Coordination in an Adaptive Traffic Signal Control System

Network Performance of the Multi-agent Look-ahead Traffic Adaptive Control System

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Network performance of Multi-Agent Look-Ahead Traffic-Adaptive Control System

Master of Science Thesis

For the degree of Master of Science at Delft University of Technology

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Delft, 17th of May 2012
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Preface

Arriving to a country as a foreign student is always a challenge to some extent. This was also the case with me, but I always thought about this trip as an adventure. During this period I had the opportunity to get familiar with the ways of learning and working not only of people from the Netherlands but from around the world. I also had an opportunity to gain insight to deeper aspects of my profession the civil engineering and its interdisciplinary fields. I am sure I would not have been able to get this thorough knowledge elsewhere. Finally I also had an opportunity to learn about myself and how I am able to adapt to the new challenges and the changing environment. I am sure the aforementioned experiences will last long and help me in my future career and life.

At this point, almost at the end of my studies at TU Delft, I hope this adventure in the Netherlands is not finished yet, but my studies were only the beginning.

Here I would like to say thank you to some people for helping me in the past year. I would like to thank Andreas Hegyi for drawing my attention to possible internship opportunities at TNO. I would like to thank Ronald van Katwijk the guest lecturer at TU Delft and my later daily supervisor at TNO for giving me an opportunity at TNO and helping me during the past months with my thesis. I would like to thank Maria Salomons for finding so much time to discuss the draft thoughts and ideas of this thesis. Last but not least I would like to thank every member of the Committee for helping me with their useful input during our meetings.

David Petres

Delft, 24th of April 2012
Abstract

Coordination between intersections has been used in traffic signal control for quite a long time. In the past, one of the new emerging technologies known as multi-agent systems were to this field as well. The objective of this thesis is to determine how beneficial network coordination is in an adaptive traffic signal control system that follows the multi-agent approach.

For this reason a thorough literature survey was carried out. First the operation of the adaptive controller was studied. Then a review of the problems that can hinder coordination was done. Two major fields for improvement were identified: platoon dispersion and the problem of unknown arrivals on the side streets. The coordination efforts of other authors in other adaptive traffic controllers were also reviewed.

During the research the effects of platoon dispersion were examined to understand to what extent this can hinder coordination. After this different strategies were used to coordinate between the distributed intersection controllers. These strategies have been tested in a simulation environment. Simulation results show that coordination of intersections in a multi-agent controller can reduce average delay of the users on the network depending on the average demand. The best performing coordination measure is platooning vehicles on the main streets at the first intersection of the arterial. This provides time for the downstream intersections to serve side streets and ensure that the main street is not stopped at the downstream intersections on the arterial. The tested coordination measures reduced delay by 10% compared to the original settings of the multi-agent adaptive controller in simulation.
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General changes:

- Smaller mistakes marked or clarifications asked by the committee members in the sent materials are corrected or clarifications added
- The term sub-chapter changed to section
- The term cooperation changed to coordination
- Chapter and section titles modified to explain the content of the chapter and section more
- Transition between the chapters and sections added where these were missing
- In chapter 4 and 5 ideas cited from different authors were put in separate paragraphs to make them easily recognizable.
- References and contributions updated (with special attention to chapter 5)
- Recommendations at the are updated and give detailed information

Structural changes:

- The research framework is moved before the literature survey but after the introduction. The reason for this is that a basic introduction is needed to the reader without background on the field of traffic signal control to understand the research question and framework [page 10]
- Every article is mentioned in the literature survey. In the research these are referred or cited again. There is one exception. The details of the model of Bonneson, Pratt and Vandehey is left in section 4.1. Moving these to the literature survey resulted in a totally fragmented text referring in every second sentence to another chapter. [page 40-41]
- Section 5.2 restructured, results are before the shortcomings [page 59]
- Conclusion is added to the end of:
  - chapter 3 (literature survey) [page 37]
  - chapter 4 (predicting platoon dispersion) [page 51]
  - chapter 5 (coordination in multi-agent adaptive control) [page 87]
  - General conclusion is given in chapter 6 [page 92]

Other changes:

- Title changed [page i]
- Abstract updated [page vii]
- Contributions mentioned explicitly in the introduction [page 1]
- Figure added about the structure of the thesis [page 2]
- Problem definition updated [page 13]
- Research question rephrased [page 17]
- Introduction of the literature survey updated [page 22]
- Conclusion to the literature survey added [page 36]
- Overview table about adaptive systems added [page 36]
- Conclusion and recommendation of platoon dispersion rewritten [page 50]
- Clarification added on centralized and decentralized approach of coordination [page 56-58]
- The direct and indirect approach led to confusion therefore, the terms were only used in explanation. Instead the terms of the problem definition (section 2.1.) used [page 57]
- Steps of the analysis on inducing coordination is added in section 5.3.3.1. [page 66-71]
- Information on sensitivity of results on entry and interconnection weights added [page 72]
- Explanatory table added about the used weights in chapter 5 [page 72]
- Conclusion of chapter 5 rewritten [page 87]
- Reaction of the main stream user to being depriorititized explicitly mentioned [page 88]
1. Introduction

The topic of this thesis is situated on the field of urban mobility and traffic signal control. Traffic signal control in itself is an interdisciplinary field that lies between traffic engineering and control engineering. Both of these disciplines have their own tacit knowledge and it seems that the best solutions can be found using knowledge of both traffic and control engineering.

In the following this chapter will give a review on traffic signal control for the readers who are not familiar with the topic. It will also introduce the latest technology in this field the adaptive traffic signal control which is the topic of this thesis.

Chapter 2 will give the research framework with problem definition, the research question and the evaluation criteria. According to the problem definition of chapter 2 there are two distinct problems to be covered by this thesis. These two problems will be analyzed and presented separately in chapters 4 and 5.

Chapter 3 will give the results of the literature survey which was done to assess the current state of art in the field of traffic signal control. This chapter also covers the field of the two problems identified in the problem definition.

In chapter 4 the research results on the field of predicting platoon dispersion will be given. The best fitting model found in the literature survey was reproduced, fine-tuned and tested in a simulation environment.

Chapter 5 will give the research results on the field of coordination in an adaptive signal controller. The controller had two implemented coordination methods without any experience on the network performance of these measures. These methods have been compared and thoroughly tested. Performance and the best settings were found from which general conclusions could be drawn on the coordination of the multi-agent adaptive controller.

In chapter 6 the conclusion of the research and the thesis will be given. It will include the experiences and conclusions on the two problem identified in the problem definition of the thesis.

Figure 1.1. gives an overview about the structure of the thesis.
1.1. Traffic control

The science of traffic control has emerged as a reaction to satisfy the need of transportation during the 19th century when the number of participants in the traffic has drastically risen. At the same time also the speed of the participants increased significantly as a result of motorization.

The general problem is quite simple. Where two roads cross each other on a plane there is a part of these roads that overlaps. This overlapping area is called the conflict area. The conflict area can only be used by one user at the same time so it should be decided which user should use it when. To formulate the problem more scientifically it has to be found out how conflicting traffic streams can be separated from each other safely and with causing the least possible hindrance.

1.1.1. Traffic streams and their Dutch standard codes

In the Netherlands traffic streams are identified by a standard coding system. In this thesis the following codes will be used:

- 01 – 12: motor cars
- 21 – 28: bicycles
- 31 – 38: pedestrians
- 41 – 52: trams, buses and emergency vehicles (and sometimes taxis)
- 61 – 72: following streams
1.1.2. Separation of traffic streams

The aforementioned separation of traffic streams can be done in time or in space. Both solutions have been researched and used extensively at many places around the world.

Multi-level interchange:

The complete separation in space is to solve the problem in 3 dimensions instead of 2. Examples of this solution are the multi-level highway interchanges. Advantage of this solution is that it has huge capacity because conflicts are simplified to merging and diverging movements. On the other hand the disadvantage of this is that it occupies large space and it is the most expensive solution.

Road-side traffic signs:

Separation in time can lead to two distinct solutions. The first one is to use road-side traffic signs that indicate the right of way for the traffic participants. According to the rules shown by the signs users can determine whether they can enter to the conflict area or have to wait. This is an error prone process because the users have to make a decision during limited time, which leads to lower capacity usage or in a worse case to safety issues. On the other hand this is the cheapest solution.
Traffic signal control:

Another solution for separation in time is to determine in advance at what time which traffic streams can use the conflict area and indicate this with a signal instead of letting the users determine it on their own. With this central approach the error prone process of human decision making in a short time is avoided. A disadvantage of this solution is that it needs extra equipment at the intersection that makes it more expensive especially at rural locations where a power supply is not present.

Roundabout:

Roundabout is a solution that uses separation in time and space at the same time. It uses fixed right of way rules as separation in time but the conflict zones of different streams are separated from each other in space. This makes the decision making easier for the drivers who do not have to divide their attention between various directions. Its advantage is that it is relatively cheap but it occupies large space and has limitations in capacity.

1.1.3. Urban traffic control

The urban environment in traffic control has different conditions and challenges than the rural. The population density is high which induces large traffic volumes. The origins and destinations or points of interest are much closer to each other therefore the network is significantly denser than in a rural network. Another challenge is that in a downtown area space is limited. It is also true that because of the large population density, inhabitants live closer to the roads where emissions are emitted by the traffic. Because of this traffic emission is a problem on the local level and considered as a health risk, not on a global level, like CO₂ emission of highway traffic.

In the previous section the possibilities for separation were shown. But there is no ultimate solution that out performs the others under any condition. In an urban environment because of the new conditions and challenges the possibilities are limited and not all of them are feasible. Usually there is not enough space for the traffic control to be able to implement separation of traffic streams in space. Therefore the common solution for the traffic control is separation in time: the road-side traffic signs for low traffic demands and traffic signal control in case of large demand roads.
1.2. **Macro and microscopic approach of traffic signal control**

As it was shown in the previous section that the common solution for urban traffic control is the traffic signal control. This control method still has two distinct approaches. These two are the micro and macroscopic approach. First a brief introduction will be given about traffic signal control then these two approaches will be explained in the following.

1.2.1. **Traffic signal control**

Traffic signal control was mentioned earlier as an option for separation of conflicting traffic streams in time. It was also mentioned that traffic signals are provided to the different traffic streams and it is decided in advance which stream should use the road when.

In most of the cases nowadays the aforementioned decision is made on the basis of the demand on the certain traffic streams. The intersection geometry can be designed to provide enough capacity for the traffic demand that was forecasted. After having the intersection geometry and capacity this capacity can be split among the conflicting traffic streams. It was mentioned earlier that traffic signal control separates conflicting streams in time, so the split of capacity is basically time splitting.

1.2.2. **Macroscopic approach**

The macroscopic approach looks at traffic as if it would be continuum system with really small particles like water molecules in a pipe. It tries to build models using assumptions based on the aforementioned examples.

According to this assumption the time between the different streams can be split up and a cycle can be created. When certain streams are following each other safety issues have to be taken into account. For this reason a certain time gap has to be maintained between the end of one stream and the beginning of the next one. This time gap differs according to the traffic stream and the geometry of the intersection. When the cycle is determined it is usually optimized to keep the necessary time gaps (the unused capacity) to the minimum.

If more intersections follow each other on an arterial a new factor has to be taken into account. It is beneficial to provide green to the large streams at the following intersection and
keep their waiting minimal. This can be achieved via using an offset value (the time used by the cars to reach the downstream intersection) between the intersections. As it is visible in the macroscopic approach a signal plan consists of basically three variables the splits, the cycle time and the offset.

1.2.3. Microscopic approach

In a microscopic approach the current traffic data can be taken into account so the signal plan is made real time for the current situation. The computational needs of this approach are much higher because it has to take into account the single vehicles with their own different features like speed or headway. This more sophisticated approach can reduce the following inefficiencies.

Problem of simplification:

The simplifications of the macroscopic approach make the modeling of traffic and the calculation necessary for traffic control simpler. On the other hand it assumes that the particles of traffic (the vehicles) and the traffic lane these particles are driven through has similar rate of size to the previous example, where the particles were water molecules in a pipe. In fact the problem is that the vehicles in the traffic are comparable in size to the traffic lanes unlike in case of water molecules and a pipe. It is also true that because of the large size and small number of the particles we can control them independently.

The aforementioned simplification makes calculations and traffic control easier but on the other hand as it usually happens, simplification leads to inefficiencies. The microscopic approach does not use the simplifications that were used in the macroscopic approach. It handles vehicles independently and takes into account the fact that the headways between the vehicles are different. This makes the microscopic more efficient.

Problem of historical data::

It was mentioned about the macroscopic approach that the variables used there can be determined in advance. For this reason historical data are used. The problem with using
historical data is that the variability of traffic variables is quite high. This can be avoided to a certain extent by creating multiple signal plans for different days of week and times of day. But the variability is high on a second by second basis also and this cannot be compensated with any measure. According to this it is visible that the macroscopic approach gives a perfect solution for an average situation, but the difference between the average and the current situation causes inefficiencies.

On the other hand using the microscopic approach a new problem arose with real time creation of signal plan: the decision and the signal plan is necessarily short sighted because of the limited prediction horizon. Although Helbing and Lämmer [2] still state that it is better to provide a 95 % right solution for the current traffic situation than a perfect for the average one.

### 1.3. Three types of adaption of signal control to traffic demand

In the following a short introduction will be provided to the possibilities how the signal control can be adapted to the actual traffic demand. These three types are: (i) the fixed time control, (ii) the actuated traffic control, and (iii) the adaptive traffic control. These types have a strong relation with the aforementioned macroscopic and microscopic approaches of traffic signal control. In the first type only fully macroscopic approach can be used with fixed time control. In case of actuated control some microscopic features of traffic can be taken into account. Using an adaptive traffic control a fully microscopic model can be used. This will be explained in the following.

#### 1.3.1. Fixed time control

In case of fixed time traffic control the three variables (cycle time, split and offset mentioned in section 1.2.2) are calculated in advance. These are based on historical data. To adapt the program of the controller for the different traffic states that hold for a longer time, like the morning and evening peak, different programs can be created. These different programs alternate according to the time of day.
The system does not use any current data from the traffic. Because of these features the system is simple and relatively cheap. However the lack of adaption leads to inefficient capacity usage, like giving green to traffic streams on which there are no cars at the moment.

There is another serious problem with this system. The traffic demands change in time, usually grow from year to year. It also can happen that new points of interest (origins or destinations) are built around the intersection and these change the distribution of the users among the traffic streams. The system is totally rigid to these changes. This leads to inefficient capacity usage therefore extra delay. According to Robertson and Bretherton [3] the aging of a signal plan causes 3 % extra delay every year.

This traffic control necessarily uses the macroscopic approach in traffic control because it does not have any data on the single vehicles approaching the intersection. This makes any microscopic consideration impossible.

1.3.2. Actuated control

Actuated traffic control was the answer to the flexibility problems of the fixed time control by traffic engineering. It is using loop detectors built in the road surface to detect the cars through magnetic induction. This detection makes it possible to use data based on the current traffic state. The system is still using a pre-determined signal plan, fixed sequence and is still cycle based. It uses the loop detectors to make changes in the signal plan to a certain extent according to the vehicles present at the different streams. These changes can be for example (i) omission of a phase or traffic stream if no waiting vehicles are present or the infrastructure downstream is blocked. The changes also include (ii) earlier realization of green if there is no demand on conflicting streams. It can also (iii) extend green until the saturation flow of the stream is high enough or the maximum time limit is reached. The changes also include the (iv) possibility of cutting off the current green because a prioritized vehicle (e.g. public transport or emergency vehicles) is approaching the intersection.

This system solves numerous problems that the fixed time control had, and performs much better on the traffic network. On the other hand it only makes short term changes in the signal plan. The aging of signal plan is still negatively affecting the efficiency to some extent.
Because of the previously made signal plan actuated traffic control uses a macroscopic approach, but in case of the decisions to change the signal plan it takes into account the single vehicles like in case of the decision to extend the green phase or not.

1.3.3. Adaptive control

Adaptive traffic control is the latest solution in the field of traffic signal control. It changes from system to system but usually uses the same detection data as the actuated control. The main difference between the adaptive and actuated system is that adaptive systems gather information using all the sensors both on the currently active streams and on those which are having red light at the moment. Using this information the adaptive systems optimizes continuously the signal plan according to the built in optimization criteria.

Earlier when the computation capacity was lower, adaptive traffic control used also a macroscopic approach like in case of the first and one of the most wide spread systems, the SCOOT system [3]. Nowadays the computational capacity is high enough and a totally microscopic approach can be used. This makes possible in case of the adaptive controllers to follow the microscopic approach that is impossible in case of the aforementioned fixed time or actuated controllers. This is the case because the microscopic approach can only be used if the controller has real time data on the single vehicles.

Experience of the implemented adaptive controllers show that the flexibility and adaption to the current traffic state even using the macroscopic approach lead to significant improvement in network travel time and delay reduction. An adaptive traffic control system that uses the microscopic approach can reduce delay or traffic emissions even further. This reduction comes from the fact that not the conflicts of the different traffic streams are taken into account anymore but the conflicts of the single vehicles.
1.4. Coordination of intersections

After the invention of signal control it was soon recognized that large benefits can be gained on network the level if the control of the different intersections is coordinated. This means intersections on an arterial do not stop the vehicles driving through the system multiple times, but only once at the first intersection. Using coordination the both the delay of the users and the number of stops can be reduced.

In this chapter a brief review was given on the background of traffic signal control that was necessary before giving the research framework that is the point of the next chapter.
2. Research Framework

After having a brief introduction to the field of traffic signal control and the adaptive traffic controllers the research framework can be shown. In this chapter first the problem definition will be given that explains what the exact traffic problem is that this thesis is searching a solution for. After this the relevance of the research will be given: why it is important to pay attention to this traffic problem. When the traffic problem is known the research question will be given that helps to keep the research on the right track. The chapter concludes with giving the evaluation criteria that will be used to evaluate the results.

2.1. Problem definition

Now we have an overview on the field of traffic signal control with special attention on adaptive control (using a microscopic approach). It is visible that these new emerging techniques have huge potential in making traffic control more efficient. The reason is that such a controller can take into account the headway differences and different features of the different vehicles. It will be shown in chapter 3 that there is some contradiction in different research papers about how coordination is possible in adaptive traffic control systems. These two reasons led to the decision to choose the field of adaptive traffic signal control and the network behavior of such a control method as the main research topic for this thesis. The adaptive controller of van Katwijk [4] that will be introduced in section 3.1. was the main tool and the test bed of the research.

This controller has good results in independent intersection control. Details can be found in table 3.1. Because of its good performance both in delay reduction and capacity increase it outperforms actuated controllers on network conditions as well. Further details can be found in section 3.1.3.2. On the other hand according to van Katwijk [4] there is still room for improvement which concerns three distinct fields.

These three fields are:

- Uncertainty of the upstream signal plan
- Inaccuracy of the predicted arrival pattern to the downstream intersection
- Unknown arrival pattern on the side streams
1. **Uncertainty (of upstream signal plan):**

Uncertainty of the upstream signal plan is an issue on the field of adaptive traffic control that was analyzed thoroughly by van Katwijk during his research when the structure of the controller was created. For this reason this source of possible inefficiency will not be further analyzed in this thesis.

2. **Inaccuracy (of the predicted arrival pattern):**

Inaccuracy basically covers the field of platoon dispersion. The phenomenon of platoon dispersion means that vehicles departing from an upstream source will not have the same time headway at a downstream detection point that they had upstream. In case of traffic signal control the upstream source is the signal head of the upstream intersection. The downstream detection point is the signal head of the downstream intersection. Between these two points the time headway changes. This change causes inefficiencies in the signal control of the downstream intersection like too early green realization or unnecessary extension of green phase. Further details about the literature survey on platoon dispersion can be found in section 3.3. This topic has high importance therefore it will be part of the research. Further details on the solution can be found in chapter 4.
3. **Unknown (arrival pattern on the side streams):**

Unknown arrival pattern on the side streams is a real challenge in a look-ahead traffic signal controller. On the side streams of an arterial there may be no traffic signals present upstream therefore it is impossible to get faraway detection data from the detectors of those. Placing faraway detection is also a problem because it has high costs especially if there is no power supply present further away from the intersection. Because of the aforementioned problems of detection on the side streams, other methods have to be searched to overcome the problem of asymmetrical (more information on the arterial than on the side roads) information set. There are two possible solutions for this problem:

- Predicting the unknown arrivals
- Providing time in the signal plan for these arrivals

In this thesis the second option will be followed. This means that the main streams of the arterial are stopped at the first intersection. Therefore the controller has time gaps without incoming traffic on the main stream. During this time it can serve vehicles arriving at the side streams and detected only few seconds before the arrival at the stop line. In the following an example will be given how the communication between the controllers can be beneficial on a network level.
2.1.1. Example of sub-optimal performance

We have a network with an arterial in East-West direction with large amount of eastbound and westbound traffic. There are two side roads (North-South) with relatively small amount of traffic.

Traffic conditions:

- The east and westbound traffic streams have so large demand that there are always cars on the arterial but capacity is not reached. Because of the larger number of users on these main streams the delay that would be caused by the controller to the main stream users is always higher than to keep the cars on the side roads waiting.
- One-one car is arriving on both of side roads. (North-South)

In the original case without communication about the signal plan between the intersection controllers neither the first nor the second intersection will schedule green time for the cars waiting on the side streams. In case there is communication, given the fact that the saturation
flow is low (at least it is under the capacity of the arterial) on the main stream, red light can be
given intentionally to the users to platoon them. With such a temporary gap on the main
stream both of the downstream intersection can serve the cars waiting on the side streams
using the same time gap. This strategy on a network level can lead to lower delay than in the
original case. Further details can be found in [4 (section 5.3.3)].

2.2. Relevance

It is hard to find the exact relevance of a single element or feature of a system when the
system is still operational without it. On the other hand in section 2.1. it was shown that there
are further possibilities to improve performance of the adaptive traffic control and the
controller of van Katwijk [4] on the field of network coordination. If the added extra element
is increasing the efficiency of the whole system then to some extent all of the benefits of the
whole system are benefits of the added extra element or feature. For this reason first the
benefits of the whole system will be shown. In the end of this thesis benefits of the better
network performance will be given using the same framework.

2.2.1. Cost-benefit analysis

The best way to compare effects that have different measurement scales is to compare them in
terms of money if these can be converted to money. This is the reason why the research will
be supported by a small cost benefit analysis.

General remarks:

- Because of the fact that data found about the implementation costs were from the
  United States the whole cost benefit analysis is done on the basis of U.S. data.
- The time horizon of 10 years was used because the source of U.S. Department of
  Transportation Research and Innovative Technology Administration suggested 10
  years as life cycle for a traffic signal controller. [6]
- The effects of any other emission than CO₂ is omitted from the analysis because these
certainly have an effect on the health and living environment of people but the relation
  is indirect and too complex to be examined in this thesis.
Results of the different controllers used in the analysis were the result of VISSIM computer simulation using the Assen network of 5 intersections. Further details can be found in the appendix. The actuated controller was provided by PEEK Traffic n.v. and is installed in reality on the site. The adaptive controller was provided by TNO and it is the controller of van Katwijk [4] without any measures of coordination between the intersection controllers.

<table>
<thead>
<tr>
<th>Building &amp; Operation Costs</th>
<th>Actuated traffic control</th>
<th>Adaptive traffic control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation cost detectors</td>
<td>$10,000.00</td>
<td>$22,000.00</td>
</tr>
<tr>
<td>Adaptive controller</td>
<td>$-</td>
<td>$50,000.00</td>
</tr>
<tr>
<td>Update signal plan</td>
<td>$750.00</td>
<td>$-</td>
</tr>
<tr>
<td>Maintenance personnel wage</td>
<td>$1,866.67</td>
<td>$1,866.67</td>
</tr>
<tr>
<td>O&amp;M Total yearly</td>
<td>$2,616.67</td>
<td>$1,866.67</td>
</tr>
<tr>
<td>Annuity factor 10 years</td>
<td>7.72</td>
<td>7.72</td>
</tr>
<tr>
<td>Total O&amp;M</td>
<td>$20,203.28</td>
<td>$14,412.53</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For 5 intersections**</td>
<td>$-151,016.42</td>
<td>$-432,062.67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation Benefits</th>
<th>Actuated traffic control</th>
<th>Adaptive traffic control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stops/user*</td>
<td>0.601</td>
<td>0.309</td>
</tr>
<tr>
<td>Number of stops on network/year</td>
<td>2678056</td>
<td>1376904</td>
</tr>
<tr>
<td>CO2 emission of cars per stop [grams]</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>CO2 emission of trucks per stop [grams]</td>
<td>259</td>
<td>259</td>
</tr>
<tr>
<td>Average CO2 emission difference [grams]</td>
<td>60,06</td>
<td>60,06</td>
</tr>
<tr>
<td>Extra CO2 emission because of stopping [tons]</td>
<td>161</td>
<td>83</td>
</tr>
<tr>
<td>Price for CO2 on world market [$/ton]</td>
<td>$20.00</td>
<td>$20.00</td>
</tr>
<tr>
<td>Total yearly extra CO2 emission cost</td>
<td>$3,216.88</td>
<td>$1,653.94</td>
</tr>
<tr>
<td>Average fuel consumption difference [liters]</td>
<td>0.0254</td>
<td>0.0254</td>
</tr>
<tr>
<td>Extra fuel consumption yearly [liters]</td>
<td>68112</td>
<td>35019</td>
</tr>
<tr>
<td>Fuel price</td>
<td>$0.83</td>
<td>$0.83</td>
</tr>
<tr>
<td>Total yearly extra fuel consumption</td>
<td>$56,840.71</td>
<td>$29,224.26</td>
</tr>
<tr>
<td>Annuity factor 10 years</td>
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<td>7.72</td>
</tr>
<tr>
<td>Total total fuel emission costs</td>
<td>$-438,867.14</td>
<td>$-225,640.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Actuated traffic control</th>
<th>Adaptive traffic control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of time</td>
<td>$15.60</td>
<td>$15.60</td>
</tr>
<tr>
<td>Average delay per user [seconds]*</td>
<td>22.18</td>
<td>12.15</td>
</tr>
<tr>
<td>Number of users</td>
<td>11140</td>
<td>11140</td>
</tr>
<tr>
<td>Travel time loss per year [hours]</td>
<td>27454</td>
<td>15039</td>
</tr>
<tr>
<td>Travel time loss in matters of money</td>
<td>$608,927.75</td>
<td>$234,608.40</td>
</tr>
<tr>
<td>Annuity factor 10 years</td>
<td>7.72</td>
<td>7.72</td>
</tr>
<tr>
<td>Total travel time loss in $</td>
<td>$-4,701,531.15</td>
<td>$-1,811,411.46</td>
</tr>
<tr>
<td>Total social cost</td>
<td>$5,291,414.70</td>
<td>$2,469,114.63</td>
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<tr>
<td>€4,025,420.09</td>
<td>€1,878,367.92</td>
<td></td>
</tr>
<tr>
<td>Total Saving</td>
<td>$2,822,300.07</td>
<td>€2,147,052.16</td>
</tr>
</tbody>
</table>

Table 3.1. Cost-benefit analysis of adaptive traffic signal control

*Simulation result;

**The test network used consisted of 5 intersections;
Installation costs:
The installation costs of the adaptive controllers and detectors were published by HDR Inc. based on real implementations of adaptive controllers. It was taken into account that the adaptive controller using a distributed structure and faraway detection (unlike the others in the original analysis) has a higher cost per intersection. Therefore it was set to $50,000 instead of the average $35,000.[5]

Installation cost for the adaptive controller is based on the U.S. Department of Transportation Research and Innovative Technology Administration data.[6]

$CO_2$ emission of trucks and cars per stop:
Depending on the traffic stream at the intersection the difference in $CO_2$ emission between stopping and driving through without hindrance varies. In this table the emission difference of through going streams have been taken into account based on simulation results. Further details can be found in table 3.4. of an earlier master thesis at TNO.[7]

$CO_2$ price on world market:
According to the Kyoto Protocol in 1997 countries have a certain amount of $CO_2$ that they can emit to the atmosphere. On the basis of these limitations countries and companies started to trade these emissions. Although the United States have not signed the protocol therefore the price should not be applicable in this case it was taken into account to get a better insight. The price is very volatile because of the current economic crisis therefore an earlier price was used.[8]

Fuel consumption difference:
In case of fuel consumption using the base data of $CO_2$ emission a conversion was done to extra fuel consumption per stop. For this conversion data of the U.S. Environmental Protection Agency was used.[9]

Value of Time:
For the VOT value a document of the U.S. Department of Transportation was used as a guideline.[10]
From this analysis a few interesting conclusions can be drawn. There is one indicator the benefit through time gain that outweighs the benefit in fuel saving by 4-6 times and CO\textsubscript{2} emission reduction by 80-120 times. This will be taken into account in section 2.4.

Another interesting consequence is that adaptive traffic control can reduce the social cost of transportation to a large extent. As it was mentioned before any further improvement in performance of the adaptive controller (like better coordination that decreases delay) adds extra benefits without any cost. Taking into account these consequences the research on this field can have a large added value.

### 2.3. Research question

The research question itself is important to keep the research on the right track. For this reason it has to tackle the main problem of the research that has to be solved so the question could be answered. In this case the following research question was formulated:

The main research question is:

- What are the benefits of coordinating the intersection controllers in the multi-agent look-ahead traffic-adaptive control system in reduction of average delay of the users on the network?

We cannot talk about coordination in a multi-agent system in the same way as in fixed time or actuated systems. In the multi-agent look-ahead traffic-adaptive control system there is no cycle time therefore coordination using an offset value is impossible. For this reason in the following in this thesis by coordination the possible methods will be mentioned that can induce more efficient (in means of delay reduction) network behavior. The average delay of users is chosen as the main evaluation criteria because it was shown in section 2.2. that this is the most important element of the total social cost of transportation. The number of stops will also be taken into account as a secondary criterion. Further details are in section 2.4.
The sub-questions are:

- What is the effect of platoon dispersion on the arrival pattern at an intersection and how can this effect be taken into account or avoided if vehicle platoons depart from an upstream intersection?

- How can coordination be realized for the two main streams of an arterial at successive intersections so that the average delay of the users on the network is minimized, if the position of vehicles is known on the network further upstream of the intersections?

As shown in section 2.1, the arrival pattern is important information needed to give a good signal plan. Such information used in the signal plan reduces inefficient usage of green times like giving green earlier than necessary. The first research sub-question is searching an answer for the problem mentioned as inaccuracy in the problem definition. Details and the answer to this research sub-question are found in chapter 4.

The second research sub-question tackles the real weak point of the controller. Despite this the controller of van Katwijk [4] still outperforms to actuated coordinated traffic control although it is a totally distributed system. According to the literature survey provided in section 3.2.2, it is possible to achieve coordination in a distributed system. The example of section 2.1.1 showed that doing so can reduce the average delay of the users on the network.

According to the cost-benefit analysis of section 2.2.1, it is beneficial for society to find a solution for this problem. On this basis the research was started and its results can be found in chapter 5.

### 2.4. Assessment plan

After knowing the research questions some details have to be given about the evaluation: on what basis the results will be evaluated. This is necessary to be defined before the research to have an unbiased evaluation of the results.

It was mentioned in the research question that all the users on the network are taken into account in the evaluation. This means that all the traffic streams at all the intersections have to be measured on the network. Separate analysis of the different streams can be conducted to
find out the effect of the different measures but final results will be measured on the basis of all the users on the network.

2.4.1. Evaluation criteria

Parameters that will be used as evaluation criteria:

- Travel time and delay
- Number of stops

In section 3.2.1. it was proved that this feature is the most important concerning the social cost of transportation. Therefore the main evaluation criteria of the research are delay and travel time. Delay is a better indicator than travel time in the means of showing the difference between the different scenarios or control measures. However travel time shows more information about to what extent the different measures influence the real life of the users.

When the user’s average delay is considered as main criteria it means that the focus is on the vehicle delay. Public transport prioritization is already an included feature in the adaptive controller and therefore out of the scope of this thesis. It has to be mentioned that in the adaptive controller of van Katwijk because of flexibility and missing sequence, public transport prioritization does not cause large delay for the other streams as in case of fixed time or actuated traffic control.4

The number of stops is also an interesting indicator. Emission reduction is not a main point of this project and number of stops affects only fuel usage and emissions directly. It was shown in section 3.2.1. that the fuel usage and CO$_2$ emission are outweighed in means of social cost by the time loss of people. There are other emissions of traffic that were not included to the cost-benefit analysis but still depend on the number of stops and low speeds like emission of small particles or NO$_x$. These emissions certainly have their effect on the living environment and the health of people through air and water pollution. On the other hand these are much harder to be taken into account because of their secondary or indirect effects. The relation between traffic control and these emissions is indirect. The aforementioned points could alone fill many MSc. theses and the point of this thesis is not finding a price for the emissions.
Therefore the number of stops will be taken into account as a secondary criterion that is still measured but it is only taken into account if the decision on the basis of delay is not clear.

Queue length is also an important indicator. On the other hand it is mainly important because if queue length is larger than the length of turning lanes it leads to extra and unnecessary hindrance of vehicles. Therefore queue length will be only used as a boundary condition to avoid spillback effects that would anyway lead to an increase in delay too.

2.4.2. Alternatives

Alternatives that are compared in the evaluation:

1. Network with actuated coordinated traffic control;
   This scenario is mainly used as a reference case to have an insight how much the adaptive traffic control in itself can decrease on the delay of users compared to the current traffic control methods.

2. Network with adaptive traffic control without coordinating the intersection controllers;
   Shows how adaptive traffic control performs on the network and what are its benefits compared to the coordinated actuated controller. This scenario will be used also as a reference case to compare the different coordination strategies to the original controller to see the advantages and disadvantages of such strategies.

3. Network with adaptive traffic control with different coordination measures between the intersection controllers;
   These scenarios will show how the different coordination measures perform and how much benefit can be gained from these measures.

The evaluation is based on the output files of VISSIM microscopic traffic simulator. From these files data is used both on an aggregated level and detailed level.
3. Literature Survey

After the having the problem definition and research question the literature survey could be started to find supporting knowledge on the professional literature.

In case of this research the first part of the literature survey was to get acquainted with the traffic adaptive signal control and the controller of van Katwijk[4] that was used during the whole research. It also included reviewing other traffic adaptive signal control systems.

After having knowledge of the adaptive signal control and the currently existing systems, the scope was narrowed down to the field of coordination. In the problem definition two problems were identified on the field of network performance in case of the controller of van Katwijk. [4] According to the two problems identified in the problem definition the following part of the literature survey can be divided into two parts: (i) network coordination and (ii) platoon dispersion.

In the following this chapter will give a review of the literature survey and of what was found. At the end of the chapter a conclusion of the literature survey will be given.

3.1. Traffic adaptive signal control

In this section further introduction will be given to the traffic adaptive signal control. It will include a brief introduction to the multi-agent systems: what the term means and how can these systems used in traffic control. It will also include information on the controller that was developed by van Katwijk (2008) [4]. This is the controller used during the research and one of the goals of the thesis is to develop the system further at certain areas.

3.1.1. Examples of adaptive traffic control systems

Several traffic adaptive controllers exist around the world. In this short summary only a brief review is provided about the most important systems. This is necessary to get an insight into the general picture about traffic adaptive control. Other systems are mentioned because they follow a new and sometimes quite different approach.
SCOOT:

The Split, Cycle and Offset Optimization Technique (SCOOT) [3] system is one of the first and most widespread systems on the field of adaptive traffic control. The core idea behind the method is from the times when the computational capacity was only sufficient to follow the macroscopic approach of traffic control. The system is optimizing in real time the 3 macroscopic input parameters (split, cycle time and offset). Because of the macroscopic approach the computational needs of the system is not high which makes the usage of a centralized approach possible. During operation the system optimizes a fixed time signal plan to adapt it to the current traffic demand. This is done on a gradual way to avoid overreaction to the effects of changing traffic situation. This happens more often in case of systems that are choosing from different fixed time plans. Further information to be found in [3,4].

Neural network based approach:

Neural networks are useful tool in general problem solving. The neural network of the human brain gave the idea to create artificial neural networks. In an artificial neural network neurons are arranged in layers interconnected with each other. The network is able to learn from feedback information. According to the difference between the predicted and the real outcome the interconnection weights can be updated[11].

Such a network is typically defined by three parameters:

- The interconnection between the layers
- The learning process: how to update interconnection weights
- The activation function that activates the neuron to convert its weighted input to output

In Singapore a neural network based control system was tested in computer simulation. This system seems to be more robust compared to a current implementation of SCATS traffic adaptive controller in Singapore due to its learning abilities. Tests were carried out in quite extreme traffic situations like several peak periods following each other in short time. This situation does not happen often in reality but the learning ability is still an interesting idea.[12] Despite the rather extreme traffic situations the learning ability of neural networks proved to be a valuable tool also in traffic engineering. It is a completely new approach which
can be useful in real time optimization problems like the adaptive traffic control itself. Further details to be found in [11,12].

**RHODES:**

The RHODES (Real-Time Hierarchical Optimized Distributed Effective System) [13] developed in the United States. It is a system using faraway detection and a predictive optimization on a three level hierarchical framework. The optimization is done through dynamic programming. The design of the controller is based on dividing the main complex problem into sub-problems which are then solved on different levels of the controller. On the top level the system solves a network load problem. On the middle level a network flow problem is solved and on the lowest level the intersection control is done. Every level is giving boundary conditions for the lower levels. Within these the lower level optimization can be done. Further information to be found in [4,13].

**PAMSCOD:**

PAMSCOD [14] was developed partly by the same authors as the RHODES system. In the design of this system extra attention was paid on the identification of platoons in the traffic flow.

Vehicle platoons are a set of vehicles following each other with a relatively small headway. In the article the authors defined this headway as two seconds, so if the headway between the vehicles is smaller than 2 seconds they are considered to be part of the same platoon.

The attention on platoons are important because by definition the larger the number of vehicles the more they influence the system performance. Platoons are also important because the saturation flow inside the platoons is high. The higher the saturation flow the less time is needed for the vehicles to drive through the conflict area. An interesting and important idea is also the prioritization of moving platoons over standing queues. This is supported by the idea that the saturation flow of platoons is higher than a standing queue after the start and acceleration. This statement however contradicts with the theory behind platoon dispersion in 2.3. section. Further details to be found in [14].
3.1.2. The multi-agent approach

It was mentioned in the previous chapter that the microscopic traffic control (taking into account the features of single participants) looks at the conflicts of the vehicles instead of traffic streams. This can improve efficiency of traffic control and reduce delay. It was also mentioned that the price of this improvement is the large computational need of such a controller. On the other hand a microscopic controller needs to create a signal plan in real time to use the full potential of the approach. The problem on a network level becomes too complex to solve it centrally in real time because of the large number of cars on the network. Another problem is the interaction between the traffic signals: how are the controllers affecting each other’s input. These problems together led several researchers to come up with a new decentralized approach for traffic control.

The multi-agent systems have a decentralized approach of problem solving that makes them a possible tool in traffic control knowing the aforementioned limitations of the earlier centralized approach.

These systems have three key characteristics; [15]

- **Autonomy**: the agents are (at least partially) autonomous
- **Local views**: no agent has a full global view of the system or the system is too complex for an agent to make practical use of that knowledge
- **Decentralization**: there is no designated agent (or the system is effectively reduced to a monolithic system)

The multi agent approach in traffic control means that every intersection is an agent on the road network that is acting according to its own interest independently of the others. The interest of the agents is to minimize the hindrance between the users of the different traffic streams. This is done by the optimization process of the agents. Such an optimization can take into account the delay, number of stops or even CO₂ emission as type of hindrance between the different users.
3.1.3. The Multi-Agent Look-ahead Traffic Adaptive Controller

At TNO and TU Delft (Netherlands Organization of Applied Scientific Research) the multi-agent look-ahead adaptive controller was developed by van Katwijk (2008) [4]. Its main features compared to an actuated controller are:

• The entire intersection is taken into account and not only the currently active green phase;
• The decision is based on a longer term analysis than the actuated signal control using information from further upstream i.e. looking to the next 120 sec;
• Have a flexible sequence of green for different signal groups;

As its name shows it uses the multi-agent approach for traffic control that was introduced briefly in section 2.1.

The first point mainly shows the difference between the currently widespread traffic actuated controllers in the Netherlands and the adaptive controller. Actuated controllers can take into account and make a good decision based on the currently active green phase. On the other hand the adaptive controller has information about the number of vehicles waiting at the stop lines of the streams currently having red light because of faraway detection. Because of the aforementioned feature the number of arriving vehicles is also known.

The second point shows that the controller is capable of using faraway detection data. This means that if there is a detection point few hundred meters upstream, the controller takes into account the vehicles detected there by predicting the arrival time at the intersection and includes them in the signal plan. The detection upstream can be done using the upstream intersection’s loop detectors or (if these are not available because the lack of upstream intersection) newly placed detectors. There is also research going on to use historical data to predict the arrival pattern.

The faraway detection of single vehicles as a feature is new and was not seen anywhere else in this form during the literature survey. It has a huge benefit, it makes possible to extend the prediction horizon. This can extend the necessarily short sighted decision making of the currently used actuated controllers.

The third point means that there is no fixed sequence of green phases in the cycle; what is more there is no cycle in the system at all. There are just sets of non-conflicting streams to
which green light can be given if it is optimal from the systems point of view at the moment of decision.

### 3.1.3.1. Operation of the controller

The controller gets information on the current traffic state through its sensors: the loop detectors. From this information it can create an expected arrival pattern. When this arrival pattern is known on all of the upstream approaches the controller knows when cars will arrive on which streams. It also knows when and between which streams will conflicts occur. Knowing these it is possible to create a signal plan that causes the least hindrance for the all users approaching the intersection. The optimization of signal plan is done by dynamic programming in the controller. This results in a decision tree shown in Figure 3.1.

![Figure 3.1. Decision tree](image)

At every time step the controller will make a decision that will affect the delay of the users arriving at the stop line of the intersection. From every decision made the system gets into a new state and the controller has to make a new decision. So the decision tree grows one level every step. Fortunately this is not an infinite process because the time horizon limits the number of levels of the decision tree. The first decision from the path having the lowest cost is implemented at every time step.
The decisions then sent to the actuators, the signal heads of the intersection. Through these signal heads the controller can influence the state of traffic flow itself that was also used as the input. The closed loop of the control sequence is shown on figure 3.2.

![Figure 3.2. Operation of the controller][7]

The agents, so the intersection controllers of van Katwijk, are also capable of communicating with each other. Not only on a level that was mentioned before but also concerning data regarding the vehicles detected upstream. The agents are also capable of an iterative process through which they can harmonize the signal plans and come up with a signal plan that causes the least hindrance for the users of the two intersections together. Further details about the controller can be found in [4].

### 3.1.3.2. Results of the Controller on network level

In order to find out the network performance of the controller of van Katwijk computer simulation was done. As test bed the microscopic simulation tool of VISSIM product of the PTV A.G. [16] was used. The network used during the test is located in the Northern part of the Netherlands in the city of Assen. The actuated coordinated controller that was used as the reference case is the product of PEEK Traffic n.v. More information about the simulation environment and the network used can be found in the appendix.

Although the adaptive controller of van Katwijk is basically optimizing on a single intersection level it is clearly outperforming traffic actuated control in network capacity and in average delay of the users as well. Results show that the capacity of the test network increased with about 20% and the delay of the users reduced depending on the demand and optimization scenario by 30-50%. Results shown in Table 3.1.
### Table 3.1. Results of different scenarios[17]

*The system was partly oversaturated and some of the vehicles could not depart;*

**The two middle rows show the performance of adaptive controller in case of “Virtual Detection” that means the controller has constant knowledge on the vehicle position. It is an ideal but unrealistic case;**

On the row of time:

- Delay means average delay of vehicles in seconds on the whole network
- Stopd means the delay when the vehicle was standing at the network somewhere
- Stops means the average number per vehicle: when a vehicle had to stop on the network
- #Veh means the number of vehicles driving through the network (in case of normal demand it should be ~11000 in case of large demand it should be ~16000)
- HGV is the abbreviation used for Heavy Goods Vehicles

Further details about the results can be found in [17].

#### 3.1.4. Other systems that follow the multi-agent approach

Helbing and Lämmer [2] also used the decentralized multi-agent approach to design a traffic controller. In their design the controller also applies the microscopic approach and solves the conflicts of the single vehicles. The controller has two operational regime. The first regime is minimizing the delay of the users. The other regime aims to maximize the capacity of the
intersection in case queues start growing during using the first regime. This way the controller can avoid that the queues grow too large and cause spillback at the upstream intersection.

Later paper of the same authors [19] shows that the system was tested against the current actuated traffic control on a test network using the software tool VISSIM. On the test network which was an arterial in Dresden the results show that the average delay of the different types of users decreased significantly. Further details can be found in [2,19]

3.1.5. “Green waves” in adaptive traffic control

The article of Greenwood, Burdiliak and Trencafsky mentions spontaneous emergence of “green waves” in case adaptive traffic signal control. [18] These green waves are not result of the usual offset coordination like in case of fixed time of actuated signal control. In this case the vehicle platoons are created at the first intersection of the signal control. Sometimes these platoons are large enough to be prioritized later on when driving through the whole arterial. This seems to be logical because main streams are usually having more traffic than side streams. When an intersection controller detects that a large platoon is arriving, it will give the platoon green signal immediately when it arrives at the stop line. This is the best strategy if the controller tries to minimize delay of all the users. Even if the system is totally distributed, the emergence of these “green waves” shows a possibility to coordinate the independent intersection controllers in a totally distributed controller.

It is also true that these spontaneous “green waves” appear in other multi-agent systems, like the aforementioned controller of Helbing and Lämmer or the controller of van Katwijk. On Figure 3.3. these “green waves” are shown through the vehicle trajectories. Further details can be found in [18,19].
3.2. Coordination in traffic signal control

Usually the problem of coordination is not simple especially in case of old downtown areas where the distance of the intersections differ largely. It is also true that every intersection on a network has a different OD therefore the time splitting among the streams cannot be the same at the successive intersections. This leads to the following problem: a locally optimal distribution of green times (with respect to minimize delay) exists for all of the intersections but in most cases this is not the same as the globally optimal distribution that is needed for the coordination. Because of this coordination of the intersections on a network there is a tradeoff between the local (intersection) and the global (network wise) optima.

3.2.1. Coordination in fixed time and actuated control

As it was mentioned in section 1.3.1. in case of fixed time control the coordination of intersections on an arterial is done by adding an offset value. This is equal to the time difference between the intersections for the users on the arterial. A requisite for this is that the intersections need to have the same cycle time.

In case of actuated control the situation is similar. Coordinated actuated systems are using a common cycle time. Wardberg, Larsen and Jørgensen in their research paper reviewed the

Figure 3.3. Spontaneous “green waves” in controller of Helbing and Lämmer[19]
current state of art on the field of actuated traffic signal control. They state that coordination is not possible without having common cycle time on the whole system.[20]

In case of actuated control in the cycle there is a coordinated part for the green wave implementation and a not coordinated part for the other streams. The controller in every cycle when the coordinated part ends can use its detectors to modify its program slightly as it was written in section 1.3.2. At the end of the uncoordinated stages the controller has to return to the coordinated stage. This can be done with different force-off strategies. [4]

Further details about coordination in case of actuated and fixed time control systems can be found in [4,20]

3.2.2. Coordination in adaptive control

In case of the SCOOT system the coordination is done on the basis of common cycle time. This can be done because the system is using a centralized approach. As it was mentioned in section 3.1.1. SCOOT optimizes the split, the cycle and the offset. The split can be changed on the intersection level using the boundary conditions to maintain the coordination. Offset optimization is done for every pair of nodes to keep the best progression on the network. The cycle optimization is done on the basis of saturation level of the intersections on the network. Depending on this the common cycle time of the system can be changed. [3]

As it was mentioned in section 3.1.1. the RHODES uses a three level hierarchical approach. With respect to the boundary conditions of the upper levels the lower levels can make their decision to optimize the signal plan for the smaller parts of the network. [13]

In case of multi agent systems the case is a little bit different. These systems do not use a common cycle anymore, so there is no common basis on which the coordination could be maintained. It was mentioned earlier in 3.1.5. section that spontaneous “green waves” emerge in these systems too. According to Lämmer and Helbing [2] it is impossible to implement any coordination method in such a system because the output of the signal plan will later on influence the vehicle input of the intersection. For this reason they have not built in any kind of coordination into their system.
On the other hand van Katwijk has built coordination into his system. Through his method the neighboring intersections can optimize their signal plan together to minimize the delay of the users on the two intersections together.[4]

According to Oliveira and Camponogara [27] the main problems of coordination are: (i) the dynamic nature of the problem, (ii) the large network size, (iii) the intrinsic complexity of the problem (like that the controllers effect their own later input) and (iv) the nonlinear behavior. The authors also state that in their article: Theoretical results ensure the convergence of the distributed iterations to a globally optimal solution. This statement is in contradiction on the statement of Lämmer and Helbing [2]. On the other hand it is in line with the findings of van Katwijk [4] Further details can be found in [2,3,4,13,27].

Based on these contradictions section 5.1. will give details about the found possibilities of coordination in the controller of van Katwijk.

3.2.3. Similarities of route choice problem and network coordination problem

According to Bovy, Bliemer and van Nes [28] there are two equilibrium states exist for route choice problem depending on the equilibrium definition: (i) the user equilibrium and (ii) the system optimum.

- The user equilibrium assignment leads to an equilibrium in which no traveler can improve his travel time by unilaterally changing routes.
- The system optimum assignment leads to the system state in which the total travel costs on a network is minimized.

This problem show similarities with the network coordination where a part of the network (one intersection controller) optimizes its own performance or the network performance is optimized by multiple controllers.

3.3. Platoon dispersion

Special attention is paid to platoon dispersion because this phenomenon is one of the problems that the research sub-questions tackle. In the following it will be shown how platoon
dispersion works and how it is possible to predict its effect. The measure of speed advice will also be introduced that reduces the effects of platoon dispersion.

The phenomenon of platoon dispersion is already known for quite a long time for civil engineers. The main phenomenon is that when a queue departs from stand still at a stop line of a traffic signal the cars have a relatively high saturation flow. When the platoon arrives at a stop line of a downstream intersection the arrival pattern is significantly different from the departure pattern. As the platoon is progressing downstream because of the (i) differences in desired speed, the headway between the vehicles starts to grow. Another effect is that the (ii) drivers try to keep larger safety distance (headway) than that they had just after the departure from the stop line. This second effect also makes the headway larger. There is a third effect that is called (iii) platoon decay by some authors. [21] This is caused by the vehicles driving in the platoon leaving the arterial at the intermediate intersections, and cars that are arriving on these intermediate intersections and join the flow of the arterial. The leaving vehicles cause that the saturation flow of platoons decrease. The newly arriving vehicles typically join the flow of the arterials in times when there are no platoons present mainly in the time gaps between platoons.

Figure 3.4. shows the effect of platoon dispersion on the arrival pattern at the downstream intersection. Further details in [21].
3.3.1. Probabilistic approach

The effect of platoon dispersion is usually tried to be tackled with a probabilistic approach. This means that using geometrical distribution a smoothing factor is calculated. This variable takes into account the distance of the two observation points through travel time. Seddon [22] suggested an improvement is his article to this probabilistic approach.

Bonneson, Pratt and Vandehey [21] in their article based on extensive field measurements in the United States also made further improvement on the basis of the method. Based on the measured data they built and calibrated a model using this probabilistic approach. With these improvements they reached more accurate prediction of the arrival pattern than the original geometrical approach used in the TRANSYT method earlier.

However the probabilistic approach is simple and easy to implement even in real time traffic control it has its certain limitations. It cannot take into account the speed changes of the platoon. Because of this prediction of arrival pattern based on measurements of the stop line detectors are less accurate than field tests on straight road segments without significant change in speed. This model was tested for implementation to the control program. Detailed equations of the model is presented in section 4.1. where the comparison is given with the earlier prediction method Further details can be found in [21,22]

3.3.2. Neural network based approach

Neural networks were introduced in section 3.1.1. as a powerful problem solving method. Qiao, Yang and Lam [23] built a method in which they used neural networks for predicting the arrival pattern of vehicles using the upstream detection data. The model was tested against the probabilistic prediction methods (both normal and geometrical distribution) on real world test site. The performance of the neural network approach was clearly better than the probabilistic ones. However the test site with its 85 meter length seems quite short especially in the light of the conclusion of chapter 4 of this thesis. Further details can be found in [23].
3.3.3. Speed advice

The phenomenon of platoon dispersion was introduced in the first part of section 3.3. The effect of this phenomenon can be counterbalanced to some extent. The method for this is to give speed advice for the vehicles. This means that the vehicles enter the arterial get a speed advice on a road side screen. If the drivers follow this speed advice they will get to the downstream intersection just in time when the light will turn green. This road side sign can give two types of advices. The first one is the aforementioned speed advice. The second one is that green wave is not possible. This happens when the given advice would be too high and it would stimulate for speeding or it would be too low that the drivers would not follow anyway.

DTV implemented speed advice on an arterial in the Netherlands using the name of ODYSA [24] for the project. It is implemented on an arterial where the intersections are located about one kilometer away from each other to create a green wave through these intersections. This would be hard without any countermeasures against platoon dispersion because the vehicle platoons would spread out. Therefore the platoon would reach the downstream intersection with quite low saturation flow. This would hinder the vehicles on the side streams highly. Using speed advice vehicle platoons could be kept together; so the difference in their desired speed can be reduced to zero. However no remarks have been mentioned about the dispersion caused by the larger headways kept for safety distance and about the platoon decay. First real world test results suggest that the main stream benefits from the speed advice. Drivers especially of heavy goods vehicles are content with the system. Users arriving from side streams are not benefiting that much from the new implemented system.[24]

Implementation of speed advice is already finished at TNO in case of the controller of van Katwijk. Results show that the speed advice is primarily beneficial for emission and CO\textsubscript{2} reduction. [10] With this method the number of stops can be reduced with avoiding the deceleration of arriving vehicles to low speeds. This helps because the number of stops and CO\textsubscript{2} emission are in close relation with each other. Further details can be found in [7,24].
3.4. Conclusion of literature survey

During the literature survey one of the objectives were to gain general knowledge and insight on (i) traffic adaptive control (ii) the network behavior of adaptive control (iii) the multi-agent traffic control approach and (iv) the controller of van Katwijk. This objective was fulfilled. Unfortunately the technology of multi-agent based adaptive control was only introduced nowadays. Field tests are not available on these technologies since these only exist so far in simulation environments. Table 3.2. shows the traffic adaptive signal control systems that were examined and had large importance therefore mentioned.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Description</th>
<th>Importance for the research</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>SCOOT</td>
<td>Split, Cycle time, Offset optimization</td>
<td>General knowledge on centralized adaptive systems</td>
<td>[3,4]</td>
</tr>
<tr>
<td>2.</td>
<td>Neural Network based approach</td>
<td>Neural network based control of intersections.</td>
<td>Learning ability of the system</td>
<td>[12]</td>
</tr>
<tr>
<td>3.</td>
<td>RHODES</td>
<td>3 level hierarchical system, passing boundary conditions to lower level decision making</td>
<td>Communication between levels through boundary conditions</td>
<td>[4,13]</td>
</tr>
<tr>
<td>4.</td>
<td>PAMSCOD</td>
<td>Based on platoon identification extension of green phase</td>
<td>Special attention to platoons</td>
<td>[14]</td>
</tr>
<tr>
<td>6.</td>
<td>Controller of Lämmer &amp; Helbing</td>
<td>Multi-agent system without communication, delay minimizing and capacity maximizing policy</td>
<td>The only other well documented multi-agent system found</td>
<td>[2,19]</td>
</tr>
<tr>
<td>7.</td>
<td>Controller of Greenwood, Burdiliak &amp; Trencansky</td>
<td>Multi-agent traffic control system</td>
<td>Spontaneous emergence of &quot;green waves&quot;</td>
<td>[18]</td>
</tr>
</tbody>
</table>

Table 3.2. Summary of the reviewed adaptive traffic control systems

On the basis of the literature survey done by van Katwijk [4] other traffic adaptive systems were also examined (SCATS, MOTION, TUC, UTOPIA/SPOT, OPAC, PRODYN). The importance of these systems were not high because all of them are operating on a cycle basis and/or do not take into account the separate vehicles in the optimization. In the controller of van Katwijk [4] the lack of cycle on which basis all the aforementioned systems optimized the performance determined that a new method has to be developed for the for coordination.

In case of the multi-agent system Greenwood, Burdiliak & Trencansky [18] it was not mentioned explicitly whether any coordination measures were used or not. In case of the system of Lämmer & Helbing [2,19] it was stated that coordination through communication is
impossible. On the other hand in the controller of van Katwijk some coordination measures were already built in. Based on the literature survey there is no published idea about coordination in a multi-agent based traffic adaptive controller. On the other hand the “optimization” of the spontaneously emerging “green waves” seem to provide an opportunity. On this basis the research was started in chapter 5.

On the field of platoon dispersion the conclusion is that there are models published by research papers on the prediction of the effects of platoon dispersion. These models can be used in an online optimization. Before the implementation the control program the efficiency of these methods have to be tested. Chapter 4 gives the results about the testing of the model.
4. Predicting platoon dispersion

In this chapter research results of the second problem (mentioned as inaccuracy of arrival pattern prediction) will be given according to the problem definition in section 2.1. First the original prediction of the controller of van Katwijk [4] will be introduced then the model given in section 3.3. of the literature survey will be introduced in detail. After this testing and comparison of the will be shown along with the results and validation with real world data. At the end of the chapter the VISSIM driving behavior and its effects on the research will be presented and the conclusions drawn.

In section 3.3. of the literature survey the phenomenon of platoon dispersion was introduced. It was also mentioned that Bonneson, Pratt and Vandehey in their article [21] based on extensive field measurements in the United States improved the already existing probabilistic method in 2010. This is the latest model based on the probabilistic approach of platoon dispersion found during the literature survey. The authors mention in their article that the major challenge concerning building a platoon dispersion model (using the probabilistic approach) is to give an accurate prediction on the smoothing factor. They made a review in their research paper on the existing models. On the basis of the review they suggested their model. In their model they took into account the trade-off between robustness to different geometry conditions and accuracy. For this reason this model was tested in computer simulation to find out how much better prediction it could provide than the original prediction of arrivals.

Original or “naive” prediction of the controller:

The original prediction of the controller does not take into account platoon dispersion. It assumes: the vehicles leaving the upstream intersection’s stop line will arrive at the downstream intersection in the same order and having the same time headway that they had at the detection point upstream. This also includes the assumption that every vehicle is using the same speed, the average speed of the users on the road section. These assumptions ignore the effects of platoon dispersion but make prediction of the arrival pattern simple and keep the computational needs low. On the other hand the controller can use the extension detectors of the current intersection located 30-40 meters from the stop line to correct its prediction on arrival pattern.
4.1. Probabilistic prediction model

In this section the model of Bonneson, Pratt and Vandehey [21] will be shown in details along with some remarks concerning the implementation. The authors developed a model on the basis of the platoon dispersion model used in the Highway Capacity Manual (HCM)\textsuperscript{25}:

\begin{equation}
q'_{a|u,j} = F \cdot q'_{u,i} + (1 - F) \cdot q'_{a|u,j-1} \quad (1)
\end{equation}

with:

\begin{equation}
 j = i + t' \quad (2)
\end{equation}

where:

- $q'_{a|u,j}$ = arrival in time step $j$ at the downstream intersection from upstream source $u$ [veh]
- $q'_{u,i}$ = discharge flow in time step $i$ at upstream source $u$ [veh]
- $F$ = smoothing factor
- $j$ = time step associated with platoon arrival time at downstream detection point
- $i$ = time step associated with platoon departure time from upstream source $u$
- $t'$ = platoon running time

As it is visible the model follows a stepwise approach. The authors tried more time step lengths. In the implementation of their model the time step length of 1 second was used. This was chosen because the controller is also working on a 1 second time step basis.

The weak point of equation (1) is that the smoothing factor is really hard to predict. On this variable several researchers did thorough research in the past decades. Bonneson, Pratt and Vandehey [21] tested input parameters that could be used in the model to predict the smoothing factor. For this reason an extensive (10 road sections and 5883 detected vehicles) calibration based on field measurement data was carried out. SAS non-linear regression procedure was used to find the best fitting coefficients to their smoothing factor estimate. According to their findings the running time and the step length is the only variable that influences the platoon arrival pattern. The way how it influences is shown on figure 4.1. and in equation 3.
Figure 4.1. Dispersion of vehicles started in 1 time step[21]

**Smoothing Factor:** [21]

\[ F = \frac{1}{1 + (b_0 \cdot T_r)/d_t + b_1/d_t} \]  
\[ (3) \]

where:
- \( F \) = smoothing factor
- \( T_r \) = average running time [s]
- \( d_t \) = time step duration (1 seconds/step)
- \( b_0 \) = calibration coefficient (predicted value 0.138)
- \( b_1 \) = calibration coefficient (predicted value 0.315)

**Platoon arrival time:** [21]

\[ t' = \frac{1 + T_r/d_t}{1/F} - 1/F + c_0 \]  
\[ (4) \]

where:
- \( t' \) = platoon arrival time
- \( T_r \) = average running time [s]
- \( d_t \) = time step duration (1 seconds/step)
- \( F \) = predicted smoothing factor from equation 3
- \( c_0 \) = calibration coefficient (predicted value 0.254)
Using this model the arrival pattern can be predicted on the basis of average running time. This data was already used by the controller to predict the arrival pattern on a step by step (second by second in this case) basis. The second input needed for the prediction is the upstream detection data. It is also already in the controller and used for the prediction of arrival pattern. This basically shows that the input data for the two (“naive” and “new”) prediction method is the same.

In the following the results of computer simulation will be shown using this model mentioned as the “new” prediction. The model had to be tested against the original “naive” prediction before its implementation to the control program to see the difference in accuracy. This comparison was done on the basis of difference in detected and predicted vehicles at the downstream detection points at every second. The smaller the difference is the better the prediction method.

4.2. Comparison of models in ideal conditions

Ideal conditions means that a test network has been built with an intersection on the start that creates platoons and a long straight road stretch on which the measurement points can be placed. Sections with speed changes are omitted therefore the first detection point (used for the prediction as input data) is not the stop line but just downstream of the intersection. Figure 4.2. shows the test network.

![Test network for platoon dispersion experiments](VISSIM)

*Red stripes are the signal heads;
**Blue stripes are the vehicle detection points: the first is just downstream of the intersection;
4.2.1. Test scenarios

To compare the two prediction methods several scenarios were built on the basis of the two main influencing factor: (i) distance and (ii) number of lanes. The average intersection distance in the European city structure is about 300 meters but there are large deviations because of the organic growth of the city centers. For this reason the accuracy of prediction models were tested on 5 different lengths:

- 150 meters
- 240 meters
- 300 meters
- 500 meters
- 800 meters

Two different lane number numbers were also used:

- 1 lane
- 2 lanes

Other parameters like demand were also tested. These did not influence the performance of the two arrival pattern prediction therefore these are not presented here.

After building the model in Microsoft Excel using the original calibration coefficients suggested by the authors the results were worse than the original “naïve” prediction (which omitted the effect of platoon dispersion). One explanation of this can be the difference in driving behavior between VISSIM simulation environment and the reality. Therefore in the following part of the research the calibration coefficients were optimized. This was done with SOLVER add-in for the every different scenario (detection length and lane number). Using these new coefficients a new prediction was made using results of a new random seed.

4.2.2. Results

Using the previous simulation framework during one hour of simulation ~750 vehicles were detected at the detection points. To compare the results of the two predictions first a cumulative curve was created from the number of vehicles passed the detectors on a second basis. Then the difference or error in the number of vehicles at every second was generated.
The squared error of the whole prediction horizon (1 hour and about 750 vehicles) was added up. Figure 4.3. shows the cumulative curve of the same platoon at distance of 300 and 800 meters.
Figure 4.3. Dispersion of a platoon as it progresses downstream

It is visible from the figure that the prediction becomes less accurate as the distance grows. It is also visible that neither of the predictions can do anything with the fast and the slow vehicles.

To get more insight besides the squared error the RMSD Root-Mean-Square Deviation was also examined. The squared error of the different predictions is visible on Figure 4.4. and in table 4.1.

<table>
<thead>
<tr>
<th>Nr. of Lanes</th>
<th>Distance [m]</th>
<th>&quot;Naive&quot; Prediction</th>
<th>&quot;New&quot; Prediction</th>
<th>Change in Error²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Error²</td>
<td>RMSD</td>
<td>Error²</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
<td>378.0</td>
<td>0.325</td>
<td>375.0</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>598.0</td>
<td>0.409</td>
<td>405.7</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>583.0</td>
<td>0.404</td>
<td>458.9</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>937.0</td>
<td>0.512</td>
<td>753.6</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>1540.0</td>
<td>0.656</td>
<td>1281.8</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>462.0</td>
<td>0.359</td>
<td>376.2</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>561.0</td>
<td>0.396</td>
<td>402.9</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>717.0</td>
<td>0.448</td>
<td>472.4</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>1063.0</td>
<td>0.545</td>
<td>788.9</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>1950.0</td>
<td>0.738</td>
<td>1555.5</td>
</tr>
</tbody>
</table>

Table 4.1. Squared error and RMSD of the two prediction methods

An interesting result is that the two predictions are closer to each other than to the original measurements. This is also visible in the sum of squared error of the “naive” and “new” prediction. The difference at detection point 800 meters is 338.7 for 1 lane and 661.2 for 2 lanes that is 25-40% of the difference from the real measurements. This indicates that there is an effect that neither the “naive” nor the “new” probabilistic prediction can take into account.

The RMSD (root-mean-square deviation) indicates that the prediction methods depending on the length of the section are between 0.3 and 0.75. It is more interesting that these differ to a small extent in case of the two methods 0.08 at maximum. Taking into account the fact that at a traffic signal 0 or 1 car is waiting this difference seems completely insignificant.

It is also interesting to see that the new prediction has the best performance at the range of 240-300 meters between the first detection point and the downstream prediction and detection
Further details on the performance of arrival pattern prediction methods can be seen on figure 4.4. and in table 4.1.

**Prediction error for 1 lane**

![Graph showing prediction error for 1 lane](image)

**Prediction error for 2 lanes**

![Graph showing prediction error for 2 lanes](image)

*Figure 4.4. Prediction error of the “naive” and “new” prediction for different distances*
As it is visible from Figure 4.4. the prediction accuracy is decreasing with the increase of distance for both of the methods. It is also visible that the relative advantage of the “new” prediction is disappearing with the increase of distance.

4.3. Comparison of models under real conditions

The results of the 4.2. section seemed somewhat small but still promising. This suggested doing tests under real conditions. By real conditions still computer simulation is meant but using stop line detection of vehicles. In this section results will be shown for which detection data at the stop line was used and the arrival pattern at the next stop line was predicted.

4.3.1. Difference in test conditions

The main difference in conditions in case of these tests was the following: The vehicle detection is not happening when the queue has already departed and headway and speed is changing steadily or remains stable. But the detection is happening in a situation when the first vehicle (if it was stopped) departs from a stand still. The second one will be detected when it is already accelerating for a few meters and so on.

In this case three intersections were tested on the Assen network (details about the network found in the appendix) using detection data on the largest north and southbound streams. The length of the different sections seemed to be ideal according to the results of section 4.2. (220-280 meters). Demand varied between 600-1000 vehicles per tested road section.

4.3.2. Results

The results on the real simulation conditions are in accordance with the predictions. All of the tested section lengths were in the range of the earlier identified ideal. Therefore all of the streams tested had better results using the “new” prediction both in squared error and in RMSD.
On the other hand as it was expected the accuracy of the “new” prediction method drops because of the not constant speed. This was also mentioned in research papers as the main disadvantage of the probabilistic approach to predict platoon dispersion.[21] This effect could only be avoided with using extra detectors downstream of the intersection but this would have extra costs.

### 4.4. Validation of results with real world data

For the reason of validating the results that came from the VISSIM simulation real world measurement data was used. The data was gathered in one of the ODYSIA test sites in the Netherlands. Results are shown in table 4.3.

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>&quot;Naive&quot; Prediction</th>
<th>&quot;New&quot; prediction</th>
<th>Change in Error²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Error²</td>
<td>RMSD</td>
<td>Error²</td>
</tr>
<tr>
<td>750</td>
<td>67964,0</td>
<td>0,887</td>
<td>50653,0</td>
</tr>
<tr>
<td>1355</td>
<td>317196,0</td>
<td>1,916</td>
<td>266720,3</td>
</tr>
</tbody>
</table>

Table 4.3. Squared error and RMSD of the two prediction methods

Though the detection lengths were different in case of real world data from the ones used during VISSIM simulation the accuracy at about 800 meters are almost the same. It shows a similar decreasing pattern as it is predictable from the VISSIM simulation results. The squared error values are much larger because of the larger number of detected vehicles. Detection data had the time span of 24 hours.

On the other hand calibration was done in case of these distances as well as in case of all the earlier cases. Results show that the original $b_0$ and $b_1$ calibration coefficients were fitting
almost the best. This indicates that the model works similarly with VISSIM driving behavior as with real world data. The only difference is that the calibration coefficients of the model have to be changed drastically.

4.5. VISSIM driving behavior

It was mentioned in section 4.2.3. that the calibration coefficients of the prediction model had to be recalibrated in the VISSIM simulation environment. The reason for this was that the error of the probabilistic prediction method using the original coefficients was even higher than the error of the “naive” prediction. It was also mentioned in section 4.4. that the real world data that was used for validation gave the best fit with the original calibration coefficients. There is large difference in the calibration coefficients depending on where the data is coming from: VISSIM or real world.

Best fitting VISSIM  
Suggestion of the authors 

\[ b_0 = 0,072 \text{ (mean)} \]  \[ b_0 = 0,138 \text{ (mean and 0,008 standard deviation)} \]

\[ b_1 = 0,285 \text{ (mean)} \]  \[ b_1 = 0,315 \text{ (mean and 0,087 standard deviation)} \]

This suggests differences in driving behavior. To investigate this difference further information has to be provided on the field of platoon dispersion that was part of the literature survey.

Causes of platoon dispersion:

- As a platoon is progressing downstream because of the differences in desired speed, the time headway between the vehicles starts to grow.
- The drivers try to keep larger safety distance (headway) than that they had just after the departure from the stop line. This effect also makes the headway larger.
- There is another effect that is called platoon decay by some authors.[21] There are vehicles driving in the platoon leaving the arterial at intermediate intersections. The leaving vehicles cause that the saturation flow of platoons decreases. There are other vehicles that arrive on the intermediate intersections and join the flow of the arterial. The newly arriving vehicles typically join the flow of the arterials in times when there are no platoons present; in the time gaps between platoons.
In VISSIM simulation the differences in desired speed existed. On the other hand the vehicle trajectories showed no sign of the increasing safety distance. The platoon decay was also not present because the lack of intermediate intersections. Overtaking also does not exist in the opposite lane in VISSIM. In case of 1 lane links this makes impossible to overtake a slow vehicle at the front of the platoon.

It was visible from vehicle trajectories that if the first vehicle of the platoon has a low desired speed there is no platoon dispersion at all. The time headway decreases to minimal and a very dense platoon progresses downstream without dispersion. Several measures were tested to reach more realistic dispersion behavior, but none of them changed the aforementioned basic behavior.

**Investigated settings:**

- Wiedemann 74 and 99 (following model)
- Right-side rule and free lane selection (lane change in 2 lanes scenarios)
- Safety distance reduction factor (lane change in 2 lanes scenarios)
- Maximum deceleration for cooperative braking (lane change in 2 lanes scenarios)

When the changes are made in these settings it also has to be taken into account that the results and driving behavior of VISSIM is validated only in case of the default settings.[16] The manual strongly suggests to use these however changing the latter two is a quite common practice on merging and diverging sections. [26] It is used in many networks and assignments.

Taking into account the aforementioned facts it is visible that the right settings of driving behavior of VISSIM are not found to simulate reality perfectly yet. There are also no useful suggestions found in the (i) manual of the program, on the (ii) FAQ of the website of the program, (iii) internet search and in (iv) research papers. For his reason the default setting remained as it is. On the other hand this issue has to be taken into account when the results are evaluated.
4.6. Conclusion

The brief conclusion is that the probabilistic platoon dispersion model that was tested works on simulation environment as well (besides the doubts that were mentioned). On the other hand the model tested provided only slightly better results than the original “naive” prediction.

In a real time traffic controller it was mentioned that the computational need has to be kept as low as possible. The “naive” prediction that is already implemented to the controller is a simple method. Although the new prediction is not a very complex model but it would still need extra computational capacity from the controller and make the program more complex. The increase in prediction accuracy dropped to 12-20% in case of ideal section length and real conditions. Under real conditions using the right detector places the “new” prediction would provide a very small increase in arrival pattern prediction accuracy. This slight increase would probably remain invisible on the better decision making of the controller therefore in the delay of the users. The reasons for this: (i) The first vehicles that are faster than average could get a green until a certain number of intersections which means less delay. On the other hand after some time/distance when these vehicles leave the platoon far behind would get red anyway. This is happening because somewhere (from the multiple intersection) it will be sub-optimal to give green to a single vehicle. At this time these vehicles will be merged again to the platoon. (ii) The controller through the extension detectors detects the vehicles lacking behind and can make last minute update in the signal plan to extend the green phase. This would also happen if the information of the last vehicle would be accurate, just earlier.

Because of the predictable very small benefits and the extra complexity that the implementation of the probabilistic platoon dispersion model would mean it was decided not to implement it in the controller of van Katwijk [4].

4.7. Recommendation

It is visible from the article of Qiao, Yang and Lam [23] that using the neural network approach much larger improvement can be achieved in accuracy of arrival pattern prediction. This model could have a better performance because unlike the probabilistic method several layers of neurons can be built into the system. This ensures that every possible influencing
factor can be taken into account even if these are influencing through an “if – then” relation. The fine tuning of the system is also unnecessary because the feedback information on the arrival pattern is known at the downstream junction. Based on this feedback information using the learning ability of the neural networks the system can update the interconnection values between the different neurons of the system. Although it is an even more complex model it is possible that the improvements achieved with that model could outweigh the extra complexity that the implementation causes in the controller. For this reason it is recommended to test the neural network approach as well.
5. Coordination in multi-agent adaptive control

In this chapter research on the third problem will be presented mentioned as unknown arrivals on the side streams in the problem definition (section 2.1.). First the theory will be presented on which basis the possible coordination strategies were built up. After this the two coordination strategies with the results will be presented. Finally the conclusion drawn from these results will be given.

In a multi-agent adaptive signal controller coordination is impossible by the same means as in actuated or fixed time signal control. The controller does not have a fixed sequence therefore there is no fixed cycle time. Without fixed cycle time coordination is not possible by adding an offset value between the nearby intersection controllers. In the following if the word coordination is used it means coordination in a broader sense and not only using an offset value. Further information on the multi-agent approach and coordination can be found respectively in section 3.1.2 and 3.2.

5.1. Solution directions for coordination

Urban traffic control is a real challenge among control engineers because it has its certain features that make the problem quite complex.

These features are the following:[27]

- The dynamic nature (e.g. of traffic demand)
- The large network size (e.g. multiple coupled intersections even in a small city)
- The intrinsic complexity (e.g. traffic signals are effecting their own input)
- The non-linear behavior (e.g. capacity of a road segment intersection)

The introduction of multi-agent approach to this area solved some of the problems. The distributed approach decomposed the central problem to several sub-problems that have to be solved by independently acting agents. With this step the large network problem reduced to problems of single intersections. On the other hand these intersections affect each other largely. Therefore the centrally complex problem becomes a set of problems that are dependent on each other. On an arterial usually the largest time slot is provided for the two
main streams. These main streams are not hindering each other therefore usually (but not necessarily) these are getting green at the same time. This results in the situation that the green given at intersection A to a platoon determines its downstream arrival time to intersection B. It can be assumed that the oncoming platoon will get green at the same time at intersection B. Therefore the platoon left intersection A effects the departure time of the oncoming platoon at intersection B which is input of intersection A. The resulting signal plan of one intersection is the input for another and the other way around. This also means that the signal plan of an intersection affects its own input later on in time.

5.1.1. Local vs. Global optimum

At this point it is interesting to see that the following research papers do not agree on what will happen:

Helbing and Lämmer [2] state that the interaction of selfish agents leads to inefficiencies such as social dilemmas according to game theory. Therefore the decentralized optimization of each single intersection does not necessarily lead to network wise optimal solution.

On the other hand Oliveira and Camponogara [27] state that: Theoretical results ensure the convergence of the distributed iterations to a globally optimal solution.

Even if the second statement is true; on an iterative basis problem solving takes usually large amount of time. If the controller is assumed to react on the changes of traffic in real time the amount of time for the iterative process is limited.

The problem of intersection (local) and network (global) optimum shows similarities with route choice modeling of travelers. Similarities are that both route choice modeling and traffic control optimization tries to find an optimal state of traffic. They are minimizing the same traffic variable: the travel time or delay on the network. Differences are that in the first case travelers try to minimize travel time or delay. In this case one traveler looks for a solution along the network so a set of intersections. In the second case the traffic controller tries to minimize the travel time or delay of the users. One part of the network (in this case a single intersection) looks for the best solution locally for all the users using that part of the network.
According to Bovy, Bliemer and van Nes [28]: For the route choice problem depending on the equilibrium definition two types of equilibrium can be distinguished: (i) the user equilibrium and (ii) the system optimum.

- *The user equilibrium assignment leads to an equilibrium in which no traveler can improve his travel time by unilaterally changing routes.*
- *The system optimum assignment leads to the system state in which the total travel costs on a network is minimized.*

Following this path it is likely that two equilibrium states exist for the traffic controller as well. One which is locally minimizing travel time or delay and another that leads to a global system optimum. It is also true because of the challenges of traffic control mentioned in section 5.1. it is impossible nowadays to find the system optimal solution which takes into account independent vehicles. It would lead to a central optimization problem with too many independent variables.

For example: Even in case of town thousands of travelers depart every morning in the peak hour. All of these people have a different route choice and departure time. On the top of this the traffic signal control system has no information about the route choice of the users well in advance. The destination is unknown to the system therefore it only has information until the next intersection.

Because of the complex central problem it is impossible to give a solution in real time with the available computational capacity.

### 5.1.2. Problem of limited time horizon

In traffic control even if there is no cyclic behavior in the controller there are certain boundary conditions that will need to have insight to the future arrival pattern. This means that in an ideal case every intersection knows the arrival pattern at its stop lines at least until the boundary conditions. A boundary condition like this is e.g. every arriving vehicle green time has to be provided in 120 seconds after the arrival. This is necessary because of safety reasons. In case of longer waiting time the probability of red light running becomes high based on that the driver assumes that the traffic controller is not operational.
It is also foreseeable that the longer the time horizon on which the arrival pattern is known (or accurately predicted) the more suitable gaps in the main stream can be found to serve side streams. The limited time horizon leads necessarily to a short-sighted optimization and to inefficiencies.

According to Lämmer and Helbing [2] if the decision of an intersection takes into account vehicles that are at the time of the decision located upstream of a previous intersection: then the decision has to be known by the upstream intersection on which the decision depends.

This kind of information loop means a new challenge that has to be taken into account.

5.1.3. Heuristic approach

According to section 5.1.1. and 5.1.2. it is expected that there is a network optimum which means a lower system delay or travel time than the sum of local optimums. It is also expected that this system optimum can only be reached using coordination measures between the intersections. The fully centralized problem solution or the system optimum is impossible to be reached in real time with current computational needs. Therefore heuristic measures will be implemented in the control program to get a better performing solution than the sum of the local optimums.

At this point it is taken into account that according to Lämmer and Helbing [2] dynamic coupling of neighboring intersections also leads to inefficiencies on a network.

According to this statement and taking into account the fact that because of the lack of information and computational capacity not to achieve the perfect solution. The point is to find a framework with which the network performance of the multi agent controller can be improved.
5.1.4. Possible coordination strategies

The possible methods for better control of the two main streams of an arterial will be provided here. The main point is to minimize hindrance between the main streams and several side streams in successive intersections of an arterial. It is visible from the example in the 2.1.1. section that coordinating the intersection controllers is beneficial. In case of coordination of two intersections two approaches are possible: (i) direct coordination and (ii) indirect coordination.

- Direct coordination between the intersections basically consists of sending arrival pattern of vehicles to the downstream intersections. The other direction of communication consists of (i) predicted delay and (ii) signal plan sent upstream.
- In case of indirect coordination the same thing is happening but the agents are communicating modified information to each other. This information is modified according to a central optimization policy. The information is modified in a way to make the result of the intersection (local) optimization similar to the network (global) optimum.

Figure 5.1. Schematics on the types of coordination

Direct coordination means that intersections are communicating directly, so the intersections send unmodified information to each other and optimizing their signal plan together. This means an iterative process including communication and optimization steps. Every iteration has an (i) information receiving stage, a (ii) decision stage about the signal plan and an (iii)
information sending stage. An example how this is implemented in the controller is provided by van Katwijk.[4] Further details can be found in section 5.2.

Indirect coordination means that there is a central optimization policy which induces the decentralized controller to act network optimally. Using the information (on traffic situation) from the intersections and according to this central policy the signal plan can be modified. For this a different (network) optimization criteria is used instead of the intersection’s (local) one. This created plan can be a set of boundary conditions or information modification as well. For example by information modification the central unit can modify the weight of delay suffered by certain vehicles. With this it can prioritize or deprioritize these vehicles in the intersection (local) optimization. This information is sent back to the intersections. According to the modified information the intersections do their own optimization of the final signal plan. Further details can be found in section 5.3.

It has to be mentioned that the two methods mentioned in this section are not opposite of each other however the given names can suggest this. These are two different methods to improve network performance and can be implemented at the same time to the controller.

5.2. **Coordination through communication**

In this section the direct coordination (section 5.1.4.) of intersections will be shown as one of the methods implemented by van Katwijk to his controller [4]. First further details are presented about the inner mechanism of the communication. Then the results will be presented and finally the conclusions drawn from these results.

As it was mentioned in the previous section the direct approach means that the intersection controllers are communicating with all the neighboring intersections. This is an iterative process where every iteration consists of 3 steps: (i) receive information, (ii) decision making and (iii) sending information (signal plan).

In the first iteration step the controller receives information from its on approaches based on the information sent by the neighboring intersection controllers. Then it creates its own signal plan which is optimal at that time step. Ending the iteration step the controller sends the information to the neighboring intersection controllers.
In the second iteration step the controller gets information on (i) the vehicles that approaching it and on (ii) the scheduled arrivals of the vehicles detected by the neighboring intersection. By this time in the decision step the controller can find the conflicts between the vehicles that are upstream of the neighboring intersections. At the end of this iteration step the controller sends the signal plan with the mentioned conflicts to the neighboring intersections. In the next iteration these conflicts could be taken into account by the neighboring intersections. Through many iteration steps the intersections come up with a common signal plan. This plan according to the statement of Oliveira and Camponogara [27] is not only intersection (local) optimum but system optimal. In theory for the first view this approach works fine.

5.2.1. The implemented direct communication

During his research van Katwijk implemented the direct communication approach to his controller. Its performance was tested in this thesis to be able to compare its results with the results of using other coordination measures. In his controller van Katwijk [4] added a possibility to set the number of iterations. The larger the number the slower the simulation is. For this reason only the scenario with one iteration was tested. This means that the controller sends the information on the arrival process to the neighboring controller and gets back information on the signal plan from the neighboring intersection. This feedback allows the controller to adapt its signal plan to the plan of the other controller but cannot react on the changes that the neighboring intersection makes in its signal plan because of the information it got. The results of this are shown in table 5.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average delay of users [s]</th>
<th>Nr. of stops per user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuated coordinated control</td>
<td>14,26</td>
<td>0,585</td>
</tr>
<tr>
<td>Adaptive control without common optimization</td>
<td>7,82</td>
<td>0,301</td>
</tr>
<tr>
<td>Adaptive control with common optimization</td>
<td>7,71</td>
<td>0,296</td>
</tr>
</tbody>
</table>

Table 5.1. Results of the implemented direct approach

*Simulation results on the new Assen network using 10 random seeds (further details about the network can be found in appendix B);
5.2.2. Shortcomings of direct approach

In section 5.1. it was mentioned that the traffic signals are effecting their own future input through the decisions that are made in the present. This happens because of the fact that the oncoming streams of an arterial usually get green at the same time. In case of dynamic coupling of intersections the decision made at a certain moment will have 1\textsuperscript{st} order effect on the vehicles that are approaching the intersection and detected directly. (e.g. The controller A will stop the vehicles or let them go.) It will also have a 2\textsuperscript{nd} order effect on the vehicles that are approaching the neighboring intersections through the chain of events mentioned in the example of section 5.1. (e.g. The vehicles stopped or let gone by controller A will have a modified arrival time at intersection B and modify the signal plan there.) The cars arriving from the neighboring intersections will have an affected vehicle trajectory by the first decision so they “carry back” the 2\textsuperscript{nd} order effect of the first decision to the original intersection. (e.g. The modifications of signal plan in intersection B (made because of the vehicles arriving from intersection A) will affect the vehicles heading to intersection A.) Following this analogy there will be 3\textsuperscript{rd} order effects on the neighboring intersections of the neighboring intersections of the original intersection and so on. (e.g. Signal plan of intersection A and B will affect the signal plan of intersection C.)

![Diagram showing effects of signal plan on a network](image)

**Figure 5.2. Effects of a signal plan on a network (green: intersection A, red: intersection B, blue: intersection C)**
If a controller has to take into account all the consequences of its decision it needs to have knowledge on the whole network. This by definition is not a multi-agent system anymore according to the definition of Wooldridge in section 3.1.2.[15] The other problem with this is that it would cost enormous amount of computational capacity which is impossible to provide now and in the near future.

If the controller does not take into account the mentioned second and third order effect of its decision just the direct (first order) ones then the optimization will be necessarily short sighted according to section 5.1.2. It also means that there is no direct communication between the agents. To overcome this problem several iteration steps has to be put after each other to optimize the signal plan. This is also impossible because it would also need much larger computational capacity than we have now to do such an optimization in real time. A feasible trade-off is to limit the number of iteration steps and accept the fact that there will be inefficiencies in the final signal plan.

In reality it also has to be taken into account that usually no traffic signals are located on the side streams of an arterial upstream. This is mentioned as the problem of unknown arrival pattern in section 2.2. This means that vehicles on the side streams are just detected at the last moment before arriving to the stop line. As a consequence a well-made signal plan through steps of iteration will have a changed input during realization. Some elements of the commonly optimized signal plan will be already implemented to reach the least possible delay when new input is added and conditions are changed. This is also an inefficiency that the direct approach cannot overcome.

5.2.3. Possible upgrade for the direct communication

During the research a possible upgrade for the direct approach was developed in theory. In the following the two dimensional network of intersections is changed to a one dimensional arterial with side streams for the sake of simplicity.

In a multi agent traffic control system agents together know quite well in advance how vehicles will drive through the system. The reason is that each intersection knows its own signal plan. The intersections can determine where and when the certain vehicles will be given green. The problem with this knowledge is that it appears distributed in the system.
Because of the decentralized nature this information is hard to be assembled at the same time. As it was mentioned the intersection controllers are communicating with the neighboring intersection controllers.

In the controller of van Katwijk [4] this communication process consists of three parts (i) observation, (ii) decision and (iii) sending the decision to the other agents. The next iteration step’s observation is getting the data from the previous iteration’s sent data of the nearby agents. This communication loop ends when the optimal signal plan is found for both the intersections together or the number of maximal iteration steps are reached.

The original idea behind the upgrade was to extend the aforementioned communication but without a feedback loop from the second intersection downstream on.

![Figure 5.3. Extending communication](image)

When the first intersection controller detects the vehicle the whole optimization is done between the first and the second intersection controller according to the example provided by van Katwijk (page 99-101) [4]. After this the modified information can be passed to the third agent which will have completely accurate information on the arrival process of upstream vehicles. The only difference is that at this stage it is only simple information forwarding and not a two way communication. A two way communication involving more than two agents on a row could lead to a never ending back and forth communication between the first and the third agent using the second agent as a mediator.
Using this method the third agent can take into account vehicles that will arrive later on and knows the gaps that can be used to serve the side streams. The third controller will modify the arrival pattern according to its signal plan and modified information can be passed downstream to the fourth intersection and so on. Taking into account the fact that the control program is using a 120 seconds time horizon the information will have to be passed only until that time and distance limit. The information will be less and less accurate from the third intersection on. The reason is that it is not optimized for all the intersections that are involved in the information communication. On the other hand when the vehicles are progressing the signal plan will be optimized at the downstream intersections as well. When the platoon leaves the first intersection the real optimization with feedback information can be started between the second and third intersection.

There are some critical remarks about this theory:

- The accuracy of information passed downstream is highly dependent on the demand of main and side streams. If the fluctuation of vehicles on the arterial is high so large percentage of the vehicles leaves the arterial and arrives at the subsequent intersections the arrival pattern is totally changed. In this case there is no point in passing it in advance.

- If the vehicles are not platooned at the first intersection the number of sufficient gaps that can be used to serve the side streams are limited.

- In reality the arrival process on the side streams is not known well in advance. For this reason extending the prediction horizon on the main stream (which is already longer than the known arrival pattern on the side streams) will have low benefits.

For these reasons the implementation of the method shown was abandoned. With this decision the research was focused on the indirect approach of coordinating the multi agent controllers. This will be the topic of the next section.

5.3. **Coordination through improving network behavior of the controller**

In this section information will be given on the indirect approach (section 5.1.4.) of coordination in the multi-agent controller. First the framework; how this approach was implemented by van Katwijk in his controller[4] will be shown. Then the possible strategies
for coordination will be given. After this the steps of the analysis are presented before the results. Finally based on these strategies the results will be presented.

In case of this approach a new feature of the controller of van Katwijk was used. This makes it possible to give weights to the vehicles in the optimization process of the controller. With these weights it can be achieved that the vehicles are prioritized in the optimization while the system is kept totally adaptive. When a car with e.g. the weight of 2 arrives at the intersection the optimization takes into account the delay of that vehicle as if it would worth twice as much. Using this possibility of changing weight of vehicles in the optimization process can be used for (i) different vehicle type e.g. public transport prioritization or (ii) different streams. For example streams that have large demand can be prioritized or platooned at certain intersections of the network. It is clear that such an increase in weight of certain users will prioritize them over the others. Such a prioritization is beneficial for the users prioritized but costs extra delay for all the other users. At this point of the research the central optimization policy has to be created mentioned in section 5.1.4. After knowing that such a central optimization policy exists and it has large enough benefits to implement in the control program it can be automatized. This means that in the following manual search for the right policy will be done. Later on an online optimization can be developed on the basis of the guidelines that will be discovered by this thesis.

5.3.1. Implemented weight changing framework

The exact implementation of weight changing was done in the following way in the control program:

Entry (local) weight:

Users of certain traffic streams can get a weight locally by the controller. For example through streams of an intersection (stream 2,5,8 and 11) can get a local weight. The default weight of a car is 1. If the weight is larger than 1 the delay counts more in the optimization. E.g. a vehicle with the weight of 5 will be given green before the others even if 4 cars are waiting on the other stream. This strategy is used at the first intersection of the arterial where no upstream information is available.
In case of local weight two possible strategies are available:

- Giving higher weight to the vehicles to prioritize them from the very first intersection
- Giving lower weight to the vehicles to platoon them at the first intersection

Because of the fact that the local weights applied on the first intersection of the arterial the term entry weight will be used in the following.

**Interconnection weight:**

The interconnection weight is the other way how vehicles can be prioritized or deprioritized. In this case weight is assigned to the vehicles at the upstream intersection. This means that the downstream intersection controller knows (through the faraway detection) when vehicles will arrive and what their weights are. However in reality it is hard to determine at the upstream intersection which vehicles will drive through the next intersection and which will turn left or right. This is not a problem in case of right turning that have less and almost the same set of conflicts as the through going stream. On the other hand it can lead to inefficiencies in case of the left turning streams. In case of interconnection weight the same options are available than in case of the entry weight (that is defined as a local weight at the first intersection). However deprioritizing the largest (main) stream of an arterial on the whole section does not make any sense. It would certainly lead to a higher average delay on the network. The framework of entry and interconnection weights can be seen on Figure 5.4.

![Figure 5.4. The system of entry and interconnection weights on the Assen network](image)

**5.3.2. Strategies**

From the implemented framework introduced in the previous section the following strategies can be followed:
• Prioritizing main streams at the whole section of the arterial
• An extreme case of prioritization on the main stream is giving a very high weight to these vehicles. With this strategy the side stream vehicles will only get green if not hindering the main stream at all.
• Platooning (buffering) vehicles at the first intersection of the arterial with giving a lower weight to make them deprioritized by the controller. Then let these platoons drive through the whole arterial with high saturation flow creating gaps to serve side streams. Platoons will not be hindered by side stream green realization downstream.

According to these coordination strategies many simulation scenarios were tested with different weight sets. In the following sections the results of these scenarios will be shown. How these weights affect the average delay of users. Analysis was done on (i) stream level, (ii) intersection level, (iii) stream type level (according to example of figure 5.4.: northbound main stream, southbound main stream, and side streams) and (iv) total network level.

5.3.3. Results of the new Assen network

In the following sections the results of the new Assen (appendix B) network will be provided and the conclusions drawn from these results. According to the weight changing framework different sets of entry and interconnection weights were tested on the Assen network. This was done to find out whether the weight changing framework is capable of reducing the delay on network level. After having proof that this strategy is capable of reducing average delay, the relation between the set of weights given and the delay of the different streams is examined. Altogether 70 set of weights (scenarios) were tested. For every set 1 hour of simulation (using peak hour demands) was run. The average of 10 random seeds gave the final result of a scenario that was used in the analysis. The purpose of manual tuning was to find out whether (i) the theory and the implemented framework is working, (ii) how much the benefits are compared to the reference case. After the positive answer is known to these questions the central optimization policy can be automatized.
5.3.3.1. Steps of the analysis

The main purpose behind analyzing the results was to find out the influencing factors of the delay both on intersection and network level. For this reason the following steps were done:

1. The weighted amount of vehicles arrived at the intersection was identified as the main driving force behind the average delay of the streams and intersections. (e.g. a vehicle arriving having a weight of 2 counts as 2 vehicles) As a result a linear trend line could be fitted on every intersection with $R^2$ of 0.85-0.9. Figure 5.5 shows the details of different intersections.

![Figure 5.5. Delay of the different intersections in seconds](image)

2. The same analysis was done on the basis of stream types. According to example of figure 5.4. stream types were identified as: (i) northbound main stream, (ii) southbound main stream, and (iii) side streams.
3. In step 2 the fit on the basis of stream types gave good results for the side streams but not the main streams. Therefore a new indicator had to be found. This indicator was the percentage of the given main stream in the total demand of the intersection.
4. On the basis of these findings a model was built for every intersection to predict the average delay of the different streams at the intersections. The framework of the model is coming from the chapter on discrete choice modeling of the course reader of Empirical Analysis course reader [29].

Figure 5.7. Delay of the different stream types in seconds (exponential trend line gave the lowest $R^2$ value)
Input of the model:
- Number of vehicles arrived at the intersection on the different streams
- Weight of the different vehicles in the optimization
- Average delay of the different streams

Predicted delay of side streams:

\[ d_{si} = ASC + \beta_{1i} * s_i + \beta_{2i} * s_{all} \]  \hspace{1cm} (5)

where:
- \( d_{si} \) = average delay of side stream \( i \) [s]
- \( s_i \) = demand on stream \( i \) [veh/hour]
- \( s_{all} \) = demand of the whole intersection (sum of the 12 streams) [veh/hour]
- \( ASC \) = calibration coefficient (constant)
- \( \beta_{1i} \) = calibration coefficient
- \( \beta_{2i} \) = calibration coefficient

Predicted delay of main streams:

\[ d_{mi} = ASC + \beta_{1i} * \left( \frac{s_i * w_i}{s_{all}} \right) \]  \hspace{1cm} (6)

where:
- \( d_{mi} \) = average delay of main stream \( i \) [s]
- \( s_i \) = demand on stream \( i \) [veh/hour]
- \( s_{all} \) = demand of the whole intersection (sum of the 12 streams) [veh/hour]
- \( w_i \) = weight of stream \( i \) (entry or interconnection weight applied for the particular stream)
- \( ASC \) = calibration coefficient (constant)
- \( \beta_{1i} \) = calibration coefficient

Weighted amount of vehicles arriving at the intersection:

\[ s_{all} = s_1 + s_2 + s_3 + s_4 + s_5 * w_5 + s_6 + s_7 + s_8 + s_9 + s_{10} + s_{11} * w_{11} + s_{12} \]  \hspace{1cm} (7)

where:
- \( s_i \) = demand on stream \( i \) [veh/hour]
- \( w_i \) = weight of stream \( i \) (entry or interconnection weight applied for the particular stream)
The predicted delay got from equation (5) was then compared with the delay got from the simulation results. The calibration coefficients were calibrated with Microsoft Excel Solver add-in. It was done with minimizing the difference between predicted and measured delay of all the scenarios. Several model settings were tried in means how the input values should be taken into account in the model. The above presented one is that which had the lowest difference between predicted and measured delay. The prediction accuracy of the model is shown on figure 5.8.

![Figure 5.8. Prediction accuracy of the model in case of intersection 46](image)

*Figure 5.8. Prediction accuracy of the model in case of intersection 46*

The average weight means: \( \frac{s_{all}}{s_1 + s_2 + s_3 + s_4 + s_5 + s_6 + s_7 + s_8 + s_9 + s_{10} + s_{11} + s_{12}} \), so the weighted demand/real demand of the intersection

It is visible from figure 5.8. that the predicted delay of the different traffic streams had on average 5-10% deviation from the measured ones.

From the model some conclusions can be drawn:

- This indicates that there are other influencing factors that should have been taken into account in the input of the model. It has a high probability that these are geometrical features which could only be identified if results were gained from several other intersections. Geometry features like: (i) which streams are present at the intersection, (i) clearance times of the different streams.
The prediction model (due to its low prediction accuracy) cannot be used without further analysis. On the other hand using the calibrated model the best fitting weight combination could be determined. To achieve this: the calibration coefficients were used as fixed input and the entry and interconnection weights were optimized with the Solver add-in minimizing delay.

After this analysis (however the best weight combination was already known) for the sake of getting familiar with the behavior of the system several further simulation was done. At this point it was also clear that both the entry and interconnection weight has an influence on the average delay on the network. For this reason a matrix structure was created and filled with data to find out how exactly the solution “surface” looks like. In the following sections the results on the basis of this solution surface is given. Table 5.2. shows the examined entry and interconnection weights. Rows and columns highlighted with red were not filled in fully for the sake of time saving therefore omitted from certain tables in the following.

<table>
<thead>
<tr>
<th>Tested weights</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,75</td>
</tr>
<tr>
<td>0,15</td>
<td>0,2</td>
</tr>
<tr>
<td>0,25</td>
<td></td>
</tr>
<tr>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>0,75</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2. Entry and interconnection weight examined

5.3.3.2. Local trade-off of prioritization

The data got from the aforementioned simulation framework was the basis of the analysis. The first interesting conclusion was that as the weighted amount of cars increased at the intersections the average delay also increased although the number of cars remained the same on the network. It indicates that increasing the weights for the main streams to prioritize them would end up in a higher system delay. However decreasing the weights of every stream equally would not change the optimization process of the controller. After this it had to be investigated that de-prioritization of which streams lead to a lower network delay. It is also
visible from table 5.3. that extreme low weights also lead to larger average delay at the intersection level.

<table>
<thead>
<tr>
<th>Intersection 45</th>
<th>Interconnection weight</th>
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<th>1</th>
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<th>2</th>
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</thead>
<tbody>
<tr>
<td>Entry weight</td>
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<td>0.15</td>
<td>9.07</td>
<td>8.92</td>
<td>8.68</td>
<td><strong>8.55</strong></td>
</tr>
<tr>
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<td>8.85</td>
<td>8.68</td>
<td>8.75</td>
</tr>
<tr>
<td></td>
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<td>9.14</td>
<td>8.94</td>
<td>9.23</td>
</tr>
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<td>13.00</td>
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<table>
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<th>5</th>
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</thead>
<tbody>
<tr>
<td>Entry weight</td>
<td></td>
<td>0.15</td>
<td>7.83</td>
<td>7.61</td>
<td>7.96</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.25</td>
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<td></td>
<td></td>
<td>0.5</td>
<td>7.97</td>
<td>7.94</td>
<td>8.01</td>
<td>8.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.75</td>
<td>8.10</td>
<td>7.98</td>
<td>8.16</td>
<td>8.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td><strong>8.26</strong></td>
<td><strong>8.03</strong></td>
<td>8.34</td>
<td>8.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8.23</td>
<td>8.23</td>
<td>8.23</td>
<td>8.23</td>
</tr>
<tr>
<td></td>
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<td>5</td>
<td>10.09</td>
<td>10.09</td>
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<td>10.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intersection 46</th>
<th>Interconnection weight</th>
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<th>1.5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry weight</td>
<td></td>
<td>0.15</td>
<td>5.69</td>
<td>5.73</td>
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<td>6.06</td>
</tr>
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<td></td>
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<td>5.61</td>
<td>5.91</td>
<td>6.39</td>
<td>6.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td><strong>5.84</strong></td>
<td><strong>6.18</strong></td>
<td>6.75</td>
<td>7.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
</tbody>
</table>

Table 5.3. Average delay of users at the different intersections in seconds

*Cells highlighted with grey are options that does not make sense because there is no point in giving a higher weight for a main stream at the first intersection than giving a lower weight; Cells highlighted with green are the best results, cells highlighted with yellow are the reference cases;*  

As it is visible from table 5.3. the results are more sensitive to the interconnection weight than the entry weight in general. However the sensitivity differs at the different intersections. These differences can be attributed to the differences in geometry. In case of intersection 46 the effect of entry weight is small because stream 5 (which is effected by the entry weight) has one lane and about the same demand as the conflicting stream 3. Below the entry weight of 1 because of the similar demand (on conflicting stream 3) stream 5 never gets green on its own “right” but only when a platoon is arriving on stream 11. This results in a situation that at
the first intersection of the arterial vehicles are let gone when an oncoming platoon is arriving on the opposite direction.

**Figure 5.9.** Average delay of users at intersection 45 in seconds

**Figure 5.10.** Average delay of users at intersection 37 in seconds

*It is visible that the average delay at the middle intersection (37) does not depend highly on the entry weight;
Figure 5.11. Average delay of users at intersection 46 in seconds

It is visible from the data of the different intersections that these have different delays on average because of their different demand and geometry. On the other hand there is one more interesting thing. The different intersections have different sets of weights that result in the lowest delay. Of course it is impossible to give different entry weight at the different intersection because that is a variable that is given only once per main stream. On the other hand the interconnection weights could be changed from intersection to intersection.

According to the aforementioned fact a tailor made solution was tested using the weight combination that performed best at every intersection. This scenario did not outperform the best results showed in table 5.3.

5.3.3.3. Global trade-off of prioritization

After looking at the data on local level also global analysis was done. This included analyzing the (i) northbound and (ii) southbound main streams and the (iii) side streams on aggregated network level. The result of this analysis is shown in the table 5.4.
Coordination in multi-agent adaptive control

Table 5.4. Delay of the different stream types in seconds

<table>
<thead>
<tr>
<th></th>
<th>Northbound main stream</th>
<th>Southbound main stream 37</th>
<th>Side streams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Interconnection weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td>1</td>
</tr>
<tr>
<td>Entry weight</td>
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<tr>
<td></td>
<td>0,15</td>
<td>9,72</td>
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<tr>
<td></td>
<td>0,25</td>
<td>9,58</td>
<td>8,98</td>
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<tr>
<td></td>
<td>0,50</td>
<td>9,21</td>
<td>8,74</td>
</tr>
<tr>
<td></td>
<td>0,75</td>
<td>8,96</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry weight</td>
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<td>9,74</td>
<td>10,57</td>
</tr>
<tr>
<td></td>
<td>0,25</td>
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</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Contains the weighted (according to the demand) average delay of the northbound main stream on the arterial of all three intersections (stream 5 according to the Dutch standard code);

**Contains the weighted (according to the demand) average delay of the southbound main stream on the arterial of all three intersections (stream 11 according to the Dutch standard code);

***Contains the weighted (according to the demand) average delay of the side streams of all the intersections together;

Cells highlighted with green are the best results, cells highlighted with yellow are the reference cases;

From this table it is visible that the main streams are benefiting as the weight of them is increasing and the side streams are worse off at the same time. It has to be noted that in case of main streams increasing the entry weight over 1 meant no further improvement but a slight increase in average delay. An explanation for this can be: in this case there is no platooning at the first intersection at all which leads to a state where a single vehicle can block a side
stream. It was mentioned earlier that a boundary condition exists in the control program. This boundary condition says that a car has to get green after its arrival to the traffic signal within 120 seconds for safety reasons. If there is no sufficient gap to provide green for the side stream the green phase of the side stream is realized after 120 seconds no matter what the arrival pattern is on the main stream. This boundary condition can lead to the worse results together with extreme prioritization.

It is also visible from the data of table 5.4. that the change in the average delay of the side streams are much larger than in case of the main streams. This is shown in Figure 5.12.

![Figure 5.12. Indication of difference in delay changes of main and side stream](image)

*Different lines show different entry weights;*

From the graphs of figure 5.13. it is visible that in case of main streams the increase of both entry and interconnection weights results in a gradual increasing trend of average delay. (Exponential trend line gives the best fit and the smallest R² value.) As the entry and interconnection weight is closer to 0 the higher the average delay becomes of the northbound and southbound main streams. It is also visible that the delays of the side streams is increasing almost linearly. On the basis of this trade-off a curve could be fitted on the data set inducing that the best result can be expected at entry weight 0.25 and interconnection weight of 1.1.
Figure 5.13. The effect of changing entry and interconnection weights
Row 1, 2 and 3 are showing the delay of northbound main stream, southbound main stream and side streams respectively;
In the first column the effect of different entry weights are visible (each graph is one row of table 5.4.);
In the second column the effect different interconnection weights are visible (each graph is one column of table 5.4.);
In both cases the linearly increasing side stream delay can be seen as the weights are increasing and the (possibly exponentially) increasing main stream delay as the side stream decreasing;
Figure 5.14. The effect of changing entry and interconnection weights (figure 5.13, using surfaces)

*Number of stripes with different color indicates the difference in scaling of the graphs;
Figure 5.15. Average delay of users on the whole network
Coordination in multi-agent adaptive control

<table>
<thead>
<tr>
<th>Network Total</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,75</td>
</tr>
<tr>
<td>0,15</td>
<td>7,24</td>
</tr>
<tr>
<td>0,25</td>
<td>7,21</td>
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<td>0,5</td>
<td>7,28</td>
</tr>
<tr>
<td>0,75</td>
<td>7,43</td>
</tr>
<tr>
<td>1</td>
<td>7,72</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5. Average delay of the users on the whole network

*Contains the average delay of all the traffic streams of 3 intersection of the new Assen network;

** The cell highlighted with green contains the best result; cell highlighted with yellow is the reference case;

From Figure 5.15. and Table 5.5. it is visible that at the aforementioned point of entry weight 0,25 and interconnection weight of 1,1 both of the curves are having minimum point. At that point the steepness of the exponential curve of the main streams becomes larger than the linear decrease of the side streams. With this weight setting the average delay decreased from 7,82 seconds to 7,09 seconds which is 9,30 % improvement.

The aforementioned phenomenon can happen because with these measures the main streams are stopped for more time (than in case of weight set 1-1). Then these are let through the system with high saturation flow during a short time. This gives more time for the controller to serve the side streams. Looking at the signal distribution of the intersection the aforementioned fact can be justified. The time the intersection controller spent with serving the main streams of the arterial deceased because of platooning at the first intersection.

5.3.3.4. Number of stops

The number of stops was chosen as a secondary criterion for the research. However the delay gave quite a clear cut solution the number of stops was also examined. The results of the different scenarios are shown in table 5.6. and figure 5.16.
Coordination in multi-agent adaptive control

*Contain network; The case; As it is pattern at a different interconnection weight.

Figure 5.16. Average number of stops per users on the whole network

<table>
<thead>
<tr>
<th>Network Total</th>
<th>Entry weight</th>
<th>0.75</th>
<th>1</th>
<th>1.1</th>
<th>1.5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
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<td>0.15</td>
<td>0.15</td>
<td>0.307</td>
<td>0.294</td>
<td>0.290</td>
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<td>0.300</td>
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<tr>
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<td>5</td>
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<td></td>
<td></td>
<td></td>
<td>0.631</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.6. Average number of stops per users on the whole network

*Contains the average number of stops of all the traffic streams of 3 intersection of the new Assen network;

** The cell highlighted with green contains the best result; cell highlighted with yellow is the reference case;

As it is visible from table 5.6. and figure 5.16. the average number of stops follows a similar pattern than the average delay. On the other hand the minimum point of the number of stops is at a different location on the surface. The minimum is at the entry weight of 0.5 and the interconnection weight of 1.5. However the location is different of the minimum point most of
the benefits (5.87 %) can be gained at the aforementioned 0.25-1.1 point (from the maximum of 6.55 % at 0.5-1.5).

It is also visible from the results that the relative change in number of stops per user is much smaller than in average delay.

### 5.3.3.5. Effect of changing demand

The results of the previous sections suggest that the different weight setting of entry and interconnection weights has high influence on the average delay on network level. These weight settings and the framework should be tested using different demand setting on the network for generalization. For this reason first the total demand was increased with 20 % then decreased with 20 %. Table 5.6. shows the effect of change in total demand.

<table>
<thead>
<tr>
<th>1,2 times demand</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry weight</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>10.23</td>
</tr>
<tr>
<td>0.25</td>
<td>10.14</td>
</tr>
<tr>
<td>0.5</td>
<td>10.39</td>
</tr>
<tr>
<td>0.75</td>
<td>10.88</td>
</tr>
<tr>
<td>1</td>
<td>11.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal demand</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
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<td>Entry weight</td>
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<td>7.14</td>
</tr>
<tr>
<td>0.25</td>
<td>7.13</td>
</tr>
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<td>0.5</td>
<td>7.30</td>
</tr>
<tr>
<td>0.75</td>
<td>7.41</td>
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<tr>
<td>1</td>
<td>7.82</td>
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<table>
<thead>
<tr>
<th>0.8 times demand</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>0.2</td>
<td>6.01</td>
</tr>
<tr>
<td>0.25</td>
<td>5.87</td>
</tr>
<tr>
<td>0.5</td>
<td>5.92</td>
</tr>
<tr>
<td>0.75</td>
<td>5.96</td>
</tr>
<tr>
<td>1</td>
<td>6.01</td>
</tr>
</tbody>
</table>

Table 5.7. Average delay of users on the whole network with different demand

*Contains the average delay of users on all the traffic streams of 3 intersection of the new Assen network;

** The cells highlighted with green contain the best result; cells highlighted with yellow are the reference cases;
The results of table 5.7. show that the change in total demand on the network does not change
the ideal weight setting. On the other hand it is also visible that the differences in average
delay decrease significantly with the decrease of demand. This means that the relative
advantage of coordination is decreasing as the demand decreases.

<table>
<thead>
<tr>
<th>Demand</th>
<th>Difference between 1-1 and 0,25-1,1 scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2 times</td>
<td>14,65 %</td>
</tr>
<tr>
<td>Normal</td>
<td>9,30 %</td>
</tr>
<tr>
<td>0,8 times</td>
<td>2,44 %</td>
</tr>
</tbody>
</table>

An explanation for this can be that the used capacity of traffic signals are not so close to
maximum. Because of this the extra time to serve side stream between the main stream
platoons is not so important therefore it has a lower impact.

Scenarios were also tested with a redefined OD matrix. The new OD matrix contained more
users on the side streams and less on the main stream. Further details about the new OD
matrix can be found in appendix B. Table 5.8. shows the results in comparison with the
original demand setting.

<table>
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<tr>
<th>Original OD</th>
<th>Interconnection weight</th>
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<tbody>
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<td>7,79</td>
<td>8,06</td>
<td>9,68</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>7,72</td>
<td>7,82</td>
<td>8,14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New OD</th>
<th>Interconnection weight</th>
<th>0,75</th>
<th>1</th>
<th>1,5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry weight</td>
<td>0,15</td>
<td>6,26</td>
<td>6,01</td>
<td>6,01</td>
<td>6,32</td>
<td>7,54</td>
</tr>
<tr>
<td></td>
<td>0,25</td>
<td>6,04</td>
<td>5,80</td>
<td>5,89</td>
<td>6,25</td>
<td>7,43</td>
</tr>
<tr>
<td></td>
<td>0,5</td>
<td>5,86</td>
<td>5,67</td>
<td>5,64</td>
<td>6,02</td>
<td>7,23</td>
</tr>
<tr>
<td></td>
<td>0,75</td>
<td>5,97</td>
<td>5,80</td>
<td>5,94</td>
<td>6,37</td>
<td>7,64</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>6,11</td>
<td>6,01</td>
<td>6,17</td>
</tr>
</tbody>
</table>

*Contains the average delay of users on all the traffic streams of 3 intersection of the new Assen network;

** The cells highlighted with green contain the best result; cells highlighted with yellow are the reference cases;
Results of the new OD setting indicate that the ideal entry weight increased from 0.25 to 0.5. This means that the smaller the demand is on the main stream the less the system is benefitting from platooning the vehicles on the arterial. This is a logical consequence taking into account the fact that the number of sufficient gaps is higher without any platooning measure. It is also visible that the interconnection weight increased from ~1 to ~1.5. This suggests that as the demand decrease on the main streams the main stream users should be prioritized. So the platoon size is not enough anymore for the users on the arterial to be not stopped at intermediate intersection.

Figure 5.17. Average delay of users with different OD settings
On figure 5.17. the “result surface” shows a similar pattern in both cases. The difference is that the minimum point has a different location in case of using a new OD matrix (with less demand on the main streams and more demand on the side streams).

5.3.4. Statistical analysis of the results

Concerning the accuracy of the results statistical analysis was carried out to determine the right sample size. The following equation was the basis of analysis.

Sample size: [29]

\[ n \geq \frac{Z^2}{d^2} \cdot \sigma^2 \]  \hspace{1cm} (5)

where:

- \( n \) = sample size (number of simulation runs with different random seeds for every scenario)
- \( Z \) = t-distribution value (1.64 in case of 90\% reliability)
- \( d \) = allowed variability
- \( \sigma \) = standard deviation of sample elements

Because of the fact that the standard deviation was unknown before the simulation, 10 simulation runs were executed to have information on the standard deviation. Table 5.9. contains the standard deviations of the different scenarios of the new Assen network.

<table>
<thead>
<tr>
<th>Network SD</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>Entry weight</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.9. Standard deviation of the simulation results
Table 5.10. gives a review on the allowed variability using confidence of 90%.

<table>
<thead>
<tr>
<th>Entry weight</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15 09</td>
</tr>
<tr>
<td>0.25</td>
<td>0.16 04</td>
</tr>
<tr>
<td>0.75</td>
<td>0.16 04</td>
</tr>
<tr>
<td>1</td>
<td>0.16 04</td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 5.10. Variability of results using 90% confidence

<table>
<thead>
<tr>
<th>Network SD</th>
<th>Interconnection weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>0.15 07</td>
<td>0.16 22</td>
</tr>
<tr>
<td>0.25 07</td>
<td>0.25 22</td>
</tr>
<tr>
<td>0.75 07</td>
<td>0.75 22</td>
</tr>
<tr>
<td>1</td>
<td>0.16 22</td>
</tr>
<tr>
<td>2</td>
<td>0.16 22</td>
</tr>
<tr>
<td>5</td>
<td>0.16 22</td>
</tr>
</tbody>
</table>

Table 5.11. Standard deviation of the simulation results

Table 5.11. indicates the effect of this variability on the results. 42 scenarios were tested on the new Assen network (with the original demand) with 10 random seeds where the 1 hour computer simulation took ~1.5 hours in real time. With respect to the facts: (i) it took more than 600 hours in real time to get these results and (ii) the variability interval of the results are overlapping only in few cases; the 10 simulation runs did during the first series were considered enough. The accuracy of the results shows: with 90 % confidence the real results do not differ more than 2 % of the measured ones.
5.4. Conclusion

In section 5.2 the coordination possibility through communication was shown. From the results of this approach and the shortcomings mentioned in this section it is visible that this approach has limitations. The shortcomings are that the lack of information limits the possibility to create a common signal plan if the input is unknown. Even if the necessary input was known to such a signal plan, the number of iterations while the fully decentralized multi agent system would find a right solution would need too much time. Therefore it would not be feasible in real time.

After this the second coordination possibility was tested which through modification of input information influenced the decision making of the controller. Using this approach (through weighting the delay of the main streams in the internal optimization of the controller) network optimal behavior was induced. Results show that the average delay of the users on the network decreased significantly using this weight changing framework. The best results could be gained when the main stream users were platooned (buffered) at the first intersection and then they were let through the corridor in platoons.

5.4.1. Effect of coordination measures

It can be told that the side streams reacted on the platooning of the main streams more sensitively. The large positive effect of the side streams on the delay outweighed the small extra delay of main streams suffered during platooning on network level. A reason for this can be that the main stream traffic (not disturbed by upstream signalized intersection) had several small gaps between the cars. These small gaps were larger than the needed headway but insufficient for the controllers of the successive intersections to give green to the side streams. Stopping the main stream for a short time to merge these gaps to sufficient ones to serve side streams means large delay reduction on the side streams. At least large enough to outweigh the small extra delay of the main stream users even if the number of the main stream users is much larger. It also has to be mentioned that the main stream users were also benefitting from platooning from the second intersection on. To these intersections the main stream users arrived in platoons and therefore they got green immediately. Because of the small number of
intersections on the network (3) these benefits could not outweigh the extra delay at the first intersection.

From the main stream users’ point of view the variability of waiting at the first traffic signal is much higher than the extra delay suffered from such a policy. For this reason the average user cannot be aware of being deprioritized to reach a better system behavior.

5.4.2. Generalization of the results

Different demand settings were tested on the network. In section 5.3.3.5 it was shown that behavior of the controller and the average delay does not change. The same entry and interconnection weights applied gave the best results in means of average delay. The only difference was the efficiency of the new interconnection measures; so how much the system benefitted from platooning the traffic the main stream at the first intersection. The measures were also tested using a different OD matrix where the number of side stream users was increased and the main stream decreased. Also new streams were added to the network on which there was no traffic in case of the first tested OD matrix. The framework also provided lower average delay in this case. Although the entry and interconnection weights were different at which the best performance was found, the general framework worked the same way. These results suggest that the general framework is not dependent on the (i) demand level, (ii) the OD matrix and (iii) the streams present at the intersections. Besides the previous statement the controller and the interconnection framework should be tested on other traffic networks which is added as a recommendation in section 5.5.

5.4.3. Similarities with un-signalized intersections

The controller of van Katwijk shows similarities with intersections that are controlled with road side traffic signs. There is large demand on the main streams of the arterial and the side stream users with relatively small demand waiting to find a gap in the main streams to merge or cross these. Because of the unknown side stream arrivals the controller can only take into account these vehicles when arrived at the stop line. The optimization of the controller looks for a sufficient gap in the main stream between the cars when a green can be scheduled for the side streams. The same is happening in case of controlling with road side traffic signs just the
side stream user is doing it on the basis of less information (because of the look-ahead feature of the controller). When the demand on the main stream is low there are several gaps in which the side stream users can be served. On the other hand when the demand is high the number of gaps that are larger than the critical gap is low. The waiting time on the side streams increases extensively. At this point the capacity of such an intersection type is called insufficient and a roundabout or signal control is placed. The signal control does the same basically what the weight changing framework. It provides large enough gaps for the side stream users to cross or to merge into the main stream with stopping the main stream. In case of traffic signal control there is a certain lower threshold under which traffic signal should not be placed. On the basis of this similarity it is likely that there is certain low demand under which such coordination is not beneficial. This similarity is also supported by the finding of section 5.4.2. The larger the demand (so the fewer gaps are present to serve side streams) the larger the improvement in network delay reduction.

5.4.4. Improvements of the tested measures and strategies

Table 5.12. shows the decrease of average delay using different coordination measures.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average delay of users [s]</th>
<th>Improvement compared to actuated [%]</th>
<th>Improvement compared to adaptive [%]</th>
<th>Nr. of stops per user</th>
<th>Improvement compared to actuated [%]</th>
<th>Improvement compared to adaptive [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuated coordinated control</td>
<td>14,26</td>
<td>-</td>
<td>-</td>
<td>0,585</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adaptive control without coordination</td>
<td>7,82</td>
<td>45,18%</td>
<td>-</td>
<td>0,301</td>
<td>48,64%</td>
<td>-</td>
</tr>
<tr>
<td>Adaptive control with common signal plan optimization</td>
<td>7,71</td>
<td>45,92%</td>
<td>1,35%</td>
<td>0,296</td>
<td>49,44%</td>
<td>1,56%</td>
</tr>
<tr>
<td>Adaptive control with network behavior improvement</td>
<td>7,09</td>
<td>50,28%</td>
<td>9,30%</td>
<td>0,283</td>
<td>51,65%</td>
<td>5,87%</td>
</tr>
</tbody>
</table>

Table 5.12. Decrease of travel time using different traffic control methods

In 5.3.2. section 3 strategies were mentioned that could be followed as prioritization strategies.

- Prioritizing main streams at the whole section of the arterial
• An extreme case of prioritization on the main stream with giving a very high weight to these vehicles.

• Platooning vehicles at the first intersection of the arterial with giving a lower weight to make them deprioritized by the controller. (creating extra gaps for the side streams)

From the results of table 5.5. (page 81) it is visible that only the third strategy is beneficial on a network level. The first one results in a slight increase of average delay because the side streams’ delay is increasing faster than the main streams’. The second results in an even worse situation because of last minute realization of green phase for the side streams.

5.5. Recommendation

Concerning the research on network performance of multi-agent traffic control 2 recommendations can be given for further research.

From the results it is visible that the basic theory of providing time gaps between the main stream platoons for the controller to serve side streams is working on the test network. However 2 OD matrix was tested during the research and the results of the new OD suggested the same results, the geometry of the intersections remained the same. It is suggested to test the theory and the weight changing framework on another network. This can prove that the results are general and not only representative on the test network. It is also suggested to use longer corridors with more than 3 intersections on them. This would help to find out whether the main streams could also benefit from such a strategy on a longer network. Now (as it is mentioned in section 5.4.) these streams are losing more time at the entry of the corridor than gain at the downstream intersections because of arriving in platoons.

Taking into account the fact that the ideal weight combination can change with the change of OD matrix and geometry a new question arose. How can the system be kept totally adaptive? However the geometry is not changing on an arterial but the demand on certain streams can significantly change according to: (i) time of the day, (ii) weekend, (iii) special events or (iv) accidents. To keep the interconnection of traffic signals optimal an online optimization method can be implemented. With this step the system can keep the coordination itself up to date. During this thesis one manual calibration was done on one network and 2 OD matrix to test the built theory. Later on the central optimization unit mentioned in section 5.1. should be
implemented to keep interconnection adaptive. However the effect of interconnection is really hard to measure in reality (because of traffic fluctuation on the corridor) and can only rely on longer term measurements than the 120 seconds prediction horizon of the controller. In section 3.1.1. the neural networks were mentioned as a tool for general problem solving. The structure of this system makes it possible to take into account every influencing factor even if these are influencing through an “if – then” relation. Using right feedback information the learning ability of the neural networks ensures that the system can update the interconnection values between the different intersections. These two features of the neural networks makes them a good candidate for the central optimization unit.
6. Conclusion

In this chapter first the research questions will be answered. After this briefly the conclusions of the separate chapters will be given.

6.1. Answering research questions

Main research question:

- What are the benefits of coordinating the intersection controllers in the multi-agent look-ahead traffic adaptive control system in reduction of average delay of the users on the network?

First of all it has to be mentioned that it is possible to reduce the average delay of users with coordinating the decentralized intersection controllers. There are two methods for this implemented in the controller. One is the common optimization of signal plans which turned out to be less beneficial because of the unknown arrivals on the side streams. The other method is to induce the decentralized controllers (with modified input to the local optimization) to act system optimally. Research results show that the second approach performs better. Using this method the average delay of users can be reduced up to 9,3 % using the best tested settings of the weight changing framework. Table 6.1. gives a clue about the benefits of such an improvement on the basis of the simulation results and section 3.2.1.

<table>
<thead>
<tr>
<th>Cost and Benefit components on the new Assen network</th>
<th>Adaptive traffic control</th>
<th>Adaptive control with new measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building &amp; Operation costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost of introduction for 3 intersections**</td>
<td>$-259,237,60</td>
<td>$-259,237,60</td>
</tr>
<tr>
<td>Stops/user*</td>
<td>0.301</td>
<td>0.283</td>
</tr>
<tr>
<td>Emission &amp; Fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total yearly extra CO2 emission cost</td>
<td>$1,611,12</td>
<td>$1,514,77</td>
</tr>
<tr>
<td>Total yearly extra fuel consumption</td>
<td>$28,467.64</td>
<td>$26,765.26</td>
</tr>
<tr>
<td>Total fuel emission costs</td>
<td>$-219,798.68</td>
<td>$-206,654.58</td>
</tr>
<tr>
<td>Average delay per user [seconds]*</td>
<td>7.82</td>
<td>7.09</td>
</tr>
<tr>
<td>Travel time loss in $</td>
<td>$-1,165,863.18</td>
<td>$-1,057,029.40</td>
</tr>
<tr>
<td>Total social cost in 10 years</td>
<td>$1,644,899.46</td>
<td>$1,522,921.58</td>
</tr>
<tr>
<td>€1,251,349.91</td>
<td>€1,158,555.78</td>
<td></td>
</tr>
<tr>
<td>Savings with controller coordination on the test network</td>
<td>$121,977.88</td>
<td>€92,794.13</td>
</tr>
</tbody>
</table>

Table 6.1. Benefits of the new coordination measures

*Simulation result;

**The test network used consisted of 3 intersections;
Sub-questions:

- What is the effect of platoon dispersion on the arrival pattern at an intersection and how can this effect be taken into account or avoided if vehicle platoons depart from an upstream intersection?

Platoon dispersion affects the arrival pattern at an intersection. It makes the dense platoons departing from an upstream source arriving during a longer time span with a lower saturation flow. This effect can be taken into account using probabilistic methods. According to the literature survey the effects can be avoided with speed advice which is already implemented in the controller. The prediction accuracy of analyzed probabilistic model on the arrival pattern is not much higher than the original prediction of the arrival pattern which omitted the effects of platoon dispersion. For this reason the implementation to the controller was abandoned.

- How can coordination be realized for the two main streams of an arterial at successive intersections so that the average delay of the users on the network is minimized, if the position of vehicles is known on the network further upstream of the intersections?

Coordination can be realized in a multi agent controller with common optimization of signal plans or inducing network optimal behavior with modified input of the optimization of local controllers. The common optimization has certain shortcomings therefore it is hard to implement it in real time according to section 5.4. The developed weight changing framework performed better in inducing network optimal behavior and reducing delay.

6.2. Summary of chapter conclusions

In this section following the structure of the thesis the conclusions will be summarized that can be found at the end of the different chapters.

6.2.1. Literature survey

The literature survey was done on two distinct topics which were identified in the problem definition as the possible problems of coordination. These problems were (i) the effects of platoon dispersion on the arrival pattern and (ii) coordination of unknown vehicle arrivals
with the known main stream arrivals. In the literature survey it was found that in adaptive systems coordination is usually done on cycle time basis. Using the multi-agent approach signs of coordination (like spontaneous “green waves” were identified) but none of the authors implemented it intentionally so far.

On the field of platoon dispersion two models were found to be a good candidate for testing. The first model was a probabilistic model which predicted the effects of platoon dispersion on the arrival pattern on a probabilistic basis. The second model was using neural networks for arrival pattern prediction.

### 6.2.2. Predicting platoon dispersion

In chapter 4 the probabilistic model of platoon dispersion was tested. The “naive” prediction that is already implemented to the controller is a simple method omitting the effects of platoon dispersion. The new prediction is not a very complex model but it would still ask extra computational capacity from the controller and make the program more complex. The increase in prediction accuracy dropped to 12-20% in case of simulation under real conditions. Under real conditions using the right detector places at the stop line of the signal heads the “new” prediction would provide a very small increase in arrival pattern prediction accuracy. This slight increase would probably remain invisible on the better decision making of the controller therefore in the delay of the users. Further details in section 4.6.

Because of the predictable very small benefits and the extra complexity that the implementation would mean it was decided not to implement the probabilistic model in the controller. It is recommended to test the second neural network based model to predict platoon dispersion. Further details to be found in section 4.7.

### 6.2.3. Coordination in multi-agent adaptive control

There are two methods how coordination is implemented in the controller of van Katwijk [4]. The first one is the common optimization of signal plan. This turned out to be the less beneficial because of the unknown arrivals on the side streams. The second one is to induce the decentralized intersection controllers with modified input in the local optimization to act network optimally. Using this approach (through weighting the delay of the main streams in
the internal optimization of the controller) network optimal behavior was induced. Results show that the average delay of the users on the network decreased significantly using this weight changing framework.

The best results could be gained when the main stream users were platooned (buffered) at the first intersection and then they were let through the corridor in platoons. The reason is that the side streams reacted more sensitively on providing gaps for them to merge or cross the main streams. According to this the average delay of the main streams increased slightly but it was outweighed by the large decrease of delay on the side streams. The problem shows similarities with the road side traffic sign controlled intersections. This suggests that there is a lower demand threshold on the main streams under which creating gaps is not beneficial anymore on a network level. Further details to be found in section 5.4.3.

The framework was tested on 3 demand settings and 2 different OD matrixes on the same network. In case of all of these scenarios the framework proved to be reducing the average delay of the users on the network. According to this (with respect to the statement at the end of the previous paragraph) the results of the framework seems general. Fine tuning of the weights of interconnection to improve network behavior of the decentralized controllers has to be done in case if the OD matrix changes. Further details can be found in section 5.4.2.

On the other hand the effects of geometry change are not tested therefore it is recommended to test the weight changing framework on another test network. Further details can be found in section 5.5.

During the research the main point was to prove that the weight changing framework is effective. It was also important to find the optimal strategy that could be followed to improve network performance of the fully decentralized multi-agent controller. The effectiveness of the framework is proved and an optimal strategy is found. Now that the optimal strategy is known it is recommended to implement a central optimization. Such a unit can keep the interconnection up to date maximizing the possible improvements of coordination. Further details to be found in section 5.5.
Appendix

A. Modeling and simulation environment

This thesis is relying heavily on computer simulation of road traffic. Therefore a brief review has to be given on the simulation environment. As simulation test bed the simulation tool of VISSIM of the PTV A.G. was used. This is one of the most wide spread simulation tool used nowadays.

a. VISSIM

Network structure:

Links in the program represent roads in reality. These roads are connected to each other with connector links to create a network. At decision points where users can make route choice nodes are added. Nodes also represent outside sources from where traffic is arriving to the simulated network and destination to where these vehicles are heading. According to a predefined Origin – Destination matrix it can be defined in the program from which outside source how many vehicles should go to the other outside destinations using the network. The program has various changeable features concerning: (i) vehicle features, (ii) traffic features or (iii) driving behavior. The change of the features can highly affect the measured variables of the traffic like the delay or queue length. In most of the cases as suggested in the manual these should be kept unchanged because only the original model is validated. Further details can be found in the manual of the program.[16]

Driving behavior:

The program has various changeable features concerning driving behavior. At some points of the research these were changed for certain reasons. In the following these will be shown.

The merging and diverging behavior of the simulation tool has challenges.[17] This is influenced by the lane change behavior of the program. To reach a more realistic behavior changes were implemented on the merging and diverging sections of the used network suggested by an assignment of Portland State University. These changes concerned lowering
safety distance reduction factor from 0.6 to 0 and raising the maximum deceleration for cooperative braking form -3.0 m/s² to an unrealistic -9.0 m/s² value. The changes were applied for example to the southern approach of intersection 46 on the Assen network. Using these settings resulted in a more realistic general diverging behavior.

b. Current environment of the controller
The control of traffic signals was done with the controller of van Katwijk (Multi-agent Look-ahead Traffic Adaptive Control System). This controller is written in Java. It communicates with VISSIM through a COM interface. Through this communication it gets the detector data and it is able to send back the signal control orders to VISSIM.

B. Networks used for the research

In this section of the appendix a brief review will be given about the networks that were used during the research.

a. The original Assen network
In section 3.1.3.2. the results of the controller without coordination were tested against the currently existing actuated control. For those tests a network of 5 intersections was used located on the North of the Netherlands in the northern part of Assen. 8 zones were defined between which the origin and destination (OD) matrix defined the number of vehicles. The network is shown on B.1. figure. The OD matrix can be found in the table B.1.

<table>
<thead>
<tr>
<th>Origin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>0</td>
<td>0</td>
<td>54</td>
<td>68</td>
<td>101</td>
<td>1024</td>
<td>40</td>
<td>43</td>
</tr>
<tr>
<td>Zone 2</td>
<td>0</td>
<td>0</td>
<td>90</td>
<td>21</td>
<td>31</td>
<td>317</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Zone 3</td>
<td>17</td>
<td>20</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>38</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Zone 4</td>
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<td>31</td>
<td>3</td>
<td>0</td>
<td>6</td>
<td>65</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Zone 5</td>
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<td>40</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>82</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Zone 6</td>
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<td>728</td>
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<td>100</td>
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<td>0</td>
<td>58</td>
<td>63</td>
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<td>Zone 7</td>
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<td>27</td>
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<td>3</td>
<td>5</td>
<td>55</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zone 8</td>
<td>27</td>
<td>29</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>59</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table B.1. OD matrix of the original Assen network
b. The new Assen network

In chapter 4 and 5 during the research a part of the original Assen network was only used. This network only contains 3 intersections; the three that were coordinated in the actuated control as well. This was done to reduce simulation time. The OD matrix of new network of Assen is shown in table B.2. The new network of Assen is shown on B.2. figure.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Zone 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
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<td>195</td>
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<td>68</td>
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<td>1024</td>
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<tr>
<td>2</td>
<td>53</td>
<td>0</td>
<td>15</td>
<td>24</td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>32</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>34</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>6</td>
<td>671</td>
<td>0</td>
<td>59</td>
<td>100</td>
<td>1011</td>
<td>0</td>
</tr>
</tbody>
</table>

Table B.2. OD matrix of the new Assen network
c. The new Assen network with new OD
In chapter 5 a new OD setting were tested on the new Assen network of 3 intersections. Table B.3. shows the new OD data that were used.

![New Assen network of 3 intersections](image)

**Figure B.2. New Assen network of 3 intersections**

<table>
<thead>
<tr>
<th>Origin</th>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
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<td>100</td>
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<tr>
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<td>59</td>
<td>100</td>
<td>1011</td>
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<td></td>
</tr>
</tbody>
</table>

**Table B.3. New OD matrix of the new Assen network**
References

1. T. H. J. Muller, A. Hegyi, M. Salomons, H. J. van Zuyleen; Traffic Management and Control; CT4822-09 course reader, Faculty of Civil Engineering, Delft University of Technology, 2011


7. J. Carrière, Reducing CO2 emissions in urban areas with adaptive traffic control and in-car speed advice, MSc. Thesis, Faculty of Mechanical, Maritime and Materials Engineering (3mE), Delft University of Technology, 2011


11. R. Babuška, Knowledge based Control Systems, SC4081 course reader, Faculty of Mechanical, Maritime and Materials Engineering (3mE), Delft University of Technology, 2010


17. D. Petres, Internship at TNO; Traineeship experience report; Faculty Civil Engineering and Geosciences, Delft University of Technology, 2011


24 Website of ODYSA project (http://www.odysa.nl/) entered 02.12.2011


27 L.B. de Oliveira, E. Camponogara, *Multi-Agent model predictive control of signaling split in urban traffic networks*, Transportation Research Part C 18 120–139, 2010

28 P.H.L. Bovy, M.C.J. Bliemer, R. van Nes, *Transportation Modeling: CT4801 course reader*, Faculty of Civil Engineering, Delft University of Technology, 2006

29 R. J. Verhaeghe, M. Minderhoud, K. Lindveld, *Data collection and Analysis: CT4831 course reader*, Faculty of Civil Engineering, Delft University of Technology, 2007