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Design of an urban traffic controller that incorporates route advice given by in-vehicle navigation systems

Reducing waiting times by adaptively creating and breaking green waves

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Rijkswaterstaat
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Colophon

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Summary

Increased mobility has caused a constant increase in the amount of traffic since the introduction of the first cars in the 19th century. This increase caused several negative effects, such as congestion or emissions of air pollutants and greenhouse gasses. One way of reducing these negative effects is making more efficient use of the existing infrastructure. Intelligent Transport Systems (ITS) are a means to do this. Integrated use of different kinds of ITS could increase the effectiveness of all components of the integrated system. In 15 years all road-users are expected to be connected through the use of smart phones or navigation devices (Ministerie van Infrastructuur en Millieu, 2013). In this thesis the possibilities are studied to make use of this connectivity and integrate the system of connected vehicles with an Urban Traffic Controller (UTC). First, some possible applications are found through a literature study and later one application is tested via multiple test cases in a simulated traffic network.

In the literature study, the state of the art of UTC is studied and the assumed Vehicle Route Guidance System (VRGS) is defined. The problem of optimizing the control of an urban traffic network, consisting of multiple links and traffic lights, in real time, has been formulated many years ago. However, the problem is too large and complex to be solved online for traffic networks consisting of more than just a few intersections. Therefore, current traffic control systems have incorporated simplifications in order to reduce computation times. Centralized systems, that solve the control problem for multiple intersections at once, have been found to use lots of historic data and only solve part of the problem online. Therefore, they are incapable of responding to changing traffic demands. On the other hand, systems that solve the traffic control problem for just one intersection are able to optimize control, based on the current traffic situation at the intersection. However, these controllers neglect the fact that a traffic network is an interconnected system and what might be the best solution for one intersection, might be a bad decision for the entire traffic network. Information from a VRGS could improve the functioning of either UTC.

From the possible applications of an integrated system, one application has been chosen to be developed into an UTC. This application is the use of the predicted route demands in an urban traffic network to choose between coordinating traffic lights, in order to create a green wave, and controlling intersections with local (vehicle-actuated) controllers. The route demands will be generated from the information sent by VRGS on the locations, intended routes and destinations of vehicles. The controller is supposed to choose the strategy that generates the lowest lost times, given the predicted demands.

The controller is defined in 5 steps. First the controller receives the link demands for the next control period from the VRGS. Then, the controller calculates the total predicted lost times for all possible control strategies. The basic strategy is to control all intersections with a vehicle-actuated controller, every other strategy includes at least one route on which a green wave is active. The strategy to be employed in the next control period is chosen, based on the lowest lost time that is

predicted. If a set of intersections is supposed to be coordinated, a transition step is introduced in order to create the desired offset between the start of connected phases. This process is repeated every control period.

A simulation study, consisting of 3 separate case studies, is performed to test the controller. In the first case study the parameters of the controller were identified to meet the characteristics of the test network. In a second test case, the method, used to predict the lost times in the network, has been calibrated. In the third and final case study, the controller is compared to vehicle-actuated control and coordinated control, used separately. The controller proved to have the potential to decrease travel times by using the proper control approach for each traffic situation. Compared to VA-control, the switching approach decreased lost times up to 14%.

In conclusion, integration of VRGS and UTC has the potential to decrease travel time losses in urban traffic networks. The developed controller has the potential to combine the benefits of coordinated and local controllers by switching between them on appropriate times. However, the controller has only been tested on a small-scale simulated network. Future research should focus on increasing the complexity of the test network and the incorporated strategies. Finally, the controller is based on the assumption that the future route demands are known, from the information sent by navigation devices. A system should be designed, that is capable of translating this information into predicted link demands.

Preface

After 10 months I am more than satisfied with this report, which is the result of my graduation work. But, I could have never made this report by myself and I would like to thank everybody that helped me along the way.

First of all I would like to thank my daily supervisors, **Andreas Hegyi** and **Goof van de Weg**. With our biweekly meetings you must have worked your way though some 15 "slightly" less structured versions of my work. But, no matter how unreadable my first reports, you always took the time to decipher them and guide me in the right direction. Andreas, during our meetings you always knew exactly what questions to ask. Even though they might have puzzled me during the meetings, they always helped me to structure my work and focus on the main objectives. Goof, your comments on my reasoning, writing and punctuation (use commas!) have improved the quality of this thesis significantly.

Furthermore, I would like to thank the rest of my thesis committee, **Serge Hoogendoorn** (head), **Henk Taale** and **Ana Jamshidnejad**. The discussions during the three committee meetings gave me invaluable inspiration to improve my work. Serge, your classes on the PPA inspired me to choose a graduation project in this direction and I would like to thank you for granting me the freedom to create my own assignment. Henk, your knowledge (and huge collection of papers) on Urban Traffic Control helped me tremendously to improve my literature study. Furthermore, I would like to thank you for your numerous calls with the ICT-section, in order to help me install all software I needed. Ana, your criticism on my use of concepts (prediction vs. estimation or decentralized vs. distributed), not only provided lively discussions during the committee meetings but also helped me considerably. The same holds for your sharp comments on my equations and the use of units.

Although you should not judge any book by its cover, I am happy to have the ITS Edulab logo on the cover of this one. The partnership between TU Delft and Rijkswaterstaat, which the Edulab is, provided me with a working place at Rijkswaterstaat where I have spent the past 10 months. I would also like to thank my roommates at the Edulab, Joost and Mark for making the days a lot less dull and also helping me if I could not find an English word or construct a code to fix a graph.

Last but not least, I would like my family for supporting me my entire study career. **Mom, dad**, thanks for allowing me to find my own path, even though it was far from the fastest route from high school to master's degree. **Maaike**, (complaining about and procrastinating of) graduating is much easier when you can share it with your little sister! And **Marieke,** thanks for putting up with me, even though you saw me half as much as usual and when you did see me I could be pretty unbearable. And of course for dragging me out of my cave from time to time, when I was completely stuck and to stubborn to take a break.

Table of contents

1 Introduction

In a yearly report on mobility (KIM, 2013), the Dutch Knowledge Institute for Mobility (KIM) wrote that there was an increase of 16% in the amount of traffic on the Dutch roads between 2000 and 2012. In the same report they mentioned that the costs for congestion and delays on the main roads are estimated to be around 1.8 to 2.4 billion euros per year. These costs consist, in the first place, of the increased travel time to get from one place to another. Furthermore, unreliable travel times and emission of air pollutants and small particles increase the negative effect of congestion and delays. While the economy is expected to recover from a crisis in the near future, traffic demands will be growing and decrease of travel time losses might be more important than ever. The creation and improvement of Intelligent Transport Systems (ITS) are a means to reach this goal, complementary to creating new infrastructure.

The question is how to decrease these travel time losses. Summing up every possible way to do so would be an entire study on its own so for the sake of argument, only the most important measures, according to the KIM-report, are mentioned. In Figure 1-1, the increase in travel times (on main roads) is explained for the period between 2000 and 2012 in the Netherlands.

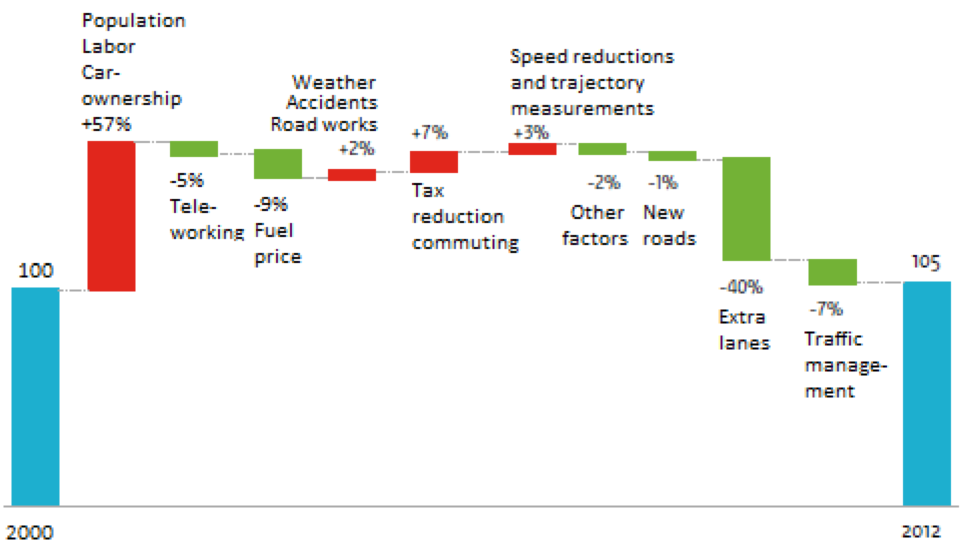


Figure 1-1 *Explanation of travel time losses on main roads in the Netherlands between 2000 and 2012 (KIM, 2013)*

A distinction can be made between measures that decrease the demand of traffic and measures that increase the supply of traffic. The demand of traffic includes the number of travellers that want to use time and space in a road traffic network to travel from A to B. The supply is the available time and space in the traffic network to enable these movements. The former category includes the promotion of teleworking and increasing the fuel price. The latter includes the creation of new infrastructure (by building new roads or adding extra lanes to existing roads) and traffic management measures. Although measures from the demand decreasing kind seem to be very effective, the increase in traffic is expected to be much higher and supply increasing measures are still needed as well. The creation of new infrastructure is a very intuitive measure to relieve congestion, but has a couple of downsides. First of all, it is quite expensive and usually takes years of planning before construction can commence. Second of all, there is not always enough space to add extra lanes to existing roads, especially on bridges and in tunnels. Third of all, the creation of new roads attracts new travellers, thus partly cancelling out the increase in supply by increasing the demand as well. In this thesis we focus on increasing the effectiveness of the use of infrastructure with the aid of traffic management.

With the rise of Information Technology the field of traffic management today has a large number of ITS at its disposal to control traffic. ITS is a collective noun to describe "all technology and methodology applied to transport on all conceivable spatial and temporal scales" (van Lint et al. 2012). ITS, developed for road traffic, can be categorized into roadside systems and in-car systems. Roadside systems are systems that are applied to all users of the network collectively. Examples are road signs, traffic lights, and Variable Message Signs (VMS). In-car systems function inside a car and inform, assist or guide a single user. Examples are navigation devices, (adaptive) cruise control and brake assist. Traditionally, traffic management was mainly performed with roadside systems but the increasing connectivity of road users opens new possibilities for the use of in-car systems for traffic control purposes. This is one of the reasons why the Dutch minister of Infrastructure and Environment started the 'Connecting Mobility' program (Ministerie van Infrastructuur en Millieu, 2013). With this program, she articulated the ambition to combine "information via smart phones, navigation systems and collective information channels on, above and next to the road" into one smart and consistent mix.

The theory of Integrated Network Management (INM) fits seamlessly into this ambition. INM, which is currently being tested in a large field test in Amsterdam (Hoogendoorn, Landman, van Kooten, & Schreuder, 2013), aims at improving traffic management measures by deploying them in an integrated and coordinated way. With this integration, not only different ITS, but also different road management levels are expected to work together to strive for a common goal. In the light of INM and the ministerial program, we focus in this thesis on the combination of roadside and in-car ITS in an urban traffic network.

Figure 1-2 *An intersection, controlled by traffic lights (source: refdag.nl)*

Figure 1-3 *An in-car route guidance system (source: tweakers.net)*

The ITS system, that is chosen for the in-car system, is a Vehicle Route Guidance System (VRGS). This VRGS is an assumed system that consists of multiple connected road users. This choice is made because every road user is expected to be connected via smart phone or navigation system (as shown in Figure 1-3) within 15 years (Ministerie van Infrastructuur en Millieu, 2013). This connectivity opens opportunities to use these systems for traffic control purposes. On the one hand, the navigation systems could provide information on the status (e.g. location, destination, speed) of the vehicle to improve the current and future state estimation and prediction of traffic controllers. On the other hand, the navigation systems create the opportunity to focus traffic control measures on individual users.

In the INM field test, which is currently being employed in Amsterdam, the integration of in-car and roadside systems is also studied. The main objective of that project is to improve throughput on the main roads. Therefore, the focus of this thesis is on urban traffic networks, to prevent the development of a system that is already being designed for the field test on INM. In urban traffic networks, Urban Traffic Controllers (UTC, controlling traffic with traffic lights as shown in Figure 1-2) are the main ITS being employed. The complexity of the urban traffic control problem, with multiple intersection controllers in a dense traffic network, has provoked a large number of UTC to be developed in the past 50 years. Still, no system is currently operational that is capable of minimizing travel times both in saturated and unsaturated conditions (Papageorgiou, Diakaki, Dinopoulou, Kotsialos, & Wang, 2003). Therefore, the possibilities to improve currently existing UTC with the use of VRGS, will be studied in this thesis.

The KIM-report, discussed in the first paragraphs of this introduction, focusses on the main roads. Therefore, it might seem strange to develop a method that reduces travel time losses in an urban traffic network. However, improving the efficiency of urban traffic networks is assumed to decrease lost times and consequent negative effects for the traffic network as a whole and not just for the urban parts of this network. First of all, most trips on the main roads have an origin and a destination in an urban traffic network. Decreasing lost times in the urban traffic network thus decreases lost times for the entire trip. Furthermore, all main roads are connected to multiple urban traffic networks and vice versa. This means that delays (queues), caused by ineffective control of the urban traffic network, could propagate onto the main roads. Therefore, it is assumed that improvements of UTC contribute to the reduction of travel time losses for the main roads as well.

1.1 Research objective

The objective of this thesis is to study how existing UTC and VRGS can work together to improve traffic conditions and decrease waiting times in an urban traffic network. This will result in a list of possible applications. As a proof of concept, one of these applications will be developed into a working algorithm and tested in a small-scale test case. The concept that will be proved with this case study is that the developed controller can improve traffic conditions within an urban traffic network.

The objective of this study is to study the possibilities to improve the workings of Urban Traffic Controllers with the aid of in-vehicle Route Guidance Systems. One application will be developed into a working algorithm that aims at decreasing travel time losses in an urban traffic network.

In order to reach this objective, the following sub-objectives have been formulated:

1. *Study the state-of-the-art of urban traffic control systems and identify possible applications of improving these systems, in the sense of decreasing travel time losses, with the use of the assumed future connectivity of road users.*
2. *Develop one of the identified applications into a control strategy that decreases travel time losses in an urban traffic network*
3. *Evaluate the developed controller by means of a simulation study.*

1.2 Research scope

In this section, the scope of the study is discussed. In order to fit the duration of the research to the limited time that is available for the project, some assumptions had to be made. These assumptions are chosen carefully to maintain the relevance of the study and to be able to fully perform all three sub-objectives.

In a utopian traffic network, all ITS will integrated and working towards a common goal. In order to get to this point, the integration of pairs of ITS could be studied first. In this thesis the integration of Urban Traffic Controllers and in-car navigation systems will be studied. In-car navigation systems are chosen because of the increased connectivity of road users, as mentioned in the previous section. UTC are chosen because of the lack of consensus on the methods to control them and the room that is left for improvement. As a result, freeways and mixed traffic networks are outside the scope of this study.

Only urban traffic controllers will be studied in depth in order to find applications to improve them with the aid of the VRGS. The VRGS is not an actual, existing system but the result of the assumption that every road user will be connected within 15 years. This assumed connection enables traffic control systems to retrieve and sent information from and to every road user. The legal issues concerning the privacy of the users and the technological challenges of communicating with these systems are not considered in order to simplify the situation. The goal of this thesis is not to design a system that is ready for implementation, but to investigate the possibilities for improving traffic control systems if such a system is in place.

The test cases will be performed in a simplified simulated test network. The network will be kept as simple as possible in order to test the behaviour of the controller, and to compare its functioning to commonly used traffic controllers. In a real-life urban traffic network the complexity of the system is increased by multiple factors. Some examples are the presence of prioritized public transport, parked vehicles, asymmetrical intersections and pedestrians. The goal of the simulation study is not to show that the developed controller is better in all circumstances but to prove that it is possible to improve traffic conditions with the combination of UTC and VRGS.

The evaluation criterion, used for the case study, is the total lost time in the traffic network. The total lost time is a derivation from the Total Time Spent (TTS) in the network, which is commonly used to test the performance of traffic control systems. The total lost time is obtained by subtracting the free flow travel time from the TTS. Other criteria, such as minimization of public transport stops, minimization of slow traffic waiting times or minimization of the emission of air pollutants might be just as important to urban policy makers but are disregarded for now, also keeping in mind the simplified test network.

1.3 Relevance

Integrated Network Management is a promising direction in traffic management research. The introduction of smart phones and navigation devices to road users will increase their connectivity. This connectivity increases possibilities for further integration of in-car and road-side traffic management measures. The relevance of this thesis is that it is an extensive exploration to the possibilities of using this increased connectivity to improve urban traffic control systems. The developed controller might serve as a starting point for further development of integrated traffic management solutions within urban traffic networks.

1.4 Thesis outline

The thesis is structured according to the sub-objectives, presented in section 1.1. The thesis outline is shown in Figure 1-4. In the second chapter the state-of the art of UTC will be studied, alongside with the possibilities for vehicle route guidance. The chapter will conclude with a number of possible applications to improve the functioning of UTC and VRGS by integrating the two systems. In the third chapter, one application is chosen and developed into a working algorithm. This application is the possibility to switch between traffic control strategies, based on the predicted route demands, as measured by communications between decentralized route guidance systems and a central computer. This controller will be tested and compared to commonly used traffic controllers in the fourth chapter. In the final chapter, the conclusions from the three objectives are summarized and some concluding statements are given on the main objective of the thesis. Furthermore, some future research possibilities are identified and the field applicability of the designed controller is discussed.

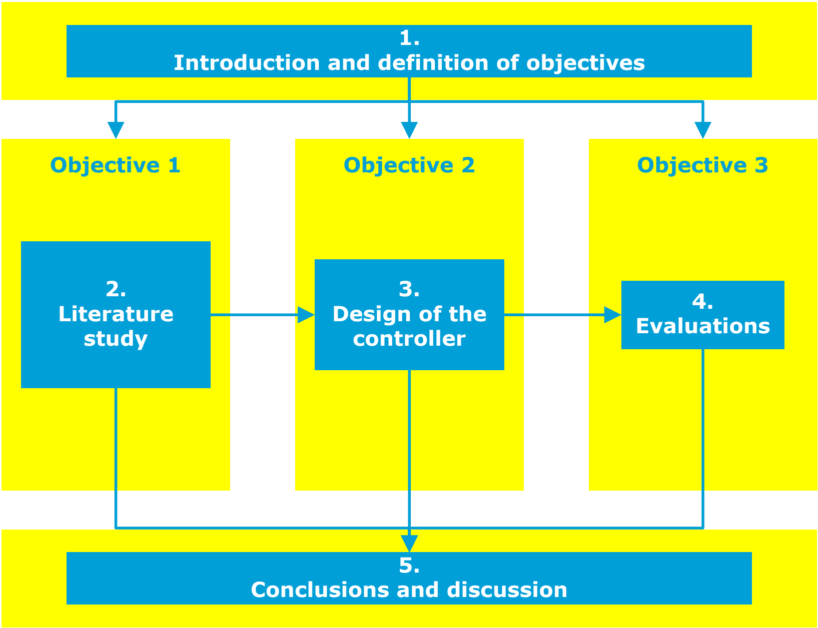


Figure 1-4: *Thesis Outline. This picture shows how the different chapters relate to the objectives, stated in section 1.1. The arrows show the line of reasoning along the document.*

2 Literature study

In the introduction, an opportunity has been defined. The opportunity is that in-car information systems will be present in the majority of vehicles occupying the roads within 15 years (Ministerie van Infrastructuur en Millieu, 2013). If these systems could be integrated with a traffic control system, they might prove to be beneficial in controlling traffic and preventing delays. In this thesis we limited this integration to urban traffic controllers and in-car navigation systems. In this chapter, the advantages of integrating the two sorts of ITS are identified through a literature study. The chapter will be concluded with a list of possible applications of an integrated controller.

The objective of this chapter has been identified in section 1.1, and is repeated here:

Study the state-of-the-art of urban traffic control systems and identify possible applications of improving these systems, in the sense of decreasing travel time losses, with the use of the assumed future connectivity of road users.

2.1 Approach

The approach to reach the objective, stated in the previous section, will be explained in this section. The section ends with an outline of the rest of the chapter.

The state of the art of Urban Traffic Controllers (UTC) will be studied in order to identify possible opportunities that arise from the integration with an assumed Vehicle Route Guidance System (VRGS). In order to find these opportunities, a general understanding of both systems (UTC and VRGS), is needed first. From the description of both systems, characteristics of UTC that influence the possibilities of integration with VRGS will be identified. This list of characteristics is the starting point of the literature study towards the state of the art of UTC.

The currently used UTC will be studied on the basis of the list of characteristics. In order to describe the evolution of UTC and to identify possible trends, a historic overview will be given. The historic overview describes the systems that have been widely used in practice or mark significant changes in the evolution of UTC. As a starting point for the selection of systems to be studied, an overview paper by Papageorgiou is used (Papageorgiou et al., 2003). This paper gives a rather complete overview of the development of UTC and has been cited a lot for this reason. Sometimes, multiple systems can be found that have the same specifications and that have been developed around the same time. When this is the case, the system that is used in the Netherlands the most, will be studied in detail. The main sources for the Dutch situation are the courseware for the TU Delft course Traffic Management and Control (Muller, Hegyi, Salomons, & Zuylen, 2011), and the guidelines for urban traffic control systems in the Netherlands (CROW 2006). The conclusion of the study will be clarified with a table, listing the characteristics specified in the first part, for each of the systems.

There will always be a time gap between the emergence of good ideas, and the time these ideas are put into practice. This means that the trends that will be identified in the study of currently used systems can be extended into the future, by studying UTC that are currently being developed. The conclusion of this part will be the expected developments of UTC in the near future as an extension to the table of characteristics.

Based on the state of the art, the expected developments in UTC, and on the assumed characteristics of the VRGS, the connections between the two systems can be identified. The next step is then to find applications that can benefit from the integration of both systems. The conclusion of this final part is a list of possible applications of an integrated system of UTC and VRGS.

2.1.1 Outline

The outline of the second chapter is depicted in Figure 2-1. In the first section, the characteristics that need to be studied will be determined on the basis of a general description of UTC and VRGS. The state of the art on these characteristics will be studied for currently used systems and research fields in the third and fourth section, respectively. In the fifth section, the possible applications of an integrated system will be defined, based on this state of the art. In the sixth section, some conclusions will be made on the objective of this chapter.

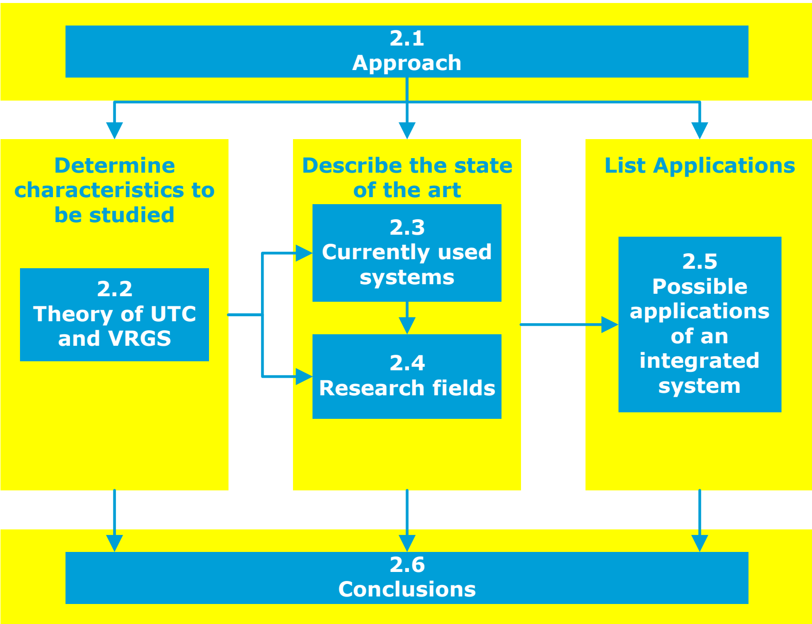


Figure 2-1 *Outline of chapter 2. The arrows show the line of reasoning throughout the chapter*

2.2 Theory of Urban Traffic Controllers and Vehicle Route Guidance Systems

In this section, a general description of UTC and VRGS will be given in order to find characteristics of UTC that determine the possibilities of integrating the systems with the VRGS. In section 2.2.1, a general description of an UTC is given. In section 2.2.2, the assumed VRGS is described. Assumptions are made since the VRGS is not an actual system. It is the result of multiple distributed systems, connected to a central computer. In section 2.2.3, the characteristics, on which the UTC will be categorized, will be given. These characteristics are based on the general descriptions of both systems.

2.2.1 Urban Traffic Controllers

In this section, the problem of controlling urban intersections is described. Traffic lights control the traffic streams at urban intersections. Urban Traffic Controllers are the control systems that determine the state of the traffic lights, i.e. the colour the lights transmit to the road users. Next to avoiding collisions between conflicting flows of vehicles, they distribute intersection capacity over the different streams. This distribution should, ideally, minimize waiting times for each user of the intersection. In Figure 2-2, a very simple control loop shows the urban traffic control problem schematically.

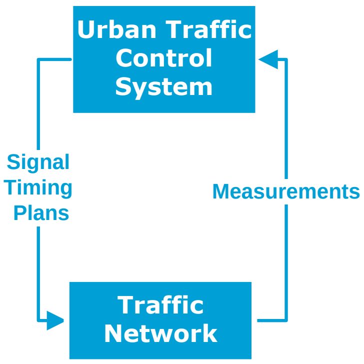


Figure 2-2: *Control loop UTC*

The traffic network consists of one or more controlled intersections, the links connecting them, the vehicles using the network and possibly some sensors measuring the traffic conditions. Based on the traffic conditions at the intersections and some control logic, the control system determines the signal timing plans for each intersection. This could either be done online, and based on the current traffic conditions, or offline, based on historic average traffic conditions, or with a combination of both. Signal timing plans determine when and for how long each approach receives a red, yellow or green signal.

In most cases, controllers use one or more of the following variables to influence the signal timing plans: stage specification, cycle time, offset and green splits (Papageorgiou et al., 2003). These variables will be described below.

Stage specification: Stages (or phases) are groups of approaches that can have right of way simultaneously. Stage specification includes grouping of approaches into stages and possibly specifying their order. Stage specification is usually done offline.

Cycle time: When a control strategy serves each of the stages in a predefined order, the cycle time is the time span before the process is repeated. Due to fixed lost times[1], a higher cycle time

[1] time to clear the intersection before another approach receives right of way

means more capacity for the intersection. On the downside, a higher cycle time also means longer waiting times. This means that the cycle time is usually minimized while still providing enough capacity to prevent building of queues behind the stop lines. Furthermore, there usually is a maximum cycle duration specified by the road authority. This maximum cycle time is needed to ensure a maximum waiting time for slow traffic (pedestrians and cyclists).

Offset: When two intersections are coordinated, offset is the time between the start of green for a traffic flow for successive intersections. Link speeds depend on the current traffic state, e.g. an increased flow on a link or more halting public transport vehicles per hour could decrease the speed of a link. Therefore, the ideal offset could differ from time to time. Coordination of traffic lights is done, for example, to create green waves.

Green splits: Green splits are the relative times that each of the stages receives right of way. This is usually the most important control variable, as will become clear in the next chapter.

2.2.2 The Vehicle Route Guidance System

In section 1, it is stated that in 15 years all road users of the Dutch traffic network are connected via smart phones or navigation devices. The resulting system, consisting of all connected vehicles we call the Vehicle Route Guidance System (VRGS). Since this system is not (yet) an existing system some assumptions have to be made to study the possibilities of integrating this system with UTC. In this section, these assumptions are explained. The main attributes of the VRGS are discussed on the basis of literature on existing route guidance systems. Similar to the case of UTC a very simple control loop for a Vehicle Route Guidance System (VRGS) is shown in Figure 2-3.

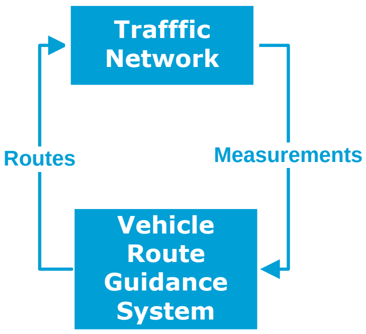


Figure 2-3 *Control loop VRGS*

The traffic network is the same as the network described for UTC. In this case, the VRGS decides on the routes advised to the drivers, possibly based on current traffic conditions in the network. Note that the VRGS consists of multiple distributed controllers, i.e. in-car navigation systems, all providing route-guidance for one vehicle.

In the next sections, the main characteristics of the VRGS will be discussed. The classifications in (Schmitt & Jula, 2006) and in (Papageorgiou et al., 2003), are used to describe the assumed attributes of the system.

The goal of the system

The objective of most route guidance systems is to guide vehicles, in order to reach the shortest travel time from an origin to a destination in the network (Schmitt & Jula, 2006). This is done by calculating the shortest path from the current location to a destination. The way the shortest path is calculated can be done in two ways: minimizing travel time for the user or minimizing the total travel time for the entire system. Systems that aim at user optimality make decisions solely in the perspective of the user of the device. In other words, travel time is minimized for the driver. System optimal strategies can take into account objectives regarding the entire traffic system, e.g. to minimize the total travel time in a network. This means that system optimal strategies do not necessarily minimize travel times for each individual user. They might increase travel times for a single user if that would benefit the total system travel time (Papageorgiou et al., 2003). In (Schmitt & Jula, 2006) this classification is described as centralized (system optimal) vs. decentralized (user optimal) systems.

Since the navigation devices are commercial systems, they are assumed to give user optimal directions to the users. In (Ministerie van Infrastructuur en Millieu, 2013), the systems are described as information systems, thus providing the user with information on the fastest route (for the user) through the network, based on the current traffic state. The effect of this assumption is that the system always moves towards user equilibrium, given the state of the network.

The responsiveness of the system

A distinction could be made between static and dynamic systems. While static systems apply route guidance based on historic or average situations, dynamic systems change route advice based on the current and predicted traffic situation as well. This is reached by communication between the in-car system and a central computer, which keeps track of the current and predicted state of the traffic network (Schmitt & Jula, 2006).

The VRGS is assumed to be a dynamic system. All in-car devices are assumed to react in some way to the current traffic state and decide on the shortest path from the current location to the destination of the vehicle. The fastest route will be recalculated before each intersection. As a result, every system needs to communicate with a central computer to receive information on the current traffic state. It is assumed that this communication goes in both directions and that in-car devices can also sent information to the central computer. In (Yamashita, Izumi, & Kurumatani, 2004), it is shown that sharing information on the route to be taken improves the accuracy of the predicted travel times.

The routing algorithms

Other than the previous points, different VRGS distinguish themselves from one another mainly in the algorithms used to calculate the shortest paths. The actual algorithms used in the in-car systems have an effect on the speed and accuracy in which they react to the current and predicted traffic situations. This determines how fast the user equilibrium is reached. Analysing all different shortest path algorithms in depth goes beyond the scope of this research but the most important differences are mentioned below.

First of all, a distinction could be made between deterministic and stochastic systems. Where deterministic systems do not take any randomness in the traffic situation into account, stochastic systems do account for unpredictable random variations. While stochastic systems are more reliable, deterministic systems are easier to implement, since their computation time is much lower (Schmitt & Jula, 2006).

Second of all, systems could be reactive or predictive. Reactive systems are based solely on the current state of the traffic system while predictive systems use a model to predict the future states. An example of a reactive system is a system that responds to a congested road and advises its user to avoid this road (Schmitt & Jula, 2006). A predictive system could anticipate on the alternative route being used more often and distribute users over the two roads in order to equalize travel times.

Finally, a distinction could be made between one-shot and iterative strategies. Where one-shot strategies use simple rules to control traffic, or run a traffic model once to calculate control decisions, iterative strategies run the model multiple times to incorporate the effect of the control decisions (Papageorgiou et al., 2003).

An advanced strategy is the use of a prediction of the route choice behaviour to optimise traffic control decisions, for example researched by Taale (Taale, 2008). An overview of this combined traffic assignment and control problem can be found in a paper by Taale and van Zuylen (Taale & van Zuylen, 2001b).

2.2.3 Characteristics that influence the possibilities of integration

The goal of this section is to determine the characteristics of the UTC that need to be studied. These characteristics need to define the possibilities of integrating the UTC with the VRGS. The UTC determines signal timing plans, based on the demands of different streams at an intersection. The VRGS determines the routes to be taken by the road users, based on the travel times of the links in the network. In theory, the changes in signal timing plans determine the average speed on a link. When a link is blocked, vehicles have to wait longer and travel times increase. On the other hand, the routes advised by the VRGS can change the demands for the links, controlled by the UTC. When fewer vehicles are guided along a route, the demand on the links that are part of this route will be lower. Thus, both systems can influence each other and integration of the systems can benefit the performance of a traffic network, where both systems are used.

However, the possibilities to integrate the systems are restricted by the characteristics of the UTC. First of all, if the UTC uses historic data to determine the signal timing plans, the routes advised by the VRGS have no effect on these decisions. Even if all vehicles are sent along one link, the UTC would not change its control decisions. Thus, the responsiveness of the UTC is an important characteristic. With responsiveness, the ability to respond to current traffic demand is described.

The effectiveness of this responsiveness to current demands depends on the control variables that are determined online. If, for example, only the offsets are determined online, only a changing demand on the link that is coordinated will change the traffic light settings.

The usability of control decisions from one system to the other also depends on the update frequency of the control decisions of the UTC. When all possible control variables are updated online, but when this is done only once every day, short term predictions on links demands are not very useful. The same holds for the usability of predictions on travel times, when they are based on the signal times of the UTC.

Communication between multiple systems is the first requirement for a combined system. If urban traffic controllers have no possibilities to communicate with a central controller, information from in-car systems is, off course, useless. The same holds the other way around, if communication is not possible, control decisions cannot be communicated to the VRGS.

Using sensors to measure the current traffic state or even using traffic models to predict the future traffic states is not new. Cameras or induction loops have been used for many years in ITS. But these sensors can only see the current state of the network and the current location of vehicles. The main advantage of using route guidance systems is that they know the destination of the vehicle and even the route that the vehicle will use to get there. These routes might be used for coordinating traffic lights to create green waves on routes that are predicted to be busy. Current systems might also facilitate coordination, it should be studied how this is done.

2.2.4 Conclusion

In this chapter, the characteristics of UTC, that define the possibilities to integrate UTC with VRGS, have been identified. In conclusion, the following characteristics have been identified to determine the possibilities of integrating UTC and VRGS, based on the description of both systems.

- Responsiveness
- Online control variables
- Update frequency
- Communication
- Coordination

2.3 Currently used systems

In this section, the systems that are currently used in practice to control traffic lights in urban networks, the Urban Traffic Controllers (UTC), will be analysed. They will be described and categorized according to the characteristics, found in section 2.2.3. The UTC are ordered chronologically, so that the developments in the field are visible. The starting point of selecting the systems is a paper by Papageorgiou (Papageorgiou et al., 2003). Systems commonly used in the Netherlands are picked according to (Muller et al., 2011) and the guidelines for urban traffic control systems in the Netherlands (CROW 2006), as is described in section 2.1. The section is concluded with the main attributes of the UTC.

2.3.1 Fixed-time Control (TRANSYT)

The simplest intersection controllers are fixed-time controllers. Fixed-time systems do not respond to current traffic situations and repeatedly run an offline optimized timing plan. At fixed times, the system can switch to another timing plan. One plan could be formulated for off-peak periods, while another plan is designed for morning peak periods and another plan is designed for evening peak periods.

TRANSYT, as described in (Muller et al., 2011) and (Papageorgiou et al., 2003), is a widely used simulation program to optimize signal timing plans for urban traffic networks. Optimization of an objective function (minimizing a weighted sum of delays and stops) is done by making small changes in cycle time, offset and split for each intersection every time step until a minimum is reached. Route choice is out of the scope of the program so minimization is done on the basis of known, historic, traffic flow patterns. Coordination between traffic lights is based on the offsets between phases of connected flows. This means that groups of coordinated intersections need to be defined before running the simulation. Coordinated intersections share a common cycle time.

2.3.2 Vehicle-Actuated Controllers

Fixed-time controllers are programmed for average traffic flows in a network. Even if these flows are the same every hour, small fluctuations can occur in the demand at intersections each cycle. Vehicle-Actuated (VA) controllers (Muller et al., 2011; Wilson & Groot, 2006) are programmed to respond to these fluctuations. Most intersection controllers in the Netherlands are VA-controllers. These controllers anticipate on the fact that arrivals at intersections are not uniform but behave stochastically. VA-controllers have a fixed structure, but the duration of green times and thus also the cycle time depends on the presence of traffic at the intersection. This presence is measured by loop detectors and cameras (cars and public transport) or pushbuttons (pedestrians and cyclists). Green times can be increased if a queue has not dissolved yet, and no traffic is waiting on a conflicting stream or the maximum green time has not been reached yet. Green times for streams can be decreased or even skipped if no traffic is waiting in the queue. An advanced VA control strategy is the MOVA (Microprocessor Optimised Vehicle Actuation) control strategy (Vincent & Pierce, 1988). When a queue is recognized at one of the approaches of a MOVA-controlled intersection, MOVA automatically switches to a capacity-optimising routine in order to clear the congested approach as quick as possible.

2.3.3 SCOOT

Usually, traffic flows do not evolve in a predictable way and demands are not constant, even for a given time of day (Papageorgiou et al., 2003). Fluctuations for example between days of the week, between periods of the year or due to events make that fixed timing plans are usually not optimized for the actual traffic situation. Traffic responsive strategies aim at controlling traffic based on the current traffic situations, rather than on historic data. SCOOT (Hunt, Robertson, Bretherton, & Royle, 1982) is one of the first and most used real-time urban traffic control systems. It was developed in the 1970's and can be seen as a real-time version of the TRANSYT system. The system uses detectors at links approaching the intersection as far from the intersection as possible. The system uses an online traffic model to predict the arrival of platoons at the traffic lights and to estimate the queue lengths. Turning rates are based on the previous cycle. Based on this information small changes to cycle time (each 2.5 or 5 minutes), offset (each cycle if synchronized) and green split (a few seconds before switching to the next phase) can be made for each intersection. Coordinated intersections operate on the same cycle times to facilitate coordination.

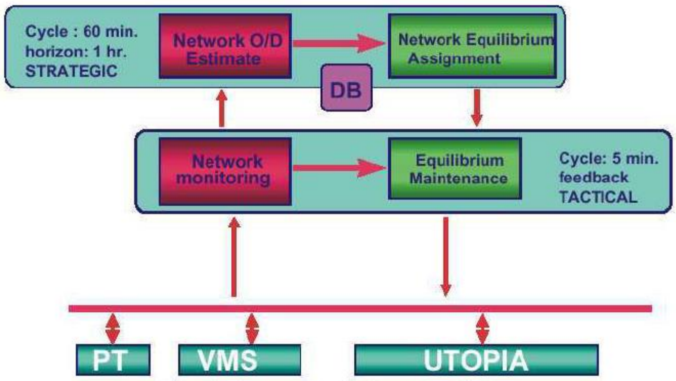
2.3.4 SCATS

SCATS (Lowrie, 1982) is an Australian system that was introduced around the same time as SCOOT and is also implemented in urban traffic networks around the world. The SCATS system uses no mathematical traffic model, but selects signal timing plans on the basis of the degree of saturation on selected approaches in the previous cycle. This degree of saturation is calculated by dividing the total green time by the unused green time. Loop detectors, directly in advance of the stop line, are used to measure unused green time (no vehicle on detector) and count the number of vehicles that passes the detector (since headways need to be subtracted from the unused green time). Intersections in subsystems (1-10 intersections) function on common cycle times and are synchronized. Sub-systems can be linked together when cycle times between the two subsystems only differ a few seconds. In that case external offsets are optimized as well.

2.3.5 Phase-based optimization methods (UTOPIA-SPOT)

In the 80's and 90's more rigorous model-based traffic-responsive strategies have been developed like OPAC (Gartner, 1983), CRONOS (Boillot et al., 1992), PRODYN (Henry, Farges, & Tuffal, 1983), RHODES (Mirchandani & Head, 2001) and Utopia (Taranto & Mauro, 1990). These strategies do not consider splits, cycle times or offsets but specify, in real-time, the optimal values of the next phase switching times. This optimization is done on the basis of traffic models that predict the future traffic situation based on possible control inputs. A rolling horizon approach is used, meaning that the system specifies these switching times for a longer period (e.g. 60 seconds) but only actually applies the results for the first couple of seconds, before new measurements are collected and new calculations are made on the basis of these measurements. Due to the high demands for computation time for all these methods, optimization of traffic light settings is done for isolated intersections while coordination is done by an upper level controller.

It is beyond the scope of this report to discuss all these methods in detail so the UTOPIA/SPOT system is chosen as an example for this class of systems, since this system has also been implemented in Dutch cities (Wilson & Groot, 2006). The UTOPIA/SPOT system (as described in (Muller et al., 2011)) is a network traffic control system that employs hierarchical control for urban networks. For the control of signalized intersections the UTOPIA (Taranto & Mauro, 1990) system is used. Another example of such a hierarchical construction can be found in (Gartner, Pooran, & Andrews, 2001) where the implementation of the OPAC system is described.



The top level controller compares the demand at the edges of the network to a database of Origin-Destination trips. A network equilibrium assignment is performed every hour to supervise the state of the network. The top level provides coordination between different traffic control systems, in this example public transport priority systems (PT), variable message signs for route guidance (VMS) and UTOPIA for traffic light control.

Figure 2-4: *UTOPIA/SPOT top level controller (source:* Muller et al. 2011)

In Figure 2-4, the system is depicted. The UTOPIA system is also a multilevel controller, consisting of an area level and multiple intersection levels. Both these levels consist of an observer to estimate current traffic states and a controller to optimize control inputs. On the intersection level, the rolling horizon approach, that the UTOPIA system deploys, uses a 120 second horizon, which is updated with new traffic counts every 6 seconds. The intersection controller communicates with adjacent intersections to find out if traffic released by the intersection can be accommodated by its neighbour. If needed, two actions can be undertaken: increasing throughput to the adjacent intersection or decreasing demand.

The area level controller works with an observer that predicts, based on actual traffic counts and statistical traffic characteristics, the main routes to be used by vehicles passing through the network. A macroscopic network model is used that works with discretized time steps of 3 minutes. A controller optimizes fictitious control signals: average speed and saturation flows within parts of the network. These optimal controls are used as input for the weightings for the terms in the objective function of the intersection controllers.

2.3.6 TUC

In the end of the previous millennium, the TUC traffic control system has been developed specifically to deal with urban traffic control in saturated conditions (Diakaki, Papageorgiou, &

Aboudolas, 2002). The strategy is based on store-and-forward modelling of traffic networks. The basic notion behind this kind of modelling is a simplification in the outflow of links: Instead of letting the outflow of a certain link be the saturation flow[2] during the green phase and 0 during the red phase, the flow is the average flow during the entire cycle. This opens the way to a number of highly efficient optimization and control methods (Papageorgiou et al., 2003).
The system uses a Linear Quadratic Regulator (LQR) approach with the objective of minimizing and balancing link occupancies for an entire network. The gain matrix for the regulator is calculated offline, based on network topology, saturation flows and turning movements. The state vector consists of the link occupancies of all the links present in the network. Note that only green splits are optimized by the controller and that cycle times and offsets need to be calculated by other, parallel, algorithms. Furthermore, the controller cannot take into account constraints like minimum and maximum green times. This means that constraints need to be matched in an extra step after the optimization of green times.

2.3.7 Other applications of traffic lights

Besides allocating intersection capacity to crossing streams, traffic lights could also be used for different traffic management purposes. Other control systems make use of the relationship between density and flow, as expressed in the fundamental diagram, to strive for an optimal number of vehicles in a controlled area. In (Hoogendoorn et al., 2013) the queues at urban intersections are used as buffer space to store vehicles approaching freeway onramps to increase the possibilities for ramp metering. In (Keyvan-Ekbatani, Kouvelas, Papamichail, & Papageorgiou, 2012) the number of vehicles in an urban area is controlled in order to optimize throughput in the network. The Network Fundamental diagram is used to find the number of vehicles in the network where throughput is the highest.

2.3.8 Conclusion

Table 2-1 shows the main attributes of the currently used UTC. The first categorization shows the way in which the systems respond to historical, current or future traffic situations. Most systems found (in the Netherlands) respond to the current traffic situation. Either by checking if traffic is currently waiting at the intersection in order to decide on changes to the fixed structure (VA control) or by making small changes to the current signal timing plan.

When looking at the control variables, the main control variable used by every non-fixed system is the green split. While changing the green splits, capacity for each link is changed directly. The cycle time is used as a control variable in most systems, either indirectly by changing the green splits (e.g. with VA control) or directly. An example of the latter case can be found in the TUC system where a parallel algorithm first decides on the cycle time before the LQ-regulator calculates the green splits. In this system, as in other centrally controlled systems, the cycle time is, however, equal for all intersections. This is also the case for systems that make use of green waves. Offsets are, naturally, only used for systems that make use of coordination of traffic lights

[2] The saturation flow is the flow a certain stream reaches when it receives right of way i.e. the queue discharge rate.

and thus not for distributed systems. Phase sequences are usually fixed. In practice, only VA-controllers may cause different phase sequences but this is only because of the possibility to skip phases. The difficulty with changing the phase sequence is on the one hand the complexity of the problem (Papageorgiou et al., 2003) but on the other hand also the fact that people might get used to phase sequences on familiar intersections, and anticipate on a green light (Wilson & Groot, 2006).

Table 2-1: *Summary of attributes of the studied UTC.*

source	Keyword	Respon-siveness			Online control variables				Update frequency			Communi-cation			Coor-dination		
		Predictive	Instantaneous	Fixed-time	Phase sequence	Split	Offset	Cycle time	At least 1 cycle	Phase	Seconds	Agent to agent	Central	No	Adaptive	Fixed	No
(Muller et al. 2011)	TRANSYT			x					x					x		x	
(Muller et al. 2011)	VA		x		x	x					x			x		x	
(Hunt et al. 1982)	SCOOT		x			x	x	x			x			x		x	
(Lowrie 1982)	SCATS		x			x	x	x			x	x			x	x	
(Taranto and Mauro 1990)	Hierarchical	x				x	x	x			x	x	x		x		
(Diakaki, Papageorgiou, Aboudolas 2002)	TUC		x			x	(x)	(x)	x				x			x	
(Hoogendoorn et al. 2013)	INM		x			x							x				

The update frequency might be important when control decisions by the UTC will be used by VRGS's. Currently used systems update their decisions based on the current situation, i.e. if a vehicle is present on a detector; keep it green, if not; show a red light and change to the next phase. Only the TUC system updates the control decisions each cycle, thus traffic light settings are known for at least one minute.

Communication between intersection controllers and a central controller or between intersection controllers has not been found in the older systems. It has been found for some modern controllers. Agent to agent communication is used in TUC and Utopia for the coordination of traffic lights. Communication with a central computer is needed in TUC since the system aims at minimizing travel times for an entire network and settings for multiple intersection controllers are changed at the same time.

The creation of green waves in current systems is usually fixed, i.e. a route always accommodates a green wave or a route never accommodates a green wave (at least not programmed). In Utopia and SCOOT intersections are synchronized to create green waves when cycle times are practically equal. This does mean that each intersection can only be part of one green wave.

2.4 Current research

In the previous section, the characteristics of currently used UTC have been studied. However, developing new methods and implementing new traffic control systems takes a lot of time. The UTC of the next 20 years might have already been described in literature. Thus, studying the state of the art is not finished with studying traffic controllers that are already in use. It is also important to analyse the work that is currently done by researchers in order to improve current systems. In this way, a direction where the field is moving can be identified. While current systems do respond to the current traffic situations, instead of controlling traffic on the basis of historic or average traffic patterns, these systems still fail to work in saturated conditions (Papageorgiou et al., 2003). Newly developed systems aim at resolving this problem. The currently proposed controllers will be described in this section. First the centralized approaches will be discussed and after that the decentralized and distributed approaches will be discussed.

2.4.1 Centralized approaches

Model Predictive Controllers (MPC) take into account the current as well as the future traffic situation. Traffic models are used to take into account the effect of control inputs to the system when specifying the optimal control signal. An objective function is used that can take into account any objective, as long as its performance can be measured with the model. Furthermore, the effect of multiple traffic control systems can be taken into consideration in the same optimization ((Schutter, Hellendoorn, Hegyi, Berg, & Zegeye, 2010) for example). The problem with urban traffic networks is that this kind of optimisation procedure takes too much computation time to be feasible in real-time, at least with currently available computers. That is why several simplifications have been proposed. The previously discussed hierarchical control methods perform optimisation on a local level and deploy higher level heuristic methods to account for synchronization. The TUC traffic control system optimizes the feedback regulator offline as described before. In (Lin, Schutter, Xi, & Hellendoorn, 2011) an urban network control problem is formulated as a Mixed Integer Linear Programming (MILP) problem with the use of a simplified macroscopic traffic model. Although computation time is reduced significantly, the model is still concluded to be infeasible for larger urban networks and hierarchical controllers are advised. Another MPC approach is formulated in (Le, Vu, Nazarathy, Vo, & Hoogendoorn, 2013), this approach is particularly interesting since it explicitly incorporates route guidance into the optimization problem. Turning fractions are defined as control inputs while compliance is assumed to be 100 %.

2.4.2 Decentralized and distributed approaches

Since a MPC that is capable of controlling an urban traffic network in real time is not (yet) formulated, lots of literature can be found on intersection controllers that only control a single intersection. A distinction can be made between distributed controllers that work truly isolated and decentralized controllers that do exchange information with their neighbour intersections.

Where the centralized systems aim at finding a global optimum with a centralized controller, decentralized and distributed systems seek to find an optimum for each intersection. Agent-based methods to control intersections are proposed for example in Wang (Wang, 2005), where he states that the focus should shift from control algorithms to control agents, optimizing their own network but at the same time working together towards a network optimum. Distributed artificial intelligence is used as a method for the agents, which are, in this case, controlled intersections. The main advantage of these approaches is mentioned to be the cheap and easy implementation. Another example of agent-based signal control can be found in the PhD-defence of van Katwijk (Katwijk, 2008).

Bazzan (Bazzan, 2005) uses game theory to represent the preferences of each agent. A payoff mechanism is described where agents are rewarded for the way they handle the traffic at their own intersection but also for the global traffic state. By striving for a maximum reward, each agent would "learn" itself the best solution for each situation. Communication with its direct neighbours can be used as a means to do this, making it a decentralized system. A problem with this approach is that it takes a long time before the agents have taught themselves the best solutions and that the system performs better in stable scenarios. An advantage is that the agent-based approach allows agents to break with synchronization for a short period to cope with local traffic conditions and to form synchronization groups with neighbouring agents (Junges & Bazzan, 2008).

In (Oliveira & Camponogara, 2010), a MPC problem is formulated for each junction, where the store-and-forward modelling approach is used for the traffic model. Compared to the TUC strategy, the approach yields the same results but without the need for configurability, thus changes to the network could be implemented rather simple. The difference with other distributed MPC approaches is the absence of a top-level controller.

Lämmer and Helbing (Lämmer & Helbing, 2008) propose self-control for traffic lights, based on an observation of conflicting pedestrian flows, where pressure differences account for a self-organization of counter-flows that resembles traffic light control. In their approach, opposing flows are served on the basis of their relative size and the constraint that each phase is served once every cycle is dropped. The system performs mainly in under-saturated conditions, since in saturated conditions the system in fact behaves like a fixed-time controller, due to maximum green constraints.

Another approach for distributed control is based on backpressure routing (Varaiya, 2013; Wongpiromsarn, Uthaicharoenpong, Wang, Frazzoli, & Wang, 2012) where each junction bases the optimal phase to be served next, solely on the traffic measurements of the surrounding links. Wongpiromsarn et al. assume infinite queuing space. These algorithms use the current state at downstream links as well.

2.4.3 Conclusion

This section investigated the current research in UTC in order to define future directions of the controllers in the field. The main question that has still not been solved is how to control an entire urban network at once, while responding to the current and future traffic state and controlling multiple intersections at once. Solving this problem to optimality is impossible online (at least with current technology) due to the complexity of large urban traffic networks. Thus, simplifications need to be made.

The first simplification is to solve (part of) the problem offline. The first systems solved the entire problem offline, for a set of historical or average traffic states (TRANSYT). Therefore, the problem was simplified to the design of a fixed-time controller. The simplifications make it possible to coordinate traffic lights for an entire network. However, due to their fixed-time nature, these systems are unable to respond to changes in the traffic state. Therefore, other systems were defined that solve most of the problem offline but allow the system to make small (SCOOT and SCATS) or somewhat larger (TUC) changes, based on the currently measured traffic state. The central control approach of these systems allows them to coordinate traffic signals. The assumptions made to be able to control multiple intersections at once make these systems slow to respond to the current traffic state and short-term changes in the traffic network. Furthermore, the offline calculations and setting of parameters make it hard to adapt the system to long-term changes in the traffic network. Current research mainly focusses on decreasing the time needed for online calculations but a system that can solve the UTC problem in real-time seems only to exist in theory.

Rather than solving the entire problem for optimality, distributed and decentralized controllers only look at the traffic situation on one intersection. Where most currently used systems (VA-controllers) only look at the demand at the upstream links of the intersection, modern systems also look at the possibilities to release traffic at the downstream links. This can either be done by measurements on these downstream links (distributed controllers) or by communications with other intersections or a central computer (decentralized controllers). These controllers can respond quicker to short-term changes and have no problems with long-term changes. However, they are unable to coordinate traffic lights.

2.5 Possible functionalities

Based on the previous sections on the definition of the VRGS and the study on the state of the art of UTC, some applications of a combined VRGS and UTC system will be identified in this section. In the next chapters, one of these applications will be chosen to be developed into a functioning controller. First, the possible benefits of a combined system will be discussed for the VRGS. After that, the possible benefits for UTC will be discussed. Finally, some applications of a fully integrated system will be mentioned. This is not a complete list of possibilities, just a result of the studied literature.

2.5.1 Using UTC variables for route guidance

The control variables, generated by UTC could be used for improving VRGS. UTC decide on signal timing plans. Another way to formulate this is to say that UTC decide on the capacity of a link. The capacity of a link is the maximum number of vehicles that can use this link per time unit (veh/h). When a higher green split is calculated for a certain link (while the cycle time does not change), this means that the capacity is increased. VRGS could use this capacity, in combination with the predicted link counts (following from the advised routes) to calculate the link speeds and calculate the fastest route. The first application is thus, to use the calculated green splits as an input for the calculation of the fastest route for navigation systems.

Rather than using the route with the shortest travel time, road users might prefer to travel the route with the least stops. If the settings of the signal timing plans are known for some time ahead, a calculation could be made on the route that incorporates the least stops for a red traffic light. The second application is, thus, to use the signal timing plans in the network, in order to find routes that minimize the number of stops for a red light.

Some UTC create green waves by coordinating traffic lights on a route. The presence of a green wave on a route could be used by in-car navigation systems to base their advised route upon. The system should, however, also take into account the presence of queues. When queues do not fully resolve each cycle, a green wave will not work since vehicles would still have to wait at each intersection. The third application is, thus, to use the presence of green waves in a traffic network to base the advised routes upon.

Gating systems, for example the one used in PPA (Hoogendoorn et al., 2013), use urban roads as buffer space by decreasing green times for the traffic that is entering a controlled area. When this buffering is active, a signal could be sent to a central computer of the VRGS. In-car systems could use this information to advice people using the road, but with a destination outside of the controlled area, to change routes. This could also increase the buffer times for the gating system. The fourth application is, thus, to use the control decisions of gating systems, in order to avoid the gated areas.

2.5.2 Using VRGS variables for traffic light control

The other way around, the control variables generated by VRGS's could be used for improving UTC. VRGS decide on routes to be advised to drivers of equipped vehicles. The used routes of vehicles and the current location of vehicles could be sent to a central computer that aggregates the data, which could be used as input for traffic control. Many studies (e.g. (Herrera et al., 2010); (Fabritiis, Ragona, & Valenti, 2008); (Furtlehner, Lasgouttes, & Fortelle, 2007)) have shown the value of GPS-equipped probe vehicles for state estimation. In this study it is assumed that the routes to be taken and the current location of the equipped vehicles are known by the system. This information could be used directly by traffic control systems. This would decrease the need for expensive road-side detector systems, such as detector loops or cameras. The fifth application of an integrated system is, thus, to use equipped vehicles as probe-vehicles for state estimation, in order to increase the observability of the controller and decrease the need for expensive road-side detector systems.

The current UTC that use coordination of traffic lights, either coordinate all the time on routes that are determined offline, or determine if intersections should be coordinated based on heuristic method and the current traffic state. If a central system knows exactly what routes will be used in the near future, it might be interesting to coordinate traffic lights on these routes instead. The sixth application is, thus, to adaptively coordinate traffic lights, based on the current and predicted route demands in the network.

Many UTC use turning rates that are either fixed or based on turning rates in the previous iteration. When lots of vehicles communicate the routes, which they will be using, to a central system, the system could fairly easily calculate the turning fractions for intersections, based on these routes. These turning rates could be used as input to the systems. The final application is, thus, to use the predicted routes in the network to determine the turning rates.

2.5.3 A fully integrated system

The previous sections have shown that both systems influence each other. An UTC could change the capacity of a link, which could change the speed on this link. These speeds could be used by a VRGS to determine the advised routes for the users of the system. Changing these routes could change the flows through the network. These changed flows could urge the UTC to change the signal timing plans and, thus, the capacity of the links inside the network. Ideally, an integrated system would optimize the travel times in a network by changing both the signal timing plans and the advised routes in the network simultaneously. However, when implementing any of the applications, the effects for both controllers should be studied.

2.5.4 Conclusion

This section investigated some possible advantages of an integrated system for UTC and VRGS.

The found applications for the VRGS are the following:

- Use UTC control decisions to determine link capacity
- Use UTC timing plans to calculate routes with the minimum amount of stops
- Use the presence of green waves to plan routes
- Use the control decisions of gating systems, in order to avoid gated areas

The found applications for the VRGS are the following::

- Use equipped vehicles as probe-vehicles for state estimation, in order to increase the observability of the controller and decrease the need for expensive road-side detector systems

- Adaptively coordinate routes in the traffic network, based on the current and predicted route demands.
- Use predicted routes to predict turning rates at intersections

A fully integrated system is found to be infeasible, but when implementing any of the applications the effects on both controllers should be taken into consideration.

2.6 Conclusions and discussion

In this chapter, a literature study has been performed in order to find possible applications of an integrated system of VRGS and UTC. The objective for this chapter has been identified in the introduction as follows:

Study the state-of-the-art of urban traffic control systems and identify possible applications of improving these systems, in the sense of decreasing travel time losses, with the use of the assumed future connectivity of road users.

2.6.1 Conclusions

In section 2.2, a general description of UTC and the VRGS was given in order to identify characteristics that define the possibilities of integrating the two systems. The found characteristics were responsiveness, control variables, update frequency, communication and coordination.

In section 2.3, currently used urban traffic control systems were analysed by describing them according to the characteristics found in the previous section. The main conclusion was that, although all systems aim for optimal solutions of the traffic control problem, the problem is found to be too complex to be solved online, with currently available computers. Therefore, all currently used systems use simplifications of this problem or partly solve the problem offline.

In section 2.4, a study towards currently researched systems has shown that there are two main directions in the simplifications used to solve the problem. The first is to keep controlling all intersections by a central controller but solve (part of) the problem offline. In this way, the benefits of a central controller are maintained but responsiveness of the systems to short-term as well as long-term changes in the traffic state is slow. The second direction is to optimize control decisions for smaller parts of the network (mostly intersections). These systems can respond quicker to changing traffic situations but are unable to coordinate traffic controllers.

Finally, in section 2.5 some applications of an integrated system that incorporates VRGS and UTC were identified. The section shows that both systems can benefit from an integrated approach were control decisions are shared between the systems.

The main conclusion for this chapter is that it is impossible to optimally solve the urban traffic control problem for multiple intersections at once online. Developed systems differ mainly in the way they handle simplifications to the problem. The VRGS is a hypothetical system that could exist if all vehicles in the traffic network are connected in the near future. Rather than existing next to each other, both systems should exchange information and control decisions, in order to improve the effectiveness of urban traffic networks and decrease lost times for every user.

In the next chapter, one of the identified applications of an integrated system will be chosen to be developed into a working controller in order to prove that integration of the two systems can indeed, benefit the urban traffic network.

2.6.2 Discussion

In this chapter, the VRGS is assumed to be solely an information system. Routes advised to users will always be made to minimize the travel times for the user of the system. This user optimum decreases the possibilities of using the VRGS for traffic control purposes since traffic control is usually focussed on decreasing the total travel times for the entire network; a system optimum. At this moment it is impossible to oblige road users to use the routes, advised by their navigation system. Road travel, owning a car, is seen as a symbol of freedom and every measure that limits the use of a car is seen as a limitation of the personal freedom of car owners. It is more important to choose your own path than to get from A to B in the fastest way possible.

The development of self-driving vehicles might change the way people think of vehicles; if you let a car make the operational decisions on traveling, why not let a traffic controller make the tactical and strategic decisions? Probably neither of these developments, self-driving vehicles or system optimal route guidance, will dominate the traffic networks on a short notice. A change in the way we think about transportation is needed if we ever want to make full use of the possibilities of traffic control. This might be the biggest scientific challenge in the next decennia; show people that traffic jams and travel time losses could be a thing of the past, if they accept that the true freedom of transportation lays in the fact that you can move anywhere you want, whenever you want. And not on the route you prefer to take.

3 Design of the controller

In the introduction of this thesis, the opportunity to use the increased connectivity of road users in order to improve traffic control systems, has been identified. In the previous chapter some possible applications of such an integrated system have been discussed, based on the characteristics of both systems. In this chapter one application will be chosen to be developed into a functioning controller. Every step that needs to be taken in the process of controlling the traffic will be described. Once the controller has been designed, it can be tested in a simulation study in order to show that integration of the systems indeed decreases travel time losses.

The objective of this chapter has been identified in section 1.1, and is repeated here:

Develop one of the identified applications into a control strategy that decreases travel time losses in an urban traffic network

3.1 Approach

The approach to reach the objective, stated in the previous section, will be explained in this section. The section ends with an outline of the rest of the chapter.

The first step is to choose one of the applications. The application will be chosen, based on the conclusions on the state of the art of the UTC, as stated in the previous chapter, i.e. the application should be usable with the characteristics of the systems in mind. Furthermore, the scope of this thesis, as stated in section 1.2, limits the possibilities of applications to be chosen. Finally, the chosen application needs to be implemented in a small-scale simulation in order to test it.

When an application is chosen, it can be developed further. First, the control principles will be explained. Then, a functional description of the controller will be made, in order to give a clear overview of the control process. This functional description will conclude with a list of control steps that have to be developed. Finally, the control steps will be described in detail and supported with literature.

3.1.1 Outline

The outline of the chapter is depicted in Figure 3-1. In section 3.2, functionality will be chosen to be developed. In section 3.3, the functional description of this application will be given. In sections 3.4 to 3.8, the controller will be described step by step. Finally, in section 3.9 the chapter will be concluded and the most important findings will be repeated. Furthermore, recommendations will be given for the simulation study and for implementation of the controller.

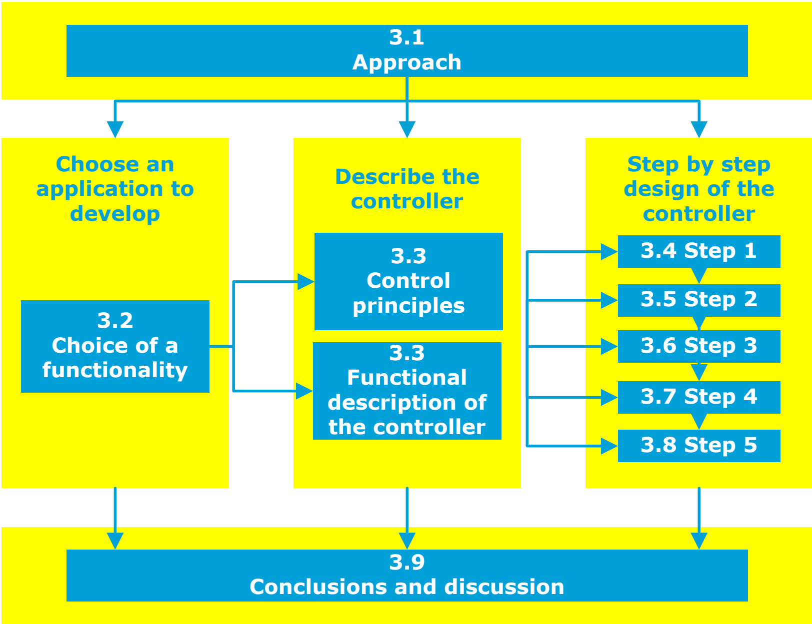


Figure 3-1: *Outline of chapter 3. The arrows show the line of reasoning through the chapter*

3.2 Choice of a functionality

In this section, one of the functionalities of an integrated controller, as defined in section 2.5.4, will be chosen to be developed. The list of possible applications is repeated below:

1) Use UTC control decisions to determine link capacity
2) Use UTC timing plans to calculate routes with the minimum amount of stops
3) Use the presence of green waves to plan routes
4) Use the control decisions of gating systems, in order to avoid gated areas
5) Use equipped vehicles as probe-vehicles for state estimation, in order to increase the observability of the controller and decrease the need for expensive road-side detector systems
6) Adaptively coordinate routes in the traffic network, based on the current and predicted route demands.
7) Use predicted routes to predict turning rates at intersections

With the simulation software, used for the case studies in chapter 4, it is not possible to adaptively guide individual vehicles through the network. Therefore, the applications that use control decisions from the UTC to control VRGS (number 1 to 4) will not be developed. The implementation of predicted turning rates into an UTC will not be used either. This would mean that changes would have to be made to existing control systems. However, the systems that use these fixed turning rates have been found to be commercial systems and the control algorithms are not publically available. Therefore, the choice is made to develop the sixth application. In order for this application to work, the seventh application is assumed to be available as an input to the controller.

The chosen goal of the controller is thus the following:

"Use predicted route demands on an urban traffic network to choose between coordinating traffic lights, in order to create a green wave, and controlling intersections with a distributed controller."

3.3 Control principles

Now, the principles that form the basis of the control approach will be discussed.

The control strategy will be developed for an urban traffic network, where all intersections are controlled by vehicle-actuated (VA) controllers. This resembles the situation in most Dutch traffic networks. As described in section 2.3.2, VA-controllers base the green times for each approach on an intersection on the presence of vehicles, as measured by loop detectors. The light will remain green until the queue is completely dissolved or until the green time has reached its maximum. The end of the queue is identified by a gap between vehicles that is larger than a certain boundary value. VA-controllers work very well in unsaturated conditions because they are able to assign just enough green time to each stream. However, since VA-controllers are local controllers, they are unable to coordinate multiple intersections.

The advantage of coordination of traffic lights on a road is the possibility to create green waves. However, in order for a green wave to last for multiple cycles, the cycle times of all intersections that are part of the green wave need to be equal. In order to meet this constraint, current coordinated controllers are either fixed-time controllers or recalculate the cycle time and offset for the coordinated intersections on fixed times. Fixed-time controllers are not able to respond to changing traffic demands and are therefore unsuitable for controlling urban traffic networks (according to the literature study in section 2.3). Coordination of traffic lights by recalculating the cycle time and offsets (for example in TUC and UTOPIA) restricts the possibilities for the controller to control traffic effectively. This is because for these systems the routes on which the green waves are active, are fixed, and once a group of intersections is coordinated, they always need to have equal cycle times. This is not a problem when the optimal cycle time of all intersections is not so far apart (which could be the case during peak hours when all optimal cycle times will be close to the maximum cycle time). However, when the optimal cycle time for a certain intersection is much lower than the cycle time determined for the green wave, this fixed coordination could increase waiting times significantly. This is especially the case for streams conflicting with the green wave.

The controller, developed in this chapter, aims at combining the flexibility of VA-controllers with the effectiveness of coordinated control. In order to do so, the controller will decide if it is profitable to create a green wave in the traffic network instead of controlling every intersection independently. This decision will be made on the basis of predicted route demands in the traffic network. These predicted demands will be calculated on the basis communication with the VRGS. A prediction method will be used to predict the delays for different control strategies. These strategies are either VA-control or coordinated control on one or more routes. Essentially, if many vehicles plan to use a certain route in the network, it could be profitable to coordinate traffic lights on this route. A prediction method will determine if this is indeed the case.

3.4 Functional description of the controller

The controller is a top level controller that decides whether or not to switch between vehicle-actuated control and coordination of intersections. Switching is done when it is possible and profitable to do so. The functioning of the controller is depicted in a flow chart in Figure 3-2.

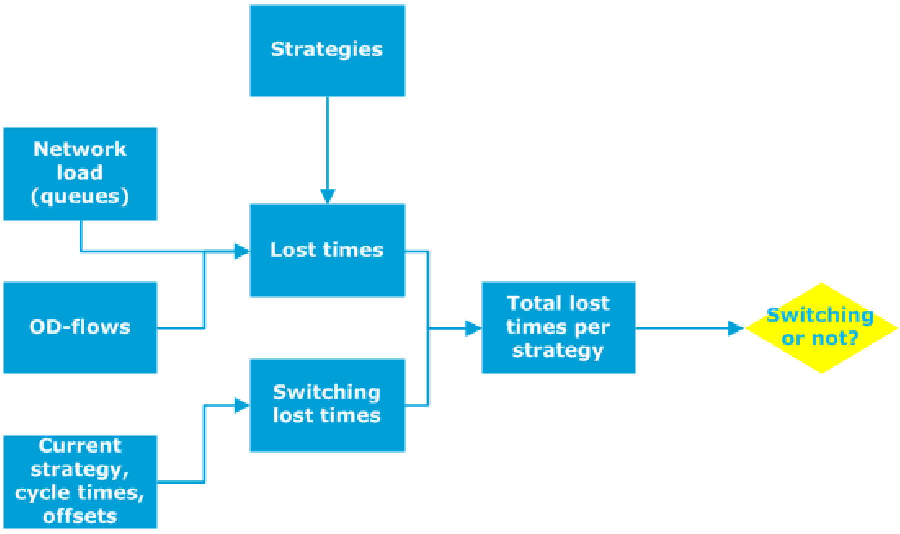


Figure 3-2 *Flow chart of the controller. The controller decides, every control period, if a switch should be made from one control strategy to another.*

The controller decides whether it is profitable to change from vehicle-actuated control to coordinated control or vice versa, or if the current control approach should be maintained. It does so by predicting and comparing the lost times for a number of possible strategies. Furthermore, the possible time losses due to the switching of strategies are predicted. The prediction of lost times is done on the basis of the route demands in the network, calculated from the inputs from navigation systems, the currently used strategy and the queues that are present in the network. In the following, the inputs to the controller will be discussed in detail.

The first input to the controller is a list of strategies that can be used to control the traffic network. The basic or default strategy (s_0) will be the same for every traffic network. This basic strategy is to control every intersection with vehicle-actuated (VA) controllers. Every other strategy includes coordinated control of traffic lights on at least one route. The intersections that are coordinated function as fixed-time controlled intersections for the duration of one control period, while all other intersections are controlled with VA controllers. In the case study performed for this thesis, it is assumed that all strategies are determined offline. However, in the case of larger networks, it might be cumbersome to calculate all possible green wave routes and to calculate lost times for each strategy. Future research should include the creation of a model to find routes that have the potential to decrease waiting times by switching to a green wave.

The second input to the controller is a set of link demands for the current time period. Each vehicle, connected to the system, sends its current location, destination and planned route (as calculated by a navigation system) to a central computer. This central computer then aggregates these values and calculates the link demands. Thus, it is assumed that there is a system present to calculate aggregated link demands for each time period. The model to calculate these demands is outside of the scope of this study, so the input for the controller will be the link demands.

Based on these inputs, the controller first calculates the total lost times for all possible strategies. When the current strategy on an intersection is VA control and a switch is made to coordinated control, some intermediate stages might be needed to coordinate offsets. These intermediate stages might increase the total lost time for the strategy. In the current controller, this switching lost time is dealt with by demanding a minimum decrease in travel times, before a switch is made.

When the total lost times for each strategy are known, the controller can make a decision on how to control each intersection in the current time period. In short, the following steps are taken when controlling the traffic network:

1. The controller receives link demands from a central computer;
2. The controller predicts the total delay for each strategy;
3. The controller decides on the strategy to be used;
4. Intersections that form a green wave are coordinated;
5. The strategy is implemented and the controller monitors the situation until new information is sent.

These steps will be described in depth in the next sections.

3.5 Step 1: Receiving link demands

The first step is to send the link demands to the controller. The traffic network contains links and junctions, which connect these links. The links are indicated with the index l, and junctions are indicated with the index j. Each junction contains input links and output links. Each stream across the junction is a different input link, which is connected to an output link. The central computer sends the expected average link demands ($q_l(k)$, in veh/h) for each link, to the controller. This information is updated for every next time period, as indicated with the time index k.

3.6 Step 2: Prediction of delays

The second step involves predicting the delays for each strategy, so that the strategies can be compared. There are different measures of performance that can be used to compare different strategies for signal control. The most common measures are delay and number of stops (Akçelik, 1998). Depending on the preferences of the user of the controller, an objective function with weightings for the different statistics can be chosen. Since the main objective of the controller is to reduce lost times, we will use the total delay as only measure of performance. With this total delay, only the delay caused by intersections is meant. Delay, caused by other factors, is not predicted with the functions that will be described in this section, because it is not assumed to be influenced by the intersection controllers. In order to predict the total delay in the network, the average delay per controlled (or input) link will be predicted, when summed up, and multiplied with the number of vehicles that use the links, these delays will give the total (average) delay for the network. In other words the total delay is calculated by equation 3-1.

$$D_s(k) = \sum_l d_{l,s}(k)\, q_l(k)/3600 \qquad (3\text{-}1)$$

In this equation, $D_s(k)$ [h] is the total delay for strategy s in time period k, $d_{l,s}(k)$ [s/veh] is the average delay for link l in time period k when strategy s is used, and $q_l(k)$ [veh] is the demand for link l in time period k. The delay for each link is a function of the signal timings, average demand and saturation flow for a link. The functions are given in the next section. In the section after that, the calculation of signal timings is given.

3.6.1 Prediction methods

Calculating the total delay will be done based on a prediction method. Two methods have been found, one by Akçelik (Akçelik, 1998) and one used in the Highway Capacity Manual (Transportation Research Board, 2000). These methods are chosen since they are advised in the handbook for intersection controllers (Wilson & Groot, 2006), commonly used to design intersection controllers in the Netherlands. An extensive study on different methods to predict delays, can be found in (Vitti, 2006) but is outside the scope of this study. In (Taale & Zuylen, 2001a), the HCM method showed to work very well for fixed-time intersections and simple VA-control, but not so good for complex VA-control, especially in saturated conditions. In order to see if the prediction methods do work well enough for the application of this study, the two selected methods will be compared in a case study in chapter 4. After this study, one method will be chosen for the controller. First the workings of the methods will be explained below.

Both methods calculate average waiting times for a controlled link, based on green times, cycle times and the capacity of that link. Both methods are based on a function with a uniform part and a random part. The uniform delay is the delay caused by clearing the queue that grows during the red period. The random delay is caused by stochasticity in traffic demand. This can cause random variations in demand from cycle to cycle. These variations can cause some cycles to be saturated, even though the average arrival rate is lower than the capacity of the controlled link. When this happens, a queue can form that is still present when the green phase ends. Vehicles in this queue will have to wait more than one cycle and experience longer waiting times. Both methods differ in the way that the random delay is calculated, and in the way they consider non-fixed-time controllers.

Both methods are designed, in the first place, to calculate lost times for fixed-time intersection controllers. However, they both extended their methods for VA controllers. The method proposed by Akçelik (Akçelik, 1998), uses the minimum cycle times and green times for the calculation of the uniform delay, and the maximum cycle times and green times for calculation of the random delay for VA-control. The minimum time, in this case, is the minimum green time, which is needed to handle the demand. In the HCM (Transportation Research Board, 2000) an iterative process is used to determine average green times, given a certain demand. These average green times are used for the calculation of lost times. Furthermore, a parameter is used to account for the controller type.

Akçelik

The formula, used by Akçelik to calculate average delays for an input link, is the following:

$$D = \frac{q * c(1-u)^2}{2(1-y)} + N_0 * x \tag{3-2}$$

Where

$D = Total\ delay\ [veh - s/s]$,

$q = average\ demand\ [veh/s]$,

$c = the\ cycle\ length\ [s]$,

$u = green\ time\ ratio\ (g/c)\ [-]$,

$g\ = green\ time\ [s]$,

$x = q/C = degree\ of\ saturation\ [-]$,

$C\ = Capacity\ [veh/h] = s(g/c)$,

$s\ = saturation\ flow\ [veh/h]$,

$y = flow\ ratio\ \ (q/s)\ [-]$, and

$N_0 = Average\ overflow\ queue\ [veh]$ which is calculated as

$$\begin{aligned} N_0 &= \frac{C*T}{4} * \left\{ z + \sqrt{z^2 + \frac{12*(x-x_0)}{C*T}} \right\} && x > x_0 \\ N_0 &= 0 && otherwise. \end{aligned} \tag{3-3}$$

Where

$T = Time\ interval, during\ which\ an\ average\ arrival\ flow\ rate, q, persists\ [h]$,

$z = x - 1\ [-]$,

$x_0 = degree\ of\ saturation\ below\ which\ the\ average\ overflow\ queue\ is\ approximately\ zero\ [-]$,

$x_0 = 0.67 + sg/600$,

The delay, d (s/veh), can be calculated by dividing the total delay, D (veh-s/s), by the flow, q (veh/s).

HCM

The HCM method uses three formulas for the calculation of delays. The first one is used for the uniform delay and is calculated as

$$d_1 = \frac{0.5c\left(1-\frac{g}{c}\right)^2}{1-[\min(1,x)\frac{g}{c}]} \tag{3-4}$$

Where

$d_1 = uniform\ delay\ [s/veh]$,

$c = cycle\ time\ [s]$,

$g = green\ time\ [s]$,

$x = degree\ of\ saturation\ [-]$,

The random delay can be calculated with two formulas. The first one is used for the situation where there is no initial queue at the start of the period and is calculated with

$$d_2 = 900T\left[(x-1)+\sqrt{(x-1)^2+\frac{8k*I*x}{C*T}}\right] \tag{3-5}$$

where

$d_2 = random\ delay\ with\ no\ initial\ queue\ \ [s/veh]$

$T = duration\ of\ analysis\ period\ [h]$

$k = incremental\ delay\ factor\ \ [-]$

$I = upstream\ filtering/metering\ adjustment\ factor\ [-]$

$C = capacity\ [veh/h]$

$x = degree\ of\ saturation\ [-]$

The k-value depends on the controller settings. This value is 0.5 for fixed-timed controllers, and calculated as a function of the saturation degree, x, for VA controllers. The I-parameter incorporates the effects of metering arrivals from upstream signals and is equal to 1 on isolated intersections. The value of the parameter depends on the weighted degree of saturation at upstream intersections for non-isolated intersections (with upstream intersection at less than 1.6 km) .

Finally, the random delay for links where there is an initial queue is calculated as

$$d_3 = \frac{1800Q_b(1+u)t}{CT} \tag{3-6}$$

Where

$Q_b = initial\ queue\ at\ the\ start\ of\ period\ T\ \ [veh]$,

$t = duration\ of\ unmet\ demand\ in\ T\ \ [h]$, calculated as

$t = min\left\{T, \frac{Q_b}{c[1-\min(1,x)]}\right\}$, and

$u = delay\ parameter\ \ [-]$, calculated as

$u = 0\ if\ t < T, else\ u = 1 - \frac{c*T}{Q_b[1-\min(1,x)]}$.

In case that there is an initial queue, the uniform delay component (d_1) must be calculated with x=1 for the period when an oversaturation queue exists (t), and using the actual x value for the remainder of the analysis period (T-t).

3.6.2 Calculation of cycle times and green times

As input to the delay prediction formulas, cycle and green times need to be calculated. Intersection controllers operate as fixed-time controllers for the duration of k seconds, when the coordinated strategy is employed. Cycle and green times need to be recalculated for each green wave every time period, k. Furthermore, the minimum cycle and green times, needed to serve the demand (Akçelik), and the average cycle and green times (HCM) need to be calculated for VA controllers.

Coordinated green times

To ensure coordination between intersections on a green wave, the intersections that are part of the green wave, need to operate with similar cycle times and similar green times for the streams. The cycle time of the green wave is referred to as c_G and the green times, for the streams part of the green wave, are referred to as g_G.

A new set, $J_G \in J$, is defined which contains all junctions that are part of the green wave. Furthermore, the sets $L_G \in L$ and $L_N \in L$, contain the incoming links that are part of the green wave and the incoming links conflicting with the green wave respectively. The following constraint is defined to ensure common cycle times on the green wave:

$$c_s(k) = c_t(k) \text{ for all } s\ and\ t\ \in J_G \tag{3-7}$$

Furthermore, to guarantee a green wave for every vehicle that passes the stop line of the first intersection, the green time on the second intersection needs to be at least as long as the green time on the first intersection. If platoon dispersion would be taken into account, the green time on the second intersection should even be longer. The following constraint defines this requirement:

$$g_u(k) \geq g_v(k) \text{ for all } u\ and\ v\ \in L_G, where\ v\ is\ downstream\ of\ u \tag{3-8}$$

The green times are restricted, in order to create a green wave. The cycle and green times should also allow for enough capacity on each of the intersections that are part of the green wave. To ensure this capacity, one more constraint is added. The constraint determines the minimum length of the cycle time. The minimum cycle time should ensure for enough capacity on the intersection, in order to meet the total demand on the intersection. A parameter, β, is introduced to divide the total flow ratio with. The parameter β has a value, smaller than 1 and it ensures that the total green ratio of the intersection is larger than the flow ratio on the intersection. A value of 1 would generate a green ratio that is equal to the flow ratio on the intersection. The constraint is now:

$$\frac{c_j(k) - L_j}{c_{j(k)}} \geq Y_j(k)/\beta \qquad (3\text{-}9)$$

In this constraint, c_j is the cycle time of intersection j for time period k, L_j is the total lost time of intersection j for time period k, and Y_j is the total flow ratio on intersection j during time period k. Rearranging the variables in the formula leads to the following constraint on the cycle time:

$$c_j(k) \geq \frac{L_j}{1 - Y_j(k)/\beta} \qquad (3\text{-}10)$$

The green time for each of the output links is constrained by the flow ratio of the link. This is shown by the following constraint:

$$g_l(k) \geq y_l(k) * (c_j(k) - L_j) \qquad (3\text{-}11)$$

In this formula, $g_l(k)$ is the green time on link l (that is part of intersection j), for time period k. The controller now needs to find the minimum cycle time that satisfies these constraints, and the constraints for the minimum and maximum cycle time and green times. When all traffic is served on a stream, increasing the green time for this stream will only increase the waiting times for the conflicting streams. That is the reason why the cycle time should be minimized, while maintaining enough time to serve all traffic on the intersection.

If this problem has no solution, this automatically means that this green wave should not be created or continued. This could be the case when the coordinated stream on the first intersection and the conflicting stream on the second intersection both have flow ratios larger than 0,5. This would mean that the total flow ratio for the coordinated controller is larger than 1, and no solution could be found.

Average green times for vehicle-actuated control

An iterative process is used to predict the average green times for VA-controllers in the HCM method. In the first iteration, the minimum cycle and green times are selected as the trial times. The trial green times for the next iteration are then calculated as the sum of the queue service time and the average phase extension time. The queue service time is the time needed to serve the average queue that builds up during the red time. The phase extension time is the average time that the green light will be extended, due to gaps smaller than the critical gap, as set in the settings for the VA controller. The process is terminated once the difference between the current trial green times and the previous trial green times is less than a specified value, e.g. 0.1 seconds, or when the next trial green time is larger than the maximum green time. In that case the average green time will be the maximum green time. This is the case in very busy periods, when the controller practically functions as a fixed-time controller.

The basic formulas are shown below. The entire method is described in the HCM 2000 (Transportation Research Board, 2000), chapter 16, page 106 onwards . The queue service time is calculated as

$$g_s = f_q \frac{q_r r}{(s - q_g)} \tag{3-12}$$

With

$g_s = queue\ service\ time\ [s]$,

$q_r, q_g = \ red\ arrival\ rate\ [veh/s]\ and\ green\ arrival\ rate\ [veh/s]\ respectively$,

$r = \ effective\ red\ time\ [s]$,

$s = \ saturation\ flow\ rate\ [veh\ /s]$,

$f_q = \ queue\ calibration\ factor, this\ factor\ accounts\ for\ randomness\ in\ arrivals$,

$f_q = \ 1.08 - 0.1\ (actual\ green\ time/maximum\ green\ time)^2$.

And the phase extension time is calculated with

$$g_e = \frac{e^{\lambda(e_0 + t_0 - \Delta)}}{\varphi q} - \frac{1}{\lambda} \tag{3-13}$$

$g_e \ = \ green\ extension\ time\ [s]$,

$q = vehicle\ arrival\ rate\ [veh/s]$,

$e_0 = \ unit\ extension\ time\ setting\ [s]$,

$t_o = \ time\ during\ which\ detector\ is\ occupied\ by\ passing\ vehicle\ [s]$,

$\Delta = \ minimum\ arrival\ (intra - bunch)\ headway\ [s]$ → $fixed\ at\ 1{,}5\ s$,

$\varphi =$ *proportion of free (unbunched) vehicles [-],*

$\lambda =$ *parameter.*

Each iteration, the trial green time is calculated for each signal group of the intersection. The trial cycle time for the next iteration is the sum of all trial green times plus the total lost times for the intersection.

Minimum green times and cycle times

The method developed by Akçelik, uses the minimum and maximum cycle times that are used by the VA controllers, instead of the average times. The maximum times are fixed for each controller and they do not have to be calculated each time period. However, the minimum times are the minimum times needed to serve the demand of an intersection and this can differ per time period. The minimum cycle time, needed to serve all vehicles on an intersection is given with

$$c_{j,min} = \frac{L_j}{(1 - Y_j)} \qquad (3\text{-}14)$$

Where

$c_{j,min} = \textit{minimum cycle time for intersection } j\ [s]$,

$L_j = \textit{total lost time for intersection } j\ [s]$ and

$Y_j = \textit{total flow ratio of the intersection } j\ [s]$.

From the minimum cycle time the minimum green time for an input link on the intersection can be calculated as;

$$g_{min,i} = \frac{y_i}{Y_j} * (c_j - L_j) \qquad (3\text{-}15)$$

And

$y_i = \textit{the flow ratio of stream } i\ [s]$.

$g_{min,i} = \textit{minimum green time for stream } i\ [s]$,

3.7 Step 3: selection of a strategy

The third step is to select the strategy that will be used for the next control period. The strategy that is currently applied in the network is referred to as s_c. The strategy where no green waves are used and all intersections are, thus, controlled by VA controllers is referred to as s_{VA}. The total delay time D_s has been calculated in the previous step for each $s \in S$. Based on these delay times a strategy for the next time period should be chosen. The following algorithm defines the strategy to be chosen:

$$s_{min} = \min_{s \in S}(D_s)$$

$$if\ \ s_{min} = s_c;\ choose\ s_{min}$$

$$else\ if\ s_{min} = s_{VA};\ choose\ s_{min}$$

$$else\ if\ D_{s_{min}} \leq (1-\varepsilon)\ D_{s_c};\ choose\ s_{min}$$

$$else\ choose\ s_c$$

Switching between VA control and coordinated control on an intersection is assumed to have a negative effect on waiting times at the intersection, since a suboptimal intermediate stage is needed to coordinate cycle times and offsets. Furthermore, a controller that keeps on switching between strategies is unwanted. Therefore, switching to coordinated control should reduce delays at least with a certain parameter ε. When switching from coordinated control to VA control, no transition step is needed. Therefore, no minimum improvement is needed to switch back to coordinated control. However, if coordination is the preferred strategy for the user of the system, the same construction (with a boundary value) can be created to switch back to VA control.

3.8 Step 4: Coordination

The fourth step is the coordination of traffic lights. If the control on an intersection changes from VA control to coordinated control, or if the cycle time or green times of the coordinated controller have changed, one or more transition steps are needed. These transition steps should adapt the cycle times, green times and offsets of intersections, which are part of a green wave, to a leading intersection.

Cycle times and green times for the coordinated intersections have been calculated in the previous step. The current offset is calculated as the difference in start time of the green phases of coordinated streams. In order to do so, the current state of each signal and the time that has passed since the last signal change should be known by the controller. With this information, the current offset (if coordinated green times would be implemented on each stream) can be calculated. In appendix B, the Matlab code that is used to calculate the current offset is added as an explanation.

The offsets will be coordinated to one leading intersection. This leading intersection is the most upstream intersection in the green wave. Other possibilities to decide on the leading intersection might be found in further research. Prior to a traffic light switching to green on any of the following intersections, the following steps will be taken to calculate the duration of the green phase for the stream that is going to receive a green light.

1. The time t_1 is the wanted offset in relation to the leading intersection
2. The time t_2 is the current offset
3. $\Delta t = t_2 - t_1$
4. If $g_{c,i} + \Delta t < g_{min}$

   $\Delta t = \Delta t + c_c$
5. The green time for the following stage g_i will be

   $g_{c,i}$ if $\Delta t = 0$

$g_{c,i} - \Delta t$	if $g_{max} \geq g_{c,i} + \Delta t \geq g_{min}$
g_{max}	if $g_{c,i} + \Delta t > g_{max}$
g_{min}	else

In order to clarify the method, an example is given below. The desired offset (t_1) is 0 in the example, in order to illustrate when the intersection controllers are coordinated. In Figure 3-3, the green times for the leading intersection (j_1) and 3 following intersections (j_2, j_3 *and* j_4) are shown. The intermediate stages are marked "IS". g_{min} = 10 seconds and g_{max} = 55 seconds, $g_{c,1} = g_{c,2}$ = 35 seconds.

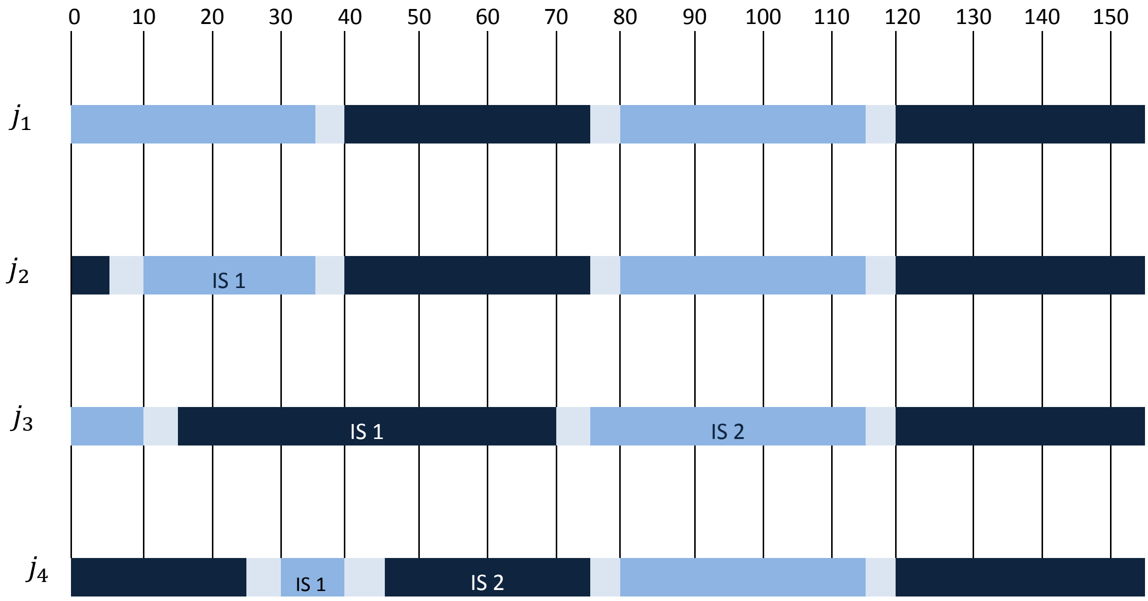


Figure 3-3 *Example of coordination process. The dark and light blue bars in the example are the phases in a 2-phased controller, the shaded parts are the lost times, which are 5 seconds between each phase.*

For j_2: $\Delta t_{1,2} = -10$

$g_c + \Delta t_{1,2} = 35 - 10 = 25$

Since $10 \leq 25 \leq 55$ so one intermediate stage of 25 seconds is needed

For j_3: $\Delta t_{1,2} = 25$

$g_c + \Delta t_{1,2} = 35 + 25 = 60$

Since $60 > 55$ the next stage is a maximum cycle of 55 seconds

Now $\Delta t_{1,2} = 5$

$g_S + \Delta t_{1,2} = 35 + 5 = 40$

Since $10 \leq 40 \leq 55$ one more intermediate stage of 40 seconds is needed

For j_4: $\Delta t_{1,2} = -30$

$g_c + \Delta t_{1,2} = 35 - 30 = 5$

Since $5 < 10$ the offset difference is increased with one cycle

Now $\Delta t_{1,2} = 5$

And $g_c - \Delta t_{1,2} = 35 - 5 = 30$

Since $10 \leq 30 \leq 55$ one intermediate stage of 30 seconds is needed

3.8.1 Improvement of transition step during the case study

During the first tests runs, both the coordinated controller and the switching controller performed considerably worse than the VA controller. The problem was found in the transition step. The following problems were found with the transition step:

- Transition steps can occur both on the coordinated stream and on the conflicting stream. When transition steps increase the phase time of the conflicting stream, a queue might occur within the green wave. When transition steps on the conflicting stream only decrease the phase time, this was a big problem, causing a queue within the green wave that did not dissolve until the end of the simulation.
- With high phase times, the transition step almost always decreases the cycle time, since increasing the cycle time is not possible. Therefore, multiple decreased phases might be implemented which decreases the throughput for the intersection significantly.

In order to overcome the problems found during the test cases, the intermediate stages are only employed on the coordinated stream. This has solved the problems for the case study but for future implementation a generic approach for determining the size of transition steps needs to be developed.

3.9 Step 5: Implement strategy and monitor performance

After a decision is made on which strategy should be used in the current time period, the control is executed. The controllers on each intersection are VA controllers. If the determined strategy for an intersection is to control the intersection with VA controllers, the controller does not have to give any input to the local controllers. If the determined strategy for an intersection is coordinated control, the central controller should take over and determine the green times for each phase. These green times are either the coordinated green times, determined as in section 3.6.2, or the green times used for a transition step (determined as in 3.8). Every k seconds, the part of the controller that determines which strategy should be used is activated again by a new input from the central computer.

3.10 Conclusions and discussion

In this chapter one application of a combined route guidance and urban traffic control system is chosen, and developed into a control system that is ready to be tested. The objective of the chapter was the following:

Develop one of the identified applications into a control strategy that decreases travel time losses in an urban traffic network

In this final section, the conclusion regarding the objective will be given, some directions on the next step in this thesis will be given and finally, some recommendations for future work on the subject will be stated.

3.10.1 Conclusions

The application that has been developed is an algorithm that adaptively switches between predefined strategies to control an urban traffic network. This means that the strategies are determined offline, as an input to the controller. The basic strategy is to control every traffic light with a VA controller. The alternative is to create one or more green waves in the network. These green waves are created by coordinating the traffic lights that are part of the green wave. This coordination means that the intersections that are part of the green wave function as fixed-time controllers for the duration of one control period. The length of this control period, k, should be long enough to allow for the controller to coordinate traffic lights (a few cycles, depending on the way the transition step is determined). However, k should also be short enough to be able to respond to changes in the demand (this depends on the size of the network). Each intersection that is part of the green wave has the same cycle time and the same green time, for the coordinated stream and also for the conflicting streams. The offset between the start of the green times of the different coordinated phases is managed by a transition step. This transition step ensures that the offset is equal to the required offset (the travel time between the stop lines of the intersections).

In order to choose the best strategy to control the traffic, a prediction method is used to predict the lost times for every possible strategy. Two such methods have been found, that differ mainly in the handling of VA controllers. One case study in the next chapter should test which of these methods is the best for predicting the lost times and comparing control strategies. Furthermore, another case study should compare the developed controller to VA and coordinated controllers, in order to see if switching between the two systems could actually decrease lost times, compared to either of the controllers used separately.

3.10.2 Recommendations

The current method chooses the best strategy from a set of predefined strategies. It might be cumbersome to define all possible coordination strategies in a large urban network. Therefore, a method should be designed, or found in literature, that searches for promising routes to coordinate. Another option would be to divide the network into sub-networks, each consisting of one route. A decision could be made, if traffic lights on the route should be coordinated or not, for each route separately. A top-level controller should make a final decision when two strategies have conflicting control decisions for one intersection. This could be the case when one intersection is part of multiple routes that are candidates for coordination.

When intersections are coordinated with each other, they are controlled with fixed cycle and green times in the controller that is described in this chapter. Most VA controllers also have the possibility to coordinate traffic lights but still make small changes according to the detected traffic. This might especially be useful if a queue originates on the coordinated route. In the case studies this would probably not happen but in real urban traffic networks other factors like parking cars, halting public transport vehicles or crossing pedestrians could cause the green wave to break down. The possibilities to increase the coordinated green times for a short period at such moments, could be researched further.

The main assumption of this method is that it is possible to generate link demand from data communicated by navigation systems. Three conditions need to be satisfied in order for this assumption to be fully true. First of all, every road user needs to use a navigation system to plan its trip. Second of all, this navigation system needs to communicate its current location, its destination and the route it is planning to take to the controller. Third of all, a model needs to be created to translate this data to expected link demands. In order for the third condition to be met, future research is needed into the creation of this model. If such a model is created, the first two conditions might become less strict, since the model can overcome the incompleteness of traffic data by using estimation or prediction methods.

4 Evaluations

In the previous chapter, a method has been described to switch between vehicle-actuated (VA) and coordinated control in an urban traffic network. In this chapter the method will be evaluated with a simulation study. The study is divided into three separate case studies. The first case study is to identify the characteristics of the simulation environment. In the second study, two methods for predicting delays will be compared and calibrated. The best of the two methods will be used in the final case study, where the switching method is compared to VA control and coordinated control, used separately. The main goal of this chapter is to prove that lost times in a traffic network can be decreased by an application, stemming from the integration of VRGS and UTC.

The objective of this chapter has been defined in section 1.1 and is repeated below:

Evaluate the developed controller by means of a simulation study.

4.1 Approach

The approach to reach the objective, stated in the previous section, will be explained in this section. The section ends with an outline of the rest of the chapter.

With this simulation study the designed controller, which switches between control strategies, will be compared with controllers that only use one of these strategies to control traffic lights. The main goal of the simulation study is to show that the controller is capable of decreasing the delays in a traffic network by switching between strategies. Before the final case study can be performed, 2 case studies need to be performed as preparation. The following case studies will be considered:

- Case study 1: Identification of the Vissim parameter for saturation flow
- Case study 2: Calibration of the prediction method, used to predict the delays for the controller
- Case study 3: Evaluation of the controller by comparison to coordinated control and vehicle-actuated control

The saturation flow is an important parameter in each of the prediction methods and in the calculation of green times for the coordinated control strategy. The parameter depends on the characteristics of the traffic network. Therefore, this parameter will be identified carefully in the first case study. In the second case study, a choice will be made between the prediction methods of Akçelik and the HCM, which are described in section 3.6.1. Both methods use a different approach to predict average lost times for VA controllers. The purpose of this second case study is to choose one of these methods and calibrate the method in the process. In the third case study, the developed controller will be compared to a coordinated controller and a VA controller. The goal of this final simulation is to test if the controller is capable of reducing lost times in a network, when compared to these other control approaches. After a situation that is ideal for the designed controller, some tests will be performed to test the limitations of the controller.

4.1.1 Outline

The outline of the fourth chapter is depicted in Figure 4-1. First, the simulation environment is explained in section 4.2. The network, parameters to be varied and the software structure will be declared. In section 4.3 to 4.5, the 3 case studies will be described and the results for each study will be given. Finally, in section 4.6 some conclusions will be made on the possibilities to implement the designed controller in a real traffic network. Furthermore, some future research directions will be identified.

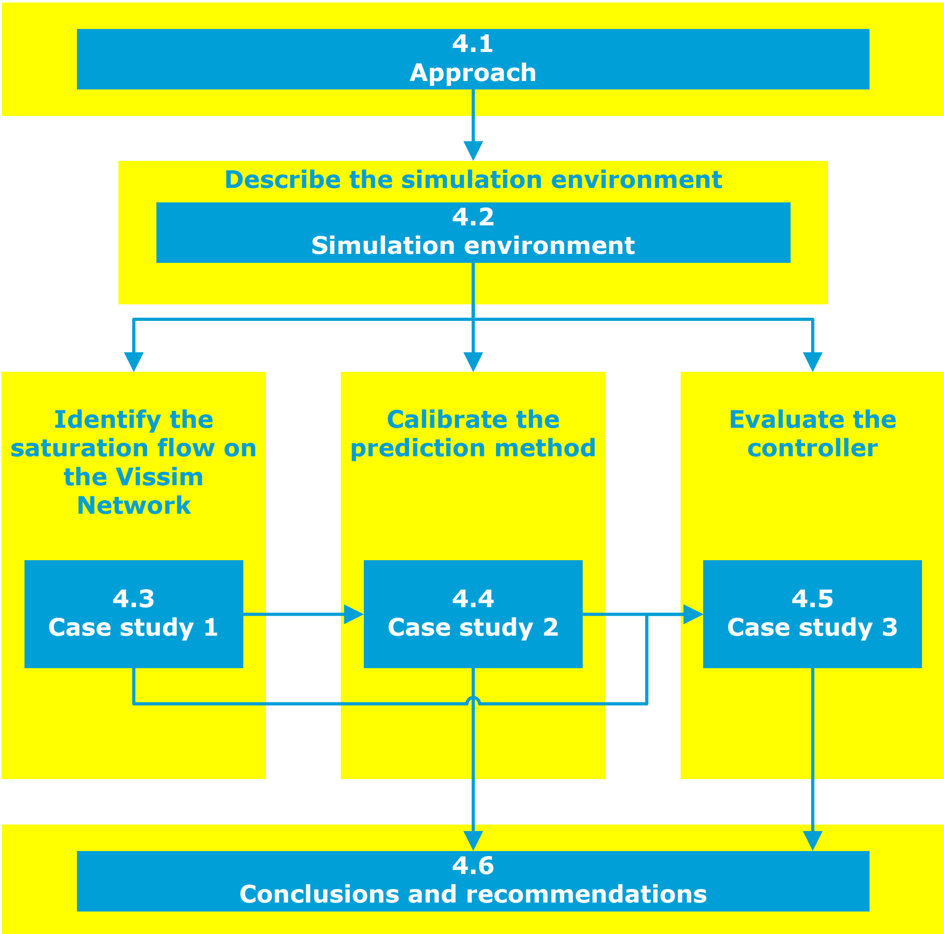


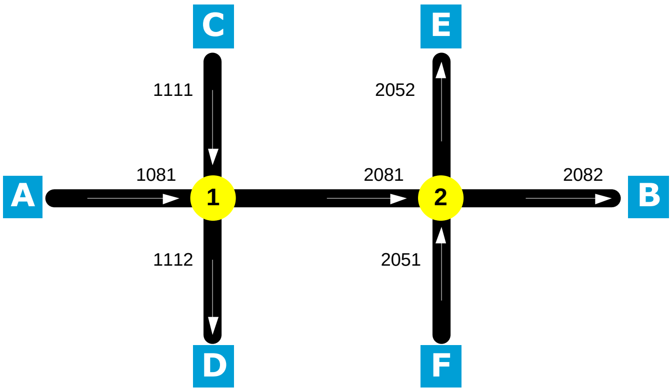
***Figure 4-1** Outline of chapter 4. the arrows show the line of reasoning throughout the chapter*

4.2 Simulation environment

In this section, the simulated environment, in which the case studies will be performed, is described. First, the network will be discussed. Then, the input parameters and variables are defined. In section 4.2.3, the used software programs are described. Finally, the methods for evaluating the results are given.

4.2.1 Network

In this section, the traffic network, used for all case studies, is described. The traffic network is designed to be as simple as possible, while still offering the possibility to coordinate a set of traffic lights. In Figure 4-2, the test network is shown.



The figure shows the network that will be used in the simulation study. The letters A-F are the origins and destinations, the numbers 1 and 2 are the intersections and the 4-digit numbers are the links. The links that have a '1' as final digit are the input links, the others are output links.

***Figure 4-2**: The test network*

The only route on which traffic lights can be coordinated is the route between A and B. This means that the only option for the controller will be to coordinate streams 1081 and 2081, as opposed to controlling both intersections with VA controllers. Each intersection is controlled by a two-phased controller. Furthermore, lost times on both intersections are fixed at 5 seconds. The minimum green time for all streams is 6 seconds, the yellow time is 3 seconds and the minimum red time is 3 seconds. The maximum cycle duration is 120 seconds. In Table 4-1, the settings for the constraints of the intersection controllers are given.

***Table 4-1**: intersection controller constraints*

Number of phases	2
Lost Time per Cycle	10 [s]
Minimum green time	6 [s]
Maximum cycle time	120 [s]
Maximum green time	55 [s]

4.2.2 Input variables

A set of scenarios will be defined as input to the different case studies. Below, each of the variables that need to be set for each of the scenarios is described. The variables are summarized later in Table 4-2.

The first variable for each scenario is a unique identification number, N^{sim}, running from 1 to the number of simulations. Furthermore, the duration of the simulations and the time periods for the control intervals need to be specified. The simulation duration is called T^{sim}. The traffic lights are controlled by a Matlab script, but the simulation is run by Vissim, as will become clear in part 4.2.3. The size of the simulation intervals is called T^{sample}. This is the duration of intervals that the simulation is running in Vissim, before communication with Matlab takes place. The controller that decides on the strategy to be used has its own time steps, $T^{control}$. This is the size of the control periods (k).

The input demand needs to be determined for each control time period, k, and for each scenario. The input demand is a vector containing the flow q1 (veh/h) which is the demand between A and B, the flow q2 (veh/h) which is the demand between C and D, and the flow q3 (veh/h) which is the demand between F and E.

The control mode determines which control method will be used to control the traffic lights in the network. The first method is coordinated control, the second VA control and the third is the newly designed switching controller. Finally, the random seeds, RS, used for the scenarios need to be defined.

Table 4-2 *Input variables for the different scenarios*

Variable name	Code	Unit
Scenario number	N^{sim}	[-]
Duration	T^{sim}	[s]
Simulation time step size	T^{sample}	[s]
Control time step size	$T^{control}$	[s]
Demand	[q1 q2 q3]	[veh/h]
Control mode	M	1 if VA; 2 if coordinated; 3 if switching.
Random seed	RS	[-]

4.2.3 Software

In this section, the software, used for the simulation will be described. Furthermore, the communications between all used programs are discussed. In Figure 4-3, the software structure of the simulation study is depicted. There are 4 software programs used for this simulation of which 3 communicate online with each other. The 4 programs are:

- Mathworks Matlab version R2013b
- PTV Vissim version 5.30
- Trafcod
- VRIGen

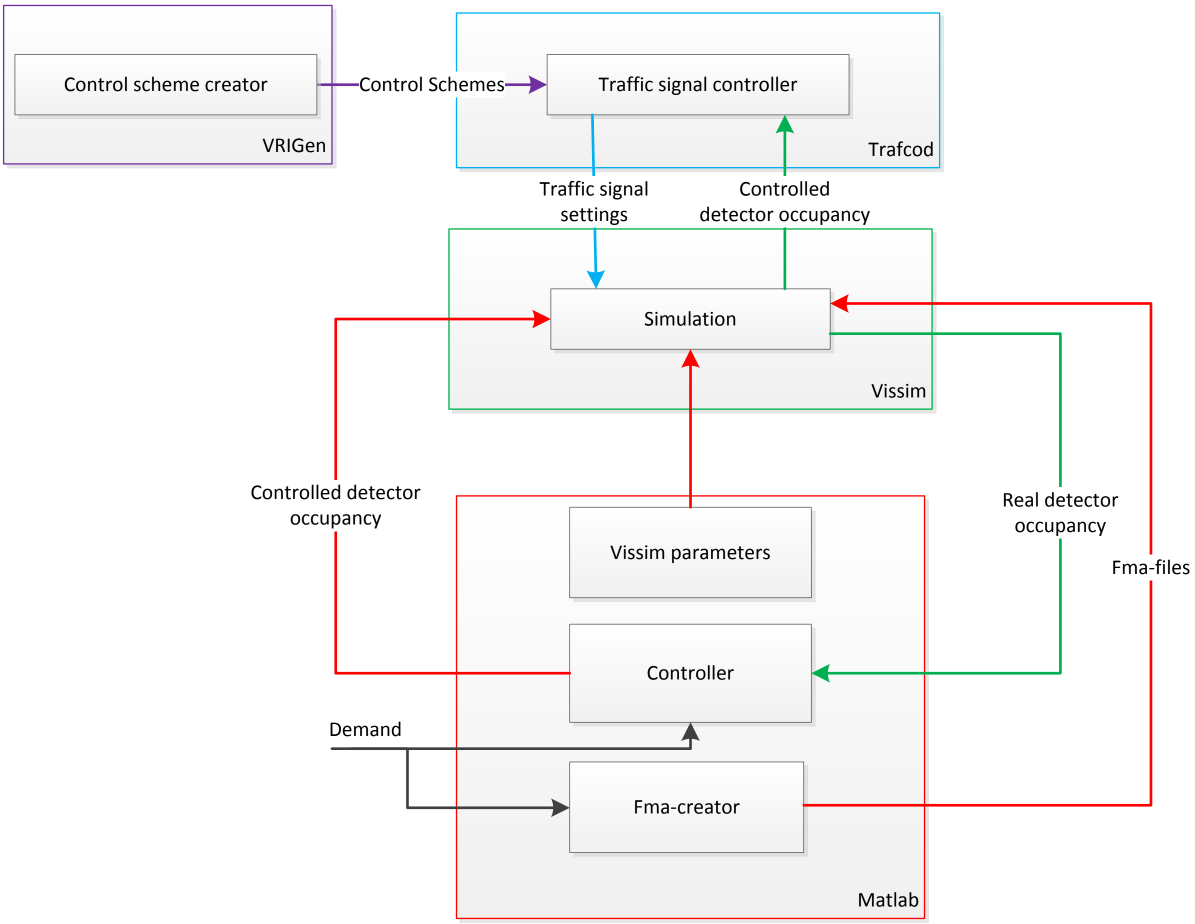


Figure 4-3 *Software structure of the simulation study, the arrows represent the information that is sent from one program to another. The colour of the arrows represents the origin of the sent information.*

Matlab

Matlab (Mathworks, 2014) is used as the hearth of the simulation software. The programming language is chosen for its capability to control Vissim via the COM-interface. Furthermore, the program provides the analytical tools, needed to analyse the outputs, generated from the simulations. Inputs to the simulation are demand patterns, which differ per scenario. One part of the Matlab script (Fma-creator) is used to translate these demands to text-files (*.fma), readable by Vissim as OD-matrices for the simulation. Furthermore, the demands are used by the controller to determine which strategy will be used in which control period. Since the demand is known for the duration of the simulation, the strategy that is used will be determined prior to the simulation in Vissim.

In Vissim, it is only possible to have one control strategy for each intersection during a simulation run. However, for the switching algorithm, a switch needs to be made between coordinated (fixed-time) and VA control. In order to do so, fake detectors are placed inside the Vissim simulation on a link outside of the network. The Trafcod VA controller is linked with these fake detectors instead of real detectors. These fake detectors can thus only be occupied by fake vehicles, since no real simulated vehicles can reach them. The fake occupancy is created by the Matlab script. For each time-instant the Matlab script determines if the detectors are occupied or not. If the strategy is VA control, Matlab simply copies the detector occupancy it reads from real Vissim-detectors to the fake detectors. As a result, the VA-controller controls traffic as if it were connected to the real detectors. If the strategy is coordinated control, Matlab occupies the fake controllers with fake vehicles just long enough to make Trafcod generate cycle times and green times, equal to the coordinated cycle times and green times. As a result, the VA-controller behaves as a fixed-time controller.

Vissim

Vissim (PTV group, 2014) is used to execute the simulation. Vissim is a microscopic traffic simulator. The program is chosen for two reasons. First of all, the model offers an interface to external software through its COM-server. Second of all, it supports the use of traffic lights and the use of external programs to control these traffic lights. Parameters used as input for the Vissim simulation are summarized in Table 4-3. All parameters are the default parameters, set by Vissim.

Table 4-3 *Vissim Parameters*

Version	5.30-10
Car following model	Wiedeman 74
Signal control decision model	Continuous check
Behaviour at red amber signal	Go (same as green)
Desired speed distribution	Uniform (min: 48 km/h, max:58 km/h)

Trafcod

Trafcod is used as an external traffic controller. Trafcod was developed at Delft University of Technology. For any controllers, other than fixed time controllers, Vissim needs an external program. Since VA-controllers are used, Trafcod is chosen as external controller. The program reads the detector occupancy from Vissim and determines the state of the signal controllers. The duration of green times and other controller settings are defined in signal timing plans, generated by VRIGen.

VRIGen

VRIGen is used to create the signal timing plans, used in Trafcod. VRIGen was also developed at Delft University of Technology. It is a tool to create signal timing plans. The signal timing plans for the VA-controllers are defined offline, prior to the case studies. The timing plans are defined on the basis of equal demand on both streams of each intersection. Therefore, the maximum green times are 55 seconds for each phase ((maximum cycle time – total lost time)/2). Other important parameters are found in Table 4-1.

Typical simulation run

In order to clarify the communication between the software programs, one typical simulation run is described below:

0. Offline creation of a traffic network in Vissim, control schemes in VRIGen and demand patterns and input parameters in Matlab (offline)
1. Matlab translates the demand to an fma-file, the file-format of vehicle inputs in Vissim and sends them, together with Vissim parameters, to Vissim (offline)
2. Matlab calculates the strategy to be used in each control period (offline)
3. Matlab calculates traffic control settings for next $T^{control}$ seconds (online)
4. Matlab activates Vissim and simulation is run for T^{sample} seconds (online)
5. Trafcod reads controlled detector occupancy from Vissim and determines traffic light states (online)
6. Vissim sends real detector occupancy to Matlab (online)
7. Matlab sends controlled detector occupancy to Vissim (online)
8. If the end of the simulation is reached; continue to 10, else if the end of the control interval is reached return to 3, else return to 4 (online)
9. Close Vissim and save results (offline)

4.2.4 Methods for comparing the results

In this section, the parameters to compare the results of the case studies are discussed. The following parameters will be used for the case studies:

- Total travel time
- Total and average lost time
- Mean squared percentage error

Total travel time

In the Vissim simulation, the travel times on 5 routes are measured for each passing vehicle. The routes are shown in Figure 4-4. Route 1 measures the travel time between A and B, route 2 measures the travel time between C and D, and route 3 measures the travel time between F and E. Route 4 and 5 measure the travel times between A and B for intersection 1 and 2 respectively.

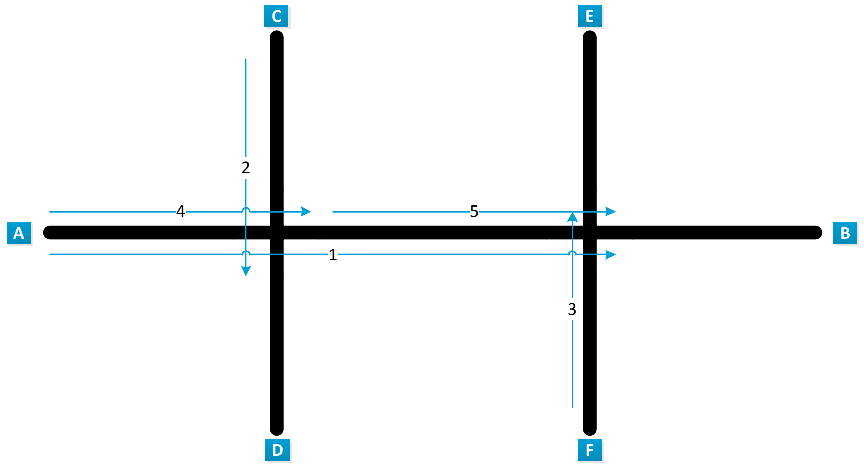


Figure 4-4 *Travel time routes. The arrows show the routes in the network for which the travel times will be measured during the case studies.*

The total travel time is calculated by adding up the travel times of each vehicle that passes through the network, in the time period over which the travel time is calculated. The travel times of route 1, 2 and 3 are used in order to calculate the total travel time.

Total and average lost time

The average lost time, t_r^{lost}(s), is calculated for each route separately. The lost times per vehicle are calculated by subtracting the free flow travel time from the average measured travel time for each route. The average desired speed in the Vissim simulation is 53 km/h so this speed is also used to calculate the free flow travel times. The average lost time is calculated with equation (4-1).

$$t_r^{lost} = t_r^{avg} - \frac{l_r}{53/3.6} \quad (4\text{-}1)$$

In the equation, t_r^{lost} (s) is the average lost time for route r, t_r^{avg} (s) is the average travel time for route r (output from the Vissim simulation) and l_r (m) is the length of link r. The total lost time, T^{lost} (veh-s/h), is then calculated as follows:

$$T^{lost} = \sum_{r=1,2,3} t_r^{lost} q_r \quad (4\text{-}2)$$

In this equation, r is the route and q (veh/h) is the demand.

Mean Squared Percentage Error

To compare the prediction methods, the predicted lost times are compared to the actual lost times in the Vissim simulation. In order to compare these lost times the Mean Squared Percentage Error (MSPE) is calculated. The relative error is used since different scenarios will be used to compare the prediction methods. These different scenarios will generate different lost times in Vissim. Therefore, an absolute error that indicates good performance in one scenario, might indicate bad performance in another scenario. Large errors are much worse to the performance of the controller than small errors. If the wrong control strategy will be chosen on the basis of a small error in the prediction of the delays, the effect on the delays can only be small while a wrong decision based on a big error can have a big effect on delays. Therefore, the squared error is used. The MSPE is calculated with the following formula:

$$j_{em} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\hat{Y}_{em.i} - Y_i}{Y_i}\right)^2 \quad (4\text{-}3)$$

where

$j = Mean\ squared\ error,$

$\hat{Y} = estimated\ parameter,$

$Y = measured\ parameter,$

$n = number\ of\ data\ points$

$i = index\ of\ data\ points\ and$

$em = estimation\ method.$

4.3 Case study 1: Identification of saturation flow

The first case study is used to identify the saturation flow in the simulation network. First the plan for the simulation will be discussed and then the results will be given.

4.3.1 Plan case study 1

As input to the simulation, some parameters have to be identified. Some parameters are set as input in the Vissim simulation, others need to be identified through a case study. The first simulation is used to determine the parameters that characterize the traffic in the Vissim simulation. First, the main purpose of the simulation is discussed, then the input scenarios are described and finally the output, that will be generated, is mentioned.

Purpose

The main purpose is to identify the saturation flow parameter, used for the lost time functions and calculations, to match the traffic situation in the simulation environment as good as possible. The definition of saturation flow, according to Papageorgiou (Papageorgiou et al., 2003) is used:

> *"**Saturation flow** is the average flow crossing the stop line of an approach when the corresponding stream has right of way, the upstream demand (or the waiting queue) is sufficiently large, and the downstream links are not blocked by queues."*

This definition states 3 requirements for measuring the saturation flow. First of all, the stream that is measured is supposed to have right of way. This means that the flow will only be measured when the light for the stream that is measured is green. Second of all, the upstream demand should be high enough. This means that every vehicle that passes the stop line should have been in the queue. In order to reach this, the demand should always be higher than the capacity of the link. Furthermore, the link should be long enough to facilitate a queue that feeds an entire green period. Third of all, the downstream links should not be blocked by queues. Since only one intersection controller is active, downstream links will never be blocked by a queue.

Input

The inputs for the first simulation are summarized in Table 4-4. 30 scenarios are executed, which only differ in the random seed that is used. The traffic is controlled by one fixed-time controller on intersection 1. This fixed-time controller has fixed green times of 55 seconds for both directions and a cycle time of 120 seconds. No communications between Matlab and Vissim are needed when the traffic lights are controlled by a fixed-time controller. This means that the size of T^{sample} and the size of $T^{control}$ are equal to T^{sim}. The demand is fixed at 1200 veh/h for route A-B and 0 veh/h for all other routes.

Table 4-4 Inputs simulation 1

Variable	Value(s)
N^{sim}	[1:30]
T^{sim}	3600
T^{sample}	3600
$T^{control}$	3600
[q1 q2 q3]	[1200 0 0]
M	2
RS	1:30

In the previous section, it is stated that the demand should be larger than the capacity of the link and the link should be long enough. The following calculations show that this is the case. The capacity of a phase is given by the following formula:

$$C_i = s_i \frac{g_i}{c_j} \tag{4-4}$$

where C_i, s_i and g_i are the capacity, the saturation flow and the green time of phase i respectively and c_j is the cycle time of intersection j, which phase i is part of. With a demand of 1200, green time of 55 seconds and a cycle time of 120 seconds, the saturation flow would be larger than 2600 veh/h, should the demand be less than capacity. Since the saturation flow is usually less than 2000 veh/h the demand is high enough.

The length of link 1081 is 500 m and the green time is 55 seconds. The length of one vehicle in the queue is assumed to be 7.5 m. If the link would not be long enough to facilitate the queue, the saturation flow would have to be more than 66 vehicles per green phase. This is more than 4000 veh/h, which is not possible on a one-lane road, thus the link is long enough to facilitate the queue.

Measurements

In order to measure the saturation flow, a detector is placed 0.5 m downstream of the stop line of stream 1081. This detector measures all vehicles that cross the stop line and the time instance when they cross this line. From this time instances the time gaps between vehicles will be measured. The gap between the last vehicle of one green phase and the first vehicle of the next green phase is ignored. The saturation flow for one simulation is than calculated by dividing 1 hour (3600 seconds) with the average time gap.

4.3.2 Results: saturation flow

The result of the first case study determines the value of the saturation flow that will be used in the other case studies. In Table 4-5 the minimum, maximum and average value for the saturation flow is given for the 30 simulations with different random seeds. The average saturation flow of 1985 vehicles/hour will be used as input for the remaining simulations.

Table 4-5 Saturation flow

Saturation flow	s (veh/h)
Minimum	1965
Maximum	2001
Average	1985

4.4 Case study 2: Calibration of prediction method

In this second case study, the prediction methods are calibrated. Furthermore, a choice is made on which prediction method will be used for the controller, the HCM-method or the Akçelik-method. First the simulation plan is given, and then the results will be discussed.

4.4.1 Plan for case study 2

The second case study is used to calibrate the prediction method, used for the controller. Furthermore, a choice should be made between the Akçelik method and the HCM-method. First, the main purpose of the simulation is discussed, then the input scenarios are described and finally the output, that needs to be generated, is mentioned.

Purpose

The purpose of the second case study is to compare the two lost time prediction methods, Akçelik and HCM and to calibrate them to the Vissim simulations. The two methods will be compared by their ability to accurately predict lost times, but foremost by their ability to pick the right control strategy for a given traffic demand. The following questions will be answered during the second case study:

1) *What prediction method is better suited for predicting lost times?*
2) *Which prediction method should be used in order to predict lost times for the controller?*
3) *What parameters need to be calibrated in order to use the chosen prediction method?*

The biggest difference between the two methods is the way in which the methods are extended to be used for VA controllers. It is expected that no big differences will be found in the performance of both methods, when calculating lost times for the coordinated control strategy. Another difference is that the HCM formula includes initial queues. However, this term can easily be added to the Akçelik formula so initial queues are not included in this case study.

Input

The methods will be compared for 64 different demand scenarios. The demand on each of the three routes varies between 225, 450, 750 and 900 veh/h. These values have been chosen in order to represent different levels of saturation. The minimum flow rate for each intersection is 0.23, when the demand on each stream is 225 veh/h. The maximum flow rate is 0.91, when the demand for each stream is 900 veh/h. Furthermore, different demand patterns can be tested. This means that there are 64 different combinations. Each of these demand patterns is used twice, once when a coordinated controller is used to control the traffic lights and once when a VA controller controls the traffic lights. The simulation time for each scenario is one hour.

When the coordinated control approach is used to control the traffic lights, the cycle time and green times are fixed and equal for the first and second intersection. The offset between the start of green on the first intersection (stream 1081) and second intersection (stream 2081) is fixed at 48 seconds, which is equal to the time it takes for vehicles to reach the second intersection. The cycle and green times are calculated offline, according to the demand for each scenario, with the method introduced in section 3.6.2. The control time step is equal to the simulation time, since no control decisions are made online.

Only Trafcod is used, in the simulation runs where VA-control is tested. This means that detector occupancies are communicated directly to Trafcod from the detectors in Vissim. The control time steps for Trafcod are 0.2 seconds but there is no communication between Matlab and Vissim. Thus, $T^{control}$ is equal to T^{sim}. The random seed is set to 1 for all simulations. The inputs for the second simulation are summarized in Table 4-6. The demand for each scenario is shown in Figure 4-5.

***Table 4-6**: Inputs simulation 2. In the table the inputs for every scenario of case study 2 are shown. There are 64 demand scenarios, which are all executed two times, once with the intersections controlled by a VA controller and once with coordinated control of the two intersections.*

Variable	Value(s)
N^{sim}	[1:128]
T^{sim}	3600
T^{sample}	3600
$T^{control}$	3600
[q1 q2 q3]	As in Figure 4-5
M	64*[1] and 64*[2]
RS	1

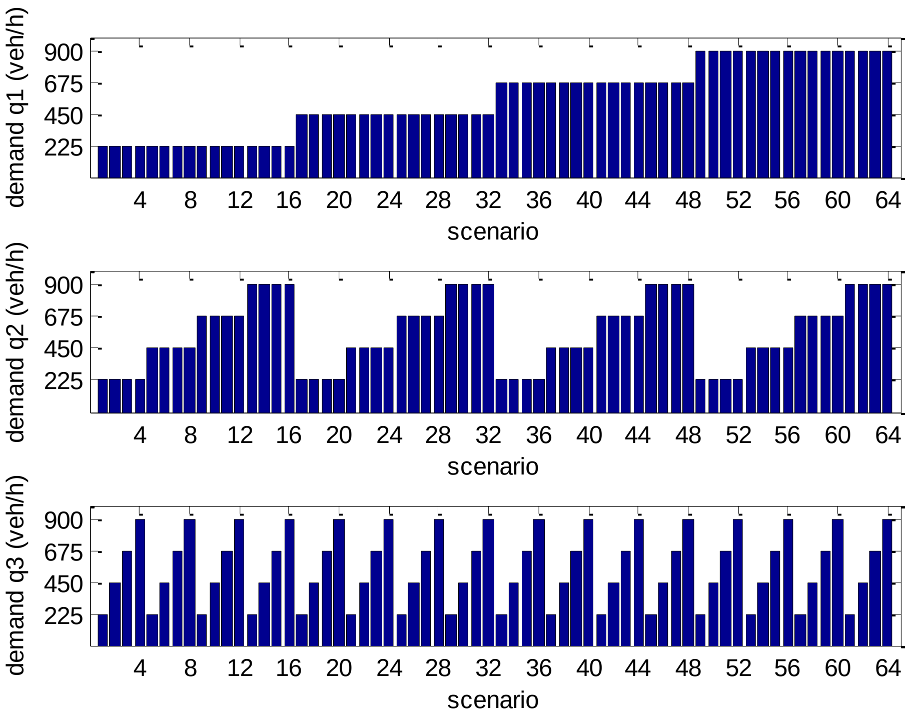


***Figure 4-5** demand case study 2. In the figure the demand for all of the 64 demand scenarios is depicted. The top figure shows the demand q1, the middle figure the demand q2 and the bottom figure the demand q3.*

Measurements

The lost times, generated by Vissim, the Akçelik method and the HCM method will be compared. The lost times will be calculated with the method introduced in section 4.2.4. The MSPE will be calculated for the total lost time, the lost time per link and the average lost time per link for both prediction methods. The MSPE will be calculated with equation (4-3).

4.4.2 Results: Calculations with advised parameter values

First, the lost times are calculated with all parameters set as advised by the documentation of the prediction methods by Akçelik (Akçelik, 1998) and the HCM (Transportation Research Board, 2000). The results for this first calculation can be found in Table 4-7. The MSPE shows that, with the parameters set as advised by the methods documentation, the HCM formulas are better for predicting delays for VA-controllers and the Akçelik formulas are better in predicting lost times for coordinated controllers. The final column shows how often the methods have made the right choice for either VA or coordinated control. The method would choose the strategy with the lowest predicted delays for each scenario, if incorporated into the controller. If the delays for this strategy indeed show to generate the lowest lost times (in the Vissim simulation), the method has made the right choice for the respective scenario. The results show that the Akçelik method is only able to pick the strategy with the lowest lost times in 68.75% of the cases and the HCM-method only in 50% of the cases.

Table 4-7: *Predicted lost times, compared to the actual lost times in Vissim. j is the mean squared percentage error for the total lost time, calculated with equation (4-2).*

Strategy	j_{VA}	$j_{Coordinated}$	Right choice
Akçelik	0.97	0.11	44/64 = 68.75%
HCM	0.12	0.29	32/64 = 50 %

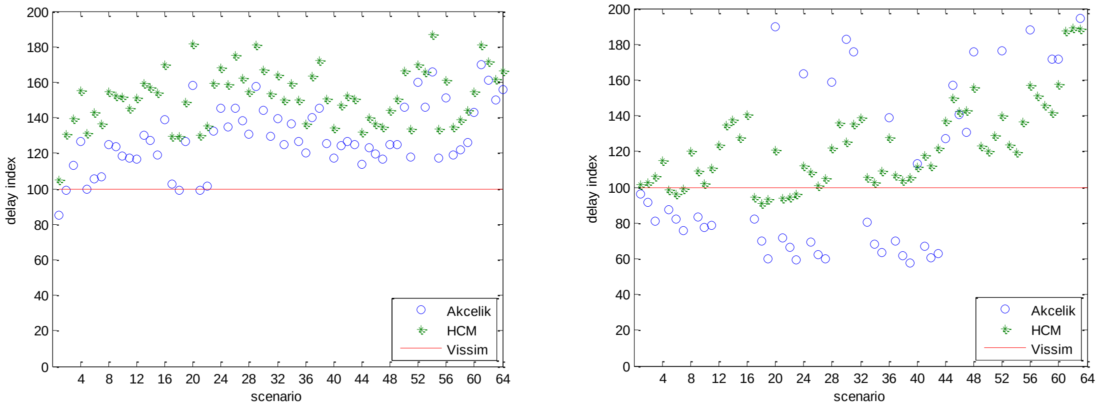


Figure 4-6 *Total delay, as calculated by the prediction methods, compared to the actual delay, measured in the Vissim simulation. The delays are indexed with the delay in Vissim set at 100. The figure on the left shows the results for the simulations where traffic was controlled with a coordinated controller and the figure on the right shows the results for VA control.*

In Figure 4-6, the delay for each scenario is plotted relative to the actual delay in Vissim. As can be seen in the figure on the left, the methods do not differ a lot in the prediction of delays for fixed-time controllers. Both methods overestimate the delays for almost every scenario, where the overestimation of the HCM method is higher. This explains the higher value of the MSPE for the coordinated strategy. In the case of VA-control, the HCM method overestimates all delays, while the Akçelik method both overestimates and underestimates the delays. The error is even bigger than 100% for some scenarios, which explains the MSPE of 0.97.

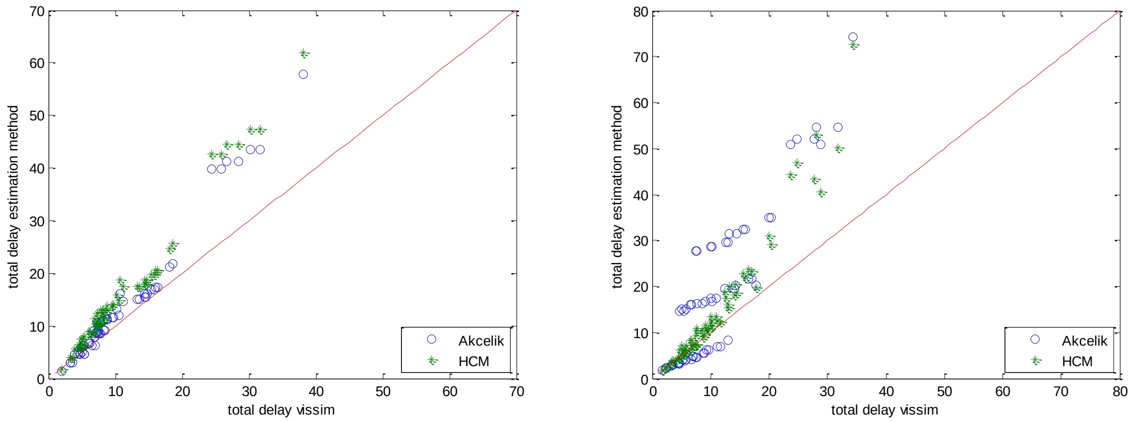


Figure 4-7 *Total delay in Vissim compared to the predicted delay, for the coordinated situation (left figure) and the VA situation (right figure). The red line shows where predicted delays and real delays are equal.*

In Figure 4-7, the real values of the delays are shown for the Vissim simulation and the prediction methods. The figure on the left shows that, with the fixed-time approach, both methods overestimate the lost times a little for the unsaturated scenarios and more for the saturated scenarios. The right figure shows that the Akçelik method clearly performs worse than the HCM-method, when used to predict lost times for VA controllers. The HCM-method is also sometimes (again especially in the saturated scenarios) way of but at least the pattern is increasing, just as the Vissim simulation.

Both prediction methods are unfit for predicting the lost times of the traffic network, both for coordinated control and VA control with the parameters set as advised. Therefore, some changes had to be made to the parameters.

The method for VA control introduced by Akçelik seems unsuited for the prediction of lost times for the studied network. Therefore, for now the choice is made to continue with the HCM-method, at least for the VA control. If it is possible to tune the parameters of this method so that the predictions are also better for the coordinated control, the Akçelik method will be dropped all together.

The HCM delay function consists of two parts, a uniform delay function and a random delay function. The uniform delay expresses the actual time it takes to clear the average queue that is formed during red times. Therefore, this part of the formula is not changed. The random delay depends, among others on a k-value and an I-parameter. The I-parameter represents the distribution of arrivals at the intersection and the k-value represents the controller type. These parameters will be calibrated in order to improve the predictions of the method.

4.4.3 Calibration of the I-parameter for coordinated control

Now, the I-parameter for the coordinated controller will be calibrated. In the first calculation, the I-parameter was chosen as 1, which represents Poisson-distributed arrivals at the intersections. This value was chosen because the creation of vehicles in Vissim follows this distribution. However, the intersections are located approximately 500 meters upstream of the vehicle input points. This might have changed the arrival pattern at the intersections due to car-following behaviour. The I-parameter is calibrated with the dataset containing the average lost times for each stream. Stream 2081 is not taken into consideration since the delay on this stream is assumed to be 0 seconds for each scenario, regardless of the demand and traffic light settings. This means that 3 data points per scenario have been created in Vissim, adding up to 192 data points. From this set, 96 data points have been randomly chosen for calibration of the I-parameter. The other 96 data points are used as control group.

The lost times have been calculated with the HCM-formula for different I-parameters between 0.01 and 1 (the I-parameter has a value between 0 and 1) and are compared to the results in the calibration set. The MSPE of the average lost time, compared to the Vissim data is calculated for each data point. In order to remove outliers, the 5 data points with the largest squared error have been disregarded. This is done because the difference between the control group and the calibration group was too large if outliers were not removed. The result is plotted in Figure 4-8.

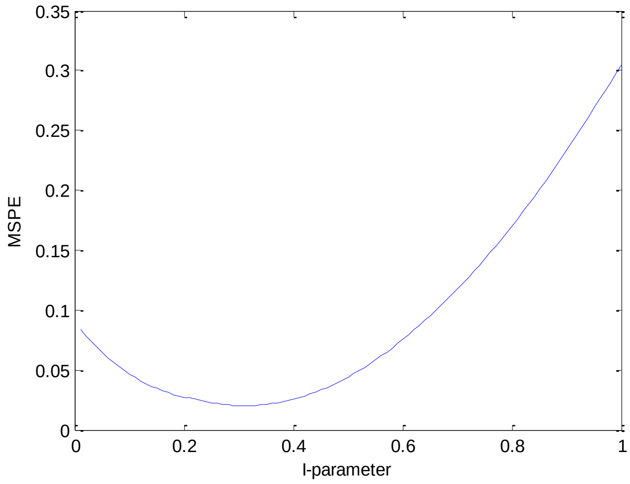


Figure 4-8 *Calibration of I-parameter for the prediction of delays with the HCM-method for fixed-time control. The figure shows the MSPE for the average lost times for different values of the I-parameter. The MSPE is calculated with equation (4-2).*

An I-parameter of 0.31 gives the best value with a MSPE of 0.020. The same calculation has been made for the control group, resulting in a MSPE of 0.021 and thus an I-parameter of 0.31 will be used from now on for calculation of the delays for the coordinated strategy.

4.4.4 Calibration of the I-parameter and k-value for VA-control

The k-value is used for the control method in the calculation of lost times. The k-value depends on the degree of saturation, x, at an input link and on the settings of the VA controller. The k-value is determined, online, by the following formula (Transportation Research Board, 2000):

$$k = (1 - 2k_{min}) * (\max(x, 0.5) - 0.5) + k_{min} \tag{4-5}$$

According to the HCM-method, the value of k_{min} is supposed to be between 0.04 and 0.5, depending on the settings of the controller. In the case of fixed-time control the value is 0.5 and in the case of VA control the value depends on the unit extension time of the controller. The advised k_{min} value corresponding to the settings for the Trafcod controller (unit extension of 1.5 seconds) is 0.04.

To test the parameters for the VA situation, both the k-value and the I-parameter were varied to find the best combination. The I-parameter was varied between 0 and 1, just as for the coordinated situation, and the k-value was varied between 0 and 0.5 since this is the maximum value. This calibration is done the same way as the calibration of the I-parameter, only this time all streams could be used and thus 256 data points were available. In Figure 4-9 the result is shown. The figure remarkably shows that the minimum MSPE for the VA situation is reached with an I-parameter of 0.22 and a k_{min}-value of 0.5. The k-value for VA controllers is determined according to the saturation degree with a minimum of k_{min} and a maximum of 0.5. Now that the k_{min} value is also calibrated at 0.5, the k-value is independent of the saturation degree of the analysed stream. This means that the only difference in the calculation for the coordinated and the VA situation is in the value of the I-parameter.

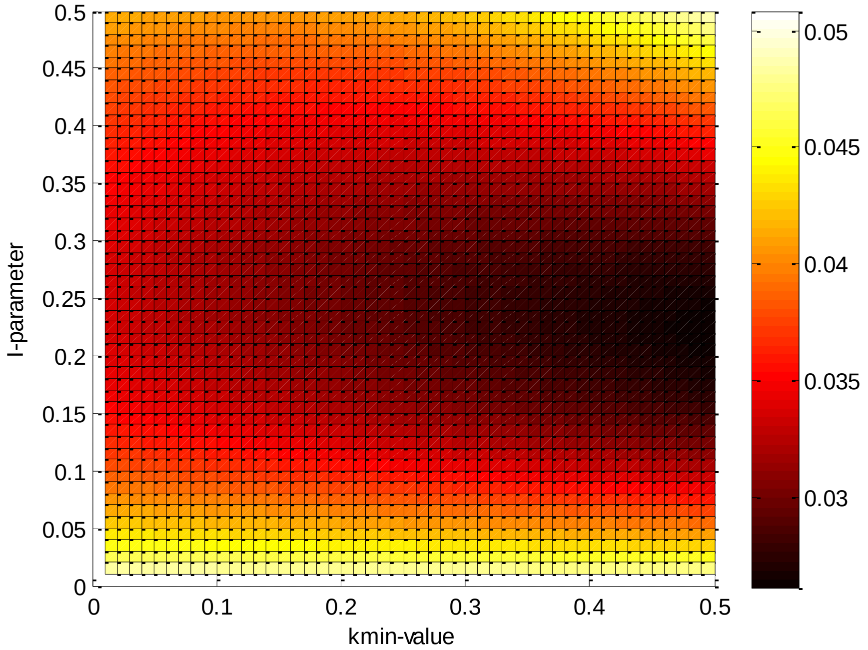


***Figure 4-9**: Calibration of the kmin-value and I-parameter for the prediction of delays for the VA controller. The colour indicates the MSPE for the average lost times. The MSPE is calculated with equation (4-2). Only the results for I-parameters less than 0.5 are shown since the MSPE grows very fast for I-parameters larger than 0.5.*

With the I-parameter set at 0.21 and the k_{min}-value at 0.5, the resulting MSPE for the calibration data points is 0.0261. The MSPE is even lower for the control group (0.0202). This shows that the method is a good predictor for the lost times in this network. Due to the results of these tests, two different I-parameters are used for the next test case. An I-parameter of 0.31 for the coordinated situation and an I-parameter of 0.21 for the VA situation.

NOTE: the value for the I-parameter at stream 2081 depends on the saturation degree of the intersection upstream of this stream (intersection 1). The calibrated I-parameter is an upper bound for the calculation of this I-parameter. This is done because delays on this stream would otherwise be overestimated. This is a heuristic method but it proved to work better than using the calibrated parameter all of the time and also better than using the calculated parameter all of the time.

4.4.5 Identification of lost time for coordinated stream

The lost time for stream 2081 was assumed to be 0 for the coordinated situation. However the Vissim-simulation has shown that this is not the case. Due to platoon dispersion, a perfect green wave is impossible. The delay, as measured in Vissim is shown in Figure 4-10. A function to relate the delay to the demand was not found so a fixed value for the delay per vehicle on this stream is chosen and the basis of the minimum value for the MSPE for this link. A value of 5.22 seconds per vehicle proved to be the best fit whit a MSPE of 0.0635. Alternatively, the HCM-method could have been used to predict the lost times for this link. However, the results in the figure show that there is no clear relation between the delays on this link and the input demands. Since the spread of the delays on the link is not that large, the choice is made to use this fixed value for now.

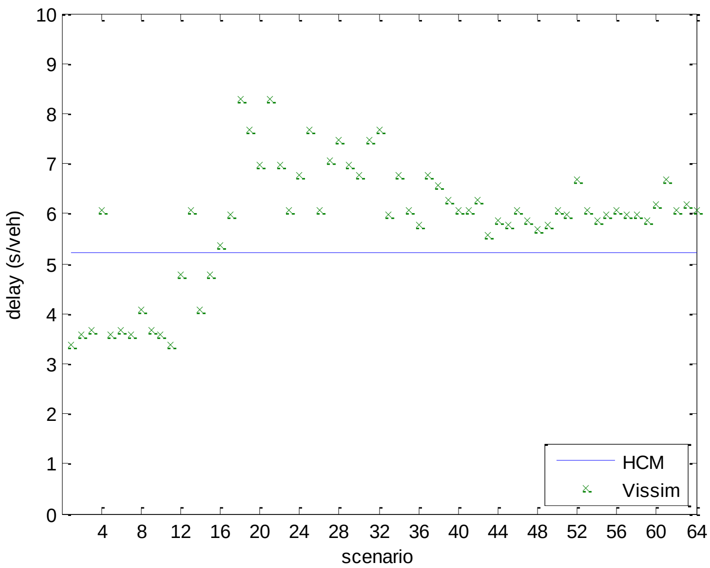


***Figure 4-10**: Coordinated delay stream 2081. The blue line is the calibrated value for the delay on link 2081. The figure clearly shows that for the under saturated scenarios (on the left), the delay is mostly overestimated. The delay seems to settle at a value of about 6 seconds for the saturated scenarios on the right of the figure. Since no direct relation is found between demands and delay, the choice is made to continue with a fixed value for the delay on link 2081.*

4.4.6 Results: calculations with calibrated parameter values

In Table 4-8, the results of case study 2, after calibration of the parameters are shown. Compared to the pre-calibrated results (Table 4-7) the predictions by the HCM-method have increased considerably. The MSPE for the HCM-method has decreased from 0.29 to 0.0117 for coordinated control and from 0.12 to 0.0153 for VA control. The MSPE of lost times for the coordinated case, that are calculated with Akçeliks method, decreased from 0.11 to 0.0985, due to the calibration of the delay at link 2081.

***Table 4-8:** Results of simulation 2 compared to the predicted lost times. j is the mean squared percentage error for the total lost time, calculated with equation (4-2).*

Strategy	j_{VA}	$j_{Coordinated}$	correct decision
Akçelik	0.97	0.10	68.75%
HCM	0.02	0.01	78.13 %

In Figure 4-11, the results for the total delay, after calibration, are shown. Compared to Figure 4-6, the HCM-method has improved considerably, for both control strategies. Most errors are now within a boundary of 20%, compared to the real delays, where the pre-calibrated errors were sometimes even 80%.

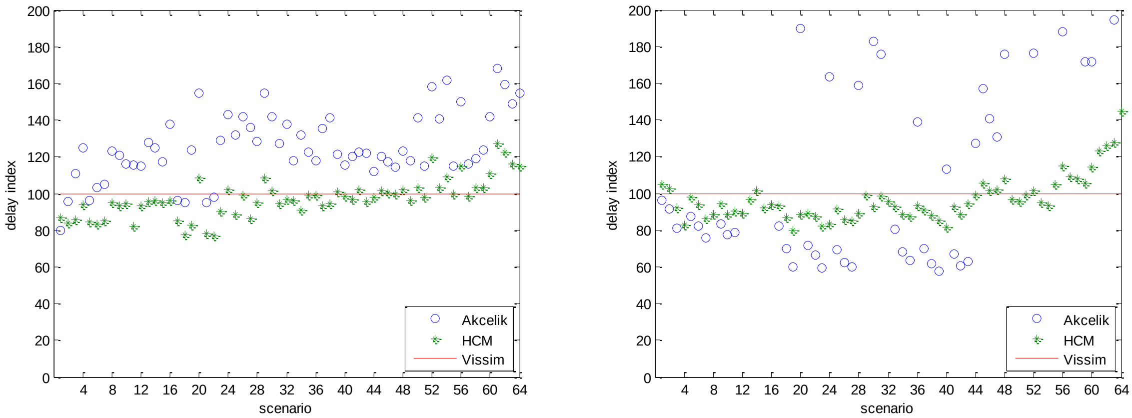


Figure 4-11 *Total delay after calibration for the coordinated situation (on the left) and for the VA situation (on the right). The delays for the prediction methods are indexed to the delays of the Vissim simulation.*

In Figure 4-12, the total predicted delay is compared to the total delay in the Vissim simulation. Compared to Figure 4-7, the method has improved significantly for unsaturated situations. In saturated situations, the method has also improved, but is still less accurate.

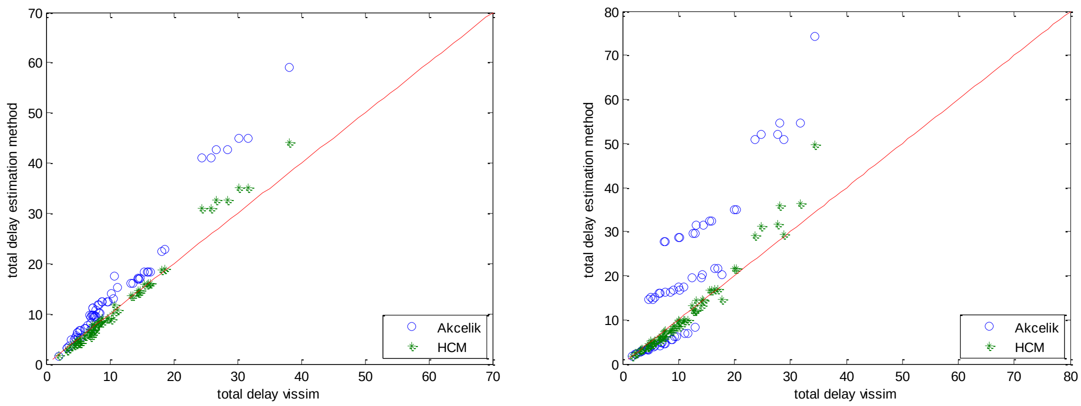


Figure 4-12 *Total delay in Vissim compared to the predicted delay, for the coordinated situation (left figure) and the VA situation (right figure). The red line shows where predicted delays and real delays are equal.*

The main purpose of the prediction method to be used is to make a decision between coordinated and VA control. Especially when the difference between lost times of the two strategies is large, it is essential that the method chooses the right strategy to be employed. Figure 4-13 shows the wrong decisions made by both prediction methods, grouped by the relative difference in lost times between the two control strategies in the Vissim simulation. The figure shows that most wrong choices are made when the relative difference between the lost times of both control methods are less than 10%. No wrong decisions are made with the HCM-method, when the difference is larger than 20%. This means that, if a wrong decision is made, it does not have a big impact on the lost times since either strategy would generate lost times that are close together. This is not the case for the Akçelik method, where wrong decisions are even made when the relative difference between the lost times of the control methods is larger than 40%.

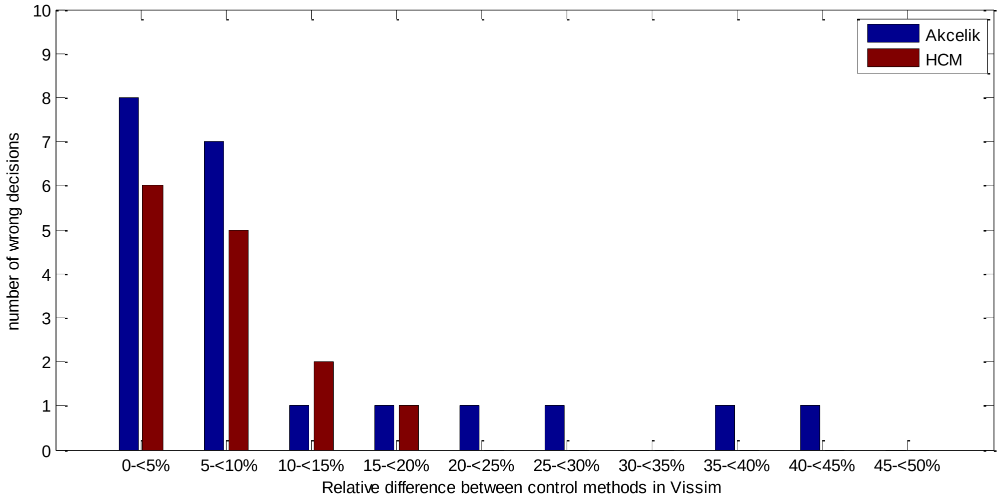


***Figure 4-13**: Wrong decisions in both prediction methods. The figure shows when a prediction method has made a wrong decision on which control strategy would generate lower lost times.*

4.4.7 Conclusion

The three questions, stated in the simulation plan for the case study will be answered according to the results in this section.

1) What prediction method is better suited for predicting delays?

After calibration, the HCM-method performed considerably better with MSPE's of 0.0117 and 0.0153 for coordinated control and VA-control respectively, compared to MSPE's of 0.0985 and 0.9721 respectively for Akçelik's method.

2) Which prediction method should be used in order to predict lost times for the controller?

The HCM-method proved to perform better than Akçelik's method, as shown by the previous question. Furthermore, the HCM-method chose the right control strategy in 50 of 64 scenarios compared to 44 right decisions with Akçelik's method. Therefore, the HCM method is chosen to predict delays for the controller.

3) What parameters need to be calibrated in order to use the chosen prediction method?

Two parameters were considered to be calibrated for the HCM-method. First of all, the I-parameter, that is used to account for randomness of arrivals at intersection controllers, showed to generate the best results when calibrated for VA-control and coordinated control separately. The k-value, that is used to account for the controller type, showed to generate the best results when the same value is chosen for VA-control and coordinated control.

4.5 Case study 3: Evaluation of the controller

The third case study is used to test whether the designed controller works as expected, and to compare it to VA and coordinated control. First the plan for this case study is discussed and then the results will be given.

4.5.1 Plan for case study 3

First, the main purpose of the case study is discussed, then the input scenarios are described and finally the output, that needs to be generated, is mentioned.

Purpose

The purpose of the third and final case study is to evaluate the controller by comparing its performance to the performance of a coordinated controller and a VA controller. The performance is judged by the total lost times within the network. The controller that generates the least lost times is the best controller for the particular demand pattern in this network. The following question will be answered with the third case study:

1) *Is the designed controller capable of decreasing total lost times in a simulated traffic network, compared to coordinated control and VA control*?
2) *Does the controller switch at the right times between control strategies*?
3) *How does the controller perform on a coordinated link*?
4) *How does the controller perform on a conflicting link*?

Input

Two demand patterns have been identified from the second case study: one where coordinated control is undisputedly the best method and one where VA control is the best. From these demand patterns, two scenarios will be tested. Each scenario has a simulation time of 3 hours and will be conducted once.

During the first scenario, the demand in the first hour corresponds to the VA demand pattern, the demand in the second hour to the coordinated demand pattern, and the demand in the third hour corresponds to the VA demand pattern again. The demands are given in Figure 4-14. Due to the sudden shifts in demand the controller should switch from VA control to coordinated control after one hour and back again after another hour.

The demand patterns are chosen according to the result of the second case study. The demand pattern for the first and third hour is 225 veh/hour for the main route and 450 veh/hour on the conflicting streams The HCM method has predicted the lost time for this scenario for VA control at 21.8% less than coordinated control and the Vissim-simulation at 29.9 % less than coordinated control. During the second hour the demand is 675 veh/hour on each route. This scenario had 22.8% less waiting times for coordinated control than VA control according to the HCM method and 19.8% less with the Vissim simulation.

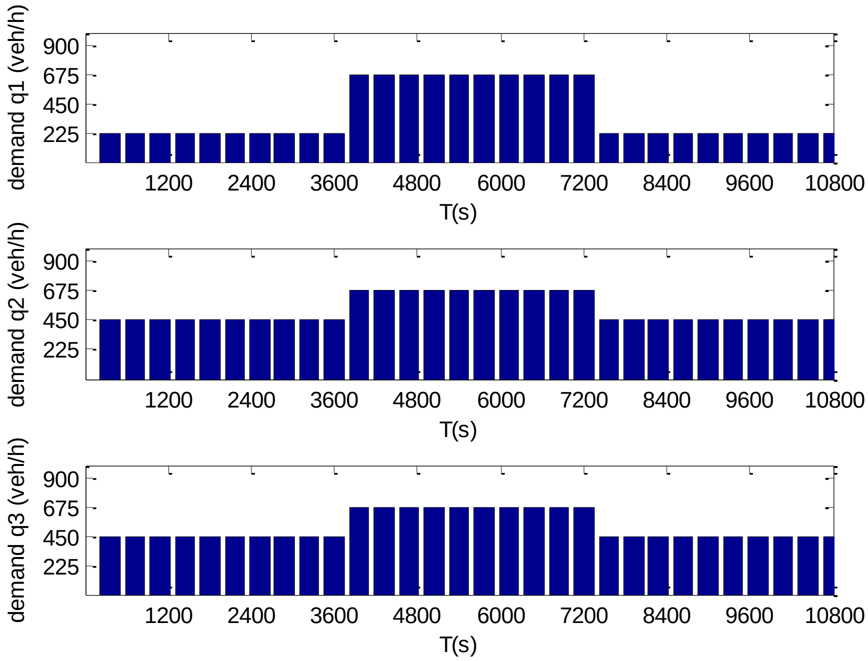


Figure 4-14 *demand simulation 3-1. In the figure the demand for every control period in the three hour simulation is shown. The top figure shows the demand q1, the middle figure the demand q2 and the bottom figure the demand q3.*

During the second scenario, a more realistic situation is chosen for the development of the demands. Instead of the stepwise increase/decrease in demand, the demand gradually changes in time. In Figure 4-15, the demands are given, where T is the time since the start of the simulation.

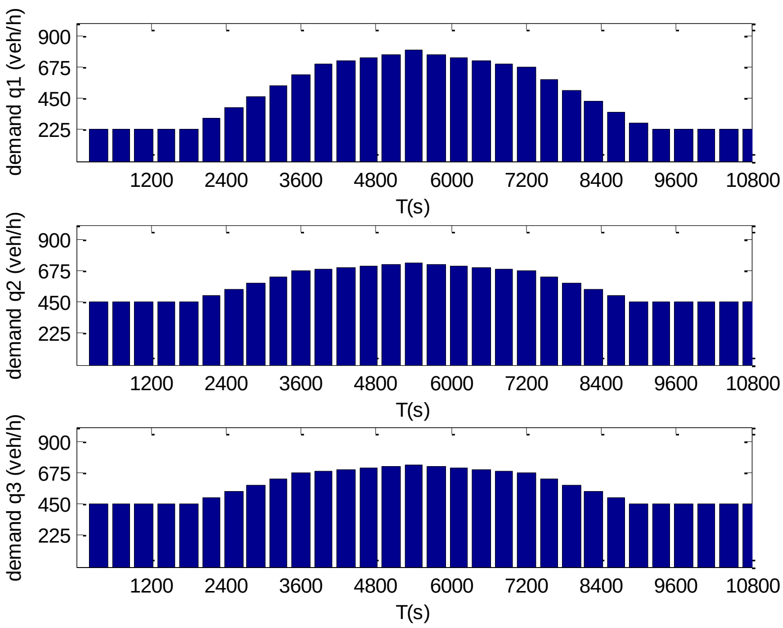


Figure 4-15 *demands simulation 3-2. In the figure the demand for every control period in the three hour simulation is shown. The top figure shows the demand q1, the middle figure the demand q2 and the bottom figure the demand q3.*

In total, the third case study counts 6 simulations. The controller will communicate with the Vissim simulation every 0.2 seconds, to manipulate the detector occupancies. The control period k, will be 6 minutes. The inputs for simulation 3 are summarized in Table 4-9.

Table 4-9 inputs simulation 3

Variable	Value(s)
N^{sim}	[1:6]
T^{sim}	10800
T^{sample}	0.2
$T^{control}$	360
M	[1,2,3]
RS	1

Output

The control approaches will be compared by the total lost time, the total lost time per link and the average lost time. Furthermore the lost time per control period will be calculated. The chosen control approach per time period will be recorded, when the SA-controller is deployed. This is done in order to see when the controller switches between VA control and coordinated control.

4.5.2 Results: Total travel time and lost time

In Table 4-10, the total travel time for both scenarios and for each control strategy is shown. The SA-approach decreases total travel times in both scenarios, compared to coordinated and VA control. When compared to VA control, the SA-approach decreases travel times on all routes in the network. Coordinated control does perform better on route AB in the first scenario but in the second scenario the travel time on AB is exactly the same for coordinated control and SA-control. In the final column of Table 4-10, the total lost time of the 3 strategies is compared. The total lost time is calculated by subtracting the free flow travel time from the travel times. The SA-approach decreases total lost times in both scenarios, when compared to VA-control and coordinated control.

Table 4-10 Total travel time (indexed; VA control is 100)

	Total Travel Time	Travel Time AB	Travel Time CD	Travel Time FE	Travel Time AB 1	Travel Time AB 2	Total Lost Time
Scenario 3-1 VA	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Scenario 3-1 Co	100,5	94,8	102,9	104,4	96,9	93,5	102,9
Scenario 3-1 SA	98,8	97,1	99,9	99,6	98,5	96,2	92,8
Scenario 3-2 VA	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Scenario 3-2 Co	99,5	94,9	101,5	103,6	98,1	92,9	97,4
Scenario 3-2 SA	97,2	94,9	99,3	98,2	97,1	93,6	86,3

4.5.3 Results: Switching times

In order to study if the controller switches between control strategies at the right times, first the switching times need to be known. Figure 4-16 shows what control strategy is chosen by each controller during the simulation runtimes. The figure show that the SA-controller switches after one and two hours (10 and 20 control periods) during the first scenario, as expected. The switch is made one period earlier from VA-control to coordinated control in simulation 3-2 (after 3240 seconds). The change back to VA-controller is one period later (after 7560 seconds). The control does not switch back and forth between coordinated and VA control

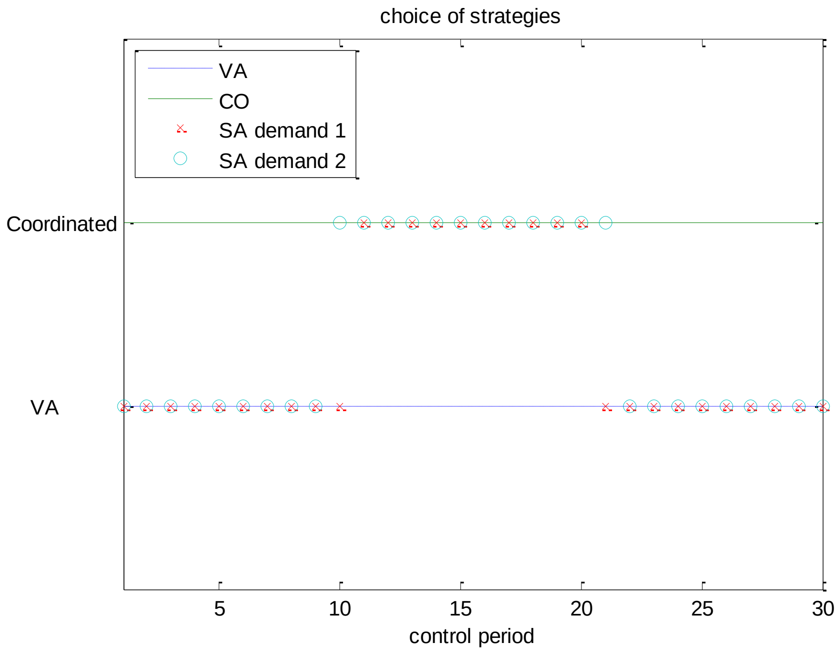
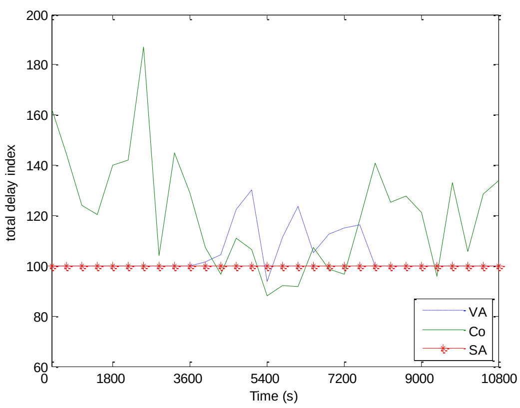


Figure 4-16 *Choice of strategies with the SA-approach. In simulation 3-1 the first and last 10 periods are controlled with the VA controller and the rest with the coordinated controller. In simulation 3-2 the first and last 9 periods are controlled with the VA controller ans the rest with the coordinated controller.*

The development of the delay through the simulation runtime is shown in order to see if the right decision is made for each control period. In order to show this development, the delay per simulation period is shown in Figure 4-17. The total delays are indexed, with the delay for the SA-approach being 100.



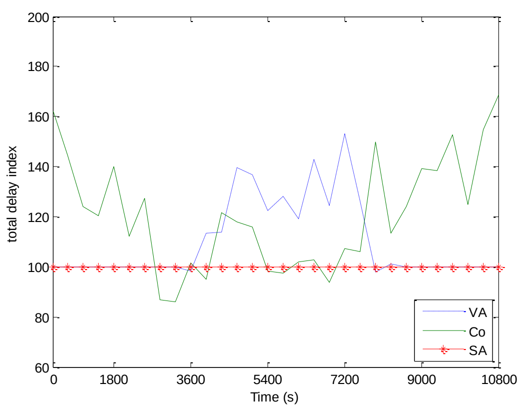


***Figure 4-17**: Total delay per control period, indexed to the total delay of the SA-approach. On the left, the delay for simulation 3-1 and on the right the delay for simulation 3-2*

In the first scenario, the switch is made at the exact same time that the demands change dramatically. The figure on the left shows that the controller has indeed chosen the strategy that generates the least lost times. However, for both strategies the lost times are far from stable, even though the demands are stable for one hour. This means that it is impossible to see if delays are caused by switching too early or too late or by another factor. In the second scenario, the coordinated approach generates lower lost times for a while before the switch is made to coordinated control (the switch is made at 3240 seconds). The experiment should be repeated multiple times with different random seeds in order to see if this is indeed caused by suboptimal switching times.

4.5.4 Results: Delay per vehicle for a coordinated stream

Traffic on stream 2081 is supposed to benefit the most from coordination of the intersection controllers. On stream 2081 lost times are decreased for the coordinated strategy, because of the creation of a green wave. Figure 4-18 shows that the SA-approach uses the coordinated approach in the second hour, thus decreasing travel times on stream 2081. In the second case study, the demand changes almost every control period. This means that the green times for the coordinated control strategy could change every control period as well and a transition step is needed every control period. This transition step could cause a queue to build in the coordinated stream, thus causing the green wave to fail. If that is the case, the average delay on this link would be larger than the 5-7 seconds caused by platoon dispersion. The figure on the right shows that this is the case for the coordinated approach from 7500 seconds onwards (the SA-approach already switched to VA control by then). The figure shows that once the coordination has failed, it takes a long time for the green wave to recover and the lost times to drop again. A change in the transition step might solve this problem. Another solution might be to actively try to dissolve the queue on the coordinated stream, e.g. by increasing the coordinated green time for some periods.

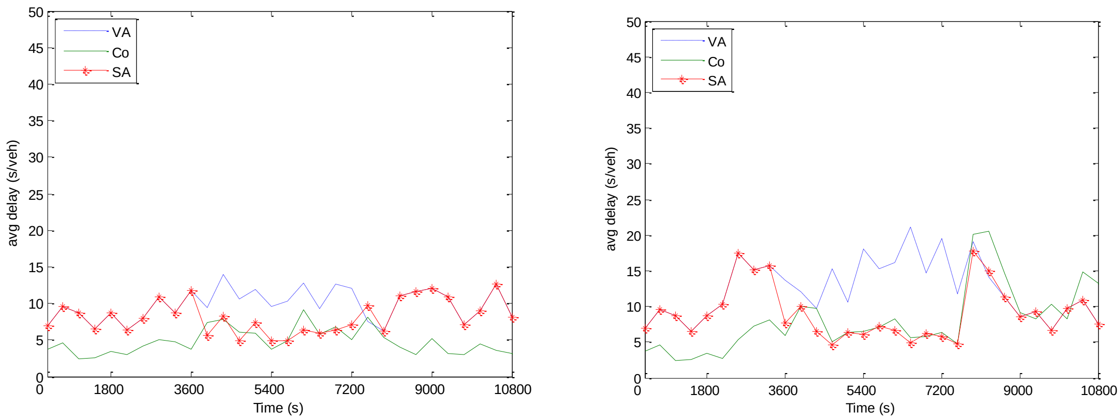


***Figure 4-18**: Average delay on stream 2081 per control period. The graph on the left shows simulation 3-1 and the graph on the right shows simulation 3-2.*

4.5.5 Results: Delay per vehicle for a conflicting stream

Stream 2051 is a conflicting stream to the green wave. Figure 4-19 shows the delay per vehicle on this stream. The figure shows that lost times are lower with the VA approach in the first and third hour. In the second hour, the coordinated approach also generates lower travel times than the VA approach. These figures show that the SA-approach works for the coordinated stream but does not increase waiting times for the conflicting stream.

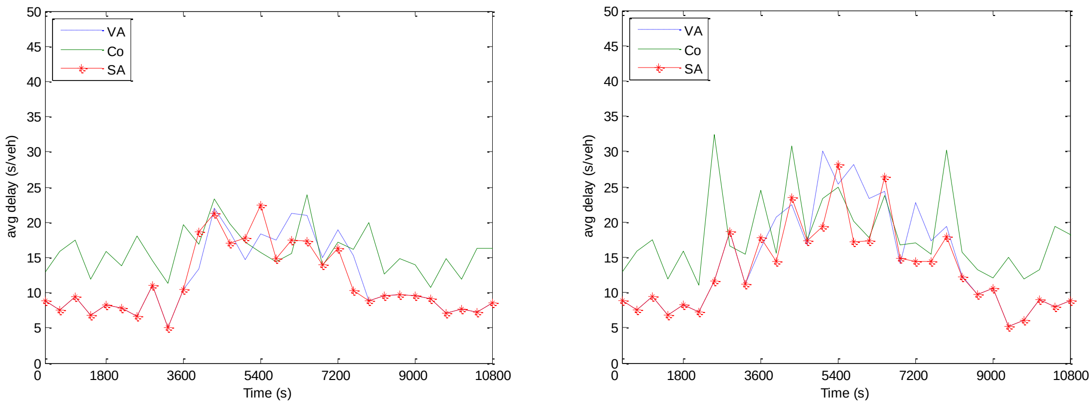


***Figure 4-19**: Average lost times for every control period on link 2051. This is the stream, conflicting with the green wave. The left graph shows the result for simulation 3-1 and the right graph shows the result for simulation 3-2.*

4.5.6 Conclusions case study 3

The third case study is concluded by answering the questions, proposed in the plan for this case study.

1) *Is the designed controller capable of decreasing total lost times in a simulated traffic network, compared to coordinated control and VA control*?

Compared to VA-control (which is the current controller in most cases in the Netherlands), coordinated control increased the total lost times with 3% for the first scenario and decreased the total lost times with 3% for the seconds scenario. The switching controller decreased the total lost times with 7% and 14% in the first and second scenario respectively. Therefore, the switching controller performs better than both the VA-controller and the coordinated controller.

2) *Does the controller switch at the right times between control strategies*?

With the current simulation results, no conclusion can be made on this topic. More replications of the second scenario are needed in order to see if the used switching-times are indeed the best.

3) *How does the controller perform on a coordinated link*?

The coordinated controller was expected to perform better or equal to the SA-controller at all times, on a stream that benefits from coordination. In the simulation for the second demand scenario, the results have shown that this was not the case. This might be due to the fact that the transition step does not work properly or to the fact that a queue has formed inside the coordinated stream. Further research is needed to see what the problem is and how it should be solved.

4) *How does the controller perform on a conflicting link*?

Figure 4-18 shows that for the two simulation scenarios, the SA-approach does not necessarily increase lost times on the conflicting stream of a coordinated intersection.

4.6 Conclusions

The objective of this chapter was stated as follows:

Evaluate the developed controller by means of a simulation study.

The evaluation of the controller was done with 3 case studies. In the first case study, the saturation flow for the simulation network was identified. In the second case study, the prediction method for the controller was calibrated and finally, the controller was evaluated. The main conclusions from this chapter is that the developed controller is capable of decreasing lost times, up to 14%, compared to VA-control.

4.7 Recommendations

The results from the second case study clearly show that the HCM-method is better at predicting lost times than the Akçelik-method, provided that the I-parameter and the k_{min}-value are calibrated first. Furthermore, the parameters need to be calibrated for the coordinated situation and the VA situation separately.

Another method should be studied for the prediction of the average lost times of coordinated streams. A fixed value is used for this parameter in the case studies in this thesis. It is expected that a relation can be found between for example the link length, the average speed and the size of the coordinated green times and the average lost times on these streams.

A heuristic method is now used to determine the size of transition steps. Future research into the best way to facilitate the changes between transition steps might be needed to find the ideal size of the transition steps.

When a queue builds on one of the coordinated links, the green wave could be broken. The lost times for the coordinated strategy in simulation 3-2 from 7200 seconds onwards (Figure 4-18) show that it could take a long time for the green wave to recover. An extra transition step might be included when this is the case, in order to clear this queue. The extra transition step should increase the green time on the link where the queue stands for a few cycles, until the queue is completely dissolved. In order to maintain the coordinated offset, the green time for the conflicting stream should be decreased by the same amount of time. A simulation study is needed to calibrate this extra transition step.

The effects of coordinating the offsets and the extra lost time that is generated by this coordination should be studied in order to determine the threshold for choosing coordinated control. In the current method the system only switches to coordinated control when lost times will decrease with at least 5%, compared to VA control. However, the switching lost time depends on the size of the offset difference.

The control period was fixed at 6 minutes for the case studies. The effects on the effectiveness of the method in relation to the size of the control period should be studied in order to determine the optimal size for this parameter.

The controller is based on 100% knowledge of the predicted demands. Another simulation study is needed to investigate the effects of penetration rates below 100%. The same network could be used as for the third case study. The input demands to the simulations could be the same as in the second scenario but the controller does not receive inputs from every vehicle. It is assumed that the controller is able to make estimation on the demand, but the quality of this estimation depends on the penetration rate. This test would show the dependency of the controller to high penetration rates of connected vehicles.

5 Conclusion, discussion and recommendations

The increasing connectivity of road users gives an opportunity for road managers to integrate in-car information systems with roadside traffic management systems. The combined use of these systems could generate new possibilities to control traffic and decrease travel time losses. In this thesis, the possibilities to combine Urban Traffic Controllers with in-car navigation systems have been studied. One of these possibilities, the adaptive creation of green waves on the basis of expected routes in an urban network, has been tested in a simulated environment. The test results have shown that it is indeed possible to decrease travel time losses with this application. In this final chapter, the conclusions of the sub-objectives are summarized and some overall conclusions are given on the main objective. Furthermore, some statements are given on the applicability of the conclusions from this thesis and possibilities to continue with the work started here.

5.1 Findings

In the introduction, the following objective was defined for this thesis:

The objective of this study is to study the possibilities to improve the workings of Urban Traffic Controllers with the aid of in-vehicle Route Guidance Systems. One application will be developed into a working algorithm that aims at decreasing travel time losses in an urban traffic network.

In the second chapter, a literature study towards the state of the art of Urban Traffic Controllers (UTC) revealed that the problem to adaptively control multiple intersection controllers to a global optimum has been defined many years ago, but solving it in real-time is not yet feasible due to the high complexity. Therefore, currently used UTC either drop the optimality condition or try to solve the problem for a single intersection instead. In practice, this means that most adaptive systems (systems that respond to the current or predicted, rather than average historical traffic conditions) are local controllers. On the other hand, controllers that coordinate multiple intersection controllers (for example to create green waves) are usually not adaptive or respond very slowly to changes in the traffic demand. Information from Vehicle Route Guidance Systems (VRGS), such as current location, planned routes or destination, could improve the information that is available for UTC about the current and future traffic situation.

In the third chapter, a controller is developed based on this improved information. Due to this information, sent by all navigation systems in an urban traffic network, the planned routes by all vehicles and therefor the route demands for some time ahead, are assumed to be known. From this predicted route demands, the controller decides if it pays off, in the sense that it decreases lost times, to create or break a green wave somewhere in the network. If this is not the case, all intersections are controlled by local (vehicle-actuated) controllers. If an improvement is predicted, the controller will overrule the local controllers for the intersections part of the green wave and ensure coordination between the intersections.

In the fourth chapter, the developed controller is evaluated. A test on a simple, simulated network has shown that switching between coordinated and vehicle-actuated control is indeed possible and can reduce lost times in an urban traffic network. . The switching controller decreased the total lost times with a maximum of 14%, compared to VA-control. For the same test case, the coordinated controller was only able to reduce lost times with 3%, compared to VA-control. The coordinated controller that was used, did recalculate green times and cycle times every control period (6 minutes), in order to show that the decreased lost times were indeed the cause of the switching algorithm and not of an improved coordinated controller.

5.2 Conclusion

The findings in the previous section show that it is indeed possible to use predicted route demands in a network for the benefit of urban traffic control systems. Due to the complexity of the problem, the design of a controller that can solve the urban traffic control problem to optimality, online, and for a large network is not feasible in the near future. Therefore, the developed controller is a promising alternative to utilize the strengths of different urban traffic controllers. While some controllers might work only in unsaturated conditions and other controllers distinguish themselves in saturated conditions, the designed controller has the potential to excel in every traffic situation.

5.3 Discussion

Although very promising, there are some limitations to the current research. In order to define possibilities for field implementation of the controller and future research these limitations are discussed in this section.

The test case was performed on a very small and simple traffic network with traffic scenarios that were picked specifically for the controller to decrease lost times. The controller should first be tested on more realistic traffic scenarios in more realistic traffic networks before implementation in the field could be a serious option.

The switching algorithm is based, in theory, on the knowledge of future route demands through a network. In order to generate this knowledge, two assumptions have been made. First of all, navigation systems are supposed to send information on current location, advised route and destination to a central computer. It could be very hard, if not impossible, to oblige users to send this information since they would feel it violates their privacy. Even if the data would be encrypted and manufacturers of navigation devices would agree to send the information, people would still have to use the devices every time they travel. This might only be reached if it would be obligatory to use a navigation system in order to use a road network, or to wait until every vehicle on the road network is a self-driving vehicle and drivers would have to program the destination in order for the vehicle to drive. Both seem not very realistic, at least not in the near future. However, the switching algorithm might also work with less than perfect route demand predictions, generated by prediction models that incorporate in-car measurements with detector data and historical measurements. This should be researched.

Due to lack of time and the inability to adaptively guide single vehicles in the simulation network, the effect of control decisions on route choice has not been analysed in the case studies. This might especially be very relevant when route guidance systems become more intelligent and respond quickly to changing traffic situations. This also offers opportunities to incorporate the presence of green waves into the route choice algorithm of navigation systems.

5.4 Recommendations for future research

Some recommendations can be made for future research. The following recommendations can be made, regarding expansion of the evaluations of the controller:

- The third case study should be repeated with different random seeds and demand patterns in order to test the limitations of the controller
- Another case study should be performed on a more complex and realistic urban traffic network
- Switching between more than two strategies should be tested

The choice of prediction methods was limited to the formulas by the Highway Capacity Manual and a formula by Akçelik. A more extensive study towards the use of estimation methods is found in (Vitti, 2006). A study towards the best method for predicting lost times, could be performed since it has not been studies extensively in this paper.

The transition step was changed during the simulation study since the original algorithm did not work properly. The solution was a heuristic method that worked for the specific situation. Further research is needed in order to define a generic solution that generates the optimal size of transition steps. The current solution is focussed on coordinating the traffic lights as fast as possible but it might be better to decrease the offset difference in smaller steps. The allocation of transition steps, to either the coordinated stream or the conflicting stream, should also be considered. Finally, the best method for choosing the leading intersection should be discovered. The current controller uses the intersection that is the furthest upstream. Other possibilities are to choose the intersection that requires the smallest changes to the other intersections or the intersection that has the highest saturation degree.

Finally, the current controller uses fixed times for the offset between intersections and for the lost times caused by platoon dispersion. In reality, the offset depends on the speed of the vehicles and the speed of vehicles depends on the number of vehicles in the network. The controller could be improved by making the offset dependant on the current traffic demand in the network. Methods to do so have already been developed, for example for the IN-TUC system, and could be introduced to the controller. The same holds for the prediction of lost times for the coordinated streams.

5.5 Recommendations for practice

The following recommendations can be made upon future implementation of the controller:

- The controller, used for coordinated control in the case studies is a fixed-time controller for the duration of a control period. Before field implementation, the controller could be changed to allow for small changes to the fixed green times, in order to prevent queues from building on the coordinated routes.
- Instead of fixed strategies an algorithm could be developed that searches for routes that could be coordinated, based on the predicted route demands. Such an algorithm could prevent the controller to have to calculate every possible coordination strategy since this might be cumbersome and require too much computation time for large traffic networks.
- A field test is required to calibrate the parameters for the prediction method in the case of VA-control. If VA-control is the current strategy the prediction method can also be calibrated on the basis of historic data.

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A. List of symbols

Symbol	Explanation	unit
l	Link index	
j	Intersection index	
k	Control period index	
s	Strategy index	
i	Control phase index	
$q_l(k)$	Link demand	[veh/s]
$D_s(k)$	Total delay	[s]
$d_{l,s}(k)$	Average link delay	[s]
$c_j(k)$	Cycle time	[s]
$g_i(k)$	Green time	[s]
$c_{c,j}(k)$	Coordinated cycle time	[s]
$g_{c,i}(k)$	Coordinated green time	[s]
$u_i(k)$	Green time ratio	
$y_i(k)$	Phase flow ratio	
$Y_j(k)$	Intersection flow ratio	
$C_i(k)$	Capacity	[veh/s]
$x_i(k)$	Degree of saturation	
s_i	Saturation flow	[veh/s]
L_j	Total lost time per cycle	[s]
t_1	Required offset	[s]
t_2	Current offset	[s]
Δt	Offset difference	[s]
N^{sim}	Scenario number	
T^{sim}	Simulation duration	[s]
T^{sample}	Simulation time step size	[s]
$T^{control}$	Control time step size	[s]
M	Control mode	
RS	Random seed number	
q1	Demand route A-B	[veh/h]
q2	Demand route C-D	[veh/h]
q3	Demand route F-E	[veh/h]
T^{lost}	Total lost time	[h]
t_r^{lost}	Average lost time for route r	[s/v]
j_{em}	Mean Squared Percentage Error for estimation method em	

B. List of abbreviations

Abbreviation	Explanation
CRONOS	Control Of Networks by Optimization of Switchovers
GPS	Global Positioning System
HCM	Highway Capacity Manual
INM	Integrated Network Management
ITS	Intelligent Transport Systems
KIM	Kennisinstituut voor Mobiliteitsbeleid (Knowledge Institute for Mobility policy)
LQ	Linear Quadratic
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
MSPE	Mean Squared Percentage Error
OPAC	Optimized Policies for Adaptive Control
PPA	Praktijk Proef Amsterdam (Field Test Integrated Network Management Amsterdam)
PRODYN	Programmation Dynamique (Dynamic Programming)
PT	Public Transport
RHODES	Real Time Hierarchical Optimized Distributed Effective System
SA	Switching Algorithm
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	Split Cycle and Offset Optimisation Technique
TRANSYT	Traffic Network Study Tool
TTS	Total Time Spent
TU	Technical University
TUC	Traffic Responsive Urban Control
UTC	Urban Traffic Controller(s)
UTOPIA	Urban Traffic Optimisation by Integrated Automation
VA	Vehicle-actuated
VMS	Variable Message Signs
VRGS	Vehicle Route Guidance System
VRIGen	Verkeers Regel Installatie Generator (Traffic Control Generator)

C. Calculation of the current offset

```
% CP(i) is the current phase on intersection i, phase 1 is the coordinated phase

% NewState{i} is the current state of stream i

% RC(i), YC(i), GC(i) are the red, yellow and green time counters for stream i,
respectively

% In this example, intersection 1 (upstream) consists of stream 1 and 2 and
intersection 2(downstream) consists of stream 3 and 4

% sim.CoGreen(k,i) is the coordinated green time for time period k, i indicates the
green time for the coordinated stream (i=1) or for the conflicting stream (i=2)


                        if CP(1)==1
                            if strcmp(NewState{1}, 'Red')
                                TimeToStart(1)=2-RC(1)+sim.CoGreen(k,2)+5;
                            elseif strcmp(NewState{1}, 'Green')
                                TimeToStart(1)=sim.CoGreen(k,1)-
GC(1)+5+sim.CoGreen(k,2)+5;
                            elseif strcmp(NewState{1}, 'Amber')
                                TimeToStart(1)=5-YC(1)+sim.CoGreen(k,2)+5;
                            end
                        else
                            if strcmp(NewState{2}, 'Red')
                                TimeToStart(1)=2-RC(2);
                            elseif strcmp(NewState{2}, 'Green')
                                TimeToStart(1)=sim.CoGreen(k,2)-GC(2)+5;
                            elseif strcmp(NewState{2}, 'Amber')
                                TimeToStart(1)=5-YC(2);
                            end
                        end
                        if CP(2)==1
                            if strcmp(NewState{4}, 'Red')
                                TimeToStart(2)=2-RC(4)+sim.CoGreen(k,2)+5;
                            elseif strcmp(NewState{4}, 'Green')
                                TimeToStart(2)=sim.CoGreen(k,1)-
GC(4)+5+sim.CoGreen(k,2)+5;
                            elseif strcmp(NewState{4}, 'Amber')
                                TimeToStart(2)=5-YC(4)+sim.CoGreen(k,2)+5;
                            end
                        else
                            if strcmp(NewState{3}, 'Red')
                                TimeToStart(2)=2-RC(3);
                            elseif strcmp(NewState{3}, 'Green')
                                TimeToStart(2)=sim.CoGreen(k,2)-GC(3)+5;
                            elseif strcmp(NewState{3}, 'Amber')
                                TimeToStart(2)=5-YC(3);
                            end
                        end
CurrentOffset=round(mod(TimeToStart(2)-TimeToStart(1), sim.CoCycle(k)));
```