actual headways and departure times and speeds. Furthermore, since the departure time of a vehicle is basically the departure time of the first vehicle on the same link plus the sum of the time headways of the other vehicles in front of the vehicle of interest, the error in this prediction will also be the sum of all the errors of the vehicles in front. However, this means that the error is smaller when a vehicle has less vehicles in front and predictions will be better for the vehicles that are closest to the intersections, which will also be the first vehicles to cross the intersection.

The expected departure times and speeds, calculated using the triangular shaped FD, are used to predict the back-pressure at the next time slot and to control the automated vehicles. The errors in the expected departure times are expected to be too small to significantly influence the back-pressure. The back-pressure is calculated out of the number of vehicles on a link within a certain range of the intersection. The back-pressure on a link therefore will only have an error when a vehicle entered or exited the link just before the next time slot where it was expected to enter or exit just after the next time slot and the other way around. The chance of this happening is not only small, but the effect on the back-pressure would be very limited. Errors will have larger effects on the trajectory control. Automated vehicles are controlled in such a way that they will depart from the intersection following the vehicle in front as close as possible to optimize the total number of vehicles that can depart from the intersection in per unit of green time. Where the expected departure time and speed of a vehicle far away from the intersection will contain a significant error, this error will get smaller as soon the vehicle gets closer to the intersection and less vehicles are in front. The trajectory of an automated vehicle gets updated and improved every time step. Finally, the automated vehicle will depart from the intersection at a time that is not significantly different than the desired departure time.

For these reasons, it is expected that the negative effects of using the triangular shaped FD will be limited and for simplicity, this shape is used for the calculation of the expected departure times and speeds.

9.2.2. Traffic safety

The trajectory control has a limitation when it comes to traffic safety. The proposed control strategy enables automated vehicles to cross the intersection exactly at the time that the traffic light switches to green and without any speed reductions. This not only shortens the clearance time of the intersection, but might be unexpected for other traffic as well. To improve traffic safety, a larger yellow time could be used in case that the first approaching vehicle is an automated vehicle, and/or automated vehicles can be controlled in such a way that they cross the intersection not exactly at switching to green, but after a certain safety margin.

9.2.3. Accelerations and decelerations

As can be seen in the speed and acceleration plots in appendix A.1 and as is discussed in chapter 8, the automated vehicles use higher accelerations and decelerations than necessary. In the proposed trajectory control, vehicles are controlled to accelerate maximal (but still on a comfortable level) in case they are driving too slow and decelerate maximal in case they are driving too fast. A solution is to set the acceleration or deceleration to the desired change in speed over a certain time interval. In this way, the accelerations and decelerations will be smaller and the oscillation of the speed around the desired speed will be decreased. According the acceleration plots for different time steps in appendix A.1, the length of the time step does especially make a difference in the length and frequency of the acceleration peaks and not in the height of the acceleration that is given to the automated vehicle. Therefore, changing the time step length has influence on the trajectory but will not be necessarily be a solution for the problem of the relatively high accelerations. The focus should be on limiting the accelerations in the trajectory control.

9.2.4. Minimal gap

A benefit of automated vehicles that is not taken into consideration for the proposed trajectory control is the fact that speed changes of automated vehicles are known such that the gap between two successive automated vehicles can be kept smaller to increase the capacity flow of a road and the use of the green time. However, this is only possible if the communication is continuously guaranteed and if the information provided by automated vehicle is accurate enough.

9.3. Simulation

A traffic simulation is used to test the proposed control method. Many assumptions and simplifications were made to set up the simulations. In this section the simulation is discussed, regarding the vehicle generation, the traffic mixture, the lack of turning vehicles in the simulation, the simulated base case, and several other assumptions.

9.3.1. Vehicle generation

For the vehicle generation, it is assumed that vehicles enter the simulated network following a Poisson process, in which the interval between a vehicle and the next vehicle always follows out of the same distribution. Consequently, the vehicles enter the network at the same average rate over the whole simulation. However, in real urban traffic we often obtain that vehicles arrive in waves, due to upstream traffic signals, or to difference in speed that drivers prefer (slower vehicles will create a platoons of vehicles behind them). On the one hand, this phenomenon could be beneficial for the traffic control method, where a wave of vehicles will result into a back-pressure that is suddenly higher. The controller decides to give green to the direction the wave of vehicles is coming from, such that the vehicles will depart from the intersection in a high discharge rate. On the other hand, the prediction of the back-pressure, based on the average traffic demand at a certain time of the day, will have a larger error.

9.3.2. Lower boundary of the back-pressure

One of the adaptations of the original back-pressure algorithm is the lower boundary of 0 for the back-pressure, see chapter 7. The lower boundary is introduced to limit the benefit for the side roads of having no queuing vehicles on the downstream link. However, this might not be the case when the proposed method will be implemented in real traffic. In case there is also a downstream intersection on the side roads, this lower boundary should not be implemented. Without this boundary, negative back-pressures can occur when there are more queuing vehicles on the downstream link than on the corresponding upstream link. The traffic controller therefore can decide to give green to the other direction to avoid the detected downstream queue of getting even longer.

9.3.3. Traffic mixture

The simulation proposed in this report is a very simplified model of a real traffic network. Where real traffic consists of different transportation modes, the traffic in the simulation only consists of car traffic. Therefore, the simulation results will differ significantly from the results the proposed method will have in real traffic. Traffic only consisting of cars with more or less the same acceleration and deceleration is beneficial when it comes to creating and controlling platoons of vehicles. Where in the used traffic simulation platoons are created by decelerating automated vehicles, it is expected that platoons in case of a mixture of different modes will also created by slower driving or slower accelerating vehicles. This will make it more difficult to control complete platoons in order to use the green times optimally.

It is possible to control other transportation modes using the same algorithm by implementing the right characteristics for each mode, however, results will be improved when the control method would include a certain strategy to deal with different traffic modes. For example, different vehicle types in the platoon can be taken into account to adapt the acceleration and deceleration of the leading vehicle to the acceleration of the other vehicles such that the platoon will not fall apart.

It is possible to predict the trajectories of cyclists and to include them in the back-pressure algorithm. However, this will probably result in a very complex traffic control solution and therefore, having a separated green phase for cyclists after a certain cycle length, based on the predicted demand, might be a more simple and cheap option. This separated green phase could be used for pedestrians as well.

9.3.4. Turning vehicles

Turning vehicles are not included in the traffic simulation, but occur in real traffic networks. Although the back-pressure for each movement can still be determined according the proposed methodology, route choice prediction will be a challenge. In the simulation the controller knows exactly the planned route of each vehicle, where in real traffic it is unknown what direction a vehicle will take until it chooses the right approach lane in front of the traffic signal. However, if route choices of the automated and connected vehicles are known, the signal control could use this information to improve its control sequence, especially in case of high shares of automated and connected vehicles.

9.3.5. Base case

Section 6.4 introduced the base case that is used to compare the simulation results of the proposed traffic control method with. In this base case there are no automated or connected vehicles and the traffic signals are coordinated based on a green wave in the two directions of the main road. There is only one length of green time possible when it comes to a green wave into two directions and for the simulated network, this green time is rather short. Shorter green times results in more yellow phases on average per unit of time and therefore less green time per unit of time. An important question is rather the base case is a good method to compare the proposed method with. Since the green wave approach is expected to be very well functioning in a traffic corridor with more or less equal block lengths it is interesting to compare its results with the proposed method. However, since the proposed method is a decentralized method, it might also be interesting to compare it with another decentralized method that already exists, such as a dynamic control approach with detectors in the roads.

The very poor performances of the signal control method in the base case are a next point of discussion. Realizing a green wave in two directions result in relatively very small green times, as can be seen in section 8.1.2. In some cases, the green time for one direction is only 2.5 seconds, which is just enough for only one vehicle to depart. In that case, the green time for the other direction is 12.5 seconds. One cycle is the sum of both green times plus the two yellow phases of 3 seconds each, which will equal 21 seconds. This means, per hour there are $\frac{3600}{21} = 171.4$ cycles. If only one vehicle is able to depart per cycle, this will not satisfy the traffic demand of 250 vehicles per hour and will result in a unlimited growing queue length. Also for other flow ratios the discharge rate does not satisfy the traffic demand. It can be concluded that this control system is a very bad option for this traffic network. The performances of the method in the simulated network are considered to be very poor. Therefore, by comparing the proposed back-pressure signal control method with this base case, the results of the back-pressure method will seem very good. In further research however, the method should be compared with a better functioning signal control method. Again, a dynamic control approach with road detectors might be a good option.

9.3.6. Time step

The time step of 0.5 seconds that is used in the simulation is rather large when it comes to the trajectory control. After each time step, the controller sets new speeds to the automated vehicles. Depending on the speed, a vehicle will accelerate or decelerate as soon as possible to the desired speed and will only accelerate slowly if the vehicle is exactly following the smooth trajectory. A larger time step might result into a trajectory that is oscillating around the desired smooth trajectory (see section 9.2.3) with more deviations, which results into more emissions and passenger discomfort.

The time step does not have a significant influence on the signal control, since the traffic controller decides only every slot time to switch or not. The slot time length used in the simulation is 5 seconds.

9.3.7. Simulation length

The simulation length is the real time duration of the simulation. Network wide traffic effects will occur over time, which means that the results of a longer simulation times provide better insight in the network wide traffic effects of the proposed control method. At the other side, a longer simulation length requires more time to simulate. Since many different simulation have to be made, the simulation length has a big influence on the total time the simulations take. In this research, 15 minutes are simulated, which is sufficient to get insight in the network wide traffic conditions. The warming-up time is not included in these 15 minutes.

9.4. Future perspective regarding vehicle automation

This report proposes methods to control traffic in a partly connected and automated environment. First of all, the automated vehicle that is controlled by an external traffic controller does not exist in current traffic and therefore, it is only a prediction that it actually will appear in future traffic. Moreover, there is no existing traffic network in which the traffic signal control systems reacts to the live information they receive from connected vehicles. Therefore, one of the only ways to find the effects of automated and connected vehicles on the network wide traffic conditions, is by creating a simulation and proposing a method to both control the traffic signals and the automated vehicles. Since the final results on the traffic conditions will be depending significantly on these proposed methods, it is not possible to find a detailed comprehensive answer to the question what the effects of automated and connected vehicles in general are on network wide traffic conditions.

A point of discussion is to what extent the assumptions regarding future traffic composition in this report match the reality. Questions that will raise are: will future traffic indeed consist of automated vehicles? When can we expect a significant share of automated vehicles in traffic? Will these vehicles indeed communicate with a central traffic control or would they operate like autonomous vehicles, without any connectivity?

On 7 November 2017, Waymo announced to be the first company to introduce their self-driving vehicles to public roads without the need of a person on the driver seat to take over in case of an emergency [44]. Although this will still be part of the test phase of the vehicles and the vehicles will only be operating in the city of Phoenix (USA), this is an import step forwards in the vehicle automation technology. It means that Waymo claims to guarantee a sufficient safety level of the vehicles. It also means that the vehicles can start 'practising' in real traffic. Using artificial intelligence, the self-driving vehicles teach themselves how to drive by practising in virtual reality, (fake) recreated cities and from now on, in real cities. Most car manufacturers are aiming to launch their self-driving vehicle on the market by 2020 [4]. A significant share of self-driving vehicles in traffic is not expected earlier than 2030.

One may also notice that the self-driving vehicles that are currently being developed are mainly focussed on navigating through traffic without any form of connection with other vehicles or infrastructure [38][29][45][13]. At the moment automated vehicles, which are connected, show up mainly in research papers. The question is if the currently developed autonomous vehicles will once provide communication to become automated. The automated vehicle would be the preferred option for society, since communication between vehicles and infrastructure could be more efficient regarding environment, traffic flow and traffic safety [33]. An automated environment requires a much greater degree of coordination between manufacturers and authorities [28]. Whether future traffic consists of automated vehicles and/or autonomous vehicles might be dependent of the extent of stimulation by governments for (or against) automated vehicles. Since theoretically automated vehicles would be the preferred option for society, this vehicle type might play an important role in future traffic.

It is clear the there are several perspectives possible in the future. This report will not go into more detail of these different perspectives, but will consider only one of the most likely situations in the near future: traffic consisting of conventional, connected and automated vehicles. Besides, well functioning autonomous vehicles are expected to behave similarly to humanly controlled vehicles, follow the same types of traffic instructions (traffic signs and signals), and therefore, are not able to be controlled by a central traffic controller and are expected not to have a significant influence on traffic compared to connected and automated vehicles.

9.5. Conclusions

This chapter provided the discussions regarding the proposed control method, the simulation and the future perspective of vehicle automations, which are all based on many assumptions. Several conclusions can be made regarding the discussions in this chapter.

The discussion points regarding the proposed traffic signal control are:

- The back-pressure range used for the determination of the number of vehicles that are taken into account for the back-pressure demands for a better alternative. An interesting alternative is adding a certain weight to vehicles depending on the distance to the intersection.
- The signal control, based on the original back-pressure theory, provides relatively longer green times to roads with a larger discharge rate. In the simulation of this research this results in relatively longer green times on the main road.
- The back-pressure range has a significant influence on the performance of the signal control. It is debatable whether the introduction of a back-pressure range leads to the desired signal sequence and what the optimal radius is for the back-pressure range.
- The throughput of the intersections in the simulations is lower than the traffic demand, which will lead to queue lengths that keep growing until the traffic demand will decrease. This has significant effects to the simulation results.
- A decentralized strategy does not provide coordination between intersection. However, coordination could improve traffic conditions. A centralized strategy requires significantly more computational power.
- The limited transparency and predictability of the control method form a challenge for implementation in real traffic.
- The dynamic slot time approach is an interesting alternative for the proposed fixed slot time approach, since it has the potency to improve the trajectories of automated vehicles.

The discussion points regarding the proposed trajectory control are:

- The triangular shaped fundamental diagram used for the calculations of the proposed traffic control differs from the fundamental diagram that would display the real relationship between the traffic density and the traffic flow on the roads in the network. However, the triangular fundamental diagram is used to simplify calculations and will not have a significant negative effect on the performance of the control strategy.
- The proposed trajectory control could lead to unsafe traffic situations, especially in situations that automated vehicles depart from the intersection exactly at the moment that the signal switches to green.

The discussion points regarding the used simulations are:

- The way in which the vehicles are generated in the network might differ from the way that vehicles enter a real traffic network, which could lead to different signal control sequence.
- In the simulation a lower boundary of the back-pressure is introduced. It is debatable whether this is necessary and/or desired in other traffic networks.
- The simulated traffic differ significantly from a realistic traffic mixture. Therefore, the proposed control method will lead to different results in real traffic and has to be adapted in order to perform optimally.
- Other traffic control methods should be tested next to the simulated green wave strategy, since this strategy does not perform well in the simulated network. Therefore, it would be interesting to test whether the proposed method performs better than other well performing methods in this traffic network.
- The relatively large time step used in the simulation only has a significant negative effect on the trajectory control.
- Different future perspectives regarding vehicle automation are possible. The most likely traffic situation in the near future is used for this research.

There are many points of discussion regarding the proposed control method and the simulation. Therefore, obtained simulation results cannot be used to provide detailed conclusions about vehicle connectivity and automation in traffic, but do clarify the factors that have an influence on the different effects.

10

Conclusions and recommendations

In this report, a method is proposed to control partly connected and automated traffic in an urban environment. The proposed method is tested in a traffic simulation of which the results are discussed in detail. This chapter provides the findings, conclusions and recommendations of the research.

This chapter first presents the findings of the research. These findings are focussed on the results from the simulations. Based on the findings, several conclusions can be made which will be presented in section 10.2. Finally, the recommendations for science and for practice will be given.

10.1. Findings

In the research of this report a literature review and a simulation conducted in order to find the answer to the research questions. This section presents the findings of this study, regarding the travel time delay, green time, queue lengths and vehicle accelerations.

10.1.1. Travel time delay

In this report, the average travel time delay is used to assess the performance of the proposed traffic control method and its effects to the network. The simulation results show that the average travel time delay depends on the traffic demand on the main and side roads, and the information and automation level. In the scenarios with equal flows on the main and side road, it can be obtained that the higher the information and automation levels are, the lower the average travel time delay is. This implicates that automated vehicles have a positive effect to the travel time delay when they are controlled according the proposed trajectory control, thanks to an efficient use of the green times.

The simulation results show that connected vehicles have a positive effect on the travel time delay in case the flows on the main and side roads are equal, but a negative effect in case the flows are not equal. This is a result of the fact that the more information the traffic controller receives, the faster it wants to switch the traffic signal. This results in relatively small green times that reduce the throughput of the intersection. The green times on both directions approach the minimum green time of 10 seconds, which means that the ratio between the green times becomes equal. This sequence results in a lower average travel time in case that also the ratio between the traffic flows on the roads is equal.

Also a relationship between the ratio between the traffic flow on the main road and on the side road and the average delay per road is obtained. The average delay on the side road is larger than on the main road for each flow ratio. This is due to the fact that the back-pressure of the two lanes on the main road easily gets larger than the back-pressure on the single lane of the side road. When the traffic flow on the side road is more than twice as large as the flow on the main road, the back-pressure of the side road more often becomes higher than the back-pressure of the main road is.

That is why the green time on the side road increases and the average delay on the side road reduces in case the traffic flow on the side road is much higher than the traffic flow on the main road.

10.1.2. Green time

The simulation results show that the green times set by the traffic controller are depending on the flow ratio and on the amount of information the controller receives from the traffic. The back-pressure of a road is based on the number of approaching vehicles minus the number of exiting vehicles on that road. The non-active road easily gets a higher back-pressure since the number of approaching vehicles is increasing and there are no exiting vehicles, unless there is spillback from a downstream intersection. Therefore, the traffic controller will switch the traffic signal to give green to the non-active road as soon as possible, which results in green times equal to the minimum green time. However, if the information level is low, the chance is higher that the controller does not have a correct image of the traffic situation which result in slightly higher green times. The results show that the average green times for a certain road get larger when that road has a higher traffic flow compared to the other road. However, the main road receives longer green times in general, since the back-pressures of the both lanes of the main road together get higher easily than the back-pressure on the single lane of the side road.

10.1.3. Queue length

Since automated vehicles avoid decelerating to a complete standstill while waiting for green signal, in this report the vehicles that drive with a lower speed than 15 km/h are considered as queueing vehicles. The simulation results show that long queues especially occur at the first intersection that vehicles on a road encounter. This means that the first intersection functions as a bottleneck and reduces the flow and therefore the queues at other intersections. This results in a queue at the first intersection that is growing over time until the traffic flow reduces. The first intersection vehicles encounter function as a bottleneck because the average discharge rate is lower than the traffic flow. The discharge rate of a road of the intersection gets smaller as the average green time per unit of time gets smaller and the number of switches and therefore, number of yellow times get larger. Since the proposed signal control results in relatively short green times, the average discharge rate becomes smaller than the traffic flow. Therefore, long queues are obtained at the first intersections that the traffic encounters. The ratio between the main flow and the side flow also affect the queue length on a road. Since the green times set by the traffic controller are not directly proportional to the flow ratio, the longest average queue occurs at the road with the highest flow.

10.1.4. Vehicle acceleration

The simulation results show that the automated vehicles have a negative effect to the accelerations and decelerations in the network. Controlled according proposed trajectory control, the automated vehicles accelerate and decelerate until they reach their 'smooth' trajectory, for which they can accelerate constantly towards the intersection to depart at the right time with the right speed. However, before reaching this smooth trajectory, the speed of the vehicles often osculate around the desire speed and the traffic controller instructs the vehicles to accelerate or decelerate. The acceleration and deceleration the controller gives is either the maximum comfortable acceleration, the maximum comfortable deceleration or a acceleration in between as soon as the vehicle reaches the smooth trajectory. This trajectory control method leads to many maximum accelerations and deceleration, but to a short total acceleration time. A high and short average acceleration results into more emissions and discomfort for drivers and/or passengers.

10.2. Conclusions

In this section the conclusions of the research are presented. The conclusions will be provided separately for the performance of the proposed signal control method, the proposed trajectory control method, the effects of the proposed control method on the network wide traffic conditions and finally, the effects of vehicle connectivity and automation on urban traffic in general.

10.2.1. Performance of the proposed signal control method

A back-pressure based traffic signal control has the potency to perform well in a partly connected and automated urban traffic environment. It offers the possibility to improve traffic conditions in a decentralized way. Information from connected and automated vehicles in the network can be used to optimize the control sequence to reduce the average travel time delay of the vehicles in the network. Automated vehicles can be controlled in such way that their speed is adapted based on the signal control sequence to increase the number of vehicles that departs from the intersection per unit of green time.

However, the signal control method that is implemented and tested in this research has several limitations, which have to be improved for optimal performance. The largest limitation is the fact that the back-pressure of the non-active road becomes higher than on the active road very fast, such that the green times get rather short. This results in a less efficient use of the green times and on average less green time per unit of time due to more yellow time per unit of time.

The proposed signal control leads to relatively longer green times on the main road than for the traffic on the side road. This is the result of the back-pressure calculation in which the total back-pressure of the main road is the sum of the back-pressures of both the lanes of the main road, while the back-pressure of the side road is equal to the back-pressure of the only lane the side road has.

A possible improvement of the method is to determine the back-pressure based on the amount of approaching vehicles and their distance to the intersection. Next, a threshold for switching could be introduced to avoid the controller of switching at a high frequency, such that the average green times and therefore the average discharge rate will increase. A last adjustment that might improve the performance of the signal control method is to use a dynamic slot time instead of a fixed slot time, which especially offers more time for automated vehicles to adapt their speed to depart from the intersection at the right time and with the right speed, using less accelerations and decelerations during their intersection approach.

10.2.2. Performance of the proposed trajectory control method

The proposed trajectory control results in a more efficient use of the green time. Automated vehicles are controlled in such way that they, and their followers, depart from the intersection on the highest possible speed. If the first vehicle to cross the intersection is an automated vehicle, it can be controlled in such way that it departs from the intersection exactly at the moment that the traffic signal turns green. Both these possibilities result in a higher number of departing vehicles per unit of green time. However, the proposed trajectory control results into more emissions and discomfort for drivers and/or passengers, due to higher average accelerations and decelerations in relatively less time. Following the rather simple trajectory control algorithm, the traffic controller sets only the maximum comfortable acceleration and deceleration until a vehicle reaches the desired smooth trajectory.

This downside of the trajectory control can be solved by setting not only the maximum comfortable acceleration and minimum comfortable deceleration to the automated vehicles in order to reach the desired smooth trajectory, but also set a certain acceleration or deceleration depending on the difference between the desired trajectory and the current trajectory of a vehicle. In this way, the vehicle can reach the desired trajectory with less speed fluctuations. Though, this requires more complex calculations where the proposed trajectory control is very simple to limit the required computational power to control all the automated vehicles in the network. A last point that requires more attention is the effect towards the traffic safety of automated vehicles and especially regarding the fact that automated vehicles depart from the intersection exactly at the moment that the signal turns green.

10.2.3. Effects of the proposed traffic control method on the network wide traffic conditions

The proposed traffic control method has both positive and negative effects on the network wide traffic conditions. Although there are several improvements possible or even required, controlling the traffic signals and the automated vehicles according the proposed methodology, travel time delays can be reduced. Within the controlled area, queue lengths are kept limited thanks to the back-pressure strategy. However, adjustments should be made to optimize the throughput of an intersection, such that it satisfies the traffic demand to avoid long queues at the edges of the controlled area. The research results show that spillback can be avoided within the controlled area, but can occur in the surrounding traffic network.

10.2.4. Effects of vehicle connectivity and automation on urban traffic

Based on this research it is difficult to conclude what the general effects are of vehicle connectivity and automation on urban traffic. First of all, the effects are depending on the both the signal control and the trajectory control method. Different control methods should be tested to conclude if there are common effects on the traffic conditions, or the effects should be obtained using the control method that is most likely to be used as soon as automated and connected vehicles in traffic are reality.

However, this research show that both automated and connected vehicles create the possibility to control traffic based on the live traffic conditions and that this can lead to better traffic conditions in case the control methods are performing well. Since nowadays vehicle connectivity and automation is a popular point of discussion and will probably become even more important as soon as automated vehicles are introduced into real traffic, one may expect that research that is focussed on finding the optimal control strategy in a partly connected or automated environment will continue. Therefore, chances are high that as soon real traffic consist of automated and connected vehicles, there will be control strategies that would improve the urban traffic conditions significantly, even for low penetration rates of automated and connected vehicles.

10.3. Recommendations

The proposed control strategy requires different improvements before it is applicable in real traffic and therefore, this research can especially be seen as a stepping stone for further research. The recommendations for further research are provided in section 10.3.1. Afterwards, the recommendations for practice will be provided in section 10.3.2

10.3.1. Recommendations for science

The recommendations for science mainly follow out of the discussions of the report, presented in chapter 9. Recommendations can be divided into recommendations regarding the signal control strategy, the trajectory control strategy and traffic simulation.

Signal control strategy

There are several measures that most likely will improve the performance of the proposed signal control strategy. For further research it is recommended to implement and test the following adjustments of the signal control strategy:

- One main limitation of the proposed strategy is the fact that the back-pressures, determined according the original back-pressure theory, results into priority for traffic on the main road of the simulation, where the two lanes of the main road result in a back-pressure twice as high compared to the side road. Although this measure might in general result into a higher throughput of the network, in the simulated network it results in a larger average delay. An alternative way to determine the back-pressure is to divide the difference in queue length upstream and downstream of the intersection by the discharge rate instead of multiplying, as the original theory proposes. However, the original back-pressure is extensively research and the results are overall positive towards the network wide traffic conditions. This alternative method should be tested as well in order to conclude whether this would improve the network conditions, and to conclude in what situations this could be a suitable alternative.

- The back-pressure range introduced in the proposed control strategy is not an optimal solution to determine the pressures on each link around the intersection. An alternative is to take all the vehicles into account that are on the links around the intersection, even if the links have different lengths, but to add a weight to each vehicle depending on the distance between the vehicle and the intersection. This alternative should be tested in further research.

- The traffic controller is able to control the speed of the automated vehicles and optimizes their departure sequence based on the signal control sequence. Using the proposed signal control strategy there is a time slot of 5 seconds between the decision of the traffic controller to switch to green and the moment that the signal actually switches to green. These 5 seconds are used to control automated vehicles and adapt their speed to let them depart on the optimal time and with the optimal speed. However, the larger this time interval is, the better the trajectories of the automated vehicles can be adapted to the traffic signal. A back-pressure approach with a dynamic slot time, instead of the used fixed slot time, might be a better solution. Research show that using a dynamic slot time in the original back-pressure control approach can improve network conditions. Beside, using a dynamic slot time, the end of a phase is known at the very beginning of the phase and therefore, automated vehicles can be controlled more optimally. Although the dynamic slot time requires rather complex calculations and predictions, it is a very interesting solution in a partly automated environment. Therefore, the recommendation for further research is to implement and test the dynamic slot time.

- The proposed signal control strategy results into relatively short green times, which significantly lower the intersection throughput. This is mainly caused by the fact that the back-pressure of the non-active road quickly becomes higher than the back-pressure on the active road. This effect would already be reduced determining the back-pressures based on also the distance between approaching and exiting vehicles and the intersection. Another recommendation is to introduce a threshold for switching to the non-active road, which results in longer green times on average. Running various simulations with different thresholds could lead to a value that results in the optimal green times to reduce the average travel time delay in the network.

- Undetected conventional vehicles are not taken into account for the back-pressure calculations although it is possible to make an assumption for how many undetected vehicles there might be on each link. It is expected that this especially will have a positive effect to the signal control in case of a low information level. In this case the signal controller will not decide based on only the few known vehicles in the network, which could be distributed unevenly and give a unrealistic image of the traffic conditions. In further research this option should be taken into consideration.

Trajectory control strategy
The following recommendations are made regarding the proposed trajectory control strategy:

- The main downside of the trajectory control are the relatively high accelerations and decelerations of the automated vehicles, due to the many speed fluctuations around the desired trajectory. The simplicity of the algorithm makes the proposed trajectory control an interesting control method, however, further research is needed to reduce the average accelerations and decelerations of automated vehicles.

- In the proposed control method, a clearance space is introduced, which is the space directly downstream of an intersection in which an automated vehicle cannot receive the instruction to slow down. The clearance space is implemented to avoid spillback due to automated vehicles that slow down directly after an intersection. However, in the proposed method the clearance space is a fixed value of 30 metres, where automated vehicles do not always cause spillback when they would decelerate in this space. In case the automated vehicle has no or only a few followers, or in case the signal of the intersection that the vehicle just crossed switches to red. There will be even more situations in case the clearance space can be neglected or reduced. This could especially improve the trajectories of automated vehicles when they are located between two successive intersections that are relatively close to each other. In that case, automated vehicles have less distance to optimize their departure time and speed, and even less distance if the first part is also the clearance space of the upstream intersection. Therefore, further research towards the clearance space is recommended.

- The trajectories of the automated vehicles are updated every time step, according the proposed trajectory control. However, the desired departure time and speed of the automated vehicles does not change until a new vehicle enters the network, or is spotted in the network. To save computational power, the trajectories of the automated vehicles could be updated only when a new vehicle is included in the vehicle set.

- Another benefit of automated vehicles which is not included in this research is the fact that the automated vehicle are connected with one another indirectly via the traffic controller. This means that as soon as an automated vehicle changes speed, other vehicles in the network are able to react directly on this speed change. The gap between two successive automated vehicles can be smaller than the minimal gap that humans take into account, since they have to deal with a longer reaction time. A smaller gap between vehicles results in a higher road capacity and a more efficient use of the green times. However, uninterrupted communication between the automated vehicles and the traffic controller is required.

Traffic simulation

The following recommendations are made for further research in case again a traffic simulation will be used to assess the control methods:

- In the simulation of this research, the simulated network is a very simplified network in comparison to a real traffic network. First of all, the simulated traffic corridor consist of only 5 intersections positioned in one straight line. Traffic on the side road can unhindered enter and exit the simulation and network effects such as spillback only occur on the main road. Next, in the simulation, vehicles are not allowed to make a turn, where vehicles in real urban networks often have the option to turn left and right as well. It would be interesting to extend the simulated network, for example into a grid network with 5x5 intersection. Also a solution for turning vehicles must be found and tested. Including these options in a traffic simulation will give more insight in the effects to a real urban traffic network. Last, since the difference in lanes between the main and side roads in the simulation of this research lead to a more complicated comparison of the different results between the main and the side road, it is recommended to test a network with an equal amount of lanes on each road.
- Also the traffic mixture is very simplified in the simulation of this research. Only car traffic is considered, where in real traffic there are many different vehicle types, and there are cyclists and pedestrians. As discussed in chapter 9, traffic consisting of different modes of transport require a more complex control method. Including different modes in further research will give more insight in the challenges and possibilities of controlling real traffic.
- To be able to compare the proposed control method, a base case has been simulated as well. For this base case a green wave strategy was implemented, which turned out to be a poor performing control strategy. In order to know whether the proposed control method is worth implementing, it should perform better than other signal control strategies. Therefore, a comparison with other control methods is recommended. Especially other decentralized control solutions, such as the original-back pressure and the dynamic signal controller, both based on detector data, are interesting alternatives.
- In this report, several simulation parameters have been introduced: the threshold for switching, the radius of the back-pressure range, the scan range of automated vehicles, the time slot length, the minimum and maximum phase duration and the clearance space. However, this research did not provide an extensive study to the optimal values of these parameters. Since changing these parameters will lead to significant different results, it is recommended to conduct a study to optimize the values of these parameters.
- To get more insight in the effect of automated vehicles on the efficiency of the use of the green times, the average departure speed and the average number of departing vehicles per unit of green time could be interesting simulation outputs, which are not retrieved from the simulation in this report.

10.3.2. Recommendations for practice

Yet, it is not possible to implement the proposed control method in real traffic. The simplified simulated traffic simulation does not give a good image of the performance of the proposed control to real traffic. Beside, the results show that the proposed control does not yet performs optimally and further research is necessary. Several recommendations can be made for implementing the proposed control method, or an improved version of the method, in real traffic:

- To obtain insight in the performance of the traffic control method in real traffic, the method should be tested in a realistic simulation. It is recommended to simulate an existing part of an urban network and to use a realistic traffic mixture.

- The main objective of the proposed trajectory control is to optimize the use of green phases and limiting the deceleration and acceleration is only a side objective. A trajectory control for real traffic will be more complex and has to deal with many different requirements and situations. Therefore, the trajectory control has to be adopted to real traffic. Nowadays, there are many companies creating autonomous vehicles, which are able to navigate through traffic using only the vehicle sensors. These vehicles would be suitable to convert into automated vehicles by providing them with communication equipment, such that they can use their own way to navigate through traffic, while receiving only the desired (one-directional) speed from the traffic controller.

- The more information there is available about the traffic conditions, the better the signal control and the trajectory control of automated vehicles will perform. Therefore, it is recommended to increase the level of information in traffic. This can be reached not only by providing vehicles of the required equipment, but also by stimulating drivers or car manufacturers to share as much information as possible. Since car manufacturers might be wanting to defend their market position by collecting but not sharing information, this might not happen automatically. Since better traffic conditions in general leads to economic benefit for companies and countries, sharing information could be stimulated by either governments and/or other parties that benefit of better traffic conditions.

- The proposed trajectory control let automated vehicles depart from the intersection exactly at the moment that the signal switches to green. Therefore, not only the clearance time of the intersection will become shorter, but other traffic might not be used to this behaviour either. This should be taken into account when implementing (a similar) trajectory control method to guarantee the traffic safety. One possible measure to limit the reduction in traffic safety due to the trajectory control is to introduce a safety margin in time between the moment of switching to green and the actual moment an automated vehicle is allowed to depart from the intersection.

- Connected and automated vehicles have a high chance to become a popular mode of transport in the future and results of this research show that they have the potency to improve network wide traffic conditions. Therefore, not only traffic and infrastructure planners, but everyone could benefit be getting ready for this new technological wave. However, it should be taken into consideration that the growing presence of automated and connected vehicles in traffic is only based on predictions.

Bibliography

[1] Arnaout, G., & Arnaout, J.-P. (2014). Exploring the effects of cooperative adaptive cruise control on highway traffic flow using microscopic traffic simulation. *Transportation Planning and Technology, 37(2),* 18Tru6–199.

[2] Arnaout, G., & Bowling, S. (2011). Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. *Journal of Industrial Engineering and Management, 4(4),* 699–717.

[3] Au, T.C., & Stone, P., (2010). Motion planning algorithms for autonomous intersection management. *Bridging the Gap Between Task and Motion Planning*

[4] Boimbraw, K. (2015). Autonomous cars: past, present and future. *12th Int.Conf. Informatics in Control (2015), Automation and Robotics (ICINCO),volume 01,* 191–198

[5] Boer, R., Zheng, Y., Overton, A., Ridgeway, G., & Cohen, D. (2007). Neighborhood Design and Walking Trips in Ten U.S. Metropolitan Areas. Retrieved February 2, 2017, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1995081/

[6] Bokare, P.S., & Maurya, A.K. (2012). Study of deceleration behaviour of different vehicle types. *International Journal for Traffic and Transport Engineering, 2012, 2(3),* 253 – 270

[7] Bokare, P.S., & Maurya, A.K. (2014). Acceleration-Deceleration Behaviour of Various Vehicle Types. Retrieved February 12, 2017, from http://www.academia.edu/7840630/Acceleration-Deceleration_Behaviour_of_Various_Vehicle_Types

[8] Bootsma, E. (2010). Why are blocks that size? Retrieved February 2, 2017, from Greater Greater Washington: https://ggwash.org/view/5326/why-are-blocks-that-size

[9] Clement, S. J., Taylor, M. A. P., & Yue, W. L. (2004). Simple platoon advancement: A model of automated vehicle movement at signalised intersections. *Transportation Research Part C: Emerging Technologies, 12(3–4),* 293–320.

[10] Cassandras, C.G., Malikopoulos, A.A., & Zang, Y. (2016). Optimal control and coordination of connected and automated vehicles at urban traffic intersections. *Proceedings of the American Control Conference*, 6227–6232.

[11] Cassandras, C.G., Malikopoulos, A.A., & Zang, Y. (2017). Decentralized Optimal Control for Connected Automated Vehicles at Intersections Including Left and Right Turns. Retrieved November 6, 2017, from http://export.arxiv.org/pdf/1703.06956.

[12] Cyganski, R., Fraedrich, E., & Lenz, B. (2015). Travel time valuation for automated driving: a use-case-driven study. *In 94the annual meeting of the transportation research board. Washington, DC: Transportation Research Board*

[13] Davies, A. (2017). Nissan's Path to Self-Driving Cars? Humans in Call Centers. Retrieved February 9, 2017, from Greater Greater Washington: https://www.wired.com/2017/01/nissans-self-driving-teleoperation/

[14] DLR - Institute of Transportation Systems (n.d.) SUMO – Simulation of Urban MObility. Retrieved October 9, 2017, from http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883/16931_read-41000/

[15] Dresner, K., Stone, P. (2008). A Multiagent Approach to Autonomous Intersection Management. *Journal of Artificial Intelligent Research 31,* 591-656.

[16] Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies, 40,* 1–13.

[17] Fajardo, D., Au, T. C., Waller, T., Stone, P., & Yang, D. (2012). Automated intersection control: Performance of a future innovation versus current traffic signal control. *Transportation Research Record: Journal of the Transportation Research Board, 2259,* 223–232.

[18] Grumert, E., Ma, X., & Tapani, A. (2015). Effects of a cooperative variable speed limit system on traffic performance and exhaust emissions. *Transportation Research Part C: Emerging Technologies, 52,* 173–186.

[19] Hall, F.L. & K. Agyemang-Duah (1991). Freeway capacity drop and the definition of capacity. *Transportation Research Record: Journal of the Transportation Research Board, 1320,* 91–98.

[20] He, Q., Head, K., & Ding, J. (2014). Multi-modal traffic signal control with priority, signal actuation and coordination. *Transportation research Part C, 46,* 65-82.

[21] Hu, J., Park, B., & Lee, Y. (2015). Coordinated transit signal priority supporting transit progression under connected vehicle technology. *Transportation research Part C, 55,* 393-408.

[22] Kamal, A. S., Imura, J., Hayakawa, T., Ohata, A., & Aihara, K. (2015). A Vehicle-Intersection coordination scheme for smooth flows of traffic without using traffic lights. *IEEE Transactions on Intelligent Transportation Systems, 16(3),* 1136–1147.

[23] Kerner, B.S. (2004). The Physics of Traffic: Empirical Freeway Pattern Features. *Engineering Applications and Theory*

[24] Khondaker, B., & Kattan, L. (2015). Variable speed limit: A microscopic analysis in a connected vehicle environment. *Transportation Research Part C: Emerging Technologies, 58,* 146–159.

[25] Krajzewicz, D., Erdmann,J., Behrisch, M., & Bieker, L. (2012) Recent Development and Applications of SUMO – Simulation of Urban MObility. *International Journal on Advances in Systems and Measurements, vol 5 no 3 & 4*

[26] Krambeck, D. (2016). Tesla vs Google: Do LIDAR Sensors Belong in Autonomous Vehicles? Retrieved February 21, 2017, from https://www.allaboutcircuits.com/news/tesla-vs-google-do-lidar-sensors-belong-in-autonomous-vehicles/

[27] Li, L., Wen, D., & Yao, D. (2014). A survey of traffic control with vehicular communications. *IEEE Transactions on Intelligent Transportation Systems, 15,* 425-432.

[28] Mahmassani, H.S. (2016). Autonomous vehicles and connected vehicle systems: flow and operations considerations. *Transportation science, Vol. 50, No. 4,* 1140-5447.

[29] Mercedes-Benz (n.d.) The Mercedes-Benz F 015 Luxury in Motion. Retrieved February 9, 2017, from https://www.mercedes-benz.com/en/mercedes-benz/innovation/research-vehicle-f-015-luxury-in-motion/

[30] Mercedes-Benz (n.d.) Mercedes-Benz Intelligent Drive. Retrieved February 21, 2017, from https://www.mercedes-benz.com/en/mercedes-benz/innovation/mercedes-benz-intelligent-drive/

[31] Milakis, D., van Arem, B., & van Wee, B. (2015). The ripple effect of automated driving. *In 2015 BIVEC-GIBET Transport Research Day.*

[32] Milakis, D., Van Arem, B., & Van Wee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future research. *Journal of Intelligent Transportation Systems, 21:4,* 324-348, DOI: 10.1080/15472450.2017.1291351

[33] Parent, M. (2013). Automated vehicles: autonomous or connected? *IEEE 14th International Conference on Mobile Data Management,* Retrieved February 13, 2017, from http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6569114

[34] Pollak, M. (2006). Knowing the Distance. Retrieved February 2, 2017, from The New York Times: http://www.nytimes.com/2006/09/17/nyregion/thecity/17fyi.html

[35] Priemer, C., Friedrich, B., 2009. A decentralized adaptive traffic signal control using V2I communication data. *12th International IEEE Conference on Intelligent Transportation Systems, 2009. ITSC '09,* 1–6.

[36] Rios-torres, J., & Malikopoulos, A. A. (2016). Automated and cooperative vehicle merging at highway On-Ramps. *IEEE Transactions on Intelligent Transportation Systems.* Advance online publication. https://doi.org/10.1109/TITS.2016.2587582

[37] SAE International (n.d.). Automated driving. Retrieved October 18, 2017, from http://www.sae.org/misc/pdfs/automated_driving.pdf

[38] Strohm, M. (n.d.). 6 firms that are testing driverless cars. Retrieved February 9, 2017, from http://www.bankrate.com/finance/auto/companies-testing-driverless-cars-1.aspx

[39] Taale, H., Van Kampen, J., & Hoogendoorn, S.P (2015). Integrated signal control and route guidance based on back-pressure principles, *Transportation Research Procedia 10,* 226 - 235.

[40] Talebpour, A., & Mahmassani, H. S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies,71,* 143–163.

[41] The Tesla Team (2016). All Tesla Cars Being Produced Now Have Full Self-Driving Hardware. Retrieved February 21, 2017, from https://www.tesla.com/blog/all-tesla-cars-being-produced-now-have-full-self-driving-hardware?redirect=no

[42] Tesla (2016). Full Self-Driving Hardware on All Cars. Retrieved February 21, 2017, from https://www.tesla.com/autopilot?redirect=no

[43] Velodyne (2016). HDL-64E. Retrieved February 21, 2017, from http://velodynelidar.com/docs/datasheet/63-9194%20Rev-E_HDL-64E_S3_Spec%20Sheet_-Web.pdf

[44] Wakabayashi, D. (2017). Waymo's Autonomous Cars Cut Out Human Drivers in Road Tests *The New York Times* Retrieved February 21, 2017, from https://www.nytimes.com/2017/11/07/technology/waymo-autonomous-cars.html?_r=0

[45] Waymo (2016). Journey. Retrieved February 9, 2017, from http://www.waymo.com/journey/

[46] Waymo Team (2016). Introducing Waymo's suite of custom-built, self-driving hardware. Retrieved February 21, 2017, from https://medium.com/waymo/introducing-waymos-suite-of-custom-built-self-driving-hardware -c47d1714563#.ft5c1g2bc

[47] Wongpiromsarn, T., Uthaicharoenpong, Y., Wang, Y., Frazzoli, E., & Wang, D. (2012). Distributed traffic signal control for maximum network throughput, *IEEE 15th International Conference on Intelligent Transportation Systems,* 588-595.

[48] Wu, J., Abbas-Turki, A., Correia, A., & El Moudni, A., (2007). Discrete intersection signal control. *IEEE International Conference on Service Operations and Logistics, and Informatics, 2007. SOLI 2007,* 1–6

[49] Xie, Y., Zhang, H., Gartner, N. H., & Arsava, T. (2016). Collaborative merging strategy for freeway ramp operations in a connected and autonomous vehicles environment. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations.*

[50] Yang, K., Guler, S. I., & Menendez, M. (2016). Isolated intersection control for various levels of vehicle technology: Conventional, connected, and automated vehicles. *IEEE 19th International Conference on Intelligent Transportation Systems* 109-129.

[51] Yuan, K., Knoop, V.L., & Hoogendoorn, S.P. (2016). Optimal Dynamic Green Time for Distributed Signal Control. *Transportation research Part C, 72,* 447 - 451.

[52] Zhang, H. M. (1999). A mathematical theory of traffic hysteresis. Transportation *Research Part B: Methodological, 33(1),* 31 – 23.

[53] Zhou, M., Qu, X., & Jin, S. (2016). On the impact of cooperative autonomous vehicles in improving freeway merging: A modified intelligent driver Model-Based approach. *IEEE Intelligent Transportation Systems Magazine.*

[54] Zohdy, I. A., & Rakha, H. A. (2016). Intersection management via vehicle connectivity: The intersection cooperative adaptive cruise control system concept. *Journal of Intelligent Transportation Systems, 20(1),* 17–32.

A

Appendix A

A.1. Speed and acceleration over time

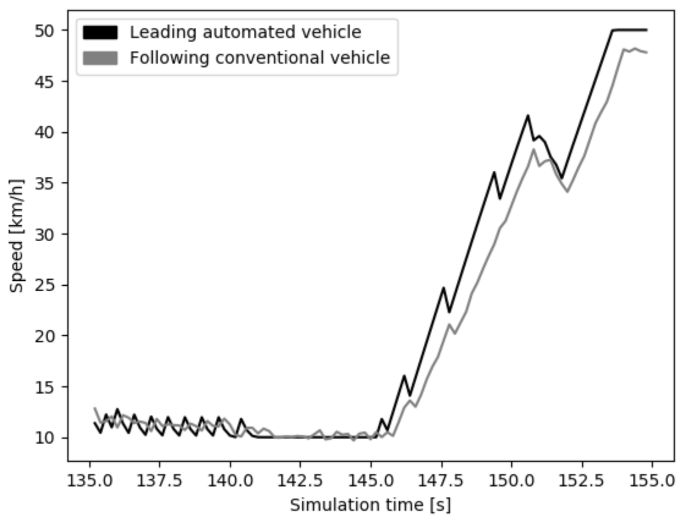

Figure A.1: Speeds of an automated vehicle and its following conventional vehicle (time step = 0.2s. The automated vehicle remains queueing speed until t=145s and accelerates until it crosses the stopping line at t=153s.)

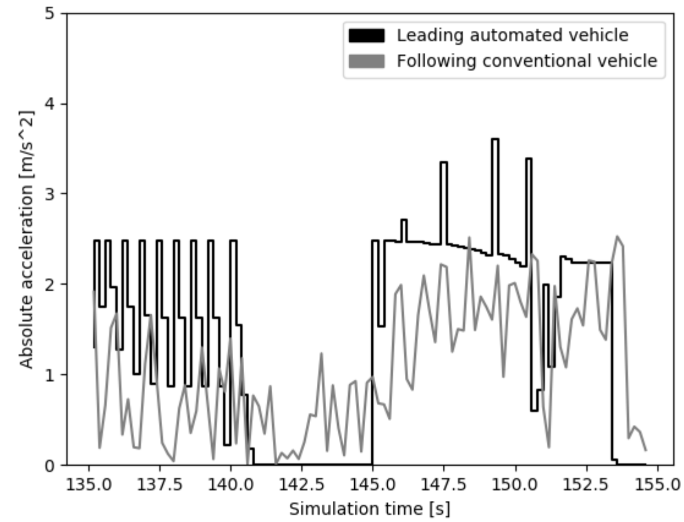

Figure A.2: Absolute acceleration of the same automated vehicle and its following conventional vehicle as figure A.1 (time step = 0.2s)

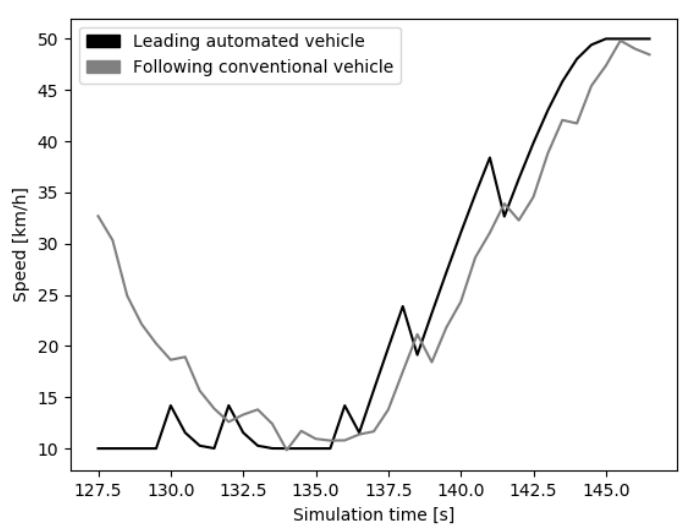

Figure A.3: Speeds of an automated vehicle and its following conventional vehicle (time step = 0.5s)

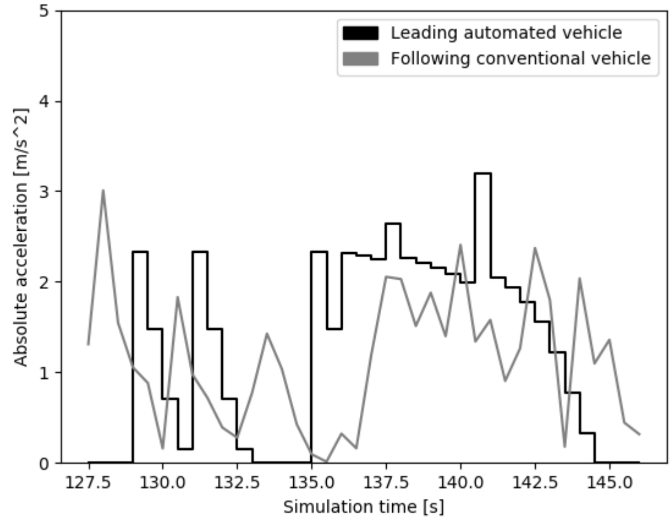

Figure A.4: Absolute acceleration of the same automated vehicle and its following conventional vehicle as figure A.3 (time step = 0.5s).

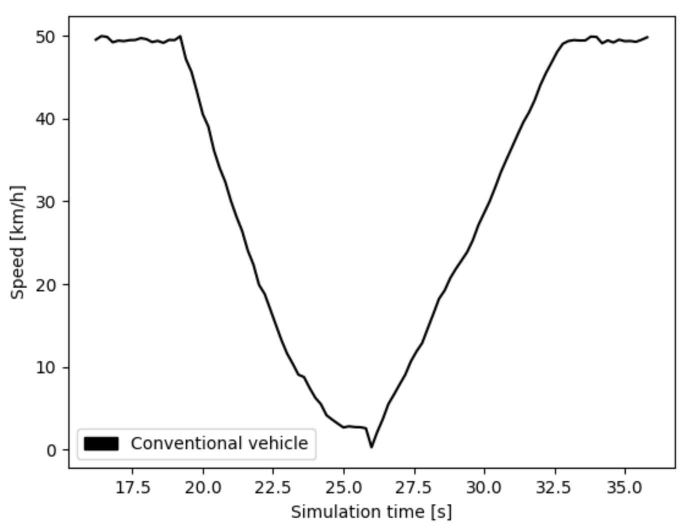

Figure A.5: Speeds of a non-following conventional vehicle (time step = 0.2s)

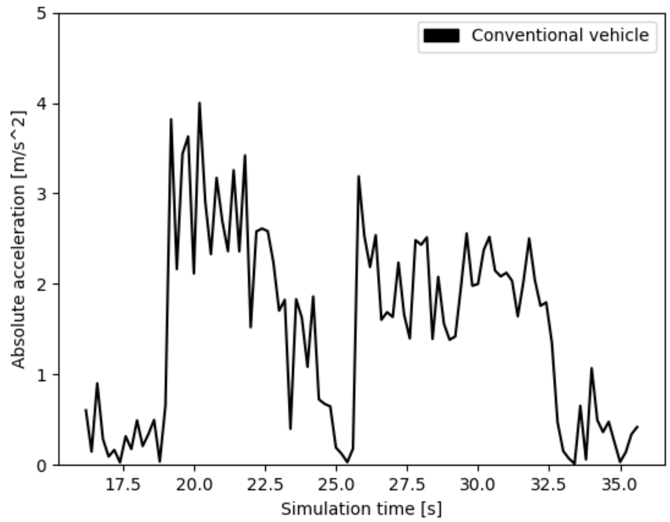

Figure A.6: Absolute acceleration of the same non-following conventional vehicle as figure A.5 (time step = 0.2s)