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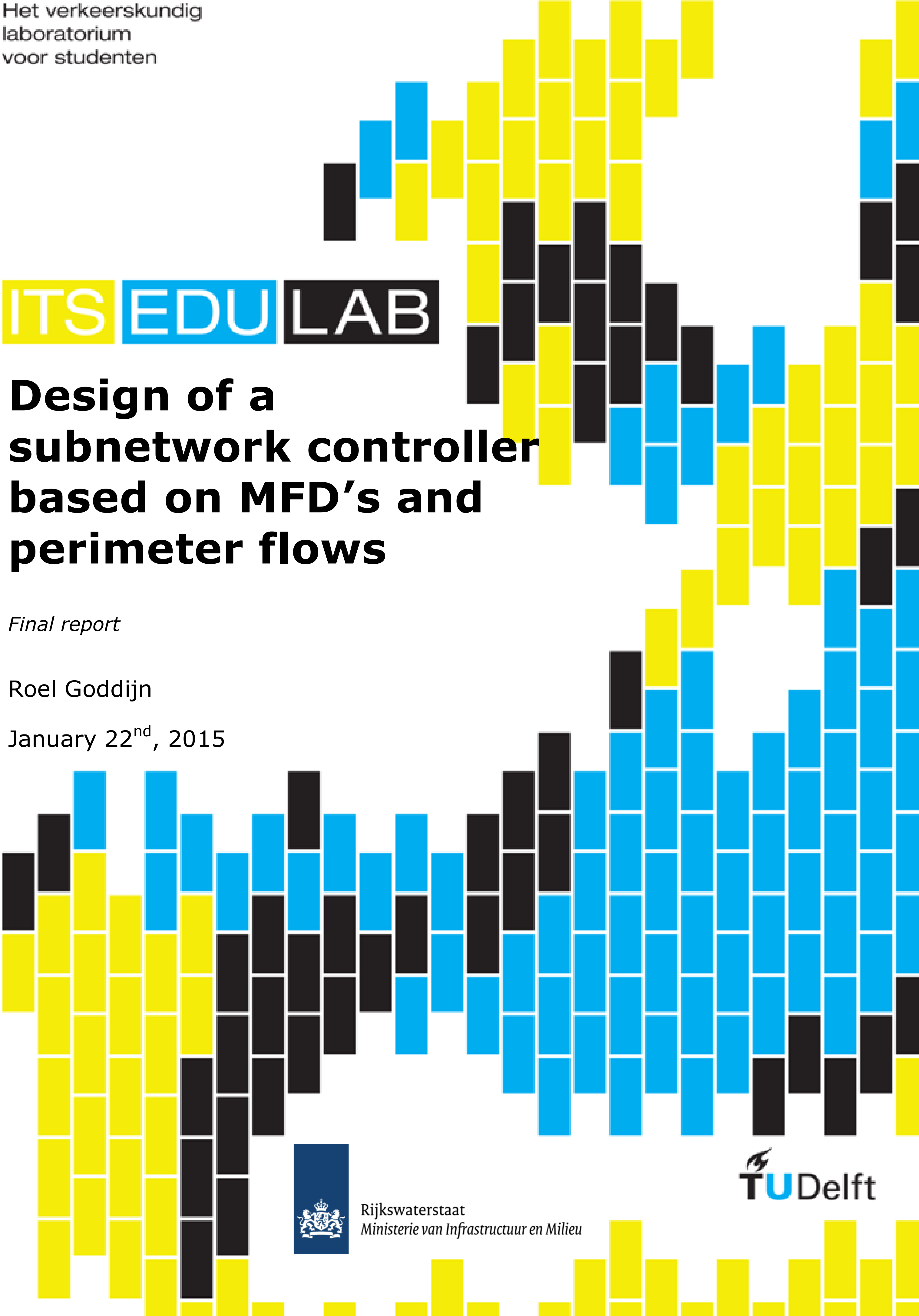

Design of a subnetwork controller based on MFD's and perimeter flows

Final report

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Preface

For completing my study Civil Engineering at the Delft University of Technology I have performed this graduation thesis which is part of my master Transport & Planning. I have performed my graduation thesis at ITS Edulab which is a cooperation between Rijkswaterstaat Centre for Transport and Navigation and the Delft University of Technology.

I would like to thank the Water, Verkeer en Leefomgeving (WVL) department in Delft of Rijkswaterstaat for creating a comfortable place to work. Furthermore, I would like to thank my complete graduation committee who helped me through my graduation with interesting questions, comments and ideas. The appointments with my daily supervisors Maria and Andreas were very helpful in fulfilling my task. They have steered me in the right direction if I got stuck on some aspects. I want to thank Andreas for helping me with the theoretical and scientific aspects of my graduation subject. My thanks go to Maria especially for helping me using simulation software such as VISSIM and program software such as Matlab.

Most important during my graduation were my family and friends. They helped me trough my setbacks and kept believing in my ability to complete my graduation thesis. I want to thank them, and especially you, Kimberley.

Roel Goddijn
Delft, January 2015

Abstract

The traffic state of a road network can be described by a so called macroscopic fundamental diagram (MFD). The average production is related to the accumulation of a specific road network in this diagram. Studies have shown that the MFD could be used in an evaluation based method of a certain road network. A promising application field of the MFD is to introduce the MFD in the steering mechanism of a traffic controller.

Due to increasing congestion on urban roads, extra road capacity might be needed. However, for economic reasons better usage of the current road capacity should be performed. Therewith, the intersection density in road networks has increased nowadays. One of the consequences is that the way of controlling a certain intersection influences the traffic state at another intersection. Therefore, traffic controllers should be connected when controlling traffic at individual intersections.

In this thesis a subnetwork flow controller has been designed. A road network which is controlled in a hierarchical setting by a main controller can be split up in several subnetworks. By controlling the perimeter flows between the subnetworks, the traffic state of each subnetwork can be controlled. In this thesis, only traffic signals at intersections have been taken into account as the control units. The designed subnetwork flow controller had to contribute to three main objectives:

1. Maintaining a constant shaped MFD,
2. Optimizing internal flows,
3. Provide desirable perimeter flows.

The subnetwork flow controller algorithm has been based upon a back pressure algorithm which belongs to the coordinated traffic responsive control strategies in existing traffic controllers. A back pressure algorithm has been chosen due to the property of balancing queues which should result in homogeneity of traffic conditions within a subnetwork. The back pressure algorithm determines pressures for every individual intersection and every traffic phase consisting of several traffic streams. For every traffic stream the downstream queue length is subtracted from the upstream queue length and multiplied with the turn ratio at which traffic can go through the intersection at that specific traffic stream. The pressure of a phase is calculated by adding up individual pressures of traffic streams which are part of that specific phase.

Due to the property of balancing queues by the back pressure algorithm and the assumption that homogeneity in traffic conditions might improve internal flows, some adjustments had to be performed only in order to provide desirable perimeter flows. A maximum deviation factor has been set up which allows a certain deviation of the actual perimeter flows with respect to the desirable perimeter flows which have been set up by the main controller. When the deviation exceeds a certain value, traffic streams have to be blocked when the actual perimeter flow is too high or have to get right-of-way when the actual perimeter flow is too low. By reducing the available phases from which the subnetwork flow controller can choose, the perimeter flows can be controlled.

In order to evaluate the performance of the designed subnetwork flow controller, simulations have been performed in VISSIM where the subnetwork flow controller (written in Matlab) has been applied. Simulations with an applied vehicle-actuated controller and basic back pressure controller have been performed first in order to derive a most desirable size of the subnetwork layout and get reference results for evaluating the performance of the subnetwork flow controller.

Simulations have been performed with subnetworks consisting of four, eight and sixteen intersections and different applied demand patterns. It turned out that a subnetwork consisting of sixteen intersections controlled by a vehicle-actuated controller or back pressure controller provides a MFD with the lowest scatter size, determined by the standard deviation of the absolute scatter deviation with respect to the constructed running median of the MFD. This low scatter resulted also in a constant shape of the MFD independent of the applied demand pattern. Therewith, with increasing size of the subnetwork the back pressure controller was able to control the traffic in the subnetwork better when evaluating total delay and internal production. This is caused by the result that gridlocks can be postponed by the back pressure controller.

When applying the designed subnetwork flow controller on a subnetwork consisting of sixteen intersections, different maximum deviation factors have been applied. It turned out that there was no significant difference in performance on all three objectives between the applied deviation factors. Moreover, it turned out that the subnetwork flow controller was able to control perimeter flows at intersections with two adjacent intersections better as three adjacent intersections. Therefore, some extra simulations have been performed with an additional value of the maximum deviation factor and different desired perimeter flows for perimeter flows at intersections with two or three adjacent intersections.

The subnetwork flow controller designed in this thesis has been proven to work properly according to the simulation results. When the subnetwork flow controller provides the desired perimeter flows (under certain circumstances), a constant shaped MFD can be maintained. However, another result is an increase in delay and thus less optimal internal flows compared to the performance of a vehicle-actuated controller. Therewith, a non constant shaped of the MFD was the result of some simulations caused by the influence of setting up the values for the desired perimeter flows and maximum deviation factor.

No optimal values for the maximum deviation factor and restrictions on setting up the desired perimeter flows have been found in the algorithm of the subnetwork flow controller. It is therefore recommended to perform extra simulations in order to derive these aspects before the subnetwork flow controller is suitable in a hierarchical control structure. It is also recommended to perform extra simulations with more different kind of demand patterns and different control time intervals. Furthermore, future research is recommended on clearance times, the measuring way of queue lengths, applying more heterogeneous subnetworks, applying different kind of dynamic traffic management (DTM) measures and evaluating method of scatter size.

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1 Introduction

Due to increasing expansion of urban areas, traffic controllers will face challenges in traffic control. The increasing need of amount of road capacity is a result of the increasing number of vehicles on roads and therewith congestion. In order to increase the amount of road capacity, new infrastructure could be build. The costs for this solution are however very high. Instead of building new infrastructure, a better utilisation of the existing road infrastructure should be reached. Designing a traffic controller which deals with congestion can be a solution. The Macroscopic Fundamental Diagram (MFD) can be used in an observation based method in order to describe the level of service of a network. Besides an observational function, the MFD could be part of the control mechanism in order to control traffic in a subnetwork. This controller can aim at different objectives such as optimizing the internal traffic flows, maintaining a constant traffic state of the subnetwork by using constant shaped MFD's and realizing desirable perimeter traffic flows. Such a traffic controller will be designed in this thesis where MFD's play an important role. First, an introduction in traffic network control will be given, especially in the scope of the subnetwork traffic controller which will be designed. The thesis research objectives and the research questions will be introduced as well. At last, the outline of this thesis will be described.

1.1 Scope of thesis

In this thesis a traffic controller will be designed where MFD's play an important role. The focus of this controller will be on a subnetwork scale. The subnetwork on which the controller will be applied is part of an urban network which will be controlled by a main controller. The way of dividing an urban network in multiple subnetworks can vary. In a reservoir based partitioning of the urban network, all subnetworks border on other subnetworks by links or intersections. A partitioning of the urban network in subnetwork based on road function is also an option. In that case, a distinction could be made in primary roads and secondary roads. Another possible partitioning is to take into account the demand and thus only include roads and intersections with a significant demand. In this thesis, it is chosen to take into account a reservoir based partition. This way of partition makes it clear to work with and requires less complex design approaches.

It is assumed in this thesis that the main controller sets up desired traffic states for all subnetworks in order to realise optimal traffic flows between the different subnetworks. This way of controlling traffic in subnetworks is currently performed in many important cities all over the world. However, using the MFD in the control algorithm of the subnetwork traffic controller has not been performed yet. By using the MFD, the traffic state of the subnetwork can be described.

The MFD is used in this thesis due to the fact that it gives an overview of all possible traffic states of the subnetwork which may occur. Therewith, information on average traffic flow and total number of vehicles present in the subnetwork can be derived at a certain moment in time such that decisions on controlling traffic may be made by the subnetwork controller on this available information.

The main controller desires a constant shaped MFD in order to maintain desirable traffic conditions. When the shape of the MFD of a subnetwork is maintained constant, the main controller can make decisions at higher level scales. The main controller is able to control several subnetworks when traffic states of each individual subnetwork can be estimated due to the availability of a constant shaped MFD. More in depth information on this aspect has been derived by performing some literature survey on the hierarchical setting in controlling traffic in a subnetwork.

A connection between a main controller and several subnetworks does exist in network traffic control. The scope of this thesis is visualised in the red ellipse in figure 1-1.

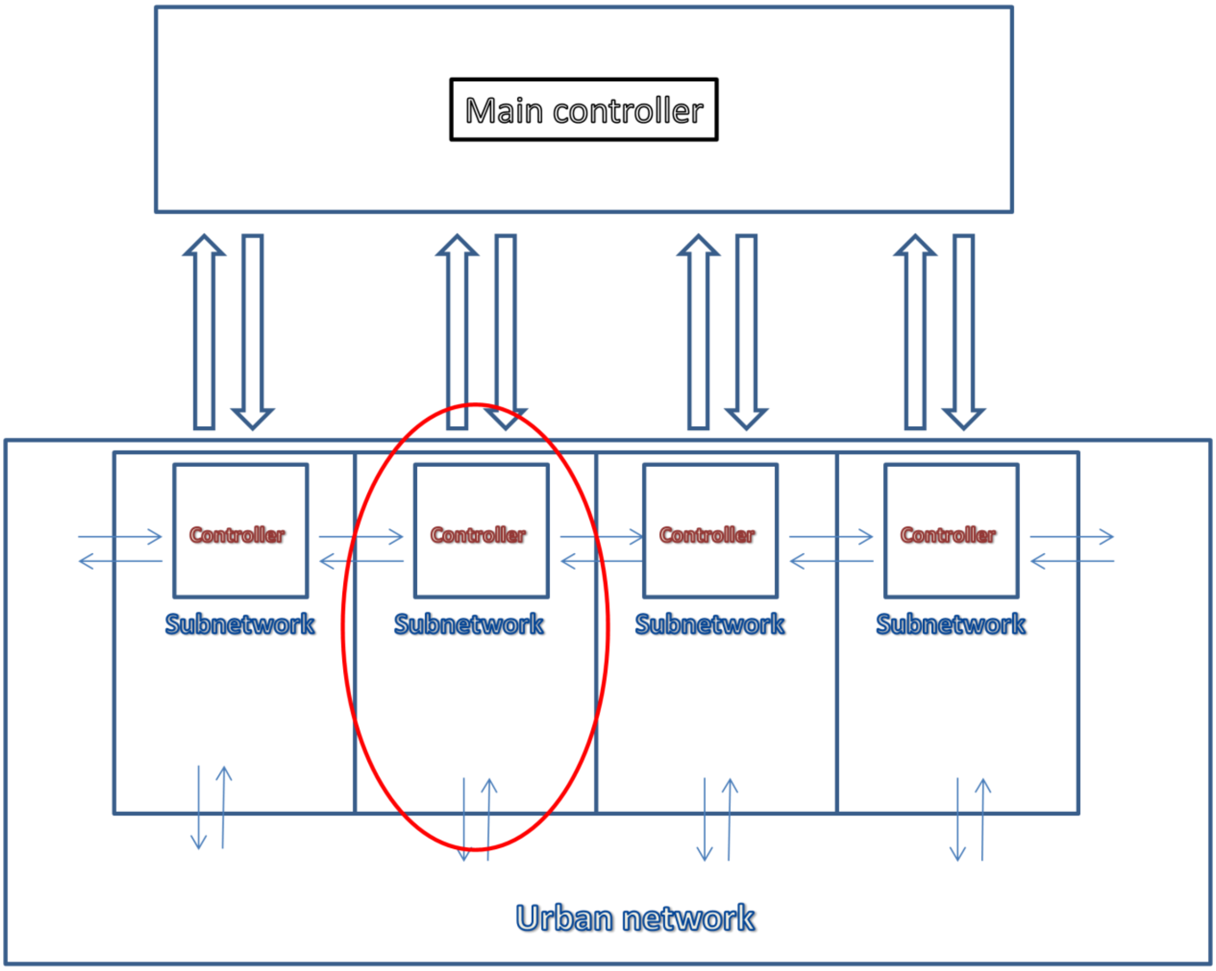


Figure 1-1: Scope of thesis

A clear information pattern is visible between the main controller (indicated by the big arrows), which sets up the desired traffic state of each subnetwork by describing desirable perimeter flows, and the subnetwork flow controller, which operates on a part of the entire urban network. This entire urban network could be a whole city where subnetworks represent different neighbourhoods. The subnetwork flow controller has to control traffic in one of these different subnetworks. The physical perimeter traffic flows between the subnetworks and physical perimeter traffic flows entering and leaving the urban network are represented by the small arrows in figure 1-1.

The traffic controller at subnetwork level is connected in three ways to other elements in the control structure. The traffic state of each subnetwork can be described by a MFD. The shape of these MFD's can vary but should be of a constant shape which is desired by the main controller. More in depth information on the MFD shape is described in paragraph 2.3.

Besides the information of the main controller, the subnetwork flow controller needs information about the current state of the subnetwork as well. The current traffic state of the subnetwork can be described by traffic measurements. Examples of these traffic measurements are number of vehicles on the subnetwork, average traffic flow on the subnetwork, way of distribution of vehicles over the subnetwork, etc. The subnetwork flow controller will have an output (control signal) which will provide information for Dynamic Traffic Management (DTM) measures like traffic signals, ramp metering signals and dynamic route information panels. The current state of the DTM measures will be changed or maintained when necessary which will influence the traffic patterns on the subnetwork. Before changing the DTM measures, the current state of the DTM measures need to be known. Therewith, sensors of DTM measures can give information about the current traffic state to the subnetwork flow controller as well. In figure 1-2 a schematic overview of the subnetwork flow controller with inputs and outputs is shown.

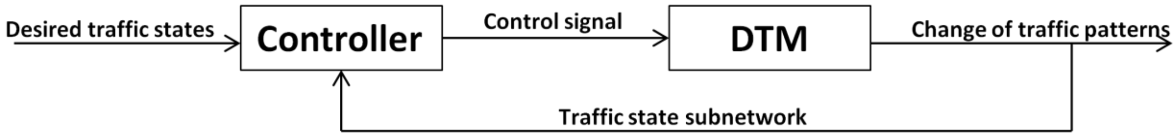


Figure 1-2: Schematic overview subnetwork flow controller

The controller in figure 1-2 is the scope of this thesis. Within this controller certain objectives, which are presented in the next paragraph, will be the focus of this controller on which it should contribute.

1.2 Research objectives

The main goal of this thesis is to design a subnetwork flow controller where the MFD plays a role in the traffic state of the subnetwork. This controller operates at a subnetwork level in the hierarchical set up of urban road networks. The designed subnetwork flow controller has to control traffic in a single subnetwork which is part of a larger urban network such that it contributes to three main objectives.

The first objective is to maintain a constant shaped MFD of the subnetwork which describes the traffic state of the subnetwork on which the subnetwork flow controller will be applied. It is assumed that the main controller from the upper level control desires such a constant shaped MFD in order to maintain a desirable traffic state of the subnetwork. Adaptions on the current state of the subnetwork need to be made by the subnetwork flow controller when the current state does not match the desired constant shape of this MFD.

The second objective is to optimize the internal flows of the subnetwork. A subnetwork can be controlled better when there are as less as possible disruptions in the traffic flows. It is better to prevent congestion instead of solving it. Optimizing the internal flows of the subnetwork will result in shorter travel times for vehicles. Therewith, when internal flows are optimized, accumulation of vehicles can be distributed over the subnetwork more equally which contributes in deriving a constant shaped MFD of the subnetwork.

The third objective is to contribute to some desirable perimeter flows. The assumption in the design of the subnetwork flow controller in this thesis is that the main controller sets up these desired traffic flows at the boundaries of the subnetwork. The objective of the subnetwork flow controller is to realise these instructions given from the upper level control. When the subnetwork flow controller contributes to this objective, the main controller will be able to control multiple subnetworks more feasible.

In order to check the performance of the designed subnetwork flow controller, some simulations will be performed. In these simulations, criteria and objectives will be set up in order to check the performance of the subnetwork flow controller.

1.3 Research questions

In order to reach the aim of this thesis and to contribute to the three main objectives of the subnetwork flow controller, some research questions have been set up. These research questions will help reaching the aim of this thesis more feasible. These research questions can be distributed over several aspects. The aspects which will be performed to reach the main goal of this thesis are analysing, designing, programming, optimizing and evaluating. The research questions are listed below.

1. Designing the subnetwork flow controller:
    a. On which criteria and objectives (input) should the subnetwork flow controller be designed to?
        i. What will the constraints (MFD and perimeter traffic flows) given by the main controller look like where the subnetwork flow controller should contribute to?
        ii. What information of the current traffic state and flows of the subnetwork should be available for the subnetwork flow controller?
    b. Which approach of traffic controlling exist in subnetwork traffic control and which kind of approach should be taken for the subnetwork flow controller which uses MFD's and provides desirable traffic flows?
    c. Which DTM measures should be controlled by the subnetwork flow controller in order to control traffic flows in a subnetwork?
    d. What should be the control signals (output) of the subnetwork flow controller in order to operate those DTM measures?
2. Implementing the designed subnetwork flow controller in a simulation program in order to test the performance:
    a. Which kind of subnetwork should be chosen, which has the desirable size to get and maintain a constant-shaped MFD, to perform the simulations on?
    b. Which objectives or criteria should be taken into account to evaluate the performance of the subnetwork flow controller?
    c. What are the performances of the subnetwork flow controller with respect to other existing subnetwork controllers?

1.4 Thesis outline

First the literature survey approach will be explained in paragraph 2.1. Paragraph 2.2, 2.3 and 2.4 combined form all executed literature survey. The hierarchical setting in traffic control (paragraph 2.2), the MFD properties (paragraph 2.3) and knowledge on existing urban traffic controllers (paragraph 2.4) are the basis for the design of the subnetwork flow controller which will be described in chapter 3. For testing the performance of the designed subnetwork flow controller, a simulation set up has been made in chapter 4. The results of these simulations are described and visualised in chapter 5. This thesis concludes with some conclusions and recommendations which can be found in chapter 6.

2 Literature survey

A literature survey has been performed in order to get insight in several aspects of urban traffic control. First an introduction is given on the framework of the literature survey. Literature survey has been performed on three aspects. These three aspects are:

- **The hierarchical setting in subnetwork traffic control**
- **The Macroscopic Fundamental Diagram**
- **Urban traffic control approaches**

In the introduction, it is made clear why the literature survey focuses on these aspects and which information is needed in order to design a proper subnetwork flow controller. The more in depth information on the performed literature survey can be found in paragraphs 2.2, 2.3 and 2.4.

2.1 Introduction

A short introduction is provided on three aspects of the literature survey.

2.1.1 Hierarchical traffic control for subnetworks

In a hierarchical setting, an urban network is controlled by different controllers at different levels. It is assumed in this thesis that the main controller, which controls an entire urban network which consists of multiple subnetworks, provides the desired traffic perimeter flows between subnetworks.

This hierarchical setting of traffic control has been used in multiple different kinds of traffic controllers. Insight in this hierarchical setting (and some application of it) will provide some information of the scope of the subnetwork traffic controller which will be designed in this thesis. Therewith, one of the objectives of the design of the subnetwork flow controller is to realise certain perimeter traffic flows at the boundaries of a subnetwork. The workings of a hierarchical setting need to be made clear in order to deal with such an objective. Since it is desired by the main controller that the MFD of the subnetwork has to have a constant shape, the position of the main controller and the subnetwork flow controller need to be explained.

2.1.2 The macroscopic fundamental diagram

A lot of studies have proven that the state of an urban subnetwork can be described by MFD's. Due to the fact that the MFD can be part of the control mechanism of the controller in this thesis, some research on the shape of, the application of and the influences on the MFD is needed.

Research on the shape of the MFD is needed in order to contribute to the objectives of the subnetwork flow controller which are set up in this thesis. Three main objectives have been set up on which the subnetwork traffic controller has to contribute as well as possible. One of these objectives is to maintain a constant MFD. This constant shape of the MFD, on which the controller has to control to, is assumed to be desired by an upper level controller in order to maintain a desired traffic state of the subnetwork. The shape of the MFD will influence the way of mathematically describing the input signals and output signals on which the subnetwork flow controller will be based.

Insight into the current fields of application of the MFD will provide potential opportunities for the MFD in urban network control. A distinction can be made in observation based usage of the MFD and (perimeter) control where the MFD will provide constraints in controlling the traffic flows.

The circumstances, in which a constant shape of a MFD can be maintained, will influence the design of the control mechanism of the subnetwork flow controller. Since the MFD has two aspects, accumulation and traffic flow (described in paragraph 2.2), control signals provided by the subnetwork flow controller should probably focus on these two traffic measurements. The provided control signals should contribute to the main objectives of the subnetwork traffic controller. Research on the influence factors on the shape of the MFD may result in other aspects, besides accumulation and traffic flows, which influence the way of dealing with a constant shape of the MFD.

The shape of, application of and influences on the MFD will also be part of this literature survey due to the possible influence of the size of the subnetwork layout which will be applied in the simulations. For testing the performance of the designed subnetwork flow controller, simulations will be performed in a simulation program where a subnetwork will be set up. It is possible that the size of the applied subnetwork can influence the shape of the MFD of the subnetwork.

2.1.3 Urban traffic control approaches

In order to design the control mechanism, a certain approach of the subnetwork flow controller will be chosen. A difference can be made between model based controllers and non-model based controllers. Each kind of these controller approaches has advantages and disadvantages with respect to the objectives of the subnetwork flow controller.

In a model based approach, actuators, sensors, models and optimization processes will be used in order to control traffic. Sensors will provide the necessary traffic measurements, while actuators (like traffic signals and ramp metering signals) will influence change of traffic patterns on the subnetwork. Traffic controllers can be mathematically described by the use of a cost or objective function which is the basis of a model based traffic controller. Optimization in this cost or objective function (minimized or maximized respectively) has to be done accounting the state of the system. A traffic model can describe this state of the system.

In a non-model based approach, traffic will be controlled without optimization of a cost or objective function. A non-model based approach focuses on the presence of vehicles at traffic signals only.

All available existing controllers (model and non-model based) can be divided in different categories. These categories are:

1. Fixed-time control strategies
2. Traffic responsive control strategies
3. Fixed-time coordinated control strategies
4. Coordinated traffic-responsive control strategies
5. Integrated urban-freeway traffic control strategies

Literature research on these existing traffic controller strategies will be performed by setting up the advantages and disadvantages of each kind of strategy. Concluded from this information, a certain existing traffic controller approach can and will be chosen to design the subnetwork flow controller onto. Therewith, the performance of all kind of traffic controllers on the proposed objectives of the subnetwork flow controller to which it should contribute can be described.
When an existing control strategy can be used in the design of the subnetwork flow controller, actual designing the subnetwork flow controller will be simpler and probably less time consuming.

2.2 Hierarchical traffic control for subnetworks

Hierarchical traffic control is an approach of controlling traffic where multiple controllers operate on different levels. Interaction between these controllers is necessary in order to control traffic in a subnetwork as well as possible. The subnetwork flow controller which will be designed will be based on this hierarchical setting of traffic control in subnetworks. Some research on this hierarchical control of traffic has been performed in order to make the scope of the subnetwork flow controller more clear. A distinction has been made in three different levels of traffic control.

2.2.1 Levels of subnetwork traffic control

Coordinating different traffic signals of different intersections is essential in order to gain optimal traffic flows in a network. A network of roads can be split up in multiple subnetworks. Each subnetwork contains multiple intersections, as in a reservoir based partition, with traffic signals which can be controlled separately from other subnetworks. All of these subnetworks combined form the total network a main controller (High Level Controller, HLC) has to control (De Moor et al. 2001). This main controller focuses on the desired flows on the perimeter of the subnetworks on which Medium Level Controllers (MLC) should focus. At a local level, the Low Level Controllers (LLC) operates where DTM (dynamic traffic management) measures are applied. Examples of DTM measures are traffic signals, ramp metering signals and dynamic route information panels. The hierarchical approach of controlling traffic is shown in figure 2-1.

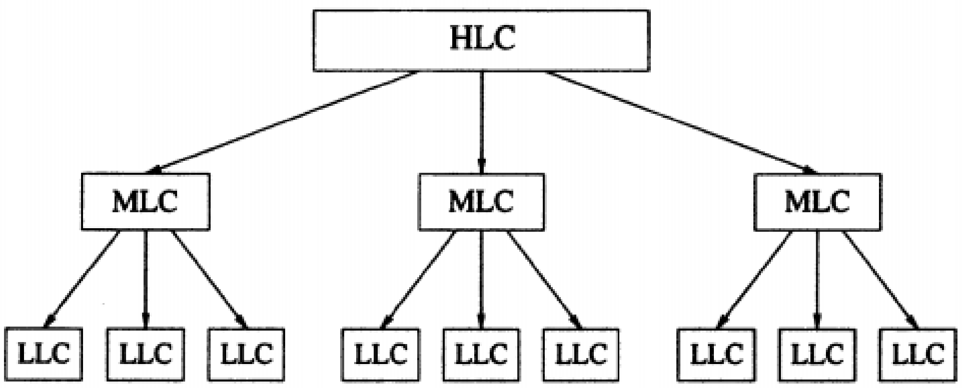


Figure 2-1: Hierarchical control in traffic

Traffic signals are the main control units in urban areas. Ramp metering signals are mainly used at onramps at highways. But since a road network does not end at the boundaries of an urban area, all kind of traffic measures could be part of a cooperative traffic control system. These DTM measures influence each other when the network of these control measures is closer. The functioning of most of the traffic measures are autonomous (Katwijk and Taale, 2012). A local disruption in the traffic flows can be dealt with by the traffic measures without needing a controller at a higher level scale. This autonomous functioning of the traffic measures is a very good property. The downside is however, that the effective functioning of the network as a whole cannot be guaranteed. It is necessary that the control measures need to be coordinated in order to gain an effective network of traffic flows. This is especially important in urban areas due to the close location of different intersections with traffic signals.

In network traffic control, a main controller can desire a certain traffic state for the entire network. This main controller can use MFD’s in order to describe this desired traffic state. At a lower scale, controllers operate on the border between multiple subnetworks where they influence the traffic flows that transfer between these subnetworks. An optimal perimeter control has to be maintained in order to meet the desired traffic state of the entire network. In Geroliminis, Haddad and Ramezani (2012) model predictive control has been used in order to solve this optimal perimeter control problem. This prediction model is formulated by MFD’s. DTM measures on a local level are taken in order to reach the desired traffic flows between the subnetworks. This control structure is shown in figure 2-2.

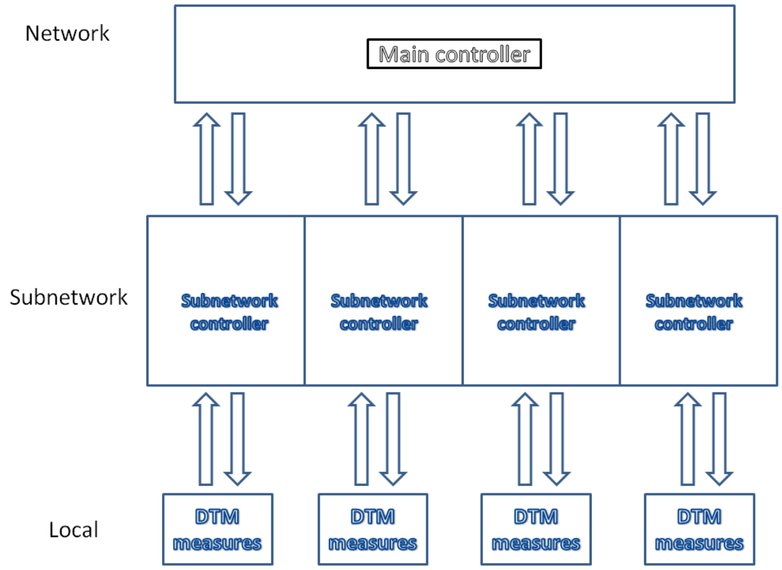


Figure 2-2: Control structure urban traffic at three levels

In order to derive optimal traffic flows, traffic measure scenarios could be implemented. Traffic measure scenarios are predefined sets of traffic measures where is stated how they should be implemented. A major drawback of traffic measure scenarios is that not all relevant situations which could occur in a network can be covered with these traffic measure scenarios.

A hierarchical control structure will be handled in the design of the subnetwork flow controller in this thesis. In this hierarchical structure, input for the controller will be given by the main controller and the local DTM measures. Due to the fact that the focus of this thesis will be at an urban level, no highways are included, traffic intersection signals will be the main and only DTM measures the subnetwork flow controller has to control. At an urban level, route information panels may be used as well in order to control traffic when certain traffic flows are too high. However, for simplicity reasons, traffic signals will be the only DTM measure which will be controlled in this thesis. The subnetwork flow controller will provide output to the main controller about the state of the subnetwork and the internal and perimeter traffic flows. Therewith, the subnetwork flow controller will provide output for the traffic signals in order to control the traffic in the subnetwork. The interactions between the different levels are shown in figure 2-2.

2.3 MFD in traffic control

It has been stated in several studies like Geroliminis and Daganzo (2007, 2008), Geroliminis, Haddad and Ramezani (2012) and Knoop and Hoogendoorn (2011) that MFD's can play an important role in traffic control in large-scale networks. In this thesis, a controller will be designed which controls traffic on a subnetwork level. The MFD will play an important role in this subnetwork flow controller. Some research on the MFD is performed in order to get more insight into the shape of, application of and influences on the MFD. The shape of the MFD needs to be investigated in order to describe it mathematically in the design of the subnetwork flow controller. Therewith, the MFD can be a tool which describes the performance of the subnetwork flow controller. Research on the fields of application of the MFD will provide information of the usage of the MFD in a subnetwork flow controller. At last, the research on the factors of influences on the shape of the MFD is performed. These influence factors will provide the main aspects on which the subnetwork flow controller has to focus during operation.

2.3.1 Shape of MFD

The traffic state of an urban road network can be described using the Macroscopic Fundamental Diagram (MFD). The number of vehicles on the entire road network, which is called the accumulation, and the traffic flow in the network are related to each other through the MFD (Geroliminis and Daganzo, 2008). To determine the traffic flow in an entire network (also known as the production), several aspects need to be taken into account. Beside the actual traffic flow in the network, the traffic flows entering and leaving the network need to be known as well. The production can also be described as the trip completion flow, which is defined as the output of the urban network. The accumulation can be found on the horizontal-axis of the MFD and the production on the vertical-axis. The MFD is based on the fundamental diagram (FD) which shows a relation between density on a particular road and the associated traffic flow on that part of the road.

Efficient monitoring and traffic management of large-scale urban networks can be very complex. The MFD aims at simplifying the micromodeling task of the urban network (Geroliminis, Haddad and Ramezani, 2012). Instead of modelling the traffic flow dynamics of each element in a large-scale urban network (urban links and signalised intersections), the collective traffic flow dynamics should be captured. These collective traffic flow dynamics are characteristics of the large-scale network such as the evolution of space-mean flows and densities in different areas of the urban network. The MFD can be used in control strategies to improve mobility and decrease delays in large-scale networks. Local strategies cannot reach these targets; they will only cope with local disruptions.

When accumulation increases, the production increases as well towards a critical point in the MFD. This increase in accumulation can cause a decrease in production when the accumulation increases beyond this critical point.

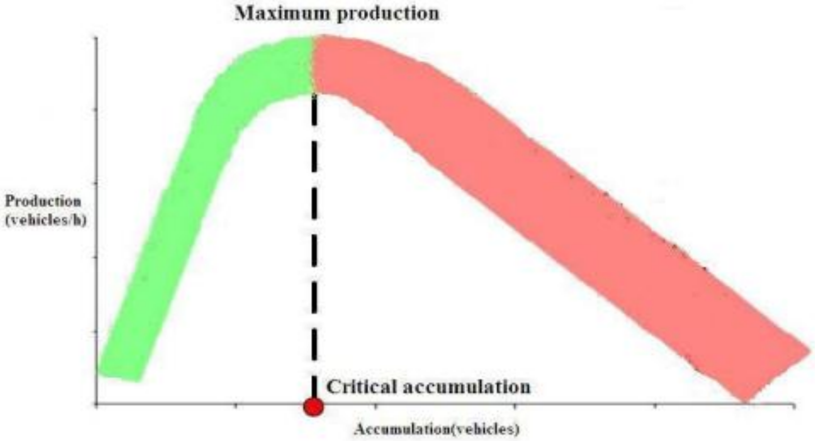


Figure 2-3: Example of a MFD (Feifei Xu et al, 2013)

The MFD of urban areas, which have a size which is still be able to control by subnetwork controllers, should be independent of demands (and also the origins and destinations of vehicles) according to Daganzo (2007). The MFD is only a property of the network infrastructure. Due to this independency on demands, the MFD can be used in order to control traffic in an urban network such that the production is maintained as closely as possible to the sweet-spot value. This sweet-spot value lies around the critical point of the MFD.

Knoop and Hoogendoorn (2011) showed that the performance of a network is a smooth function of the average network density (also known as the accumulation) and the spatial variation of density. Therewith, they concluded in their study that these kind of two-variable MFD's can be used for network control, for instance at ramp metering installations or at a more aggregate level perimeter control. Saberi et al. (2012) expect a chaotic pattern of the MFD when the spatial distribution of link densities is inhomogeneous while the average network density (accumulation) remains high and roughly unchanged for successive time intervals.

2.3.2 Fields of application MFD

In network traffic control, a main controller can set up desirable traffic flows at the boundaries of subnetworks. Controllers at boundaries have to maintain in that case an optimal perimeter control in order to realise these desirable traffic flows. Each subnetwork needs to be controlled by DTM measures. It has already been studied how the traffic flows between these subnetworks need to be controlled (Aboudolas and Geroliminis, 2013). But it has not been studied yet how to provide these perimeter flows by controlling an entire subnetwork.

In Knoop et al. (2011) a multilevel control is proposed. A decentralized control architecture on the basis of escalation and coordination is used. As long as the conditions on a local scale are sufficient, local controllers can manage the traffic. When the situation escalates, controllers at a higher scale should provide instructions based on the traffic conditions on that level. In case a network reaches a critical accumulation, a main controller could communicate to the perimeter controllers of subnetworks to lower the inflow of traffic in order to decrease the accumulation. The MFD could be a way to communicate this and therewith evaluate. In Feifei Xu et al. (2013) the road network has been quantitatively divided into three levels based on the value of weighted speed and weighted density. In this study, the MFD has been used as an evaluation tool as well.

A promising field of application of the MFD is supporting control strategies in urban networks. So far, MFD has only been used in order to evaluate the traffic state of (sub)networks. Besides using the MFD as an evaluation tool, other traffic evaluation parameters are used as well. The total travel time is one of these possible traffic evaluation parameters.

In Feifei Xu et al. (2013) and Daganzo (2007) it is stated that the MFD is not sensitive to origin-destination demand. This is an advantage when using MFD for traffic control. So far, studies like Aboudolas and Geroliminis (2013) and Geroliminis, Haddad and Ramezani (2012) have been performed on perimeter control. In these studies an optimal perimeter control for two-region urban cities is formulated with the use of MFD’s. These controllers operate at the boundaries of an urban network.

Besides using MFD’s as an evaluation tool, MFD’s can also be used in a controller in order to realise desired traffic flows. The way of using MFD’s is influenced by the kind of subnetwork which has been chosen to implement the subnetwork flow controller on. Due to studies like Ji and Geroliminis (2012) and Dabin Liao et al. (2013) influences of characteristics of subnetworks on the shape of the MFD are already known.

2.3.3 Influences on shape of MFD

It has been proposed and tested by Geroliminis and Daganzo (2007, 2008), that traffic can be modelled at an aggregate level in large-scale urban regions. It only holds however when the neighbourhoods are uniformly congested. It is also observed in these studies that when wide scatter-plots of speed and density from individual fixed detectors were aggregated, the points of the plot grouped along a smoothly declining curve. Furthermore, it is stated in these studies that the MFD is independent of the demand and is thus a property of the network itself.

Invariant MFD’s can arise in the real world according to Geroliminis and Daganzo (2007, 2008). It is however not studied very well in these studies under which circumstances (types of networks and demand conditions) an invariant MFD can arise. This invariance of the MFD is important for decision makers when they want to improve mobility by using demand-side policies according to Geroliminis and Sun (2010). In this study, it has been demonstrated (by using real data) that a strict homogeneity of traffic states on the network is not necessary to observe a well-defined MFD. The framework of the MFD was proposed under the assumption that congestion is evenly distributed. It has been tested that in a MFD plane two points are close to each other when the spatial distribution of link occupancy is the same for two different time intervals with the same average network occupancy. These two time intervals have the same average flow in that case and thus are close to each other on the MFD plane. Furthermore, it was concluded from the data results that congestion was evenly distributed when different occupancies of the network were analysed.

In Buisson and Ladier (2009) it is proved that heterogeneity of traffic conditions has a strong impact on the shape of the MFD. By relaxing some of the homogeneity assumptions made by Geroliminis and Daganzo (2007, 2008), this study analysed the results on which kind of MFD could be provided. To build the MFD, Buisson and Ladier (2009) used the global unweighted mean values of flow and occupancy suggested by Geroliminis and Daganzo (2007, 2008). Various types of heterogeneity may cause scatter of the MFD:

- Difference between the types of selected roads (highways vs signalized intersections vs unsignalized roads)
- The appearance, disappearance and distribution of congestion
- Difference in data measurement location

Homogeneity is a key factor in realising unscattered MFD's. According to Buisson and Ladier (2009) this homogeneity should be reached for the congestion level of the network and for the distance between the loop and the downstream traffic signal.

Laval (2010) has provided MFD's of a grid network which is of a Manhatten-type. The free-flow branch of the MFD has been provided by regulating the inflow to the network, while the congested branch of the MFD has been provided by regulating the outflow from the network. A distinction has been made in traffic flows in a north-south and a west-east direction. It turned out that the scatter of the congested branch of the MFD's is more significant when each direction has been analysed separately. It turned out that when all flows were aggregated in one entire MFD, the scatter turned out to be less. However, when too many flows are aggregated, the scatter may increase. So, a medium has to be found in the number of links which will be aggregated. Moreover, the size of the network is of influence on the scatter of the MFD.

2.3.4 Conclusions

Accumulation and traffic flow are the main traffic measurements which need to be taken into account when describing the subnetwork flow controller mathematically. Important points on the MFD is the so called sweet-spot which lies around the critical point of the MFD. Traffic states on single links have to be maintained near this sweet-spot in order to prevent congestion.

In many studies, further investigation is proposed on including the MFD in the control mechanism of a subnetwork controller. Besides using the MFD in the control mechanism, the performance of the controller has to be measured as well in this thesis. The MFD can be used in that case as an evaluation tool as described in several studies.

The shape of the MFD should be independent of origin-destination demands, while the size of the subnetwork may influence the scatter of the MFD. Homogeneity of traffic conditions in subnetworks is the key word in maintaining a constant shape of the MFD according to several studies. It is therefore important that the subnetwork flow controller, which will be designed in this thesis, has to focus on these aspects of traffic states.

2.4 Urban traffic control approaches

It has been stated that there are five different traffic control strategies in urban traffic control. These categories are:

- Fixed-time control strategies
- Coordinated fixed-time control strategies
- Traffic responsive strategies
- Coordinated traffic responsive strategies
- Integrated urban-freeway traffic control strategies

Each of these traffic control strategies has different advantages and disadvantages for designing a subnetwork flow controller where the MFD can be part of the control mechanism. Several existing developed traffic controllers will be described shortly. Literature survey on these different kinds of traffic controllers has been performed in order to decide if the subnetwork flow controller in this thesis will be based on one of these existing traffic controllers. The focus of the literature survey will be on the objectives and performance of these existing traffic controllers. In order to decide if the to be designed subnetwork flow controller will be based on an existing controller, depends on the ability of the controller to distribute traffic over a network in order to derive a desirable constant shaped MFD. Therewith, the subnetwork flow controller has to realize desirable traffic flows at the boundaries of a subnetwork. First, descriptions of the different strategies will be given. And finally, comparison of the different traffic controllers with respect to the objectives of the subnetwork traffic controller of this thesis will be performed.

2.4.1 Fixed-time control strategies

Aspects in a control strategy are approaches, traffic streams, saturation flows, cycle times and traffic signal phases (Papageorgiou et al. 2003). Intersections exist of multiple approaches from different directions. Each approach, consisting of a single or multiple lane(s), provides certain traffic streams. The saturation flow (veh/h) is the maximum flow of vehicles which can cross the stop line of an approach during a certain green phase. The cycle time is the total time in which every traffic stream can be served at least once with a certain green time. In total there are four different kind of influencing traffic conditions by using traffic signals: phase specification, split, cycle time and offset. The specification of the optimal amount of phases (within a phase, several traffic movements can get right-of-way simultaneously) is necessary especially for complex intersections which have a lot of traffic streams. An optimal number in phases would decrease the total lost time in the total cycle time which is caused by clearance of the intersection by vehicles. Split is the relative green duration that should be optimized to the demand of the traffic streams. An optimal cycle time should be derived in order to minimize the total vehicle delay. A long cycle time may increase the capacity, but it may also increase delays due to longer waiting times during red phases. And last, the offset is the time difference of phases between two successive intersections which should be optimized in order to create “green waves” for platoons of vehicles. But this is part of a coordinated fixed-time control strategy.

Traffic signals at intersections are the most important traffic measures to control traffic in urban areas. Due to increasing demand in traffic in the past, an optimal control strategy needed to be developed in order to minimize the total time spent by all vehicles in a network. The first working traffic signals in traffic control are of a fixed-time control strategy kind.

Fixed-time strategies are derived off-line by certain optimization codes based on historical constant demands and turning ratios for each stream (Papageorgiou et al. 2003). A fixed-time strategy is also called an isolated strategy when the strategy is applicable on only a single intersection. These kinds of strategies are only applicable on undersaturated traffic conditions. Most fixed-time strategies are phase-based strategies. In these strategies, optimal splits, cycle times and phases are determined. Examples of these phase-based strategies are SIGSET and SIGCAP. In SIGSET a nonlinear total delay function derived from Webster for undersaturated conditions is used as an optimization objective while SIGCAP uses a linear programming problem. SIGSET minimizes the total delay while SIGCAP maximises the total capacity.

According to Hunt et al. (1981) fixed-time control strategies are simple to adapt in terms of input and output for the controller. Standard traffic scenarios are set up for morning and evening peaks in traffic flows. Disadvantage of such a fixed-time control strategy is that control scenarios can only be calculated for traffic conditions which can be foreseen. Sudden changes in demand, like event demand, cannot be handled properly with high delays as a consequence. Due to the fact that fixed-time strategies are based on historical data and not upon information of the current traffic situation, the controller cannot be programmed to automatically perform traffic management adjustments such as restricting the total inflow of vehicles in a certain (congested) area.

2.4.2 Coordinated fixed-time control strategies

Coordinated fixed-time control strategies are like single fixed-time strategies only applicable on undersaturated traffic conditions. MAXBAND is a coordinated fixed-time control strategy which was developed by Little (1966). MAXBAND specifies the offsets of multiple intersections as to maximize the number of vehicles that can travel without stopping at any successive traffic signal. This appearance is also known as "green waves". In MAXBAND the splits are assumed to be known so that the duration of the red times of phases need to be adapted such that a platoon of vehicles can drive without stopping through multiple intersections.

Another, and more applied, coordinated fixed-time control strategy is TRANSYT which has been developed by Robertson (1969). In Papageorgiou et al. (2003) it is stated that TRANSYT is the most frequently used signal control strategy. Therewith, TRANSYT is often used as a basis for other developed control strategies which have a traffic-responsive control approach. TRANSYT has initial settings which are: pre-specified phases, minimum green durations for each phase and specific choice of splits, offsets and cycle times. The concept of platoon-dispersion is used to model flow progression along a link. Links and nodes form a traffic model in which an optimal offset coordination is enabled.
TRANSYT is a computer program which stimulates traffic flows between several intersections. Discrete time steps are used in order to stimulate traffic behaviour on links. The objective function is a linear combination of delays and stops (Muller et al. 2011). Optimization is done for each intersection individually. But by optimizing the offsets between the intersections, coordination of intersections is provided.

The main draw-back of coordinated fixed-time strategies is that it also depends on historical data and not real-time measurements of traffic conditions (Papageorgiou et al. 2003). For coordinating a few intersections, demands can be assumed constant at certain times of the day. Differences need to be made nevertheless in morning and evening demand and peak and off-peak demand.

2.4.3 Traffic-responsive control strategies

Fixed-time control strategies are isolated strategies which focus on a single intersection only. A traffic-responsive strategy can be an isolated strategy as well. Instead of historical data, traffic-responsive strategies make use of real-time traffic measurements which are provided by inductive loop detectors. These inductive loop detectors are usually located around 40 meters upstream of the stop line of an approach. Vehicle demand will be detected by these inductive loop detectors and adaptions to the traffic control system can be made immediately. Total vehicle delay will be minimized due to less green time for traffic streams which have actually no demand and shorter lengths of queues.

Vehicle-interval method is a strategy which can be applied to two-phase intersections (Papageorgiou et al. 2003). Each phase has a minimum green time. When no vehicles pass the detector during this minimum green time, proceeding to the next phase is the result. When a vehicle is detected in this minimum green time, a certain critical interval is created. When a vehicle is detected within this critical interval, green time will be extended and a new critical interval will be created. When no vehicles are detected, the strategy will proceed to the next phase as well. A maximum green time is taken into account in order to prevent a very long waiting time for vehicles at conflicting traffic streams.

Another version of a vehicle-interval method kind approach is MOVA (Vincent et al. 1986) which has been introduced by Miller (1963). In this approach every time step a question will be answered: "Should the switching to the next phase take place now, or should this decision be postponed by a time step?". In order to answer this question, the MOVA tool calculates the time gains or losses if an action is postponed.

2.4.4 Coordinated traffic-responsive control strategies

A lot of traffic-responsive control strategies have been developed the last decades. The trend in traffic control on a network scale is clearly towards coordinated traffic-responsive control strategies. Coordinated traffic-responsive control strategies are potentially more efficient, but are also more expensive. Costs increases due to installation, operation and maintenance of the real-time control system. Often a decentralised control structure has been applied where maintenance of local controllers also need to be carried out. Therewith, costs are made due to the placement of inductive loop detectors and other communication systems (systems for main controllers and local controllers).

There are many differences between the current existing traffic controllers. Examples of these coordinated traffic-responsive control strategies are SCOOT, SCATS, OPAC, PRODYN, RHODES, UTOPIA, TUC and back pressure.

SCOOT

SCOOT has been developed by Hunt et al. (1981), but has been adapted many times. SCOOT (Split, Cycle and Offset Optimisation Technique) is a traffic-responsive control strategy which is based on the fixed-time control strategy TRANSYT.

The SCOOT controller adjusts the signal timings in frequent and small steps in order to deal with the current traffic situation. An online computer is used to analyse the real-time traffic measurements in order to calculate the timings which minimise congestion. A prediction of the effect on the traffic caused by adjustments to the signal timings is the purpose of SCOOT. Besides that, SCOOT aims at providing information for traffic management decisions on the short and long term.

A so called Performance Index (PI) is used to decide which signal timings the controller should provide. If every vehicle travels through green, the PI is zero. The objective of SCOOT is to maintain a low PI as possible. The SCOOT controller is an optimization controller which uses the measurements of saturation flows in order to control cycle times and green durations. The detectors which SCOOT uses to analyse traffic measurements are located far upstream as possible from the stop lines. When a queue is in danger for upstream intersections, in SCOOT several intersections can be grouped in a so called sub-area. Nevertheless, due to the far upstream location of detectors, the queue length measurements are not as accurate as wished due to change of direction at the latest moment of some vehicles.

SCATS

Sims et al. (1980) developed a coordinative traffic-responsive controller for the city of Sydney named SCATS (Sydney Coordinated Adaptive Traffic System). SCATS aims at controlling traffic flows at arterial roads specifically. Due to the fact that SCATS consists entirely of computers, it can adapt very easily to changing demands. SCATS uses a bi-level approach which is in comparison with the hierarchical scope of this thesis. In SCATS an upper level controller selects a network-wide traffic signal plan. The local controllers (at intersection level) adjust the signal settings in order to respond to the current traffic conditions on the road.

According to Lowry (1982) SCATS determines the cycle times, green lengths and offsets for the next cycle by using information from inductive loop detectors. The saturation is the most important traffic measurement which is used in the controller algorithm.

OPAC, PRODYN, RHODES, UTOPIA

OPAC (Gartner, 1983), PRODYN (Farges et al. 1983) and RHODES (Mirchandani et al. 1998) are model-based optimization methods. These strategies do not consider splits, offsets or cycles explicitly. They calculate in real-time the optimal values for the switching times. In order to provide these optimal switching times, these control strategies solve in real-time an optimization problem with a sampling time of 2-5 seconds. The aim of these strategies is to minimize the total time spent by all vehicles in the network.

The solution algorithms of these model-based optimization methods are very exponential complex when providing a global minimum. Therefore, application of these strategies to a whole network is not very feasible (conceptually, it can though). Decentralization of control actions is a solution to the complexity of controlling traffic in a network. UTOPIA, which has been introduced by Taranto et al. (1990), is such a decentralized traffic signal control system. Predictions of routes to be taken by vehicles are made in the control mechanism of the traffic controller. A rolling horizon concept is used to perform these predictions (every few minutes predictions are made for a few minutes father away in the future). UTOPIA (Urban Traffic Optimization by Integrated Automation) is a traffic-responsive control strategy which aims at minimizing the delay for public vehicles.

A disadvantage of all of these strategies is that the signal controllers are not suitable for saturated traffic conditions. Saturated traffic conditions are however common traffic conditions in modern cities, especially during demand peaks. The strategies do not consider saturated traffic conditions due to the fail of considering the downstream traffic conditions in their real-time decision-making at individual intersections (Diakaki et al. 2002).

TUC

The British SCOOT and the Australian SCATS perform control adjustments on interim changes of splits, offsets and cycles based on real-time traffic measurements. These strategies cannot respond as a real traffic-responsive strategy during rapidly changing traffic conditions which may occur during events or daily peaks in demand. Moreover, the green phase durations at a specific intersection depends on real-time measurements form the adjacent upstream approaches only (Diakaki et al. 2002). Due to the lack of traffic-responsive behaviour of SCOOT and SCATS and the disadvantages of the more advanced model-based traffic control strategies OPAC, PRODYN, RHODES and UTOPIA, Diakaki et al. (2002) developed the traffic control strategy TUC which should deal with this lack of application on large-scale networks.

TUC is based on a so called store-and-forward modelling approach which has been originally introduced by Gazis and Potts (1963). This approach describes the network flow process so as to exclude the use of discrete variables. This permits the use of highly efficient optimisation and control methods (such as linear programming, nonlinear programming, quadratic programming and multivariable regulators) with polynomial complexity for coordinated traffic control in large-scale networks. Saturated conditions and un-saturated traffic conditions can be controlled as well in that case. TUC uses a multivariable regulator approach in order to calculate in real-time the network splits, while cycle time and offset are calculated by parallel algorithms.

TUC manages to keep the link queues within desirable limits, which results in spreading the vehicles over the network. Upstream intersections are protected from queue spillback and a high network throughput can be maintained.

Back pressure

Another traffic-responsive control strategy which has the aim of dividing the congested traffic conditions over the whole network is the back-pressure approach. The back pressure algorithm (Ying et al. 2011) uses the queue length of neighbouring intersections in order to make routing decisions. Vehicles are adaptively routed throughout the network in response to congested traffic conditions. The control mechanism routes in such a way that lightly loaded queues receive most of the traffic.

A drawback of the back pressure algorithm is that queue estimates are necessary in order to control traffic. It is very difficult to estimate queue lengths real time. Furthermore, back pressure might only replace the congestion to another place instead of solving it when a network is fully loaded and congestion is present at multiple intersections or on a main arterial road.

2.4.5 Integrated urban-freeway traffic control strategies

The last category of traffic control strategies is the integrated urban-freeway traffic control strategy group. Integrated control strategies should consider control measures, like traffic signals, ramp metering and dynamic route information panels, simultaneously towards one major objective. The problem of control integration of these different measures is present due to the high dimensions of the network under control. It appears that only store-and-forward modelling seems the only feasible solution for integration of control measures (Papageorgiou et al. 2003). In Glasgow three traffic control strategies have been connected in the control strategy IN-TUC in order to deal with the integration of traffic measures; TUC for urban signal control, ALINEA for ramp metering and a reactive one-shot route guidance strategy for user optimum which uses dynamic route information panels.

2.4.6 Application control strategies

Which existing traffic controller can be used for the design of the subnetwork flow controller, with a control mechanism based on the MFD, depends on the performances and applicability of these traffic controllers. First, one of the different control strategies has to be chosen which have been described in the previous paragraphs. The potential use of a certain control strategy is influenced by meeting the different control objectives which have been set up. The subnetwork flow controller needs to optimize internal flows, realize certain perimeter flows and maintain a MFD of the subnetwork which has a constant shape. According to the performed literature research on the MFD and the hierarchical control approach, homogeneity is the key factor when maintaining a constant shape of the MFD. Which traffic controller will be used in the design of the subnetwork flow controller in this thesis will depend on this key factor. In what way are those traffic controllers able to perform a homogeneity traffic state in the subnetwork?

Application of fixed-time control strategies

A fixed-time control strategy is not the most desirable approach for a subnetwork flow controller with a control mechanism based on the MFD. A fixed-time control strategy focuses on a single intersection while the objective in this thesis is to control traffic in a subnetwork. Therewith, fixed-time control strategies are not able to cope with sudden changes in demand. In this thesis, it is desirable that adjustments can be performed directly on the green phases of the traffic signals when the main controller sets up a desirable traffic state and desirable traffic flows. Furthermore, adjustments on the green phases on the wishes of a main controller cannot be executed within every cycle.

Due to the fact that fixed-time control strategies use traffic scenarios which are based on historical data, not all traffic conditions will be served most optimal. The objective of the subnetwork traffic controller is to optimize the internal flows. Therefore, a fixed-time controller is not feasible as a basis in this thesis.

Application of coordinated fixed-time control strategies

Coordinated fixed-time control strategies such as MAXBAND are based on historical data as well. For controlling traffic in a subnetwork where multiple intersections are part of, demands can vary a lot. Therewith, due to changing demands in the future, aging of the optimal traffic control settings in such a strategy is the result. Events such as incidents or road maintenance may also influence the demands on which a coordinated fixed-time control strategy cannot adapt immediately.

Making adjustments on an existing coordinated fixed-time control strategy traffic controller will probably be easier as using a traffic-responsive control strategy as a basis for the design of the subnetwork flow controller. The mathematical description of traffic-responsive control strategies are more complicated. Nevertheless, the aim of the controller is to control traffic in an entire subnetwork. Changes in traffic signal settings might be necessary very suddenly in order to maintain the constant shape of the MFD. A traffic-responsive control strategy is more feasible in that case.

Application of traffic-responsive control strategies

The advantage of traffic-responsive control strategies for subnetwork traffic control is that changes in demand can immediately (or within a single cycle time) applied in the controller inputs. Event traffic can be handled in that case. Nowadays, all traffic signals on intersections have a traffic-responsive control strategy in a way. For a controller which will operate at a subnetwork level and which has to contribute to multiple objectives as in this thesis, it is important that an un-isolated intersection approach will be handled.

Propagation of congestion in an urban network is one of the aspects which influence the shape of the MFD. A traffic-responsive control strategy which operates at a single intersection will optimize the local traffic patterns at that intersection. Traffic may however be allowed to travel towards the next intersection, while this intersection has to deal with congestion already. When a coordinated traffic-responsive control strategy will be handled, long queues and therewith congestion can be prevented due to the distribution of this congestion by the subnetwork flow controller.

Application of coordinated traffic-responsive control strategies

A coordinated traffic-responsive control strategy seems to be the most feasible approach for controlling traffic in a subnetwork. This kind of controllers can deal with the key factor homogeneity in traffic states. Mathematically, coordinated traffic-responsive control strategies are more complicated. Within this category, multiple controllers have been developed in the past years. Advantages and disadvantages of each of these traffic controllers have been described. These advantages and disadvantages are based on the feasibility of reaching the objectives on which the controller has to cope with.

The application of each coordinated traffic-responsive control strategy has been described individually.

SCOOT

Due to the use of saturation flow, the SCOOT detector has been placed as far upstream as possible from the stop line. The SCOOT detectors can therefore not perform the counting of vehicles divided in several directions they will take very well, due to changing direction of vehicles just before they reach the intersection. For a subnetwork flow controller which must be able to provide desirable perimeter flows, counting vehicles on different directions is very important in order to estimate the queue lengths at each direction. Therefore, SCOOT is not the most feasible kind of traffic control strategy for this thesis. For constructing the MFD, the vehicle counting of SCOOT is nevertheless sufficient.

Therewith, due to the fact that SCOOT is a commercial traffic controller, the mathematical algorithm of the controller is not available.

SCATS

Saturation is the most important traffic measurement in SCATS. In this thesis, the most important traffic measurements are accumulation and traffic flow on links in the subnetwork. Therewith, SCATS is also a commercial traffic controller which results in no available information of the control algorithm. This makes is unfeasible to use as a basis for the subnetwork flow controller.

OPAC, PRODYN, RHODES, UTOPIA

OPAC, PRODYN, RHODES and UTOPIA are more advanced traffic controllers with respect to other traffic controllers. The main disadvantage of these controllers is that saturated traffic conditions cannot be handled. In a subnetwork where distribution of traffic is important in order to maintaining a constant MFD, saturated conditions may occur while spreading the traffic over the network. Sometimes it is necessary to store vehicles at a certain location in order to optimize the internal traffic flows and realising the specific traffic flows at the boundaries of the network which have been set up by the main controller. OPAC, PRODYN, RHODES and UTOPIA do not consider saturated traffic conditions due to the fail of considering the downstream traffic conditions in their real-time decision-making at individual intersections (Diakaki et al. 2002).

Besides the fact that UTOPIA has been developed particularly for public vehicles (in this thesis no distinction has been made in different motorized vehicles), the mathematical algorithms are very complex to adapt for the subnetwork flow controller.

TUC

The traffic controller TUC can be applied on networks which have saturated and unsaturated conditions on links as well. TUC manages to keep the link queues within limits. Upstream links are protected from spillback because of that. Furthermore, TUC provides in maintaining a high network throughput. These are all qualities of the traffic controller which contribute to the objectives of the subnetwork control with a MFD control mechanism.

For the objectives of the subnetwork flow controller, homogeneity of the traffic state in the subnetwork is important in order to derive a desirable MFD of the network. TUC uses maximal storage capacity of each link in the mathematical algorithm. The aim of TUC is to minimize and balance the relative occupancy of this maximum capacity on the network links. Furthermore, the number of vehicles in network links is the main aspect of the mathematical algorithm of the traffic controller. TUC changes the green settings of the traffic signals in order to minimize and balance the total relative occupancy of the network links. TUC is therefore a feasible traffic-responsive controller in order to design a controller which has a control mechanism based on MFD’s.

BACK PRESSURE

A control algorithm which has a back pressure algorithm as a basis aims at dividing the congested traffic conditions over the whole network. Highly loaded queues will be relieved from more traffic while lightly loaded queues receive most of the traffic. Due to this algorithm, homogeneity of traffic conditions will be the result in the network.

For the subnetwork flow controller in this thesis it is important that distribution of congestion is performed in order to maintain constant shaped MFD’s. Due to the back pressure algorithm, this distribution will be performed by the controller. Therewith, a maximum throughput will be realised by a back pressure based traffic controller according to Ying et al. (2011). One of the objectives of the subnetwork flow controller is that internal traffic flows will be optimized as well. A back pressure traffic controller thus meets this objective. Ying et al. (2011) performed however simulations on a certain urban network. It cannot be said that an urban network with a different layout will have a maximum throughput as well.

Another advantage of the back pressure traffic controller is that it does not need demands in the algorithm. The controller only needs knowledge of turn ratios. Furthermore, in contrast to TUC (which prescribes a centralized control), the calculations in back pressure control are local. The traffic controller only needs knowledge of the queues of adjacent links. This will result in less information infrastructure which is needed in order to operate in an urban road network.

A controller based on TUC has to be adapted when changes in the network do occur. A controller based on the back pressure algorithm does need some changes locally only when changes in the layout of the network are performed.

Application of integrated urban-freeway control strategies

The Praktijk Proef Amsterdam (PPA) is a large-scale test in order to reduce or prevent traffic jams in the Amsterdam region (Kooten et al. 2014). The PPA uses traffic signals, ramp metering signals and in-car systems in order to divide the traffic over the Amsterdam road network. Service levels have been determined by evaluating the MFD of the entire road network. In this thesis, the focus is on urban traffic only. Freeway traffic is not within the scope of this thesis. Further analysis on integrated urban-freeway traffic control strategies will therefore not be performed.

2.4.7 Summary

In order to introduce the MFD in the control mechanism of the subnetwork flow controller, aspects of influences on the shape of the MFD need to be known. The scatter of the MFD is therewith the most important aspect. Various types of heterogeneity may cause scatter of the MFD:

- Difference between the types of selected roads (highways vs signalized intersections vs unsignalized roads)
- The appearance and disappearance and distribution of congestion
- Difference in data measurement location

Homogeneity is a key factor in maintaining a constant shaped MFD. According to Buisson and Ladier (2009) this homogeneity should be reached for the congestion level of the network and for the distance between the loop and the downstream traffic signal.

Five different control strategies exist in traffic control. For this thesis, the coordinated traffic-responsive control strategy is the approach which should be taken in order to control traffic in a subnetwork. In a coordinated-traffic responsive control strategy neighbouring intersection are also taken into account which is necessary in dividing the congested traffic conditions over the network. In that case homogeneity in traffic conditions can be reached better compared to other control strategies. Control strategies which do not connect several intersections are less able to derive homogeneity in traffic conditions in the subnetwork. A coordinated fixed time control strategy is despite that it connects intersections not desirable due to the lack of flexibility in controlling traffic. As a result, homogeneity in traffic conditions may be less compared to a coordinated traffic responsive control strategy.

TUC and back pressure seems to be the most feasible traffic control strategy for network wide traffic control. Due to the fact that upstream intersections are protected from queue spillback and a high network throughput can be maintained in the TUC strategy, the objectives of the subnetwork flow controller are feasible to reach. The back pressure controller strategy has the advantage, in contrast to TUC, that changes in network layout will not result in major adjustments on the traffic controller. Changes in layout will cause the TUC controller to be redesigned totally. Furthermore, it can be assumed that the back pressure algorithm within the subnetwork flow controller results in a balancing of the queues in the entire subnetwork due to the fact that it is one of the properties of a back pressure approach. This balancing of the queues results in homogeneity of traffic conditions.

This homogeneity of traffic conditions is crucial for maintaining a constant shaped MFD. Therefore, a back pressure approach will be the basis of the subnetwork flow controller in this thesis.

An overview of the advantages and disadvantages of the different coordinated traffic-responsive controllers are shown in table 2-1.

Traffic Controller	**Advantage**	**Disadvantage**
SCOOT	Based on fixed-time strategy TRANSYT, which is often used in controlling traffic.	Vehicle counting far upstream which results in no information of direction vehicles and therewith queue lengths
SCATS	Is able to adapt to changing demands situations very fast and smoothly	Saturation is main traffic measurement.
OPAC, PRODYN, RHODES, UTOPIA	These control strategies solve in real-time an optimization problem.	Saturated traffic conditions cannot be handled. Complex algorithms.
TUC	Is able to handle saturated and unsaturated traffic conditions. Balancing of queues is performed which will result in homogeneity of traffic conditions.	A redesign of the controller is needed when the network layout changes. Complex algorithm to work with.
Back Pressure	Aims at homogeneity of traffic conditions by dividing the traffic load over different links which results in a well-scattered MFD. No complex algorithm.	Queue estimates are necessary in order to control traffic.

Table 2-1 : Overview advantages and disadvantages coordinated traffic-responsive controllers

Due to the fact that the subnetwork flow controller will be designed upon a back pressure algorithm, a more in depth description including the mathematical description of this back pressure algorithm is provided in appendix A.1.

3 Design subnetwork flow controller

The back pressure algorithm, which has been introduced in the previous chapter, will be the basis of the subnetwork flow controller in this thesis. This chapter will describe how the algorithm is adapted in order to contribute to the main objectives of the subnetwork flow controller. Especially the third objective, realizing some desirable flows which have been set up by the main controller, will be dealt with. Concluding from the objectives and the back pressure algorithm, a design framework has been set up in paragraph 3.1. Paragraph 3.2 deals with some aspects which can influence the performance of the designed controller. These aspects of influence have to be kept in mind during designing the subnetwork flow controller. In order to get an overview of the proposed adjustments to the back pressure algorithm, a flow diagram has been made in paragraph 3.3. From this flow diagram, an adapted algorithm has been made and described in paragraph 3.4. And finally, paragraph 3.5 takes a view on including the MFD in the control algorithm of the subnetwork flow controller.

3.1 Design framework

The design of the subnetwork flow controller will be mathematically described after the approach has been set up. The back pressure algorithm described in the previous chapter will be the basis of the subnetwork flow controller. When the subnetwork flow controller has been designed and described mathematically, a Matlab script will be written in order to apply the controller in a simulation environment and test the performance. The microscopic traffic simulation program VISSIM is chosen to perform the simulation due to the connection with Matlab where the algorithm can be written in.

It can be assumed that the back pressure algorithm within the subnetwork flow controller results in a balancing of the queues in the entire subnetwork due to the fact that it is one of the properties of a back pressure approach. This balancing of the queues results in homogeneity of traffic conditions. This homogeneity of traffic conditions is crucial for maintaining a constant shaped MFD. Furthermore, each existing traffic controller, all described in the previous chapter, aims at optimizing the traffic flows such that the total amount of delay is minimized. So, it can be assumed that a back pressure approach deals with a constant shaped MFD and an optimization of the internal flows. For realising certain desirable perimeter flows, adjustments on the back pressure algorithm are necessary.

For realising the desired perimeter flows by the subnetwork flow controller, the subnetwork flow controller will be split into two parts. The first part is the basic back pressure algorithm which should contribute to the first two objectives. The second part should also deal with realising these desired perimeter flows. From now on, the controller which only contributes to the first two objectives will be called the back pressure controller. The subnetwork flow controller should contribute to all three main objectives and is thus an extended back pressure controller.

Due to the fact that the back pressure algorithm needs all queues and turn ratios in the subnetwork, the subnetwork flow controller algorithm can be designed based upon this information as well. Moreover, the layout of the back pressure algorithm will be the basis for the subnetwork flow algorithm. By using the same kind of information and calculations, it can be assumed that both algorithms can be combined or replaced with each other very smoothly.

The idea then is that the subnetwork will be controlled standard by the subnetwork back pressure controller. When the main controller provides information on the desirable perimeter flows and the perimeter flows do not match these desirable values, the subnetwork flow controller has to be executed. A change to this new controller has to be made smoothly. When the desired perimeter flows are realized by the subnetwork flow controller algorithm, the back pressure controller has to be executed again. This repeats whenever the perimeter flows change again.

A basic goal of a traffic controller is that it should deal with one of these traffic measurements: total vehicle delay as low as possible, average total trip time as low as possible, average total flow as high as possible, etc. In traffic control, all of these objectives are linked with each other. For example, a high average total flow will result in low average trip time. For realizing the second objective in this thesis, optimizing the internal flows, all of these traffic measurements are valuable. But, since the MFD plays a major role in this thesis and a back pressure algorithm basis will be applied, it is likely to take into account the average total flow (also known as the production). Nevertheless, the total vehicle delay is also important due to the fact that all other traffic controller performances are tested on this kind of traffic measurement.

Some uncertainties in the algorithm and the design process are described in paragraph 3.2. These uncertainties have to be dealt with during the design of the subnetwork flow controller or should at least be kept in mind while testing the performance of the controller in VISSIM.

3.1.1 Overview of design framework

An overview of the design framework based upon the three main objectives of the subnetwork flow controller is provided in table 3-1. These first three steps together will provide the mathematical description of the subnetwork flow controller.

Design step of controller	Objective	Contents
1	Maintaining a constant shaped MFD of the subnetwork	Subnetwork back pressure controller need no adjustments probably. Applying back pressure algorithm design.
2	Optimizing the internal flows	Check performance of back pressure algorithm at this objective. Adjustments or additions on the algorithm may or may not be necessary.
3	Realizing desirable perimeter flows	An additional algorithm part is necessary for the subnetwork flow controller.

Table 3-1: Framework design subnetwork flow controller

3.2 Aspects of influences on performance design

The back pressure algorithm does not deal with certain aspects which may influence the design of the subnetwork flow controller. Some short descriptions of several aspects are given.

3.2.1 Low demand

The back pressure algorithm calculates a certain pressure for every traffic movement. When the demand is very low at a certain approach, this demand is likely not to be served in a long time due to a low pressure. A constraint might necessary which has to provide green time for traffic streams which have a low demand. The level of service of a traffic stream with low demand can be very low when such a constraint is not applied. The level of service of a certain traffic stream is here mentioned as the relative green duration with respect to all green durations of the different phases.

3.2.2 Green phase duration and time step back pressure algorithm

A maximum green phase duration might needed also in order to maintain a certain level of service of other traffic streams which have not right-of-way in that particularly phase. Therefore, the green durations might need to be controlled by setting up a certain time step in the control algorithm which determines when the new orders by the controller will be given to the VRI's.

The time step of the back pressure algorithm in which pressures of all phases will be calculated will influence the performance of the subnetwork flow controller on computation effort as well. A large time slot will need less computation effort, but results in less up-to-date green times of the phases. A small time slot will result in very up-to-date green times, but may also lead to a rapid change of green times. The value of the time slot is therefore also of influence on the performance of the design of the subnetwork flow controller.

3.2.3 Queue length and capacity

As stated in the literature survey of this report, a drawback of the back pressure approach is that queues are necessary in order to control traffic. When there is no or few traffic, a negative pressure of a certain phase can occur. The subnetwork flow controller has to deal with such negative pressures.

The way of measuring the queue length is also an aspect which might influences the performance of the design of the subnetwork flow controller. A clear definition of a queue is needed. Which definition will be handled in this thesis is described in the simulation set up, paragraph 4.6.

In the real world queues have a finite capacity. When a queue length exceeds the capacity of a certain approach, spillback may occur. Spillback influences traffic flows on other parts of the subnetwork. Therefore, it is desirable to maintain a queue capacity as long as possible in order to decrease the influence on the performance of the design of the subnetwork flow controller.

3.2.4 Clearance time between phases

The back pressure algorithm calculates which phase has the highest pressure and then applies this phase. So far, according to the literature survey, it is not known if the back pressure algorithm takes into account the clearance time between different phases when deciding which phase will be served next due to the absence of information on this topic. The clearance time might influence the decision of giving a certain phase right-of-way in the next time step and thus influence the performance of the design of the subnetwork flow controller. It can be expected that the performance will be different when a different order of phases will be handled while the demand has not changed. Yellow time is part of the clearance time. Additional clearance time between phases can be added in order to make sure no vehicles are presence on the intersection. In paragraph 4.6 (application of the controller algorithm) topics as application of clearance time in this thesis is explained.

3.2.5 Available phases

The back pressure algorithm takes into account available phases. Which phases are available influences the performance of the design of the subnetwork flow controller. Phases can consists of one, two, three or four traffic movements. When some phases are not available, it may occur that some green capacity will not be used by the controller. But when all possible phases are available, the same result may occur. This is caused when a certain phase with two traffic movements has a higher pressure as a phase with three traffic movements (with the same two traffic movements) while there is actually traffic on the third traffic movement. Due to a very low queue length at that third traffic movement, a negative pressure may occur and thus result in a total pressure of the phase with three traffic movements which is lower has the pressure of a phase with two traffic movements.

3.3 Design visualised: a flow diagram

The new algorithm for realizing desirable perimeter flows will be based upon the computation of pressure of phases in the intersection control, just like the subnetwork back pressure controller. In order to design the subnetwork flow algorithm, a flow diagram has been set up which provides the mathematical framework for the design.

It is obvious that the subnetwork flow controller (which will consist of the back pressure controller and an extension part in order to derive desirable perimeter flows) takes a central place in this flow diagram (figure 3-1). Other aspects of the flow diagram are: traffic measurements, traffic signal settings, the main controller and external information. All of these factors are connected with each other by arrows. Each arrow indicates a flow of information from or to the subnetwork flow controller. The subnetwork flow controller uses the incoming information on current traffic states, traffic signal settings and other information to calculate pressures and determining which phase has to get right-of-way.

From the information on the traffic measurements it has to be decided which control algorithm has to be executed; the back pressure algorithm or the subnetwork flow control algorithm. Deciding on which control algorithm at a specific intersection should be applied, a constant γ has been set up which will have the value zero or one. When the perimeter flows have a rate which is desired or an internal intersection has to be controlled, the back pressure control algorithm should be executed. In that case the constant γ has a value of zero. When the perimeter flows are too high or too low at an intersection at the border of the subnetwork, the subnetwork flow control algorithm has to be executed. In that case the constant γ has a value of one.

The back pressure algorithm needs information on the length of the queues ($Q_a(k)$ and $Q_b(k)$) of each timeslot k, the maximum flow rate ξ_i of each traffic movement M_i (the maximum saturation flow has been taken in this thesis), the current traffic signal settings p* and external information which could disturbance the traffic rates ($z_i(k)$). This information is needed in order to calculate the pressures for all different phases.

The subnetwork flow controller needs extra information in order to realize the desirable perimeter flows. This extra information is information on the current perimeter flows ($\xi_{out}(k)$) and the desirable perimeter flows ($\xi_{desired}(k)$). The subnetwork flow controller should take into account the difference between these two flows ($\xi_{outd}(k)$) in order to decide which control signals have to be given to the traffic signals. The main controller provides also a maximum desired deviation of the perimeter flow with respect to the desired perimeter flow (indicated by θ).

The control algorithm of the subnetwork flow controller will have an output which is the same as the back pressure algorithm (S^* and P^*). A flow diagram is shown in figure 3-1.

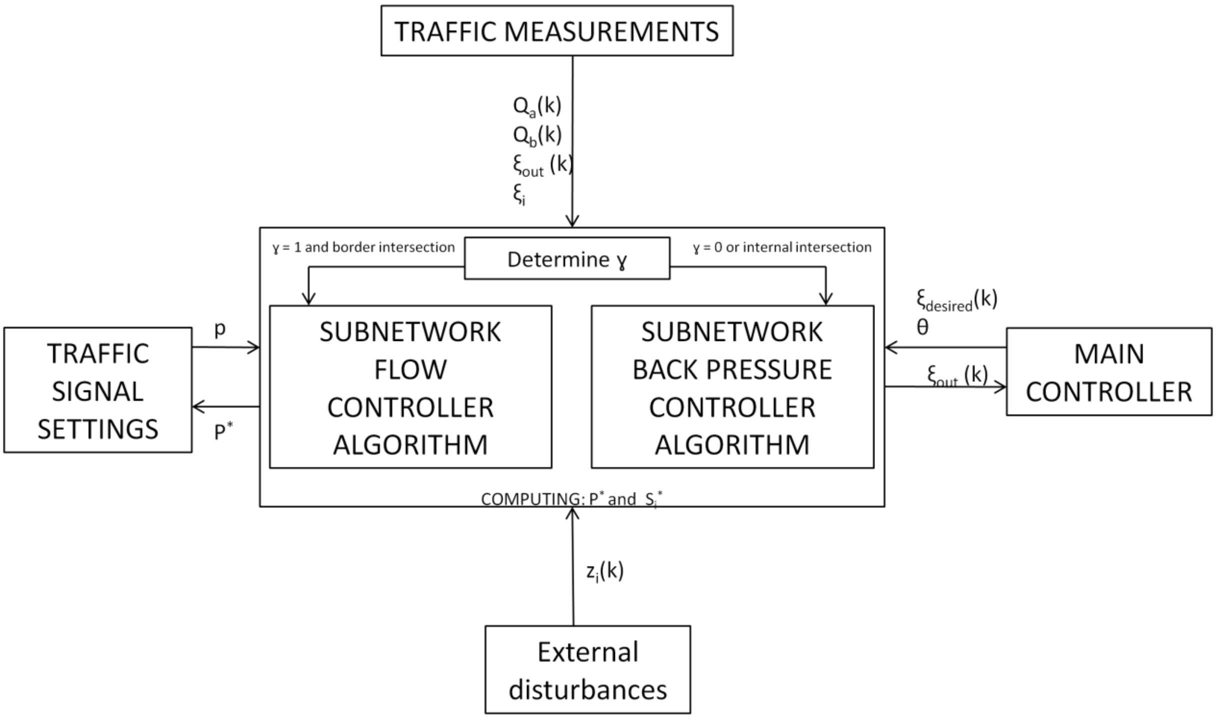


Figure 3-1: Flow diagram design subnetwork flow controller

3.4 Subnetwork flow controller algorithm

The flow diagram, which has been set up in the previous paragraph, is translated into an algorithm. The basics of the algorithm are the same as the back pressure algorithm. The layout of the subnetwork flow algorithm is also taken the same as much as possible. Some adjustments have been made and are described. The result is one algorithm in which the back pressure algorithm and subnetwork flow algorithm are combined.

The traffic controller operates at a time slot $T_k \in \mathbb{R}^+$ with $k \in \{1,\dots, N\}$ and $N \in \mathbb{N}^+$ representing the total number of time slots . For each $a \in \{1,\dots,n\}$ and $i \in \{1,\dots, m\}$ the number of queued vehicles on L_a are represented by $Q_a(k) \in \mathbb{N}_0$ and the traffic state around J_i by $z_i(k) \in Z_i$ at the beginning of timeslot T_k.

For each perimeter link $L_{out} \in L$ in road network R, $\xi_{desired}(k) \in \mathbb{N}_0$ represents the desired flow rate on that particular link at a specific time slot T_k which has been set up by the main controller. $\xi_{outd}(k) \in \mathbb{Z}$ is computed which represents the deviation of ξ_{out} with respect to $\xi_{desired}$ which are measurements of the previous time slot T_{k-1}. $\xi_{out}(k-1) \in \mathbb{N}_0$ represents the measured traffic flow rate at each $L_{out} \in L$ which will be measured every time slot T_k. By adding the difference between $\xi_{out}(k-1)$ and $\xi_{desired}(k-1)$ to the to the deviation ξ_{outd} at the previous time step T_{k-1}, $\xi_{outd}(k)$ is computed which thus represents $\xi_{outd}(k-1) + (\xi_{out}(k-1) - \xi_{desired}(k-1))$. The rate $\xi_i(p,L_a,L_b,z_i(k))$ represents the flow (in number of vehicles per unit time) at which vehicles can go from L_a to L_b through intersection J_i under traffic state z if phase p_i is activated. When the number of vehicles want to travel from L_a to L_b is very high (captured in traffic state $z_i(k)$), saturated flow can be assumed. Then the pressure of each phase $p_i \in P$ will be calculated by adding up all pressures of all available traffic movements (L_a,L_b). The pressure of a traffic movement will be calculated by multiplying the traffic rate $\xi_i(p,L_a,L_b,z_i(k))$ with the difference of the upstream and downstream queue of that specific traffic movement represented by $W_{ab} = Q_a(k) - Q_b(k)$. When $(L_a,L_b) \notin p_i$, it means that in phase p_i the traffic movement (L_a,L_b) does not have right-of-way, the pressure of that specific traffic movement has been set to zero when adding up pressures of all available traffic movements when determining the pressure of phase p_i.

A desired maximum deviation of $\xi_{out}(k) \in \mathbb{N}_0$ with respect to $\xi_{desired}(k) \in \mathbb{N}_0$ is determined by the main controller by setting up $\theta \in [0,1]$. The algorithm then can be described in three aspects: an absolute deviation smaller as θ times $\xi_{desired}(k)$, a deviation smaller as $-\theta$ times $\xi_{desired}(k)$ and a deviation larger as θ times $\xi_{desired}(k)$.

Constant γ represents the decision of executing the basic backpressure algorithm or the subnetwork flow control algorithm. When the absolute deviation is smaller as θ times $\xi_{desired}(k)$ it means that a desired perimeter flow is realised. In that case, the basic back pressure algorithm will be handled (γ is zero). A pressure will be calculated for all phases $p_i \in P_{all}$. When the deviation is smaller as $-\theta$ times $\xi_{desired}(k)$, it means that $\xi_{out}(k) \in \mathbb{N}_0$ is too low with respect to $\xi_{desired}(k) \in \mathbb{N}_0$. When that is the case (γ is one), of all phases $p_i \in P_{out}$ which contains $M_{out} \in M$ (M_{out} representing a traffic movement with direction L_{out}), the pressure of each phase is computed (S_i). The phase with the highest pressure S_i will get right-of-way. When the deviation is larger as θ times $\xi_{desired}(k)$, it means that $\xi_{out}(k) \in \mathbb{N}_0$ is too high with respect to $\xi_{desired}(k) \in \mathbb{N}_0$. In that case ($\gamma$ is one), of all phases $p_i \in P_{notout}$ which do not contain $M_{out} \in M$, the pressure of each phase is computed (S_i). The phase with the highest pressure S_i will get right-of-way.

Only the outflow (not the inflow) is in this way controlled by the subnetwork flow controller. The outflow of a certain subnetwork perimeter will be the inflow of an adjacent subnetwork. The subnetwork in this thesis will be part of an entire urban network which consists of several subnetworks. $\xi_{desired}(k)$ will be chosen in a way by the main controller such that a desired constant shaped MFD of the subnetwork can be maintained.

In the new designed subnetwork flow controller algorithm, which is shown on the following page, the basic back pressure and subnetwork flow control algorithm can be seen integrated in one algorithm. The basic back pressure algorithm will be performed basically when $|\xi_{outd}(k)| < \theta\ \xi_{desired}(k)$, visualized in step 5 of the subnetwork flow controller algorithm. In all other cases, the subnetwork flow algorithm will be executed (step 6 and 7).

Subnetwork flow controller algorithm based on maximum pressure of phases

Algorithm: computation of phase P^* to be activated during time slot T_k at intersection J_i.

Input: $z_i(k)$, $Q_a(k)$ for all a ϵ {1,…,n} and $Q_b(k)$ for all b ϵ {1,…,n} such that $(L_a,L_b) \in M_i$. ξ_i of each $L_a \in L$. Furthermore, θ representing the maximum permitted deviation on perimeter flow set up by the main controller. And at last, $\xi_{out}(k)$ and $\xi_{desired}(k)$ of each $L_{out} \in L$.

Output: $P^* \in P$ to be activated during time slot T_k

```
Foreach $(L_a,L_b) \in M_i$ do
    $W_{ab} \leftarrow Q_a(k) - Q_b(k)$;
Foreach $L_{out} \in L$ do
    $\xi_{outd}(k) \leftarrow \xi_{outd}(k-1) + (\xi_{out}(k-1) - \xi_{desired}(k-1))$
    If $|\xi_{outd}(k)| < \theta\ \xi_{desired}(k)$ then
        Foreach $p_i \in P_{all}$ do
            $S_i \leftarrow \Sigma_{(La,Lb)\ \epsilon\ pi}\ \xi_i(p,L_a,L_b,z_i(k))W_{ab}$;
            If $S_i = \max(S_i)$ then
                $S^* = S_i$;
                $P^* \leftarrow p_i$;
    If $\xi_{outd}(k) < -\theta\ \xi_{desired}(k)$ then
        Foreach $p_i \in P_{out}$ do
            $S_i \leftarrow \Sigma_{(La,Lb)\ \epsilon\ pi}\ \xi_i(p,L_a,L_b,z_i(k))W_{ab}$;
            If $S_i = \max(S_i)$ then
                $S^* = S_i$
                $P^* \leftarrow p_i$
    If $\xi_{outd}(k) > \theta\ \xi_{desired}(k)$ then
        Foreach $p_i \in P_{notout}$ do
            $S_i \leftarrow \Sigma_{(La,Lb)\ \epsilon\ pi}\ \xi_i(p,L_a,L_b,z_i(k))W_{ab}$;
            If $S_i = \max(S_i)$ then
                $S^* = S_i$
                $P^* \leftarrow p_i$
```

The subnetwork flow algorithm as described on the previous page has been tested continuously on a single intersection during the design. This has been done in order to determine if the designed algorithm works properly. A set of available phases has been set up in this test phase from which the controller has to choose from. When the simulations on subnetwork level will take place, some more information is needed on the available phases. More on this topic will be handled in paragraph 4.6. In this paragraph all aspects of the application of the subnetwork flow controller algorithm within the simulation program VISSIM will be handled.

The following questions have been asked continuously during designing the subnetwork flow controller algorithm and checked visually on a single intersection simulation in the microscopic simulation program VISSIM:

- Does the controller give right-of-way to all traffic streams? Moreover, no traffic streams are skipped?
- Does the controller give right-of-way to the phase which has the highest pressure?
- Is the controller able to choose a certain phase from a set of available phases?
- Is the controller able to transition between different activated phases?
- Does the controller exclude certain phases from the set of available phases when the desired perimeter flow is too high or too low?

When all questions had a positive result, a final design of the subnetwork flow controller had been obtained which is the algorithm on the previous page and is able to be tested on subnetwork scale. When results on subnetwork scale of the subnetwork flow controller are not as desired, adaptions may be performed on the designed algorithm.

3.5 MFD: overrule control mechanism

So far, the new designed algorithm will realize perimeter flows in the subnetwork which are desired by the main controller. The first objective of the subnetwork flow controller is however to maintain a constant shaped MFD. This constant shape of the MFD is dependent on the scatter size. The algorithm does not provide this constant shaped MFD particularly due to the assumption that the back pressure algorithm will balance the queues in the subnetwork and therewith provide homogeneity in the traffic conditions.

This assumption needs nevertheless to be checked. When checking the shape of the MFD during the execution of the subnetwork flow algorithm, the performance can be described. When the MFD is not of a constant shape described by a certain maximum allowed deviation for example, an overruling principle by the MFD-objective could be applied.

The overruling principle by the MFD will cause the subnetwork flow algorithm to shut down and only applying the basic back pressure algorithm. The result is that the desirable perimeter flows will not be realized anymore. When the MFD has been recovered, the subnetwork flow algorithm has to be executed again. The largest challenge in this overrule principle is to decide when the MFD is constant shaped. This part should be the steer mechanism of the overruling principle. Just like the defined maximum deviation which has been handled in the subnetwork flow algorithm for realizing desirable perimeter flows, a certain maximum deviation could be handled in this principle as well. The maximum deviation of the shape of the MFD from a constant shaped MFD could be defined in advance. This maximum deviation could be described by setting up a maximum standard deviation.

Furthermore, a time period has to be defined in which the MFD-objective will be checked. A check every second is not profitable due to the fact that traffic conditions do not change every second. Accumulation and traffic flow are the main aspects of the shape of the MFD. These two aspects need time to change. Therefore, it is better to define a time period of ten to fifteen minutes for example. A check of the MFD every ten to fifteen minutes will contribute to the first objective of the subnetwork flow controller: maintaining a constant shaped MFD.

The MFD overruling principle has not been executed in this thesis due to a shortcoming of time. Checking the shape of the MFD will be done nevertheless, because it is one of the objectives. How and when this performance checking will be described in the next chapter.

4 Simulation set up

The designed subnetwork flow control algorithm needs to be tested in a simulation environment in order to check the performance on the objectives which have been set up in this thesis. In this chapter the simulation set up will be described. First, the goals of the simulation will be mentioned in paragraph 4.1. Within these goals, some experiments which will be performed will be described. Which traffic scenarios with respect to the traffic demand will be applied in the simulations will be described in paragraph 4.2 .A simulation framework, paragraph 4.3, will visualize the to be performed simulations and in which order they will be executed. Paragraph 4.4 will describe the application and layout of certain subnetworks in the simulations. The layout and other properties of the subnetworks will influence the way of simulating the subnetwork flow controller algorithm. Which simulation performance parameters will be used within the simulations will be mentioned in paragraph 4.5. And finally, paragraph 4.6 will describe the way the subnetwork flow controller algorithm will be applied into the simulations.

4.1 Simulation goals

The simulation of the subnetwork flow controller algorithm as designed in the previous chapter will be executed in the microscopic simulation program VISSIM. COM interface will be used to apply the subnetwork flow controller algorithm and to collect results from the simulations. In order to decide how the subnetwork flow controller algorithm will be applied exactly and which parameters are needed in order to evaluate the performance of the subnetwork flow controller algorithm, the goals of the simulation have been made clear. A distinction has been made in the objectives of the subnetwork, in the application of the subnetwork flow controller and in some experiments which will be performed within the simulations.

4.1.1 Objectives of subnetwork flow controller

The first objective of the subnetwork flow controller is to maintain a constant shape of the MFD. By performing simulations where the subnetwork flow controller algorithm will be applied on a subnetwork with different traffic loads, the ability of maintaining such a constant shaped MFD can be tested. The MFD should be independent on these different origin-destination demands. The subnetwork size is of influence on the scatter of the MFD and thus on maintaining a constant shaped MFD. The subnetwork flow controller algorithm is assumed to provide such a constant shaped MFD due to the property of the back pressure approach of balancing queues which results in homogeneity of traffic states in the subnetwork. Therefore, no special algorithm changes have been made to the back pressure algorithm for reaching this objective within the design of the subnetwork flow controller algorithm.

The second objective of the subnetwork flow controller is to optimize the internal flows of the subnetwork. This objective is also assumed to be reached by the back pressure algorithm due to the fact that each existing subnetwork controller has the objective of minimizing total delay. When the subnetwork flow controller is applied within a simulation in VISSIM, certain simulation traffic measurements can be provided which can represent the performance on this second objective of the subnetwork flow controller. Which simulation performance parameters will be provided in the simulations are described in paragraph 4.4.

The third and last objective of the subnetwork flow controller is to realize certain perimeter flows which have been set up by the main controller. By simulating the subnetwork flow controller as designed in the previous chapter in VISSIM, the performance on the ability of reaching this objective can be tested. Therewith, simulations can provide information which can help optimize the subnetwork flow controller algorithm in such a way that all objectives can be reached more optimal.

4.1.2 Application of three subnetwork controller algorithms

In order to check the performance of the designed subnetwork flow controller algorithm, some reference performances are needed. Therefore, three different subnetwork controller algorithms will be applied within the simulations:

1. Vehicle-actuated controller
2. Subnetwork back pressure controller
3. Subnetwork flow controller

Since the back pressure approach is a coordinated traffic-responsive control strategy, simulations will be performed with a basic vehicle-actuated controller which is a traffic-responsive control strategy. By using a traffic-responsive control strategy which is not coordinated, the effect of coordinating the intersections by subtracting the queue lengths can be judged. The performance on maintaining a constant MFD by the subnetwork back pressure controller can be checked by comparing the MFD generated by this controller with the MFD generated by a vehicle-actuated controller.

When the subnetwork back pressure algorithm has been shown to work properly, based upon the simulation performance parameters (paragraph 4.4), the shape of the MFD and the layout of the subnetwork, the subnetwork flow controller will be applied. The objectives of the subnetwork flow controller can then be tested and evaluated.

In order to get some reference performances to check the performance of the subnetwork flow controller, a description of the experiments which will be performed within the simulations are described in the next paragraph. Within these simulation experiments, some optimizing of parameters of the subnetwork flow controller algorithm will be performed.

4.1.3 Simulation experiments

Subnetwork layout

From the literature survey, it has been made clear that the layout of the subnetwork influences the scatter of the MFD. It has been proven by De Jong (2012) that adding or removing intersections influence the scatter of the MFD. Therefore, the first simulation experiments which will be performed are simulations with a vehicle-actuated controller and a subnetwork back pressure controller where different subnetwork layouts will be tested. When the vehicle-actuated controller and subnetwork back pressure controller are not able to maintain a constant shaped MFD created with different applied demand patterns, the subnetwork layout of the simulation environment will be changed. A subnetwork size will be chosen eventually which provides a MFD with the least scatter and a most constant shape compared to the other subnetwork sizes. More detail on the applied subnetworks will be explained in paragraph 4.3 of this chapter. Evaluation performance parameters on the shape of the MFD will be provided in paragraph 4.5 of this chapter.

Algorithm parameters

Some new parameters (θ and $\xi_{desired}(k)$) have been introduced within the subnetwork flow controller algorithm. A constant value of these new parameters have not been set up yet. Reason for not choosing a certain value for these new parameters is that it could influence the performance of the subnetwork flow controller.

The optimal value for θ need to be tested which will be done by some experimental simulations within VISSIM. θ represents a maximum allowed deviation factor with respect to $\xi_{desired}(k)$. The following values of θ will be tested:

- $\theta = 0.1$
- $\theta = 0.5$
- $\theta = 1.0$

For these values of θ has been chosen in order to check the effect of enlarging θ. A maximum deviation 10% with respect to the desired flow may seems legitimate. It can be assumed that a difference in performance between a maximum deviation of 10% ($\theta = 0.1$) and 15% ($\theta = 0.15$) may be insignificant. Therefore, values of 0.5 and 1.0 will be taken.

It is imaginable that the main controller cannot choose every value for $\xi_{desired}(k)$. For example in traffic states with a low demand, a high desired perimeter flow cannot be chosen due to the lack of available vehicles. Therefore, demand and desired perimeter flow will be changed within the simulations simultaneously. The value of the desired perimeter flow $\xi_{desired}(k)$ in the simulations will have a different value if there is a low demand compared with a high demand. The following constant desired perimeter flows values have been applied at the specific demand patterns:

- Low demand: $\xi_{desired}$ = 750 veh/h
- Medium demand: $\xi_{desired}$ = 750 veh/h
- High demand: $\xi_{desired}$ = 950 veh/h
- Very high demand: $\xi_{desired}$ = 950 veh/h

These values have been chosen at random but maintained lower as the demand for each perimeter link. Vehicles part of that demand will be presence in the network and thus desired perimeter flow cannot equal demand. More detailed information on the different demand values can be found in paragraph 4.4.

Besides the new introduced parameters which have to be tested, the time step on which the algorithm will be performed has to have a certain value. This time step, described by T_k, influences the changing rate of the activated phase of the intersection control. At the beginning of every time step, the subnetwork flow controller algorithm will be executed. The algorithm computes which phase as to get right-of-way for the oncoming time step. There might be an optimal value of this time step to perform the simulations on. A green duration of a traffic movement has to have a fixed green time duration in order to avoid a flasher effect. This fixed green time duration is normally set to four seconds minimum for motorized vehicles. Therefore, the time step parameter will have a value of four seconds minimum. The maximum possible value of this parameter is not known yet. It can be assumed however that there is a value for T_k which results in a most optimal performance in terms of the simulation parameters. In this thesis, no experiments will be performed on the value of the time step T_k. More on the chosen value of T_k can be found in paragraph 4.5.

Overview of simulation experiments

Summarizing, the following experiments will be performed in the simulations:

- Changing the layout of subnetwork
- Changing the value of θ
- Changing the value of demand
- Changing the value of $\xi_{desired}(k)$

These experiments will be executed by the so called trial-and-error way.

4.2 Simulation framework

In order to make clear which simulation processes which will be performed in VISSIM, a flow diagram has been set up. The flow diagram represents the processes which have to be performed in order to result in a most optimal working subnetwork flow controller. As mentioned before, first some simulations will be performed with a vehicle-actuated controller and a basic back pressure controller. The layout of the subnetwork for testing the performance of the subnetwork flow controller will be determined upon the performances of the vehicle-actuated controller and basic back pressure controller upon different subnetwork layouts. When a certain subnetwork layout has been chosen, the subnetwork flow controller will be introduced within the simulation processes. The simulation framework is visualized in figure 4-1.

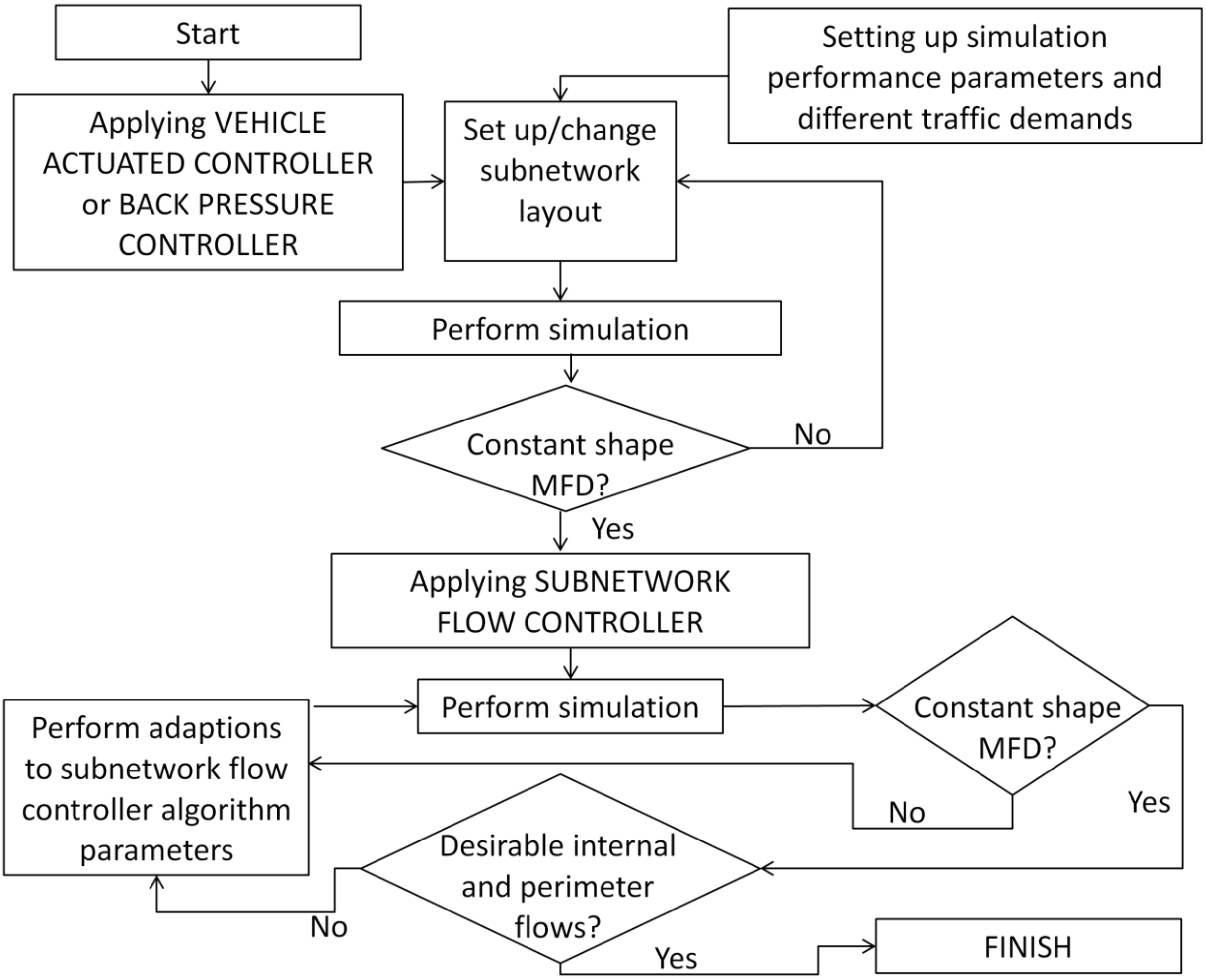


Figure 4-1: Simulation framework

The simulation framework shows that the vehicle-actuated controller and back pressure controller will be applied first. In order to apply these controllers, the algorithm of both of them have been written as a Matlab script. More on the application of the controllers is described in paragraph 4.6. For each controller, a simulation process will be performed. First the layout of the subnetwork will be set up. The layout will influence the performance of the controllers on maintaining a constant shaped MFD. More on subnetwork application will be described in paragraph 4.3.

The subnetwork will be designed within VISSIM. Before starting the simulations, VISSIM needs to know which traffic measurements have to be recorded during the simulations. Therefore, the simulation performance parameters need to be known. These simulation performance parameters have to help judging the performance of the controller on the three main objectives. Traffic demand is another input for VISSIM. Different traffic loads will be applied within the simulations. Before starting the first simulations, it has been made clear which demand patterns will be handled. These specific traffic demand patterns are described in paragraph 4.4.

When the subnetwork layout has been set up, simulation parameters are known and a certain traffic demand has been set up, the first simulation can be performed. After the simulation, the

MFD of the subnetwork will be constructed. When the shape of the MFD provided by different applied demand patterns does not match a constant shape or of a large scatter size, the subnetwork layout will have to be changed. By creating a subnetwork which can provide a MFD with a small scatter size, testing the influence of the subnetwork flow controller algorithm on the shape of the MFD is more feasible. When it is not possible to maintain a constant shaped MFD with a vehicle-actuated controller or backpressure controller, the second stage of the simulations will be performed nevertheless. A certain subnetwork layout with a MFD which has a shape which reaches closest to the desirable properties will be handled in that case. The influences of the subnetwork flow controller on the MFD can be tested in that case as well.

As soon as a certain subnetwork layout is able to maintain a MFD according to the properties of a constant shape MFD, the second stage of the subnetwork simulations will be performed. In this second stage, the subnetwork flow controller algorithm will be applied. A Matlab script is again written which cooperates with VISSIM by COM Interface. From the first stage of the simulations, a subnetwork layout will be chosen in order to perform the second stage simulations on. The layout of the subnetwork will not change in further simulations.

When the subnetwork flow controller has been applied within the simulation environment, new simulations will be performed. The shape of the MFD will be checked again after each simulation. When the MFD does not have a desirable shape, some subnetwork flow control algorithm parameters will be changed. The parameter which will be changed is the maximum allowed deviation factor, with respect to the desired perimeter flow set up by the main controller, represented by θ. When a desirable shape of the MFD has been reached, the performance of the controller on the internal and perimeter flows will be checked. When the perimeter flows and internal flows are not realized as desired, adaptions to the subnetwork flow control algorithm parameter can be performed again. When the results on the second and third objective (concerning internal and perimeter flows) are positive, performing simulations will be ended. In order to prevent getting stuck in a never ending loop, the values of the subnetwork flow control algorithm parameter, which will be changed within the simulations, are set up in advance, described in paragraph 4.1.

4.3 Subnetwork application

A subnetwork layout has to be set up in order to perform the simulations. Two different kinds of simulations will be performed as mentioned before. Simulations with a vehicle-actuated control and a back pressure control in order to determine a most desirable subnetwork layout which provides a MFD with a low scatter. Furthermore, some simulations with the subnetwork flow controller will be performed on this most desirable subnetwork layout. The layout of a subnetwork consists of multiple signalised intersections in order to test the ability of controlling traffic in a subnetwork according to the three main objectives. First a description of a single intersection is given. And finally, the total layout of all different subnetworks which will be handled within the simulations are described.

4.3.1 Layout single intersection

Each intersection in the subnetwork will consist of twelve different traffic movements. In this thesis, traffic streams 001 till 012 are considered. All intersections will have the same layout for simplicity reasons. In order to apply each controller to the subnetwork intersections, the algorithm has to be written once in Matlab and copied to all intersections in that case. In figure 4-2, the schematic layout of a single intersection with twelve traffic streams is visualised.

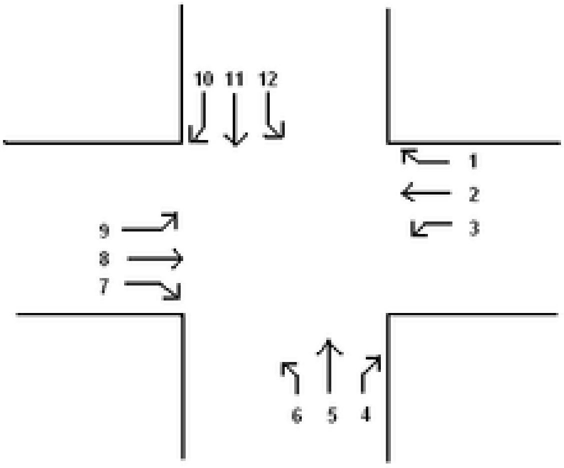


Figure 4-2: Single intersection with twelve traffic streams

4.3.2 Subnetworks

De Jong (2012) performed some experimental simulations on different kind of subnetwork layouts where the influence of subnetwork layout on the shape of the MFD was tested. It turned out that a subnetwork, which consists of only signalized intersections at the borders of the subnetwork, has less scatter when deriving the MFD than a subnetwork with internal signalised intersections. A subnetwork layout which consists of certain arterial roads within the subnetwork turned out to have more scatter and thus a less well shaped MFD. The controller which has been used in these simulations is a fixed time controller. Other studies however, have proven when more flows on links are aggregated, a MFD with less scatter can be maintained. In this thesis, a back pressure algorithm basis is used in the design of the subnetwork flow controller. A property of such an approach is to balance the queues and thus reach homogeneity in traffic conditions in the entire subnetwork. Therefore, it can be expected that a subnetwork which consists of multiple internal and border intersections will maintain a MFD with less scatter and a constant shape when applying different demand patterns. This needs to be tested nevertheless.

Three different subnetwork grid layouts in terms of size will be tested in this thesis:

- Subnetwork with four intersections
- Subnetwork with eight intersections
- Subnetwork with sixteen intersections

A subnetwork consisting of four intersections is a subnetwork with the smallest number of intersections which still can be described as a subnetwork. All intersections are border intersections in a subnetwork with four intersections.

Like a subnetwork layout consisting of four intersections, a subnetwork layout consisting of eight intersections will have border intersections only. The layout of a subnetwork with eight intersections is twice as big as a subnetwork with four intersections.

The subnetwork grid layout with sixteen intersections consists of four internal intersections and twelve border intersections. In case a subnetwork with sixteen intersections turned out to maintain a constant shaped MFD the best with a vehicle-actuated control and back pressure control, the internal intersections will be controlled by the basic back pressure approach when applying the subnetwork flow controller in the second stage of the simulations. Due to no available perimeter links adjacent to these internal intersections, subnetwork flow control is not possible. This phenomenon has been explained in figure 3-1 by introducing ɣ.

Intersections with two possible perimeter links, located in the corner of a subnetwork, are chosen to restrict with only one perimeter link. Again simplicity reasons in writing the subnetwork flow algorithm is the reason.

The three different subnetwork grid layouts are constructed in a schematic way. It does not represent the real world, but it is constructed this way for simplicity reasons. The layout of all three different subnetwork layouts is shown in figure 4-3, figure 4-4 and figure 4-5.

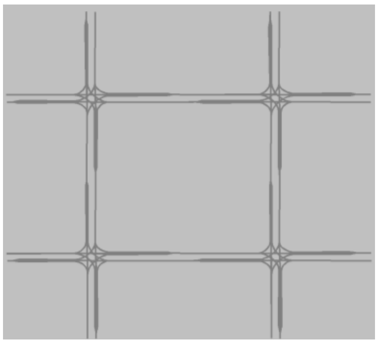


Figure 4-3: Subnetwork layout consisting of four intersections

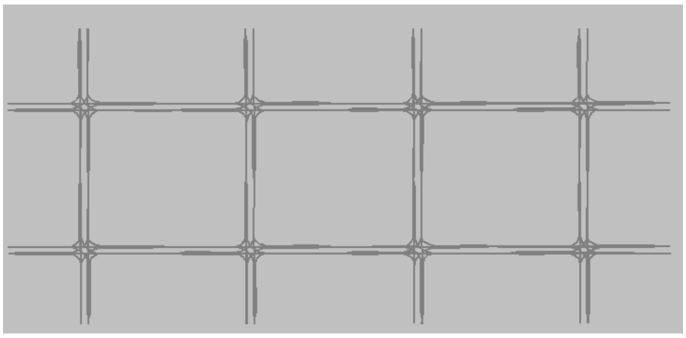


Figure 4-4: Subnetwork layout consisting of eight intersections

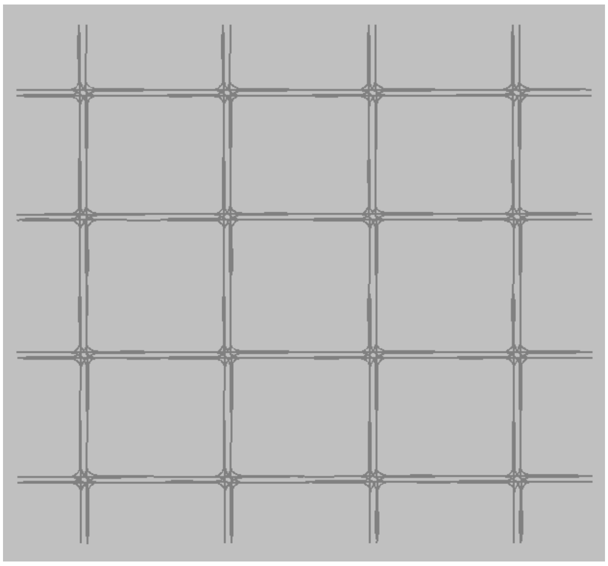


Figure 4-5: Subnetwork layout consisting of sixteen intersections

In figure 4-6, the border between two subnetworks with four intersections is visualised. Intersections are located totally within a subnetwork. The border is located on a perimeter link just downstream of an intersection.

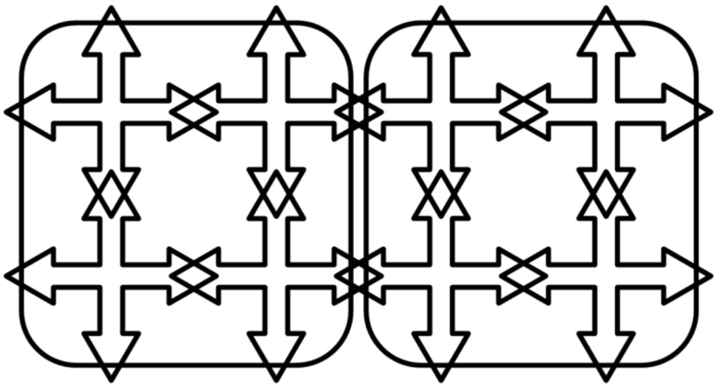


Figure 4-6: Location border between two subnetworks (example subnetwork with four intersections)

4.4 Traffic demand in simulation

Different traffic demands will be applied within the simulations in order to check the performance of all three different controllers on maintaining a constant shaped well-scattered (least scatter as possible) MFD. According to several studies, the shape of the MFD should be independent of the traffic demand. In the simulations, four different traffic demand patterns will be handled. The demand patterns for the subnetwork of four intersections are of a different kind as for the subnetworks with eight of sixteen intersections of course. By trial and error, certain demand patterns are chosen which can be divided in the categories: low demand, medium demand, high demand and very high demand. Independently of the size of the subnetwork, low demand in a subnetwork with four intersections will result in an approximately the same density of vehicles as low demand in a subnetwork of, for example, sixteen intersections.

It is chosen to divide the traffic demand evenly (homogeneous traffic demand) over each subnetwork in order to get as soon as possible a well loaded subnetwork. Therefore, all input links have given the same traffic demand. When traffic is not balanced at the inputs that well, it would take longer simulation times. From each input link, a link which originates in another subnetwork, a certain traffic demand will be available for each output link (also known as perimeter links). The value of this traffic demand is for every input link towards any perimeter link the same. An exception has been made for eight origin-destination pairs in each kind of subnetwork. These origin-destination pairs are located at the corners of each subnetwork. A traffic stream which enters the subnetwork but leaves the subnetwork after passing only one intersection, has given a fixed value of 350 vehicles/hour as demand. This has been done in order to create a traffic load at those particular traffic streams which will be served occasionally. A value of 350 veh/h has been chosen at random but should be compared with the combined demand of all other origin-destination pairs at that specific approach. When the traffic demand would be very low, it can be expected that this traffic stream will not be served as explained in paragraph 3.2: Aspects of influences on performance design.

Only cars are considered as motorized vehicles in the simulations. This has been done in order to maintain all conditions the same. In table 4-1, an overview is given of the constant demand values of each origin-destination pair for all kind of demand loads and subnetwork layouts (except the corner traffic streams as described before).

		Subnetwork layout		
		Four intersections	**Eight intersections**	**Sixteen intersections**
Demand load	**Low**	90	50	30
	Medium	110	70	55
	High	140	90	70
	Very high	150	110	110

Table 4-1: Overview origin-destination demand values for different subnetwork layouts

4.5 Simulation performance parameters

Simulation performance parameters are needed to in order to test the performance of the subnetwork flow controller on the three objectives which have been set up. A distinction in description of needed simulation performance parameters has been made here in aspect of different objectives. Some simulation performance parameters are however useful for testing several objectives.

4.5.1 Objective 1: Constant shaped MFD

The first objective of the subnetwork flow controller is to maintain a constant shaped MFD independent of the different applied demand patterns. Several traffic measurements are needed in order to derive a MFD of the subnetwork.

The production and accumulation are needed in order to derive the MFD of the subnetwork during the simulations. The production and accumulation will be computed by adding up all traffic measurements which will be provided by each individual link. For computing the production of the subnetwork, the number of vehicles in a certain time period can be counted and translated in a certain hourly traffic flow. For computing the accumulation of the subnetwork, the total number of outgoing vehicles will be subtracted from the total number of incoming vehicles every time period and added to the present number of vehicles in the subnetwork. More on the time period which will be handled in the simulation is described in paragraph 4.6.

The subnetwork size is of influence on the scatter of the MFD. In order to evaluate the scatter of the MFD, the standard deviation will be calculated. This standard deviation will be determined based upon all data points compared to the running median of the MFD. A running median with a window of eleven data points has been taken. A step of one data point has been taken when determining the running median. By determining the absolute deviation of all data points of the MFD with respect to this running median, the standard deviation can be calculated. MFD’s with the lowest standard deviations can be pointed out as MFD's with the lowest scatter and thus better in maintaining a constant shape. A running median has been chosen instead of for example the average value due to the fact that the running median results in a smoother rising and declining line trough the total scatter of the MFD.

For all three kind of controllers (vehicle-actuated, back pressure and flow) MFD's will be derived and compared.

4.5.2 Objective 2: Optimizing internal traffic flows

The second objective of the subnetwork flow controller is to optimize the internal traffic flows within the subnetwork. The internal flows can be optimized on several simulation performance parameters.

With the following traffic measurements, the performance of the subnetwork flow controller on optimizing the internal flows can be tested:

- Total number of vehicles reaching destination (veh): The more vehicles reach their destination, the higher the internal flows must have been. This can be computed by subtracting the number of vehicles left in the subnetwork at the end of the simulation form the total number of loaded vehicles in the subnetwork.
- Average travel time (s): The lower the average travel time is, the higher the internal flows will be when a same demand pattern is applied. The average travel time can be computed by dividing the total time spent by the number of vehicles loaded into the subnetwork.
- Total time spent in the subnetwork (s): The more time has been spent by vehicles in the subnetwork, the lower the internal flows turn out to be. The total time spent in the subnetwork by vehicles can be computed by subtracting the start time from the end time of each vehicle in the subnetwork.
- Total delay (s): The higher the total delay of all vehicles, the lower the internal traffic flows are. The total delay can be computed by subtracting for each vehicle the free flow travel time from the actual travel time and added up.
- Average delay (s): A low average delay results in high internal traffic flows. This can be computed by dividing the total delay by the number of vehicles loaded into the subnetwork.

All traffic measurements will give a result on the performance of the subnetwork flow controller. Therefore, one of these five traffic measurements can be chosen. Since all other traffic controllers in other studies have been tested on total delay of the subnetwork, total delay is also the main simulation performance parameter in this thesis. Therewith, a distinction will be made in inflow production, internal production and outflow production.

By computing the inflow, internal and outflow production, something can be said on the results of the performance of the subnetwork flow controller with respect to the total delay of the subnetwork. These three different kind of flows are computed every time step again by counting the number of vehicles on every link.

And again, for all three kinds of controllers in this thesis, these simulation performance parameters will be derived from the simulations and compared.

4.5.3 Objective 3: Realizing desirable perimeter flows

The third objective of the subnetwork flow controller is to realize desirable perimeter flows which have been set up by the main controller.

On each link which leaves the subnetwork, the traffic flow has to be measured. This will be done for every time step. The deviation to the desired perimeter flow will be calculated as described in the algorithm of the subnetwork flow control algorithm. The performance of the subnetwork flow controller on this objective will be tested by generating cumulative graphs which represent the total number of vehicles which have left the subnetwork in total simulation time.

A comparison with the vehicle-actuated and back pressure controller will not be made, due to the fact that these controllers do not control the perimeter flows. The cumulative vehicle graphs are nevertheless needed in order to test the different values of the maximum deviation factor (θ).

4.6 Control algorithm application

The vehicle-actuated controller, back pressure controller and flow controller will be simulated by using the microscopic simulation program VISSIM. COM interface will be used for the communication between Matlab and VISSIM.

COM interface is a communication tool for getting traffic measurements from the simulations in VISSIM and importing them into Matlab. In Matlab these traffic measurements will be used to give new control orders to the simulation in order to control the traffic. COM interface sends again these orders back to VISSIM. COM interface works simultaneously with VISSIM in a way that it can derive traffic measurements continuously. COM interface can however also be used for getting traffic measurements which will show the performance of the executed subnetwork controller.

Matlab scripts are written in order to translate the mathematical algorithm of the back pressure and flow controller into a working control structure. A special algorithm has not been written for the vehicle-actuated controller. This controller will be applied in subnetwork control by using VRIGen and TRAFCOD. VRIGen is a program in which an optimized control structure can be constructed based upon the cycle time, layout of the intersection and the associated conflict matrix. This optimized control structure will consists of green, red and yellow times, phase execution order, extension green times, etc. TRAFCOD will be used to simulate a controlled intersection. TRAFCOD uses the output of VRIGen.

VRIGen and TRAFCOD will also be used in the back pressure and flow controller, but in a different way. How each control algorithm has been applied in VISSIM, Matlab, VRIGen and TRAFCOD is described in nine different aspects:

1. Detector loops and control detectors
2. Available phases
3. Clearance time between phases
4. Time step algorithms, time slot length algorithms and simulation time VISSIM
5. Green, yellow and red time durations
6. Turn rations traffic movements
7. Queue length and capacity
8. Data collection of traffic measurements
9. Route choice

4.6.1 Detector loops and control detectors

The vehicle-actuated controller will be controlled by detector loops which are placed within the subnetwork in VISSIM. When a detector is occupied by a vehicle, TRAFCOD will decide (according to the control settings constructed in VRIGen) when the traffic stream, at which the vehicle is present, will get right-of-way. No control orders will be given from Matlab by COM interface. The detector loops of the vehicle-actuated controller are place just before each stop line and approximately 50 meters upstream of the stop line. The upstream detector is in that case the extension detector.

For controlling traffic by the back pressure controller and subnetwork flow controller, these specific detector loops cannot be used. Instead, control detectors will be used which are located outside the subnetwork in VISSIM. They have the same properties as the vehicle-actuated detector loops, but will not be occupied by vehicles. They will be occupied by a control order executed by COM interface based upon the computations of the back pressure or flow controller algorithm in Matlab. When a certain phase has to get right-of-way in a specific time step (based on the pressure calculations), the detectors of those specific traffic streams will be set to occupied. Traffic signals will be set to green when associated control detectors are occupied.

It is important to name the control detectors in VISSIM in such a way that no mistakes in the algorithm in Matlab will be made. Every control detector will be controlled individually and therefore it has to be clear which control detector (placed outside the subnetwork) belongs to which traffic stream.

4.6.2 Available phases

As mentioned before in paragraph 3.2 on the aspects of influence on the performance of the design of the subnetwork flow controller, the available phases will have to be determined for each controller.

The vehicle-actuated controller will be executed by VRIGen and TRAFCOD. No control orders will be given from Matlab by COM interface as described before. Therefore, which phases are available for the vehicle-actuated controller will be determined by the most optimal control structure computed by VRIGen. Due to the control of traffic by detector loops, the vehicle-actuated controller will give right-of-way to vehicles which are present at the intersection when possible. When all detectors are occupied, the intersection will be controlled according to the most optimal control structure which is determined beforehand by VRIGen.

The back pressure controller can choose of all possible phases which consist of two, three or four traffic movements. Within Matlab, these possible phases are constructed. By allowing the controller to choose from all possible phases, a more flexible way of controlling traffic can be performed. This was made clear during the test phase of the subnetwork flow controller algorithm on a single intersection. Therewith, the subnetwork flow controller will exclude some phases from the available phases when the deviation of the perimeter flow with respect to the desired perimeter flow exceeds a certain value. In order to maintain flexibility in controlling traffic in this controller as well and to maintain the back pressure controller as a reference for the performance of the subnetwork flow controller, all possible phases of two, three or four traffic movements are taken into account.

4.6.3 Clearance time between phases

The transition between activated phases is an element in traffic control which is handled by the clearance time. Between each phase which has right-of-way a certain time period has to be taken into account in order to clear the intersection from any vehicles. In basic traffic control some traffic streams will get right-of-way a little earlier due to lower clearance time as another traffic stream.

In this thesis, extra clearance time between phases will be set to zero seconds for all three different controllers. The only clearance time which is present is the yellow time between green times of successive traffic streams. The vehicle-actuated controller will give green to a traffic stream whenever there is traffic detected at this traffic stream and this specific traffic stream has no conflict with other traffic streams which have right-of-way.

The back pressure and flow controller are however controlled by the control detectors. These controllers decide which phase has to get right–of-way. This will be done once every time step. The result is that every traffic stream will have at the same time red unless that specific traffic stream is part of the next phase which will get right of way. When that is the case, the fixed green time will turn into waiting green during the yellow time between two successive phases.

4.6.4 Time step algorithms, time slot length algorithms and simulation time VISSIM

Time step algorithms

A time step in the algorithm of three seconds has been handled in order to give the right control orders in terms of giving green, yellow or red to the traffic signals. The value of three seconds has been chosen in order to construct a yellow time of three seconds. More on the green, yellow and red times is described in paragraph 4.6.5.

Time slot length algorithms

The algorithms of the back pressure and flow controller will control the subnetwork with a time slot length of the algorithm of twelve seconds. That means that every twelve seconds the controllers decide upon real-time traffic measurements which phase has to get right-of-way in the next time slot. A time slot length of twelve seconds prevents a flasher effect of the traffic signals.

Simulation time VISSIM

The simulation time which has been handled in VISSIM is 3600 seconds. The vehicle-actuated controller and back pressure controller will control traffic from the beginning of the start of the simulations. The flow controller starts however controlling the perimeter flows from the twentieth time slot (after 228 seconds) of the algorithm. The first nineteen time slots will be controlled by the basic back pressure algorithm. This has been done in order to fill the subnetwork with enough traffic in order to control the perimeter flows properly. These first 228 seconds are included in the performance evaluation nevertheless except when evaluating the perimeter flows.

4.6.5 Green, yellow and red time durations

Fixed green, yellow and guaranteed red time durations have to be set up for all three controllers before controlling the traffic in VISSIM. For the vehicle-actuated controller, these settings have been applied within VRIGen. A fixed green time of six seconds, a yellow time of three seconds and a guaranteed red time of three seconds has been handled. For the subnetwork back pressure and subnetwork flow controller, these settings have been described in Matlab.

Within Matlab, the time step and time slot length of the algorithm determines the fixed green time, yellow time and guaranteed red time. For all algorithm time slots, these values are constant. Due to the three seconds time step in the algorithms, a yellow time of three seconds can be maintained. For determining which phase has to get right-of-way, a time slot length of twelve seconds has been maintained. In that case, the fixed green time for the back pressure and flow controller has been set to: 12 – 3 = 9 seconds. Due to the fixed green time of nine seconds and the yellow time of three seconds, the guaranteed red time duration is twelve seconds. This is caused by the fact that the controllers will send a control order to VISSIM once every twelve seconds.

The yellow use and start loss has been maintained for every controller the same. These values have been obtained from the standard settings of VRIGen. It is however possible within VISSIM simulations that yellow use is higher. In table 4-2 an overview of the timer settings is shown.

Controller	Fixed green (s)	Yellow time (s)	Guaranteed red (s)	Start loss (s)	Yellow use (s)
Vehicle-actuated	6	3	3	1	1
Back pressure	9	3	12	1	1
Subnetwork flow	9	3	12	1	1

Table 4-2: Timer settings of different controllers in seconds

4.6.6 Turn ratios traffic movements

VRIGen takes into account the saturation flows in vehicles per hour (maximum at which vehicles can pass a stop line at a traffic signal) when constructing the most optimal control structure. The back pressure and subnetwork flow controller use turn ratios (veh/h) in order to calculate the pressure of phases. In this thesis, these turn ratios are set equally to the maximum saturation values as in VRIGen. For these two controllers, the turn ratios have to be defined within Matlab. A distinction has been made in left turning traffic, through going traffic and right turning traffic. Values of these three directions differ due to the angle which vehicles have to take in order to take the turn which can cause some time loss. By taken the same values for all three controllers, the turn ratios will have no influence on the difference on performance of the three controllers. An overview of the turn ratios is provided in table 4-3. The standard values of saturation flows in VRIGen are used.

	Left turning traffic	**Trough going traffic**	**Right turning traffic**
Turn ratio (veh/h)	1715	1800	1530

Table 4-3: Turn ratios different directions based upon standard settings VRIGen

4.6.7 Queue length and capacity

Queue definition

In this thesis, a queue definition has been taken which VISSIM uses standard. Within VISSIM a vehicle is in queue when the speed of that specific vehicle is below ten km/h. Furthermore, when the headway between two successive vehicles is below twenty meters, the second vehicle is in queue as well. This queue definition is needed in order to determine the queue lengths for the algorithms of the back pressure and subnetwork flow controller.

Queue length

The back pressure and subnetwork flow controller make use of queue counters within VISSIM. These queue counters are located at the stop lines of each traffic stream. These queue counters determines the queue length (in meters) of each traffic stream by determining if a vehicle is in queue position. A drawback of determining the queue length this way is that vehicles at the end of a queue can be still in queue position while the first vehicles have already passed the stop line of the traffic stream. The result is that a queue will be solved instantly (within a second, the queue can reduce from for example 60 meters to 0 meters) when the last vehicle exceeds the ten km/h speed queue definition.

The vehicle-actuated controller does not use queue counters to decide if there are vehicles in queue position. Instead, the vehicle-actuated controller controls the intersection based on the presence of vehicles at the approach of a traffic stream only. Vehicles will be detected by detector loops as stated before. Thus, queue lengths are not taken into account by the vehicle-actuated controller, only the presence of vehicles at approaches of traffic streams.

Queue capacity

A queue capacity as long as possible is desired in order to prevent spillback to other intersections in the subnetwork. It is however not realistic to construct these very long approaches. Within VISSIM the queue capacity has been set to 150 meters (the approach links have a size which equals 150 meters). 150 meters is still a very large queue capacity compared to intersections in the real world. For the back pressure and subnetwork flow controller, a maximum queue length of 150 meters has been taken in order to prevent large queue length due to spillback. When spillback may occur and this maximum was not set, the queue counters may take into account a queue length of an upstream traffic stream. This has to be prevented , because vehicles stay in queue position of a specific queue counter whether they are located at that specific traffic stream or at an upstream traffic stream.

4.6.8 Data collection of traffic measurements

Data collection points are placed at each link within VISSIM in order to determine the production and accumulation in the subnetwork. Every second, vehicles will be counted and the information will be send to Matlab by COM interface. The data collection points have been placed at input links, internal links and output links. In Matlab all these links are defined. This has been done in order to make a distinction in inflow production, internal production and outflow production. These measurements will be used to determine the performance of each subnetwork traffic controller on optimizing the internal flows.

The data collection points which measure inflow production are located just after the input parking lots (input points of VISSIM). The data collection points which measure internal production are located at links just downstream of each intersection. Each intersection has therewith four data collection points which could measure internal production. Intersection which are located at the corner of the subnetwork have however only two adjacent intersections. Therefore, these intersections have only two data collection points which measure internal production. Intersections which have three adjacent intersections have, with the same explanation, three data collection points which measure internal production. The outflow production is measured by data collection points which are located at each out link of the subnetwork just downstream of the intersections.

4.6.9 Route choice

Due to the layout of each kind of subnetwork (four, eight or sixteen intersections), vehicles have multiple options in route choice. Which route a specific vehicle will take has been defined within VISSIM. VISSIM assumes in their route choice model that not all drivers use the best route in terms of travel time but all routes available can be used. However, more traffic is assigned to ‘better’ routes than to ‘worse’ routes. The quality of a route has been determined by a general cost function of the route where the utility of each route will be calculated. Each vehicle which enters the subnetwork during the simulation has an own origin-destination pair. When that specific vehicle enters the subnetwork, the utility for each possible route will be calculated. Based on these calculations, the vehicle will take the ‘best’ route. No distinction has been made for the three controllers in route choice determination. For more information on route choice within VISSIM, see the user manual of VISSIM (PTV, 2005).

5 Simulation results

All simulations have been performed in VISSIM as described in the previous chapter. The performance on contributing to the three main objectives by the vehicle-actuated, back pressure and subnetwork flow controller will be described. The performance of each different kind controller will be described individually. Some input parameters will be described first for each controller. For the vehicle-actuated and back pressure controller, performances will be shown on maintaining a constant shaped MFD and scatter size and optimizing the internal flows. From these results, conclusions will be made upon the influences of the subnetwork layout on the shape of the MFD. For the subnetwork flow controller, performances will be shown on all three objectives; maintaining a constant MFD, optimizing internal flows and providing desirable perimeter flows.

5.1 Vehicle-actuated controller

The first simulations in VISSIM have been performed with a vehicle-actuated controller. The results of the performance of the vehicle-actuated controller will be the reference results for the back pressure and subnetwork flow controller. Twelve simulations with a vehicle-actuated controller have been performed in total.

5.1.1 Simulation input parameters

The only parameters which are of influence on the performance of the vehicle-actuated controller and will be changed in between the simulations are the size of the subnetwork (subnetwork layout) and the demand of the subnetwork.

More detailed information on the value of demands has already been described in paragraph 4-4. For now, the values of demand for the different subnetwork layouts are shown again in table 5-1.

		Subnetwork layout		
		Four intersections	Eight intersections	Sixteen intersections
Demand load	**Low**	90	50	30
	Medium	110	70	55
	High	140	90	70
	Very high	150	110	110

Table 5-1: Overview origin-destination demand values for different subnetwork layouts

5.1.2 Maintaining a constant shaped MFD

MFD's have been derived for each kind of subnetwork layout. According to several studies, the shape of the MFD should be independent of the demand pattern in theory. Therefore, the MFD's constructed with different demand patterns are combined in a single MFD for each kind of subnetwork layout. A distinction in applied demand pattern has been made clearly visible. The combined MFD's are shown of simulations with different demand patterns. Furthermore, running medians have been determined of each combined MFD. From these running medians, the absolute deviation of all data points have been determined from which the standard deviation has been calculated in order to evaluate the scatter size.

Four intersections

In figure 5-1 the combined MFD is shown of the simulations with a vehicle-actuated controller and a subnetwork layout of four intersections.

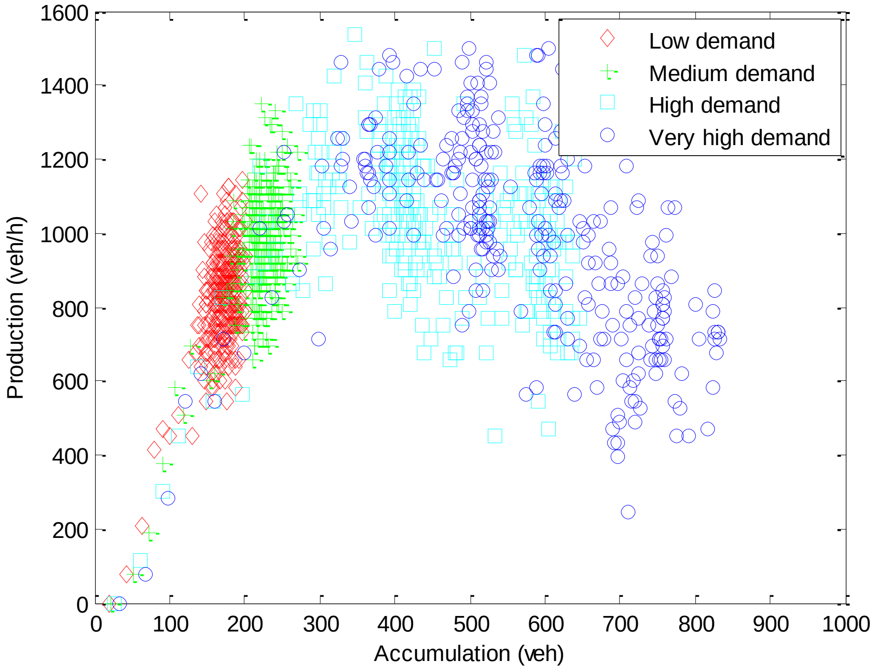


Figure 5-1: MFD of subnetwork layout with four intersections controlled by a vehicle-actuated controller

A free flow and congestion branch can be identified more or less in figure 5-1. There is however a lot of scatter. This can be seen in figure 5-2 where the running median has been determined. The absolute scatter deviation (figure 5-3) has been used to determine the standard deviation of the MFD which is in this case 98,6 veh/h. Due to the large scatter, a sweet spot value (a maximum production at a certain critical accumulation) is very difficult to identify. This derived shape of the MFD of simulations with a subnetwork layout of four intersections has, due to the large scatter, not the most desirable shape in order to maintain a constant shaped MFD based on different demand patterns.

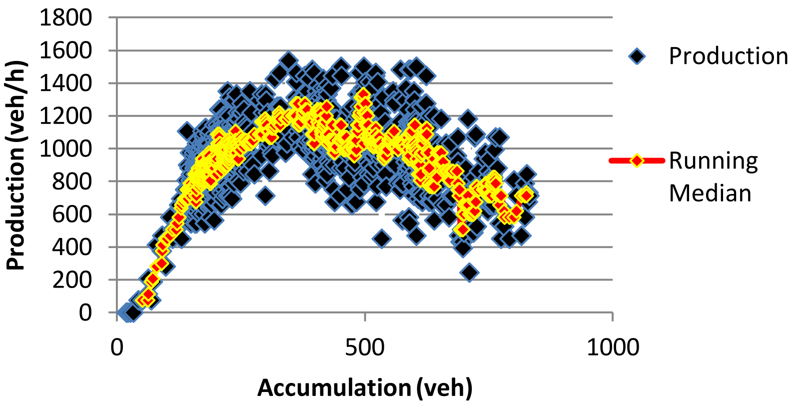


Figure 5-2: Running median of MFD subnetwork layout consisting of four intersections

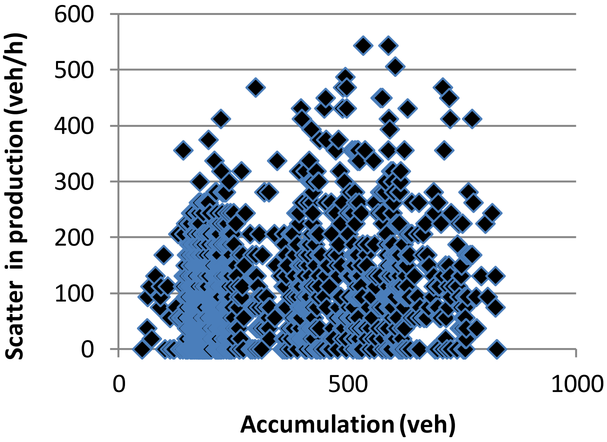


Figure 5-3: Absolute scatter deviation of all data points MFD subnetwork layout consisting of four intersections

Eight intersections

In figure 5-4 the combined MFD is shown of the simulations with a vehicle-actuated controller and a subnetwork layout of eight intersections.

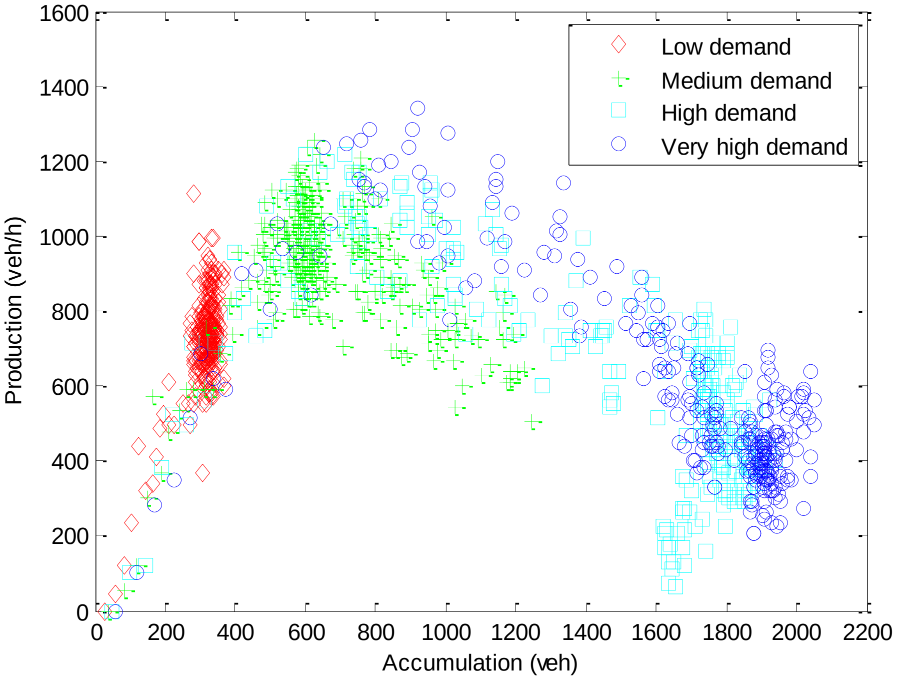
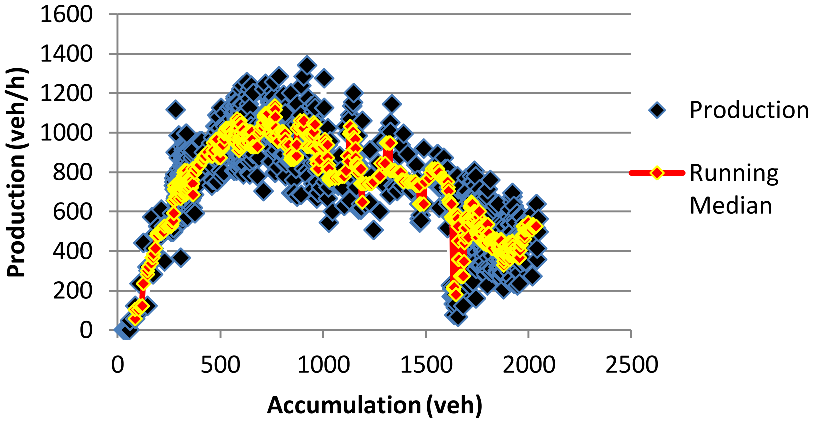


Figure 5-4: MFD of subnetwork layout with eight intersections controlled by a vehicle-actuated controller

The scatter is visually less in figure 5-4 compared to figure 5-1. In order to evaluate how much less the scatter is, the running median (figure 5-5) and absolute scatter deviation from all data points to this running median (figure 5-6) have been determined again. The result is that the standard deviation of the scatter of the MFD of the subnetwork consisting of eight intersections controlled by a vehicle-actuated controller turned out to be 81,3 veh/h. This is less as the standard deviation of the subnetwork consisting of four intersections (98,6 veh/h). A subnetwork layout consisting of eight intersections is therefore more desirable as a subnetwork layout of four intersections.

Compared to the subnetwork layout consisting of four intersections, the subnetwork consisting of eight intersections has got a lower maximum production. This production is however the total average production. More insight on the production results can be found in paragraph 5.1.3.

The accumulation has been increased of course due to the increase of size of subnetwork layout.



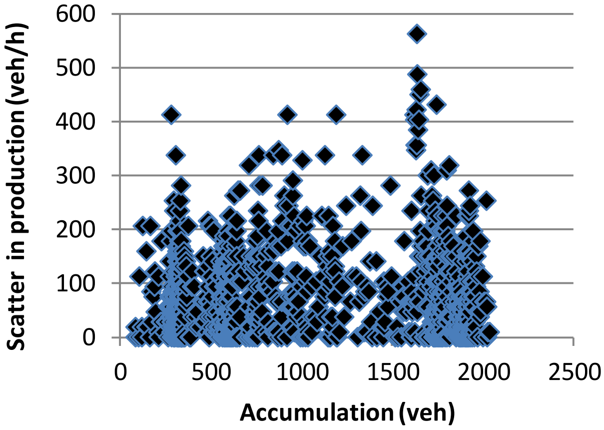


Figure 5-5: Running median of MFD subnetwork layout consisting of eight intersections

Figure 5-6: Absolute scatter deviation of all data points MFD subnetwork layout consisting of eight intersections

Sixteen intersections

In figure 5-7 the combined MFD is shown of the simulations with a vehicle-actuated controller and a subnetwork layout of sixteen intersections.

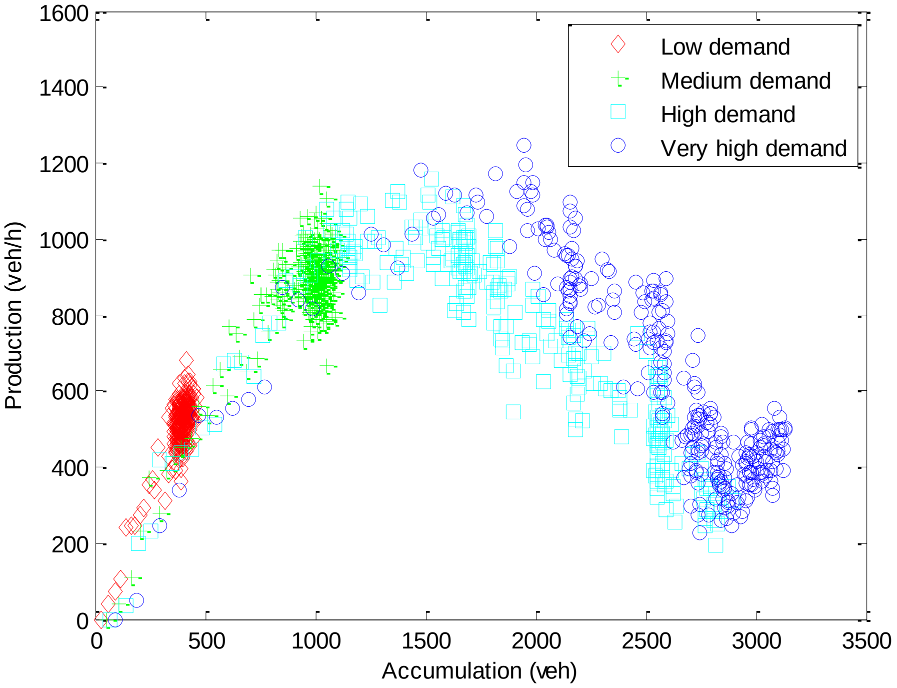


Figure 5-7: MFD of subnetwork layout with sixteen intersections controlled by a vehicle-actuated controller

In figure 5-7 the scatter of the MFD seems to be less compared to figures 5-1 and 5-4 . The scatter has a standard deviation of 62,1 veh/h which is the lowest compared to the MFD’s of subnetworks layout consisting of four intersections (98,6 veh/h) and eight intersections (81,3 veh/h). In figure 5-8 and figure 5-9 the running median and absolute scatter deviation is shown again. It can be seen that the absolute scatter deviation in figure 5-9 is lower compared to the other subnetwork layouts which thus results in a lower standard deviation in scatter. A constant shape of the MFD cannot be identified. The high and very high demand data points do not match each other. This can be caused by coincidence or explained by saying that the MFD of a vehicle-actuated controller is dependent on the applied demand pattern. A different result may appear when a different seed is applied in VISSIM.

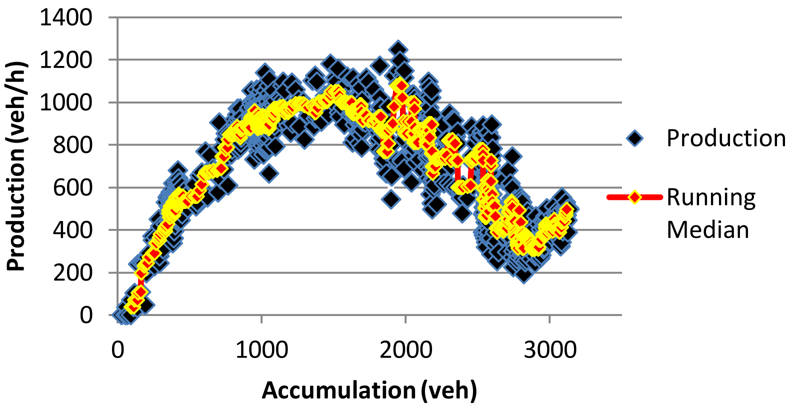


Figure 5-8: Running median of MFD subnetwork layout consisting of sixteen intersections

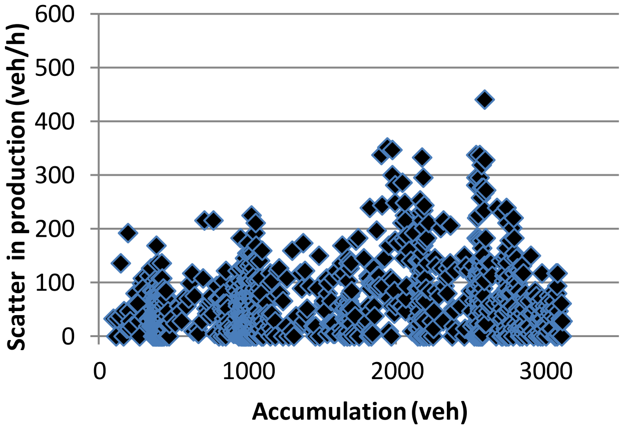


Figure 5-9: Absolute scatter deviation of all data points MFD subnetwork layout consisting of sixteen intersections

Conclusions

Comparing all three subnetwork layouts, it can be said that a subnetwork which consists of sixteen intersections and is controlled by a vehicle-actuated controller provides a MFD which has the lowest standard deviation in scatter size. A constant shaped MFD can nevertheless not maintained by the vehicle-actuated controller. This can be seen in the different location of data points of the different applied demand patterns. It can therefore also be said that the MFD controller by the vehicle-actuated controller is not independent of demand. However, the results have been obtained by single simulations only. Performing multiple simulations with the same applied subnetwork layouts and demand patterns may result in different results.

In table 5-2 an overview is shown of all standard deviations on the scatter of the MFD’s

	Standard deviation of MFD
Four intersections	98,6 veh/h
Eight intersections	81,3 veh/h
Sixteen intersections	62,1 veh/h

Table 5-2: overview standard deviation MFD's with different subnetwork size

5.1.3 Optimizing internal flows

The second objective of the subnetwork flow controller is to optimize the internal flows. In order to check the performance of the vehicle-actuated controller on this objective graphs of delay and production are provided.

For showing the delay results of the different simulations a distinction has been made in total internal delay (total delay in hours of all vehicles incurred within the subnetwork) and total latent delay (total delay in hours of all vehicles incurred outside the subnetwork due to blocking of vehicles at the input links).

The production realised within the simulations have been divided in three aspects. A distinction has been made in inflow production (number of vehicles per hour that have entered the subnetwork), outflow production (number of vehicles per hour that have left the subnetwork) and internal production (number of vehicles per hour that travel through the subnetwork. Due to the simulation time of 3600 seconds, the production results also represents the total amount of vehicles which have been entered, exit, or travelled through the subnetwork respectively.

Again, these performances will be described by the three different subnetwork layouts.

Four intersections

In figure 5-10 the total delay of simulations with four intersections has been visualised. In figure 5-11 the production has been visualised which has been divided in three aspects; inflow production, outflow production and internal production.

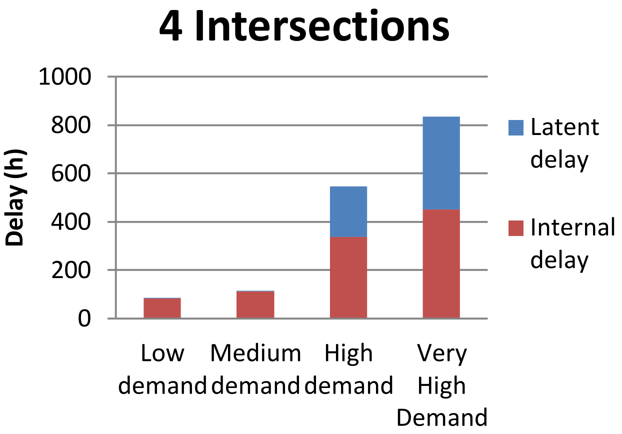


Figure 5-10: Internal and latent delay four intersections

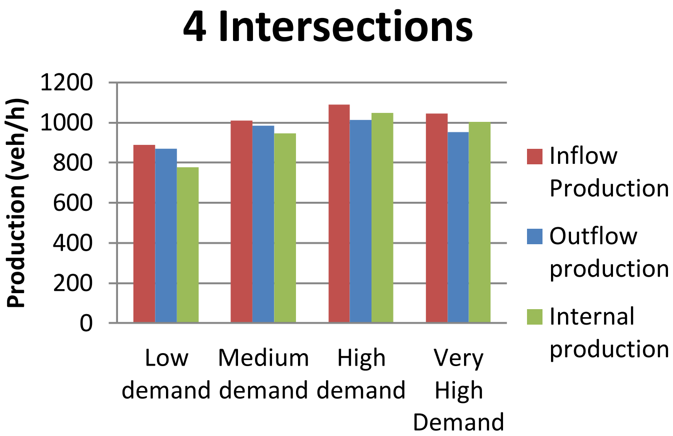


Figure 5-11: Inflow, outflow and internal production four intersections

In figure 5-10 it can be seen that when the demand is higher, the total delay will be higher as well. When the demand has been set to high demand or very high demand, the latent delay part has been increased largely. This large increase in latent delay is caused by blocking of vehicles at the input links. In case of the very high demand simulation, a gridlock has been occurred which causes even more latent demand.

In figure 5-11 it can be seen that the inflow production is higher as the outflow production and the internal production in every simulation with a different demand pattern. This is caused of course by the fact that some vehicles which have entered the subnetwork did not reach their destination yet at the end of the simulation. It can be seen that a gridlock has been occurred in the simulation with a very high demand pattern due to the lower inflow, outflow and internal production compared to the simulation with a high demand pattern.

Eight intersections

In figure 5-12 the total delay of simulations with eight intersections has been visualised. In figure 5-13 the production has been visualised.

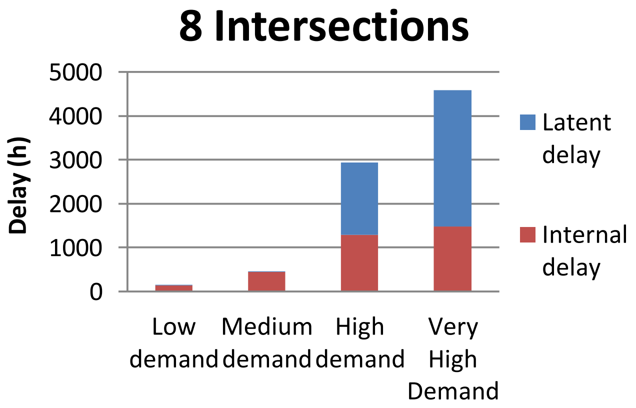


Figure 5-12: Internal and latent delay eight intersections

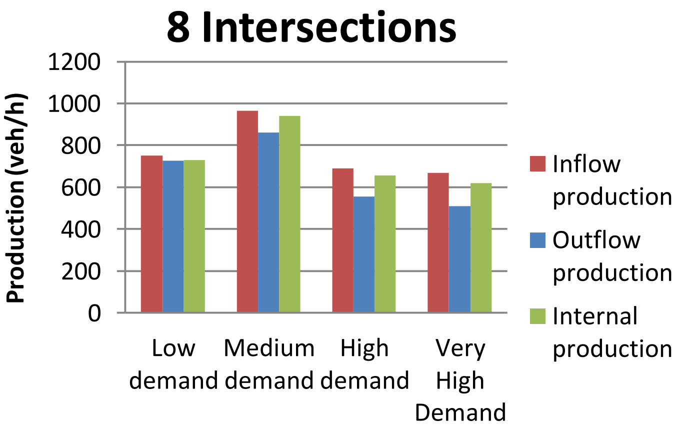


Figure 5-13: Inflow, outflow and internal production eight intersections

Figure 5-12 shows that increase of total delay in the simulations with a high or very high demand is mainly caused by the total latent delay. In both cases (high demand and very high demand) a gridlock did occur.

The effect of the gridlocks can also be seen in figure 5-13. All three kinds of productions are lower in the simulations with high or very high demand patterns. The difference between inflow, outflow and internal production of a certain demand pattern is nevertheless the same. Compared to the results of the simulations with a subnetwork consisting of four intersections, the difference in height between different production aspects are the same.

Sixteen intersections

In figure 5-14 the total delay of simulations with sixteen intersections has been visualised. In figure 5-15 the production has been visualised.

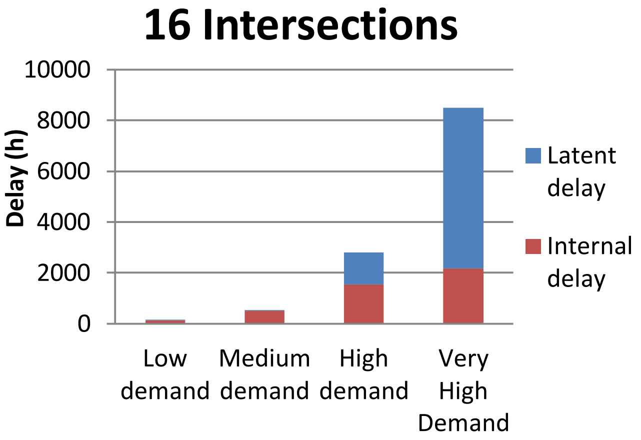


Figure 5-14: Internal and latent delay sixteen intersections

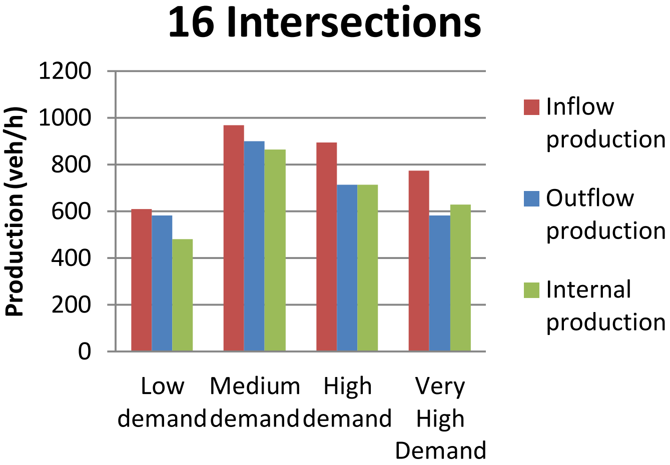


Figure 5-15: Inflow, outflow and internal production sixteen intersections

A subnetwork layout consisting of sixteen intersections results in an even greater influence of the total latent demand on the total delay of subnetwork. In simulations with a high demand and very high demand pattern, a gridlock did occur again caused by spillback.

In the simulation with a low demand, the internal production turned out to be less as the outflow production. This is caused by the fact that the internal production is measured on links which are located within the subnetwork. Vehicles which travel trough the corners of the intersections did actually not enter the subnetwork (according to the location of the data collection points) and thus are not measured within the internal production but only in the inflow production and outflow production. This applies for every performed simulation in this thesis.

Conclusions

At this point, nothing can be said on the performance of the vehicle-actuated controller on optimizing internal flows. The results described above are the reference results for the back pressure and subnetwork flow controller. Nevertheless, it can be said that gridlocks did occur which influence the total delay and production of the subnetwork. These events caused an increase in total delay due to a very large increase in total latent delay. Comparing the total delay and production of different subnetwork layouts is not possible due to a difference in demand patterns (low demand at a subnetwork with four intersections does not equal a low demand at a subnetwork with eight intersections for example) and a difference in size of the subnetwork.

5.2 Back pressure controller

The second set of simulations has been performed with a back pressure controller in VISSIM. The results of the performance of the vehicle-actuated controller will be the reference results for the back pressure controller. A most desirable subnetwork layout will be chosen for performing simulations with the subnetwork flow controller.

5.2.1 Simulation input parameters

The parameters which are of influence on the performance of the back pressure controller and will be changed in between the simulations are the size of the subnetwork (subnetwork layout) and the demand pattern applied in the subnetwork.

5.2.2 Maintaining a constant shaped MFD

Again, the combined MFD's for different subnetwork layouts will be shown of simulations with different applied demand patterns.

Four intersections

In figure 5-16 the combined MFD is shown of the simulations with a back pressure controller and a subnetwork layout of four intersections.

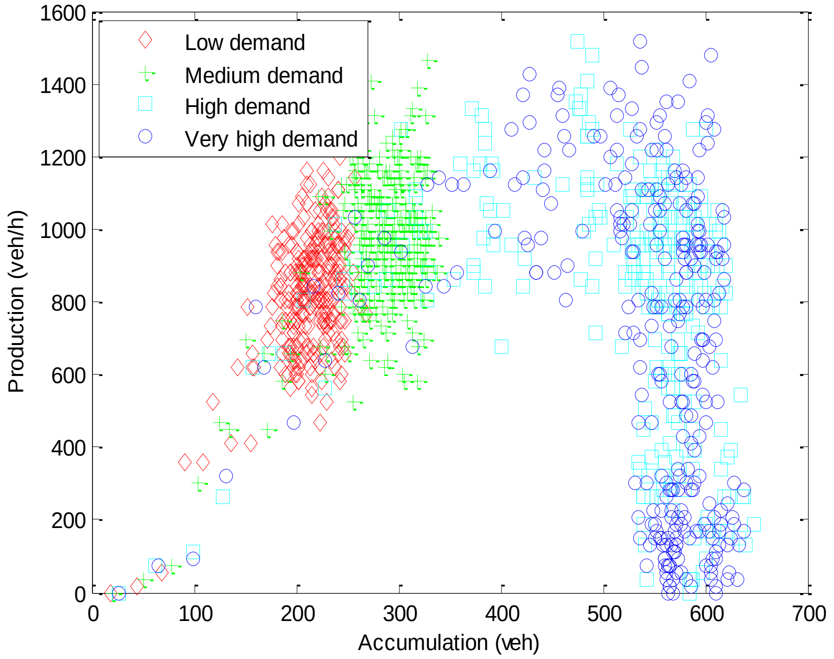


Figure 5-16: MFD of subnetwork layout with four intersections controlled by a back pressure controller

In comparison with the MFD of the subnetwork consisting of four intersections controlled by a vehicle-actuated controller (figure 5-1) the shape of the MFD is less independent on the applied demand pattern. In order to quantify the scatter, the standard deviation of the scatter of the MFD has been determined again by constructing the running median (figure 5-17) and determining the absolute scatter deviation (figure 5-18). It turned out that the standard deviation of the scatter of the MFD of a subnetwork consisting of four intersections and controlled by the back pressure controller is 193,8 veh/h. This result is far higher as the standard deviation of the same subnetwork layout controller by the vehicle-actuated controller. This can however be explained by the fact that the standard deviation has been calculated based on the vertical absolute deviation in production flow with respect to the running median of the MFD. At high accumulation, all values of production may appear. This makes clear that a total gridlock may occur under certain specific circumstances but also that few congestion may occur under the right circumstances.

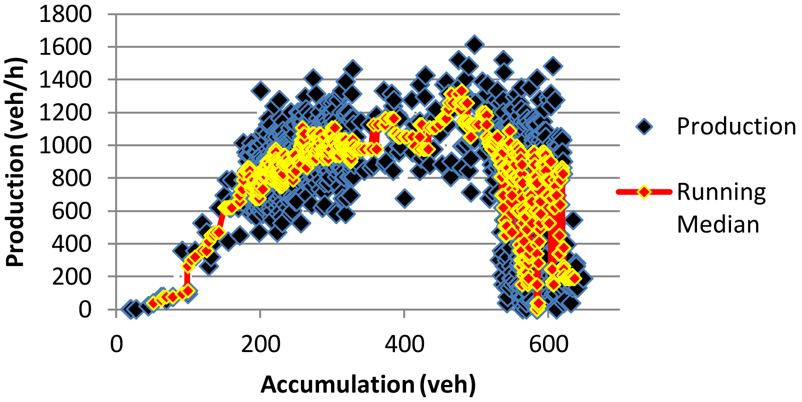


Figure 5-17: Running median of MFD subnetwork layout consisting of four intersections

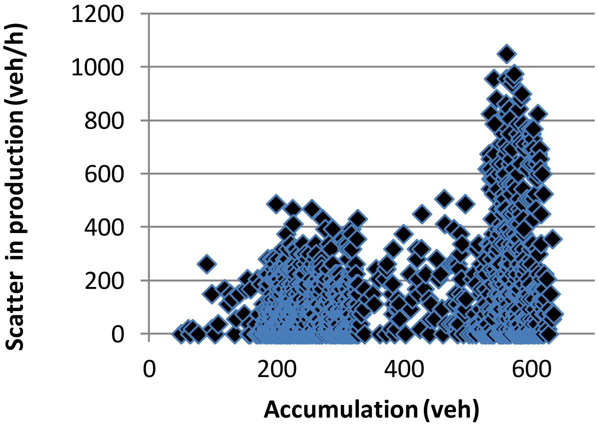


Figure 5-18: Absolute scatter deviation of all data points MFD subnetwork layout consisting of four intersections

Eight intersections

In figure 5-19 the combined MFD is shown of the simulations with a back pressure controller and a subnetwork layout of eight intersections.

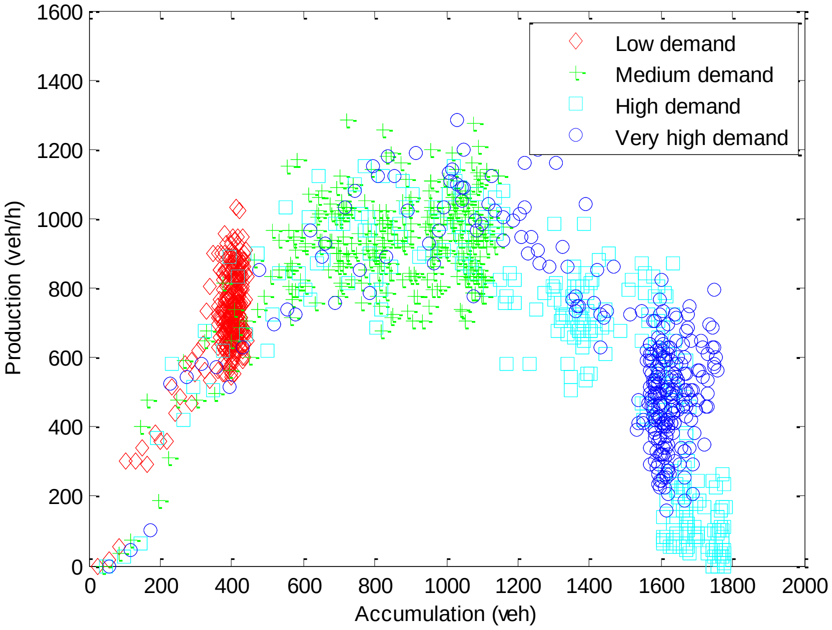


Figure 5-19: MFD of subnetwork layout with eight intersections controlled by a back pressure controller

It can be seen in figure 5-19 that a constant shaped MFD can be derived independently of the demand. There is however still some significant scatter present in the MFD of the back pressure controller applied on a subnetwork which consists of eight intersections. The standard deviation of this scatter is 94,8 veh/h. It can be seen again in figure 5-20 that the running median is not smooth at high accumulation and thus the absolute scatter deviation (figure 5-21) is also larger with respect to the results of the vehicle-actuated controller applied on a subnetwork consisting of eight intersections (standard deviation of 81,3 veh/h). A total gridlock occurred within the simulations due to the fact that there is no production at a maximum accumulation. But it can also be seen that there is still a high production possible at maximum accumulation. This influences again the standard deviation factor due to the fact that the absolute scatter deviation has been determined in a vertical way.

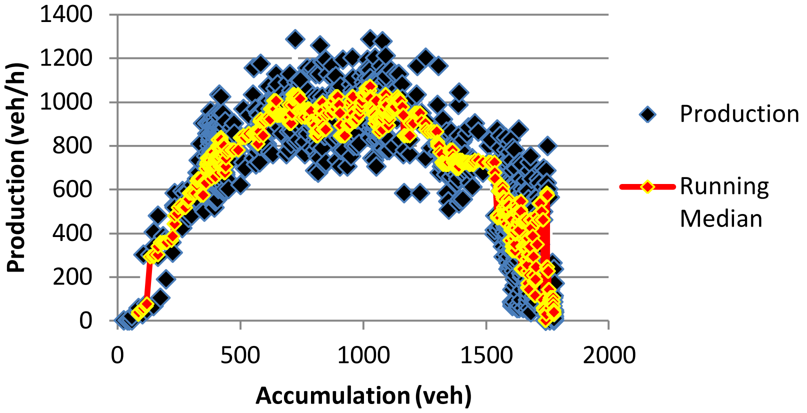


Figure 5-20: Running median of MFD subnetwork layout consisting of eight intersections

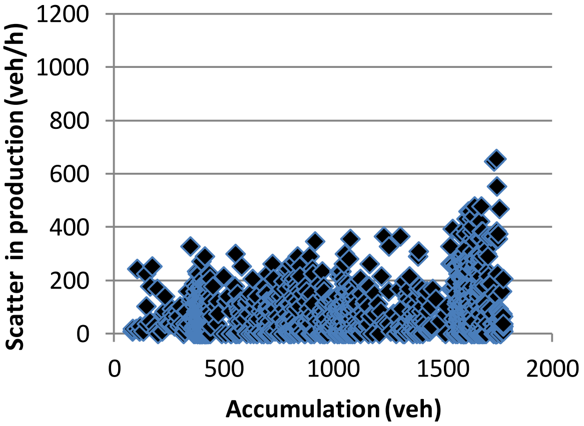


Figure 21: Absolute scatter deviation of all data points MFD subnetwork layout consisting of eight intersections

Sixteen intersections

In figure 5-22 the combined MFD is shown of the simulations with a back pressure controller and a subnetwork layout of sixteen intersections.

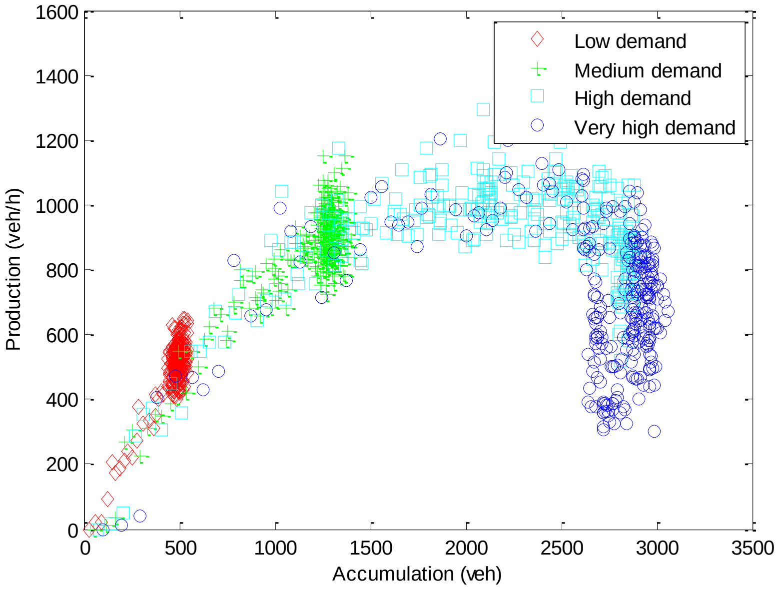


Figure 5-22: MFD of subnetwork layout with sixteen intersections controlled by a back pressure controller

From all presented MFD's so far, the MFD of the subnetwork consisting of sixteen intersections controller by the back pressure controller seems to have the least scatter. But again, at high accumulation different production values have been obtained. This effect, caused by a partial gridlock, can be seen in the result of the standard deviation of the scatter again. This gridlock did only occur on a certain direction within the subnetwork. Vehicles were still able to travel through the subnetwork to the other direction. It can be said that a partial gridlock did occur in that case. The running median of the MFD (figure 5-23) is again not very smooth at high accumulation. It turned out that the absolute scatter deviation (figure 5-24) resulted in a standard deviation of 84,6 veh/h which is higher as the result generated by the vehicle-actuated controller at the subnetwork consisting of sixteen intersections (62,1 veh/h). It is nevertheless clear that the shape of the MFD is of a constant shape and thus independent of the applied demand patterns.

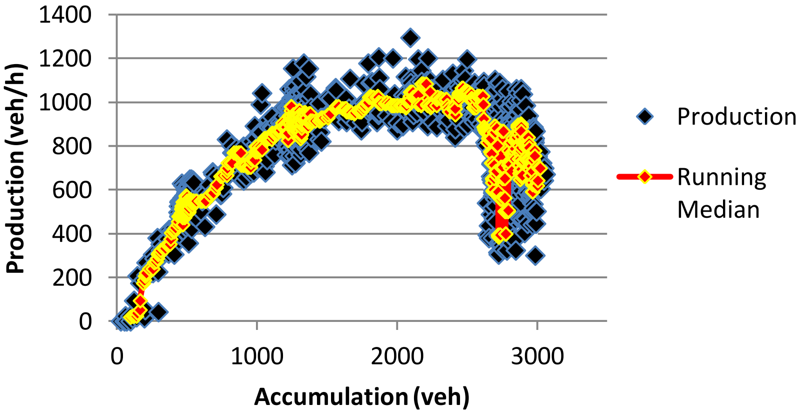


Figure 5-23: Running median of MFD subnetwork layout consisting of sixteen intersections

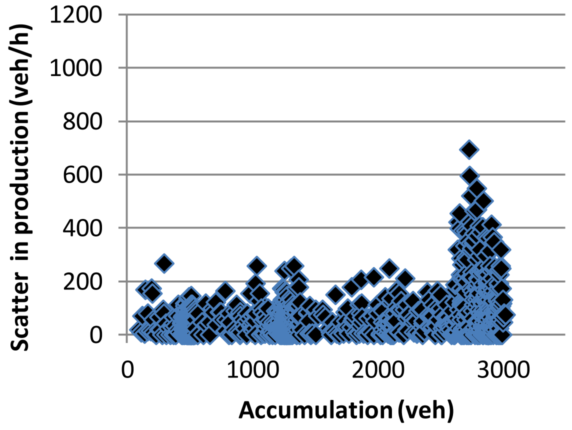


Figure 5-24: Absolute scatter deviation of all data points MFD subnetwork layout consisting of sixteen intersections

Conclusions

It can be concluded that a subnetwork layout consisting of sixteen intersections is able to derive a MFD which has the least scatter according to the standard deviations of the scatter (table 5-3).

		Standard deviation of MFD	
		Vehicle-actuated controller	Back pressure controller
Subnetwork layout	Four intersections	98,6 veh/h	193,8 veh/h
	Eight intersections	81,3 veh/h	94,8 veh/h
	Sixteen intersections	62,1 veh/h	84,6 veh/h

Table 5-3: Overview standard deviations different subnetwork layouts and applied controllers

When evaluating the absolute deviation scatter of both the vehicle-actuated controller and back pressure controller visually, the scatter may seem less of the MFD's provided by the back pressure controller. The standard deviation however shows a different result. The difference between the vehicle-actuated and back pressure controller on the standard deviation in scatter is however influenced by the fact that no total gridlock did occur when the back pressure controller was applied. Therefore, at maximum accumulation lots of different production values have been measured in the simulations. Therewith, due to the fact that the absolute deviation scatter has been determined vertically, the standard deviation of the scatter of the MFD provided by the back pressure controller turned out to be larger as the standard deviations provided by the vehicle-actuated controller.

However, the MFD's of the subnetworks controlled by the back pressure controller seem to be more independent of demand in comparison with the MFD's generated by the vehicle-actuated controller. This can be seen by the fact that data points of different applied demand patterns are located more on top of each other and thus result in a more constant shaped MFD.

Comparing the MFD's of both applied controllers on different subnetwork layouts can be visualised by plotting the running medians of the MFD's in one figure. This is done for the three different subnetwork layouts in figure 5-25, figure 5-26 en figure 5-27.

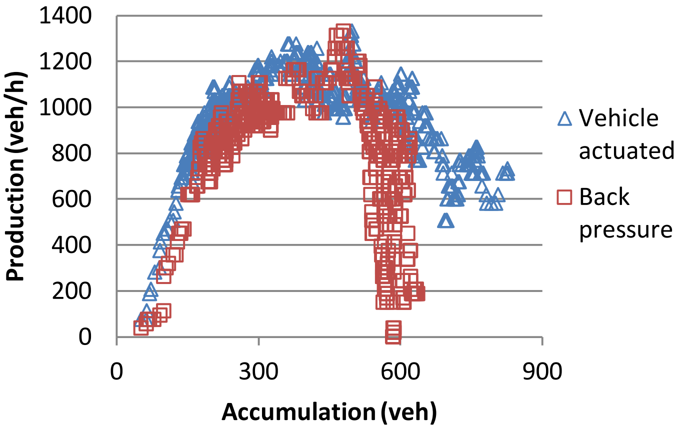


Figure 5-25: Compared running medians of vehicle-actuated and backpressure controller on subnetwork consisting of four intersections

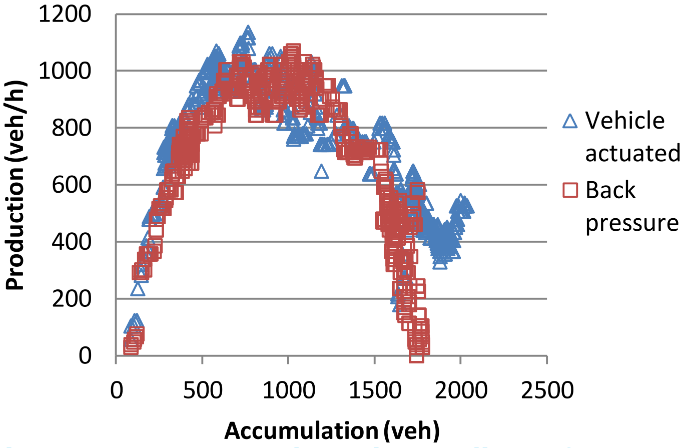


Figure 5-26: Compared running medians of vehicle-actuated and backpressure controller on subnetwork consisting of eight intersections

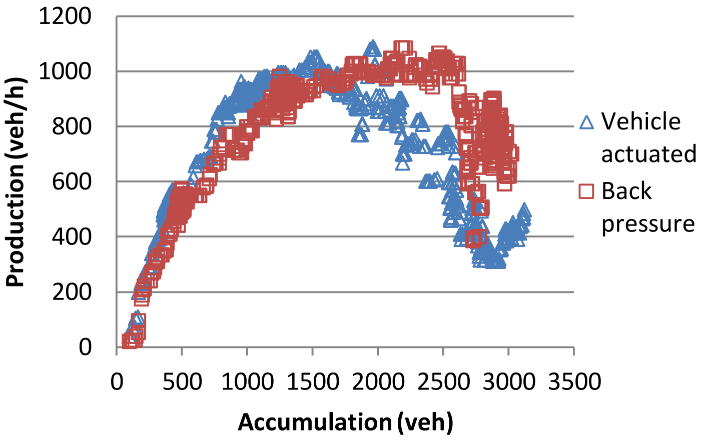


Figure 5-27: Compared running medians of vehicle-actuated and backpressure controller on subnetwork consisting of sixteen intersections

Figure 5-26 shows that the running median of the MFD of the vehicle-actuated controller is higher at higher accumulation and thus performs better in case a subnetwork of four intersections is applied. The same result can be seen in figure 5-27 when a subnetwork consisting of eight intersections is applied. But when a subnetwork consisting of sixteen intersections is applied, the result is that the back pressure controller can maintain higher production flows at high accumulation (figure 5-27). More on the production of the back pressure controller will be handled in the next paragraph 5.2.3.

5.2.3 Optimizing internal flows

The performance of the back pressure controller on the second objective, optimizing the internal flows, will be the reference for the performance of the subnetwork flow controller. The performances on the second objective will be described by the three different subnetwork layouts again. The results of the performance by the vehicle-actuated controller are included in the graphs in order to compare the results.

Four intersections

In figure 5-28 the total delay of simulations with four intersections has been visualised. In figure 5-29 the production has been visualised.

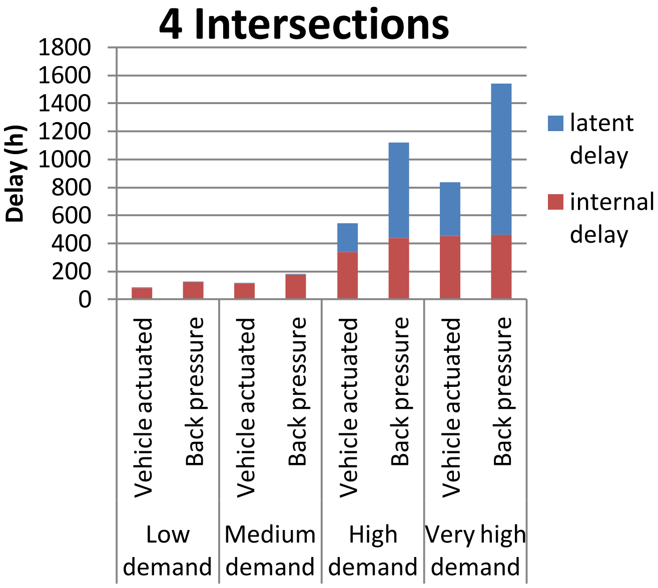


Figure 5-28: Internal and latent delay four intersections

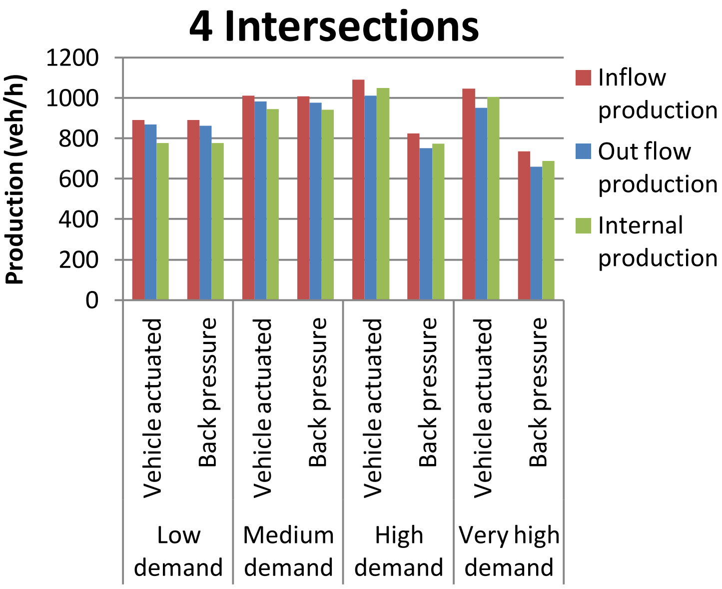


Figure 5-29: Inflow, outflow and internal production four intersections

Figure 5-28 shows that an increase in total delay is generated by the back pressure controller at all kind of demand patterns compared to the vehicle-actuated controller. The internal delay has however not changed significantly with respect to the change in latent delay. It means that vehicles were held outside the subnetwork for a longer time before allowing them to enter the subnetwork. At low and medium demand, no latent delay occurred, only a small increase in internal delay. This increase can be explained by the fact that the back pressure controller has less smooth green times as the vehicle-actuated controller. The back pressure controller has a control time step of every twelve seconds while the vehicle-actuated controller controls continuously.

At low and medium demand, no distinction in production is present between the vehicle-actuated controller and the back pressure controller (figure 5-29). At higher demand, back pressure performs worse with respect to the vehicle-actuated controller. A combination of small size of subnetwork layout and larger time step of control of the back pressure control algorithm has caused that the back pressure controller was not able to prevent a gridlock in time.

Eight intersections

In figure 5-30 the total delay of simulations with four intersections has been visualised. In figure 5-31 the production has been visualised.

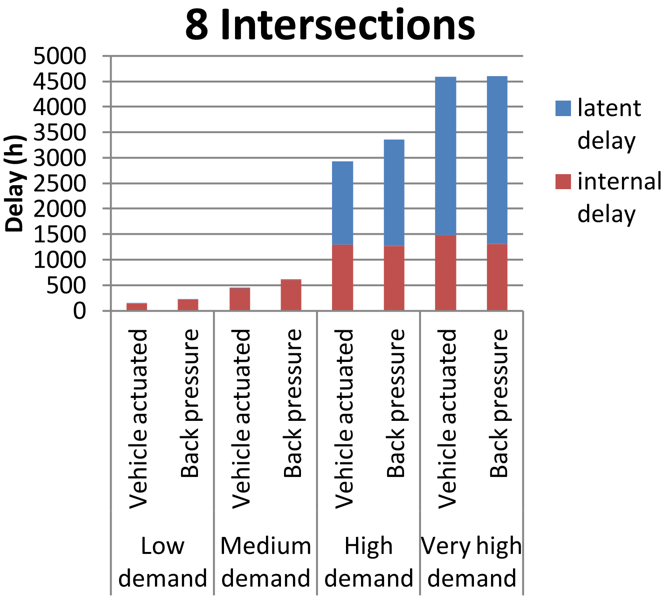


Figure 5-30: Internal and latent delay eight intersections

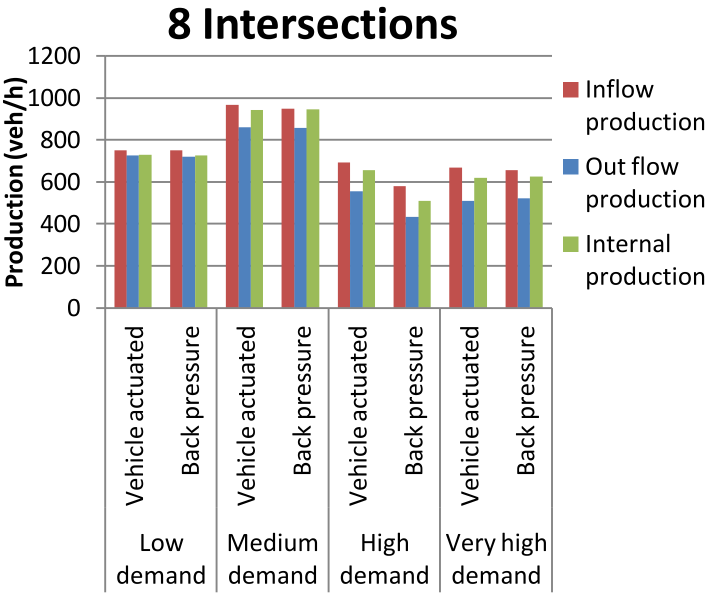


Figure 5-31: Inflow, outflow and internal production eight intersections

Taking a close view at the internal delay results of a subnetwork consisting of eight intersections (figure 5-30), it can be seen that the back pressure controller performs worse at a low and medium demand. However, the back pressure controller performs better at high and very high demand patterns. The total latent delay causes however again that the results of the back pressure controller are worse again when analyzing the total delay.

In figure 5-31 it is shown that no distinction in performance on the production can be made at low and medium demand patterns. The simulation with a high demand pattern shows that the back pressure performs worse with respect to the vehicle-actuated controller. This is mainly caused by the increase of vehicles which are not able to enter the subnetwork and thus cannot reach their destination (shown in the increase in total latent delay). At very high demand, the back pressure controller performance more or less the same as the vehicle-actuated controller.

It can be concluded that a subnetwork layout of eight intersections is more desirable as a subnetwork layout of four intersections. The simulations with four intersections have shown a significant increase in total delay by the back pressure controller compared to the vehicle-actuated controller. At the simulations with eight intersections, this increase in delay by the back pressure controller is less (sometimes even a decrease in internal delay) compared to the total delay of the vehicle-actuated controller.

Sixteen intersections

In figure 5-32 the total delay of simulations with four intersections has been visualised. In figure 5-33 the production has been visualised.

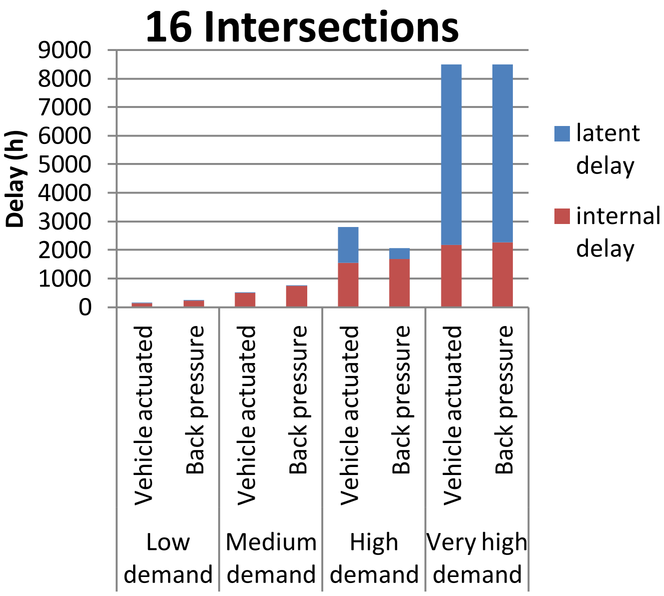


Figure 5-32: Internal and latent delay sixteen intersections

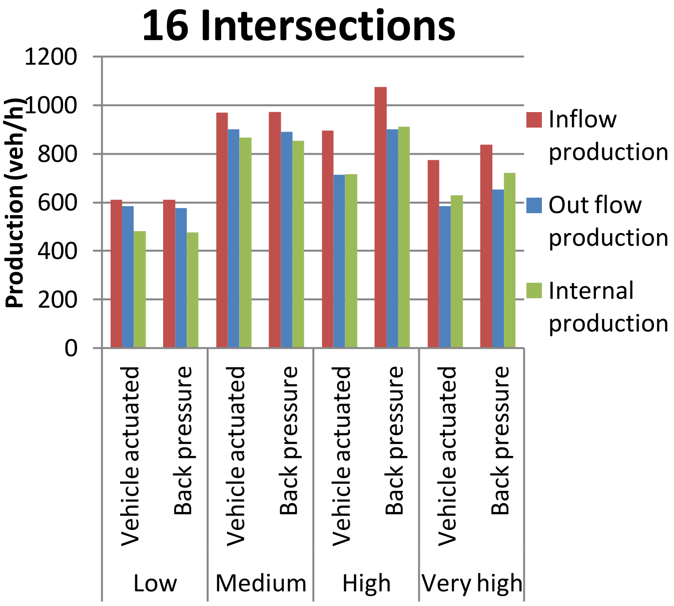


Figure 5-33: Inflow, outflow and internal production sixteen intersections

The simulation with a very high demand pattern on a subnetwork consisting of sixteen intersections caused a gridlock which is very well shown in figure 5-32 due to the very high total latent delay. At high demand, the back pressure controller is able to delay the introducing of a gridlock. The total latent delay is lower at this simulation which also results in a lower total delay with respect to the performance of the vehicle-actuated controller. At all other demand patterns, the back pressure controller performance on total delay is a bit worse. This effect might be caused by the time step of control in the algorithm of the back pressure controller.

Taking a view on the results of the production in figure 5-33 it can be seen that the back pressure controller performs better on all kind of production and demand patterns. The outflow production is less in all simulations due to vehicles which have remained in the subnetwork at the end of each simulation. The internal production of the simulation with a very high demand is higher as the outflow production. This means that the controllers (vehicle-actuated and back pressure) are able to let traffic remain travelling within the subnetwork at certain locations. Reaching their destination is however more difficult or not possible at all.

Conclusions

By increasing size of the layout of the subnetwork and increasing demand pattern, the back pressure controller performs better in comparison with the vehicle-actuated controller based on the results on total delay and production of the back pressure controller. Therefore, based on these results, a subnetwork layout consisting of sixteen intersections seems most desirable compared to four and eight intersections.

In table 5-4, some percentages are shown of the differences on internal production and delay of the back pressure controller with respect to the vehicle-actuated controller.

	Low demand		**Medium demand**		**High demand**		**Very high demand**	
	Total Delay (h)	**Internal production (veh/h)**	**Total Delay (h)**	**Internal production (veh/h)**	**Total Delay (h)**	**Internal production (veh/h)**	**Total Delay (h)**	**Internal production (veh/h)**
Four inters.	+48%	0%	+56%	0%	+105%	-26%	+84%	-31%
Eight inters.	+55%	0%	+41%	0%	+14%	-22%	0%	0%
Sixteen inters.	+63%	0%	+43%	-1%	-26%	27%	0%	15%

Table 5-4: Performance of back pressure controller compared with vehicle-actuated controller on total delay and internal production

5.3 Subnetwork flow controller

Based upon the results and conclusions which have been made on the performance of the vehicle-actuated controller and the back pressure controller on the different subnetwork layouts, a subnetwork layout consisting of sixteen intersections is the most desirable size in comparison with a subnetwork layout consisting of four or eight intersections. The MFD of the subnetwork consisting of sixteen intersections shows the least scatter. Therefore, simulations with the subnetwork flow controller applied have been performed only on the subnetwork which consists of sixteen intersections. First the simulation input parameters will be described again. Following the results on all three objectives of the subnetwork flow controller.

5.3.1 Simulation input parameters

The change of subnetwork layout is not of influence anymore on the simulations with the subnetwork flow controller applied. Instead, some other parameters will be changed in between the simulation. In order to judge the performance of the subnetwork flow controller with respect to the vehicle-actuated controller and back pressure controller, the same different demand patterns will be handled.

Furthermore, different values of the maximum deviation factor θ will be applied:

- $\theta = 0.1$
- $\theta = 0.5$
- $\theta = 1.0$

Therewith, the desired perimeter flow will be changed according to the change in demand pattern. The following constant desired perimeter flows values have been applied at the specific demand patterns:

- Low demand: $\xi_{desired} = 750$ veh/h
- Medium demand: $\xi_{desired} = 750$ veh/h
- High demand: $\xi_{desired} = 950$ veh/h
- Very high demand: $\xi_{desired} = 950$ veh/h

Explanation on the chosen values can be found in paragraph 4.1.3

5.3.2 Maintaining a constant shaped MFD

In figure 5-34, figure 5-35 and figure 5-36 the combined MFD's of the simulations with the subnetwork flow controller applied are shown with a maximum deviation factors of 0.1, 0.5 and 1.0 respectively.

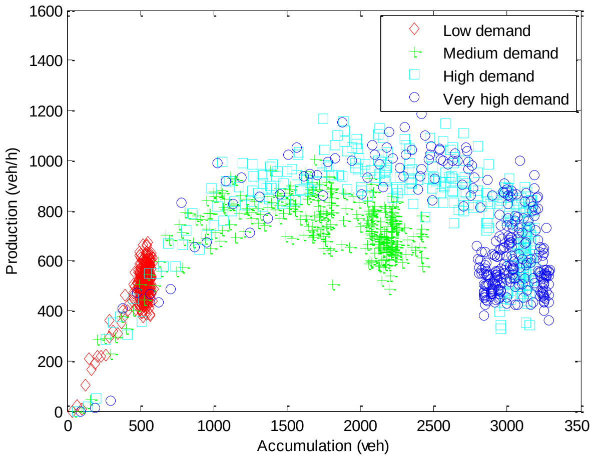


Figure 5-34: MFD of subnetwork controlled by the subnetwork flow controller and a maximum deviation factor of 0.1

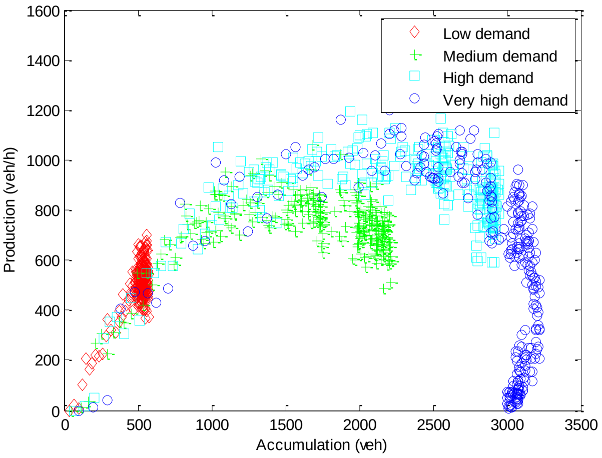


Figure 5-35: MFD of subnetwork controlled by the subnetwork flow controller and a maximum deviation factor of 0.5

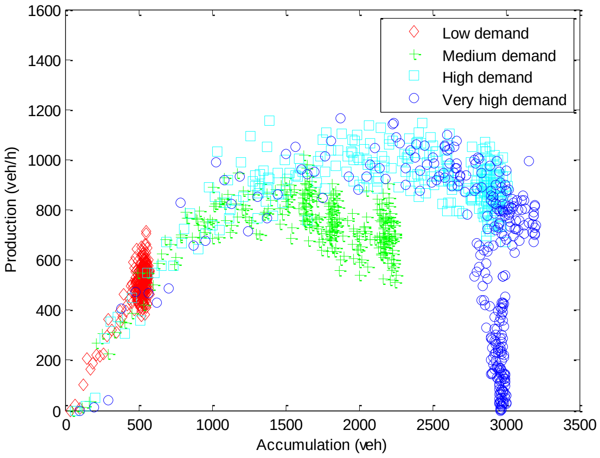


Figure 5-36: MFD of subnetwork controlled by the subnetwork flow controller and a maximum deviation factor of 1.0

It can be seen in all three MFD's that the accumulation and production results of the simulation with a medium demand do not match the shape according to the other simulations and thus results in a non-constant shaped MFD. This is caused by the fact that different desired perimeter flow values have been applied within the different simulations. When a medium demand is applied in the simulation, the desired perimeter flow is also lower with respect to the simulations with a high and very high demand pattern. Traffic will be blocked earlier when trying to exit the subnetwork in that case. The result is that the production drops earlier as well at a same accumulation value. The simulations with a low demand pattern do not have enough traffic in order to view this effect again while the desired perimeter flow is lower also.

A significant difference in scatter can nevertheless be noticed between all three combined MFD's visually, especially at high accumulation. The standard deviation of the scatter of each MFD has been determined again (table 5-5). The vertical scatter at high accumulation is of high influence on the standard deviation. This can be seen in the absolute scatter deviation at high accumulation. Therewith, due to the non constant shaped MFD in all cases (caused by the results of the simulation with a medium applied demand) a second peak in the absolute scatter deviation can be noticed which influences the standard deviation value as well. The running medians and absolute scatter deviations of the MFD's with different applied maximum deviation factors θ are provided in figures 5-37 till 5-42.

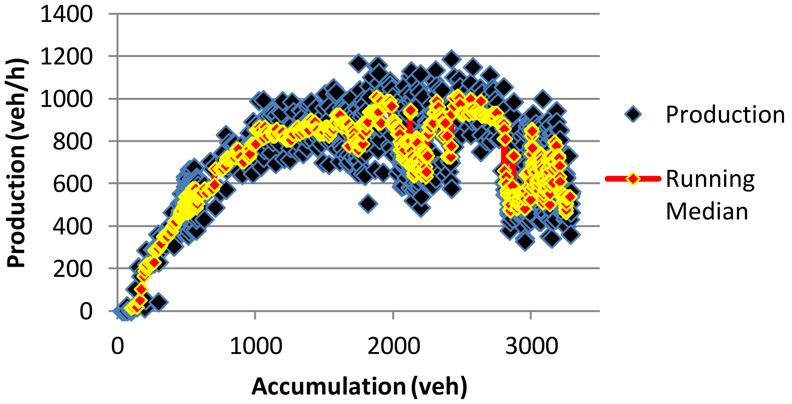


Figure 5-37: Running median of MFD of simulation with an applied maximum deviation factor θ of 0,1

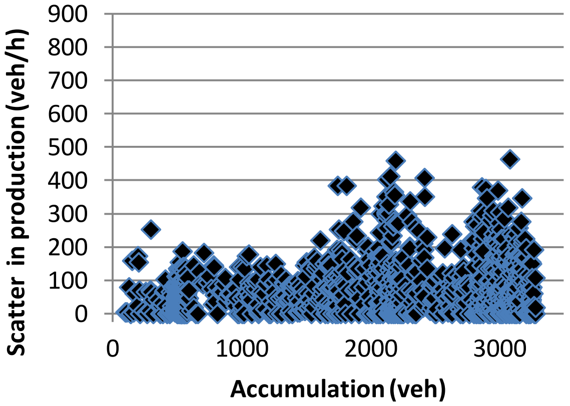


Figure 5-38: Absolute scatter deviation of MFD of simulation with an applied maximum deviation factor θ of 0,1

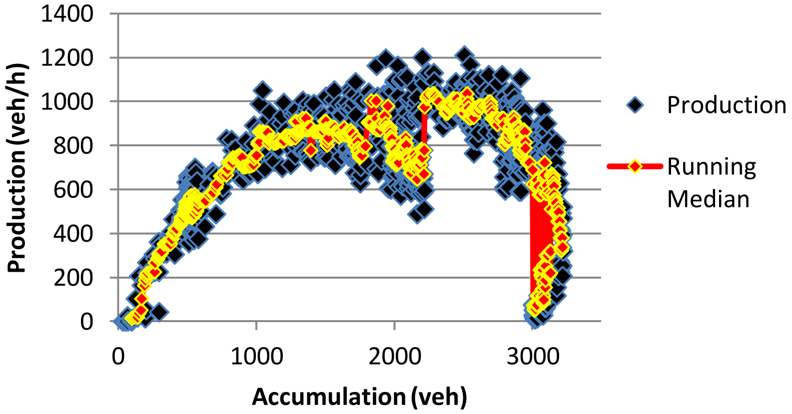


Figure 5-39: Running median of MFD of simulation with an applied maximum deviation factor θ of 0,5

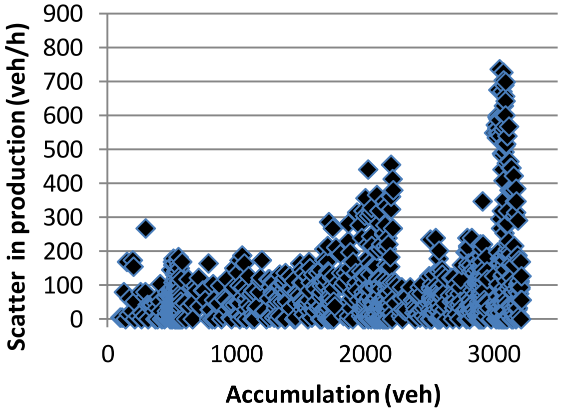


Figure 5-40: Absolute scatter deviation of MFD of simulation with an applied maximum deviation factor θ of 0,5

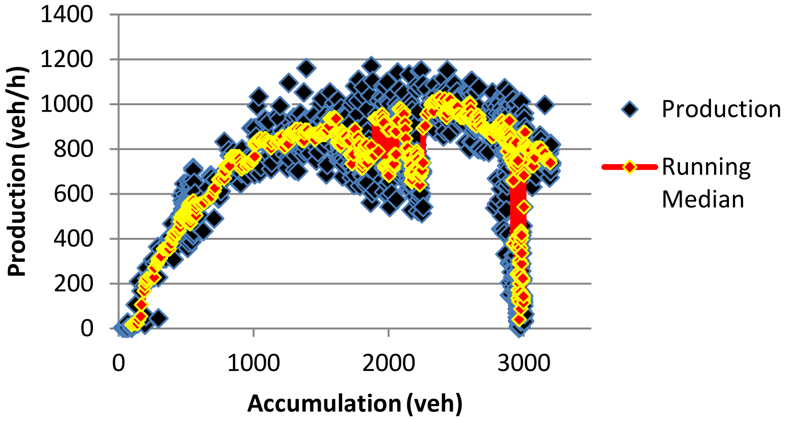


Figure 5-40: Running median of MFD of simulation with an applied maximum deviation factor θ of 1,0

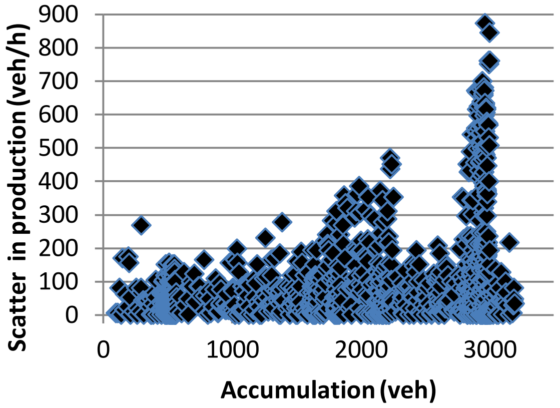


Figure 5-41: Absolute scatter deviation of MFD of simulation with an applied maximum deviation factor θ of 1,0

Maximum deviation factor θ	Standard deviation of MFD
0,1	78,7 veh/h
0,5	118,6 veh/h
1,0	141,3 veh/h

Table 5-5: Overview standard deviations of MFD's with different applied maximum deviation factors

Visually, it seems that every applied maximum deviation factor θ has the same result (excluding the results at high accumulation). The only difference on the results on the different applied maximum deviation factors so far is that the simulation with an applied very high demand and θ equals 0.1 did not get in a total gridlock as the other simulations. A partial gridlock did occur however. This effect cannot be explained yet and is therefore dedicated to coincidence due to a lack of number of performed simulations. Extra explanation of this result and some extra simulations on the applied maximum deviation factors θ will be performed and described in paragraph 5.3.5.

5.3.3 Optimizing internal flows

Figure 5-42 shows the results on the total delay consisting of internal and latent delay of all three kinds of controllers. The results of the subnetwork flow controller are split up in each applied maximum deviation factor. Furthermore, a secondary axis has been made on the right of the figure. This axis only belongs to the simulation results performed with a very high demand. Differences in all simulation results are therewith better noticeable. In appendix A.2, all specific values of internal and latent delay of the simulations with a subnetwork layout consisting of sixteen intersections and different controllers can be found.

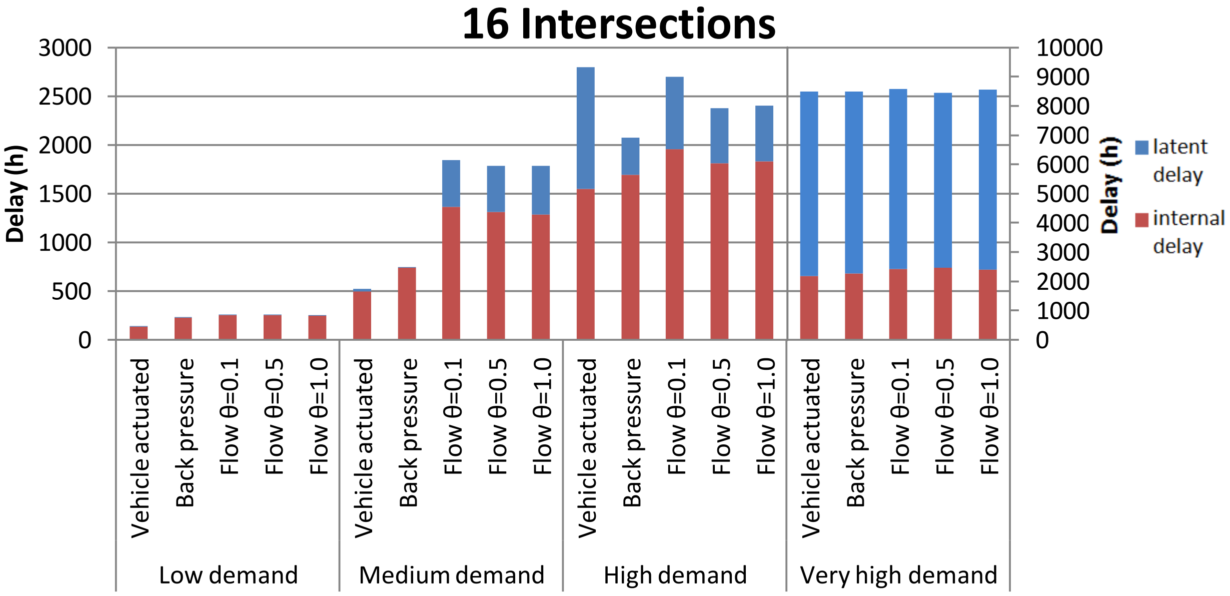


Figure 5-42: Internal and latent delay sixteen intersections

At most different demand patterns, the subnetwork flow controller performs worse as the vehicle-actuated controller and the back pressure controller. This is the case for both internal and latent delay. This result does not mean that the subnetwork flow controller controls traffic in the subnetwork worse. Due to the objective of providing desirable perimeter flows, extra delay may be a consequence when controlling the subnetwork towards this objective. When the actual perimeter flow is too high, traffic will be blocked from exiting the subnetwork and thus causes extra delay within the subnetwork. This waiting of vehicles may cause blocking the input location of the subnetwork and therewith an increase in latent delay. This effect is especially visible in the simulations with a medium demand pattern.

Differences in results on the different applied maximum deviation factors θ are not very significant. It seems that when θ equals 1.0, the best results can be gathered with respect to the other applied values of θ. More on the performance of the different maximum deviation factors θ can be said when analyzing the perimeter flows. This will be done in paragraph 5.3.4.

Figure 5-43 shows the results on all kinds of production for all different applied controllers and maximum deviation factors θ. In appendix A.3, all specific values of productions of the simulations with a subnetwork layout consisting of sixteen intersections and different controllers can be found.

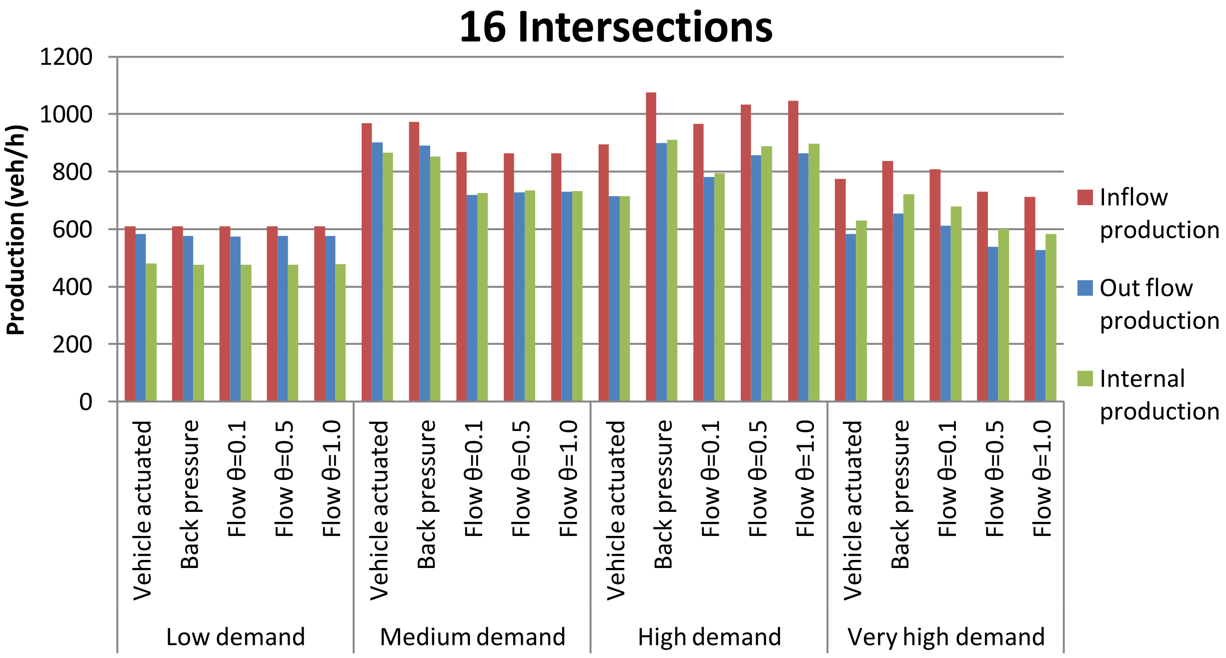


Figure 5-43: Inflow, outflow and internal production all kind of controllers

At low demand, no distinction can be made between the performances of the three different kinds of controllers. Again, the subnetwork flow controller performs worse when applying a medium demand pattern with respect to the vehicle-actuated and back pressure controller.

With increasing demand, the internal production exceeds the outflow production for all kind of controllers. This effect is however largest at the results of the back pressure and subnetwork flow controller (vehicle-actuated controller: 8%, back pressure controller: 10% and subnetwork flow controller: 11%). It means that the back pressure and subnetwork flow controller are able to control traffic within the subnetwork better at high demands as the vehicle-actuated controller. This effect is the result of holding vehicles outside the subnetwork and therewith causing an increase in latent demand. Furthermore, it can be said that despite the fact that vehicles are blocked from exiting the subnetwork, the back pressure controller is able to control traffic with a higher internal production in comparison with the other controllers.

Again, the difference in performance on the second objective, optimizing internal flows, between the different applied maximum deviation factors θ is not very significant. At low and medium demand patterns, there is hardly any difference at all. However, when applying a high demand pattern, the simulation with an applied maximum deviation factor θ of 1.0 shows the best results on inflow, outflow and internal production. But when the demand pattern change to very high demand, it turned out that an applied maximum deviation factor θ of 0.1 shows the best results. However, due to a lack of performed simulations, the significance of these results cannot be determined. Due to coincidence, these results may have been shown up.

That the back pressure and subnetwork flow controller perform better in terms of internal production can also be visualised by graphs in which the cumulative production within the subnetwork has been plotted against the simulation time. Since the difference between applied maximum deviation factors θ is not significant. The cumulative production graphs of simulations with a maximum deviation factor θ of 0.1 are provided only in figures 5-44 till 5-47.

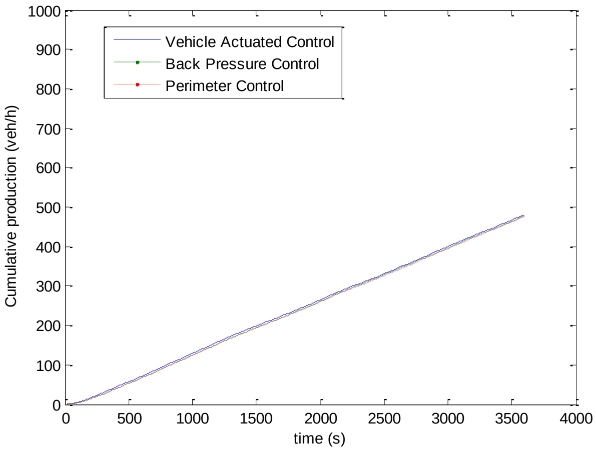


Figure 5-44: Low demand result on cumulative internal production

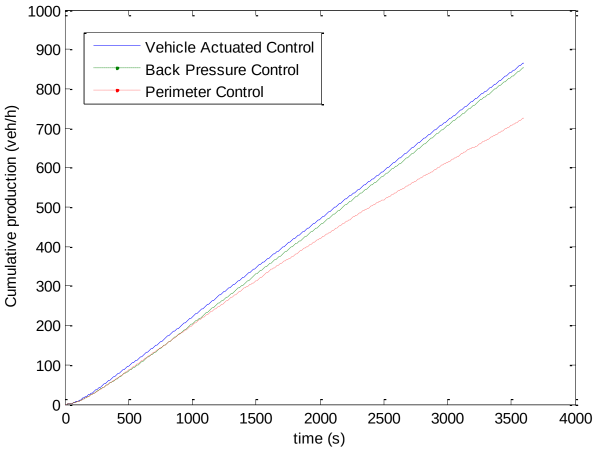


Figure 5-45: Medium demand result on cumulative internal production

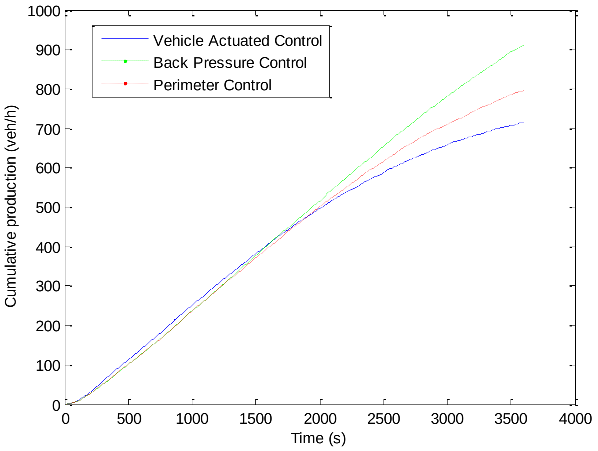


Figure 5-46: High demand result on cumulative internal production

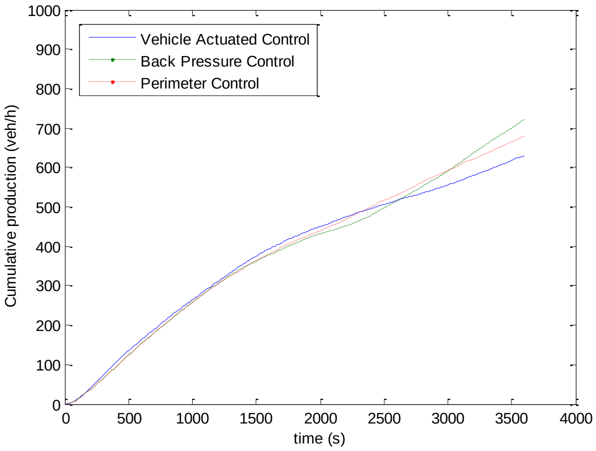


Figure 5-47: Very high demand result on cumulative internal production

5.3.4 Deriving desirable perimeter flows

The third and last objective of the subnetwork flow controller is to provide some desirable perimeter flows which are set up by the main controller. The subnetwork consisting of sixteen intersections has in total twelve perimeter flows which are controlled by the subnetwork flow controller. Results of all these perimeter flows will not be provided. Two types of perimeter flows will be discussed instead:

- Perimeter flow derived at intersection with two adjacent intersections
- Perimeter flow derived at intersection with three adjacent intersections

These two types are taken into account due to the different location in the intersection which causes a different number of adjacent intersections.

After performing al simulations with the subnetwork flow controller applied, it turned out that all results on deriving a desired perimeter flow were more or less the same for all different kind of applied maximum deviation factors θ. Therefore, the results with different applied demand patterns will be shown with an applied maximum deviation factor θ of 0.1 only. The results of the simulations with the other applied maximum deviation factors θ can be found in appendix A.4. Extra explanation of this result and some extra simulations will be performed and described in paragraph 5.3.5.

<u>Perimeter flows at intersection with two adjacent intersections</u>

The performance of the subnetwork flow controller on providing the desirable perimeter flows will be visualised by graphs in which the deviation of cumulative number of vehicles which left the subnetwork at a specific perimeter link has been plotted over time. When the subnetwork flow controller controls the subnetwork perfectly with respect to providing the desirable perimeter flows, the deviation in cumulative number of vehicles equals zero.

The desired perimeter flows which have been used within the simulation have been defined in paragraph 4.1.3. These desired perimeter flows have been set up in terms of vehicles per hour. Due to a simulation time of 3600 seconds, the cumulative number of vehicles which left the subnetwork should equal the specific desired perimeter flow in the simulation. However, due to the fact that the subnetwork flow controller will be executed from algorithm cycle twenty and on (that is after 228 seconds), the actual cumulative number of vehicles that left the subnetwork at a specific perimeter link has to be compared with a different value. This value is the desired perimeter flow decreased with a factor (3600-228)/3600. This results in the following desired cumulative number of vehicles for each different demand pattern:

- Low demand: Desired cumulative number of vehicles = 703
- Medium demand: Desired cumulative number of vehicles = 703
- High demand: Desired cumulative number of vehicles = 890
- Very high demand: Desired cumulative number of vehicles = 890

In figure 5-48 till figure 5-51, the results on deviation of the cumulative number of vehicles at the perimeter link of an intersection with two adjacent intersections for different applied demand patterns and a maximum deviation factor θ of 0.1 are shown.

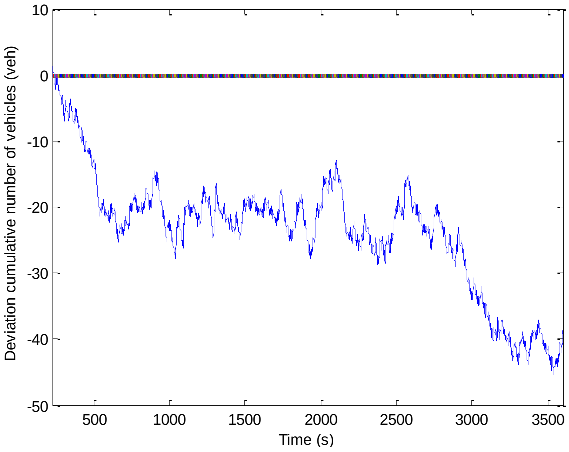


Figure 5-48: Low demand simulation result on desired cumulative number of vehicles

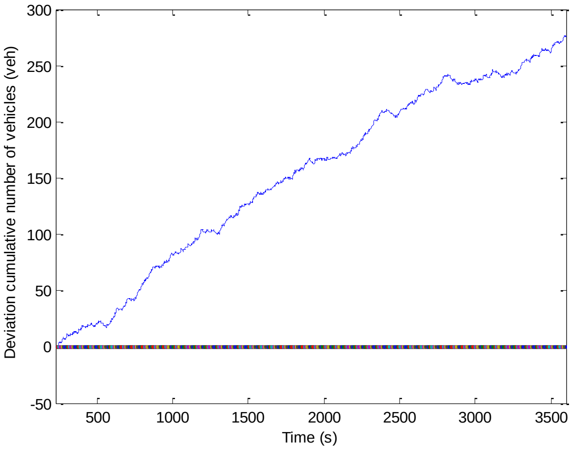


Figure 5-49: Medium demand simulation result on desired cumulative number of vehicles

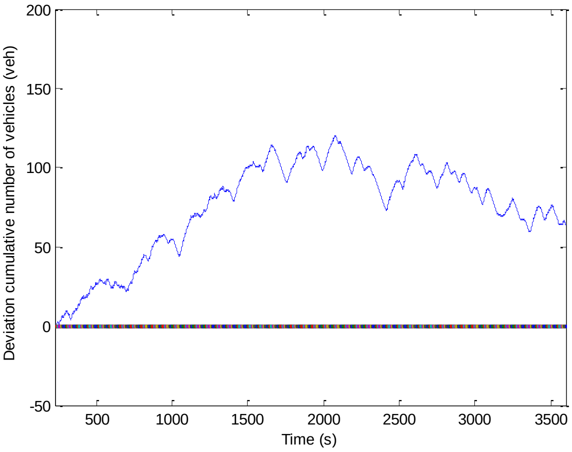


Figure 5-50: High demand simulation result on desired cumulative number of vehicles

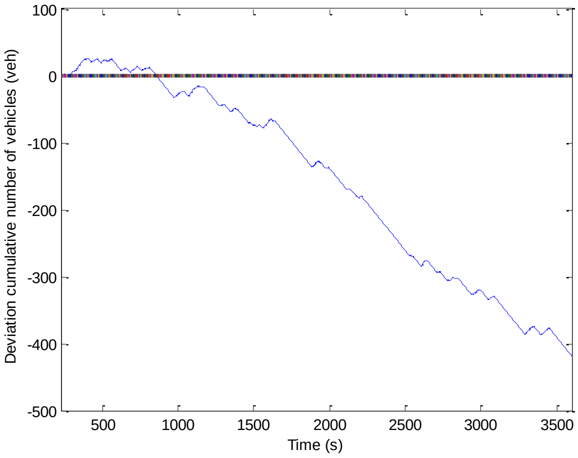


Figure 5-51: Very high demand simulation result on desired cumulative number of vehicles

It can be seen in figure 5-48 that the subnetwork flow controller is able to provide the desired perimeter flow. The cumulative deviation at the end of the simulation is around forty vehicles. This is approximately a 6% deviation. But since a simulation time of 3600 seconds has been handled, it cannot be said if this result is a stable result.

The subnetwork flow controller is not able to provide the desirable perimeter flow when demand increases. This is shown in figure 5-49 where the result is shown of the simulation with an applied medium demand pattern. A final cumulative deviation of approximately 40% is reached. A non stable deviation on the cumulative number of vehicles has been the result. This effect can be explained by the fact that the desired perimeter flow has been set too low. Moreover, the demand is far higher as the desired perimeter flow.

The results of the simulation with a high demand pattern show that the subnetwork flow controller is able to provide the desired perimeter flows again. In figure 5-50 a final cumulative deviation of approximately 8% has been reached. This is caused by the increase of desired perimeter flow from 750 to 950 vehicles per hour. It seems to be a stable result. But again, a simulation time of 3600 seconds has been applied. The results may not be stable next hour of simulation.

When the very high demand pattern has been applied in the simulation, the subnetwork flow controller is not able to derive the desired perimeter flows at all. A final deviation of approximately 47% has been reached in figure 5-51. This is caused by the occurrence of a gridlock within the simulation. Most vehicles were not able to reach their destination anymore after some time. This unstable result in deviation of cumulative number of vehicles poses questions on the effectiveness of applying a very high demand pattern on testing the ability of the subnetwork flow controller on providing desirable perimeter flows.

Perimeter flows at intersection with three adjacent intersections

In figure 5-52 till figure 5-55, the results on deviation of the cumulative number of vehicles at the perimeter link of an intersection with three adjacent intersections for different applied demand patterns and a maximum deviation factor θ of 0.1 are shown.

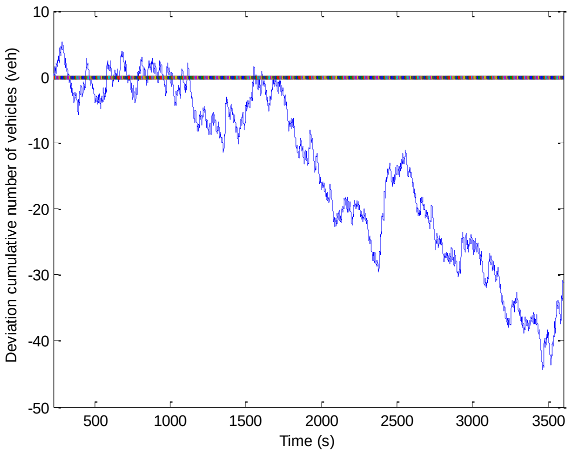


Figure 5-52: Low demand simulation result on desired cumulative number of vehicles

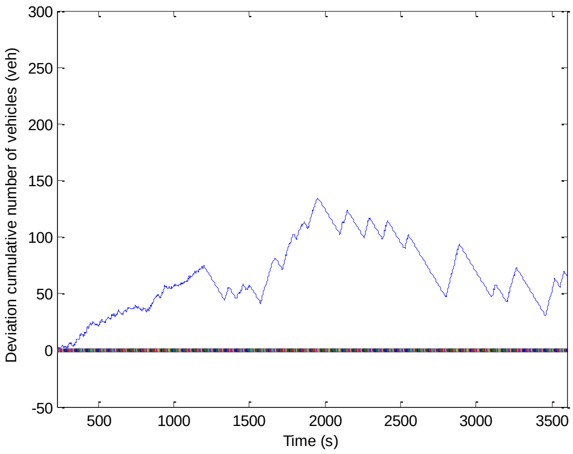


Figure 5-53: Medium demand simulation result on desired cumulative number of vehicles

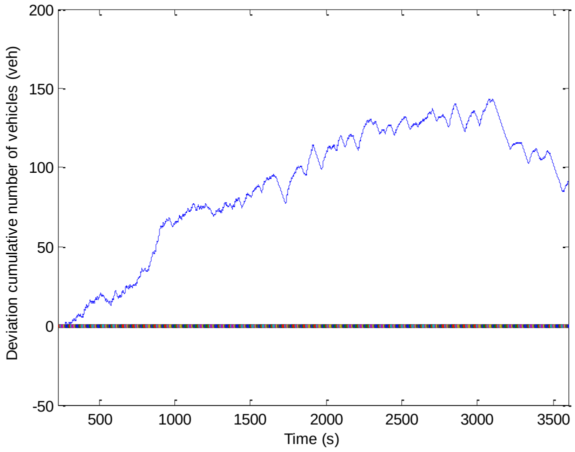


Figure 5-54: High demand simulation result on desired cumulative number of vehicles

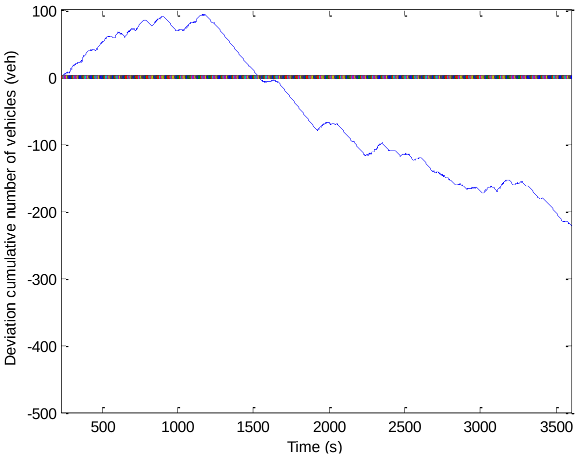


Figure 5-55: Very high demand simulation result on desired cumulative number of vehicles

In figure 5-52 it is shown that the subnetwork flow controller is able to derive the desired perimeter flow pretty well. A final cumulative deviation on the number of vehicles which left the subnetwork of approximately 5% has been reached. If this result is stable can however be questioned. In the simulation with a medium demand (figure 5-53) and a high demand (figure 5-54) the subnetwork flow controller is able to derive desired perimeters as well. A final cumulative deviation on the number of vehicles has been reached of approximately 10% and 9% respectively. These results seem to be stable. Extra simulation time would give more insight in this aspect. When a demand pattern of very high demand has been applied (figure 5-55), the gridlock effect is visible again with a final cumulative deviation on the number of vehicles of approximately 22% . It is remarkable that the subnetwork flow controller is able to control intersections with three adjacent intersections better with respect to intersections with two adjacent intersections. The explanation of this effect depends on the desired perimeter flows which have been set up. Extra explanation will be provided and extra simulations will be performed in order to go in detail of this effect in paragraph 5.3.5.

5.3.5 Extra simulations

Two remarkable results have been obtained from the simulations with an applied subnetwork flow controller so far. These two remarkable results are:

- No significant difference in performance on all objectives can be noticed between different applied maximum deviation factors θ (0.1, 0.5 and 1.0).
- The subnetwork flow controller is able to control intersections with three adjacent intersections better as intersections with only two adjacent intersections based on the performance of deriving the desired perimeter flows.

In order to try explaining these remarkable results, a short description on the cause and influences on these results will be given. Moreover, extra simulations have been performed in order to show if other chosen algorithm parameters might have different performance on all three objectives.

Applied maximum deviation factor θ

A desired maximum deviation of the perimeter flow with respect to the desired perimeter has been set up by the main controller with $\theta \in [0,1]$. During the simulations, the deviation of the perimeter flows on the desired perimeter flow of each perimeter link has been determined every time slot T_k of the algorithm. Each time slot has a length of twelve seconds. Due to the twelve seconds length of each time slot, the perimeter flow has been determined every twelve seconds also. The perimeter flow has been described however in vehicles per hour. It means that the number of vehicles which are counted by the data collection points within these twelve seconds are transferred to an hourly flow.

When for example three vehicles are counted within a time slot, the perimeter flow is 3 * (3600/12) = 900 vehicles per hour. But due to the fact that the deviation of the perimeter flow to the desired perimeter flow has been determined in a cumulative way (each time slot, the deviation of the perimeter flow on the beginning of the previous time step has been added to the deviation made in the previous time step: $\xi_{outd}(k-1) + (\xi_{out}(k-1) - \xi_{desired}(k-1)))$ and the maximum deviation factor θ has been applied every twelve seconds, a transfer to an hourly flow did not had to be performed. Therewith, the maximum deviation factor θ was meant to represent an hourly deviation. The result is that the factor of 3600/12 = 300 has caused a mismatch between the maximum deviation factor and the measured perimeter flow. Therefore, the maximum deviation factor range of [0,1] has been taken far too small and thus results in the same results of each applied maximum deviation factor θ. Instead a range of [200,400] should be taken. So far, results have been shown for an applied maximum deviation factor θ of 0.1. In order to investigate the mismatch, these simulation results will be compared to simulations with an applied maximum deviation factor of 1.0 * 300 = 300.0 instead of 1.0. Four extra simulations have been performed representing each a different demand pattern.

Number of adjacent intersections

The difference in controlling the intersections of two or three adjacent intersections is caused by the way of setting up the demand patterns and the desired perimeter flows. At intersections with two adjacent intersections (intersections in the corner of the subnetwork) have a high origin-destination demand value for traffic which does not enter the subnetwork but uses this intersection only. The total demand for the perimeter link of an intersection with two adjacent intersections and a subnetwork of sixteen input links becomes therewith (in case medium demand pattern is applied): 15*55 + 1*350=1175 veh/h. While the total demand for the perimeter link of an intersection with three adjacent intersections and a subnetwork of sixteen input links (in case a medium demand pattern is applied) is: 16*55=880 veh/h. When applying the same value of desired perimeter flow for both types of intersections, it is obvious that the controller is able to control one of those types better.

Therefore, four extra simulations have been performed where a different desired perimeter flow has been applied for intersections with two and three adjacent intersections in order to investigate the effect on the performance of the subnetwork flow controller. The applied desired perimeter flows for intersection with two adjacent intersections have been taken higher as those of intersections with three adjacent intersections.

The following desired perimeter values have been used in the extra simulations:

Intersection location	Low demand	Medium demand	High demand	Very high demand
Two adjacent intersections	750 veh/h	950 veh/h	1150 veh/h	1150 veh/h
Three adjacent intersections	550 veh/h	550 veh/h	750 veh/h	750 veh/h

Table 5-6: Value of desired perimeter flow for different kind of intersection locations and different kind of demand patterns

The problem which did occur in setting up the desired perimeter flows in the subnetwork flow algorithm could also occur in practice. The main controller is not allowed to choose every value of desired perimeter flow. The demand is of influence on restrictions which have to be set up on choosing desirable perimeter flows. More research is needed in order to define which restrictions have to be set up.

Results extra simulations

Maintaining a constant shaped MFD

In figure 5-56, the combined MFD is shown of the four simulations where a maximum deviation factor of 300 has been applied. In figure 5-57, the combined MFD is shown for the four simulations where different desired perimeter flows for intersections with two and three adjacent intersections have been applied. Here, a maximum deviation factor of 0.1 has still been applied. The results can be compared with the combined MFD in figure 5-58 which is shown earlier.

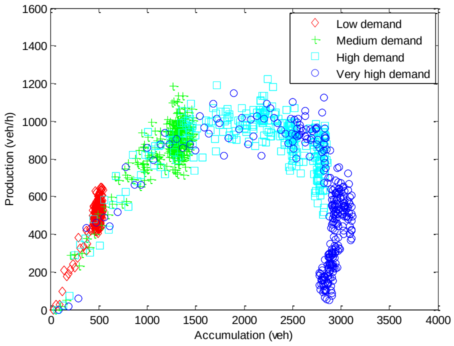


Figure 5-56: MFD with an applied maximum deviation factor θ of 300

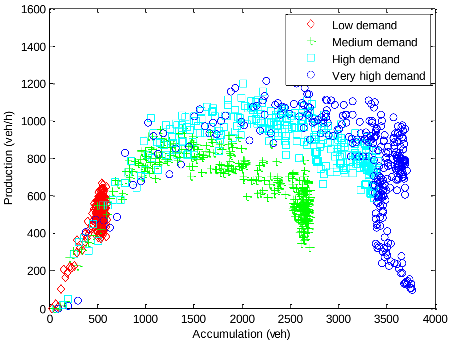


Figure 5-57: MFD with different applied desirable perimeter flows for two type of intersections (θ = 0.1)

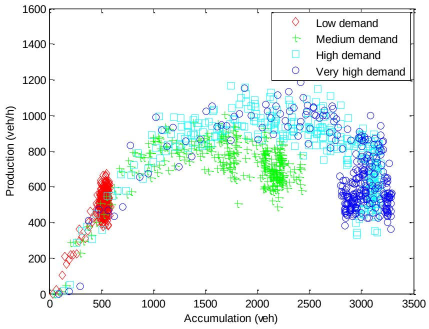


Figure 5-58: MFD with an applied maximum deviation factor θ of 0.1

It turned out that the change of applied maximum deviation factor to 300 did influence the size in scatter (figure 5-56). A standard deviation of the scatter of the MFD of 103,8 veh/h is the result. Only the production and accumulation results of the simulation with an applied medium demand pattern did change significantly which results in a more constant shaped MFD with respect to the MFD with an applied maximum deviation factor of 0.1. This has influenced the standard deviation significantly. It can be expected that the standard deviation should be lower with respects to the standard deviation of the MFD with an applied maximum deviation factor of 0.1 (78,7 veh/h). However, scatter at high accumulation influenced the standard deviation of the scatter significantly. The scatter of the simulation with a medium demand can be explained by the fact that no congestion measurements have been obtained in the extra simulation when a medium demand pattern has been applied. This is caused by the fact that a larger deviation perimeter flow is allowed and thus vehicles are able to leave the subnetwork earlier. This has also the effect that the maximum accumulation in the extra simulation decreased from approximately 3400 to 3100 vehicles.

Figure 5-57 shows that the change in desirable perimeter flows did not influence the shape and scatter of the MFD significantly when visually inspecting comparing them. However, the standard deviation of the scatter of the MFD of the extra simulation turned out to be 111,3 veh/h. This is caused by the increased absolute scatter deviation caused by the medium demand pattern and at high accumulation.

The running medians and associated absolute scatter deviation graphs can be found in appendix A.5. Table 5-6 shows an overview of the standard deviation factors of the extra simulations.

Maximum deviation factor θ	Standard deviation of MFD
0,1 (constant desired perimeter flows)	78,7 veh/h
300	103,8 veh/h
0,1 (different desired perimeter flows)	111,3 veh/h

Table 5-7: Overview standard deviations of MFD of extra simulations

In order to compare the MFD's on production, the running medians of the extra simulations have been plotted (figure 5-59) in a single graph together with the reference result of the subnetwork flow controller with an applied maximum deviation factor of 0.1 and different applied desired perimeter flows for intersections with two and three adjacent intersections. It can be seen in figure 5-59 that applying different desired perimeter flows has a positive effect while increasing the maximum deviation factor to 300 a negative effect. This result can be explained on the occurrence of an early gridlock in case a maximum deviation factor of 300 has been applied and better associated desired perimeter flows in comparison with the applied demand patterns in case different desired perimeter flows for intersections with two and three adjacent intersections have been applied. More on this result will be explained when evaluating the internal flows.

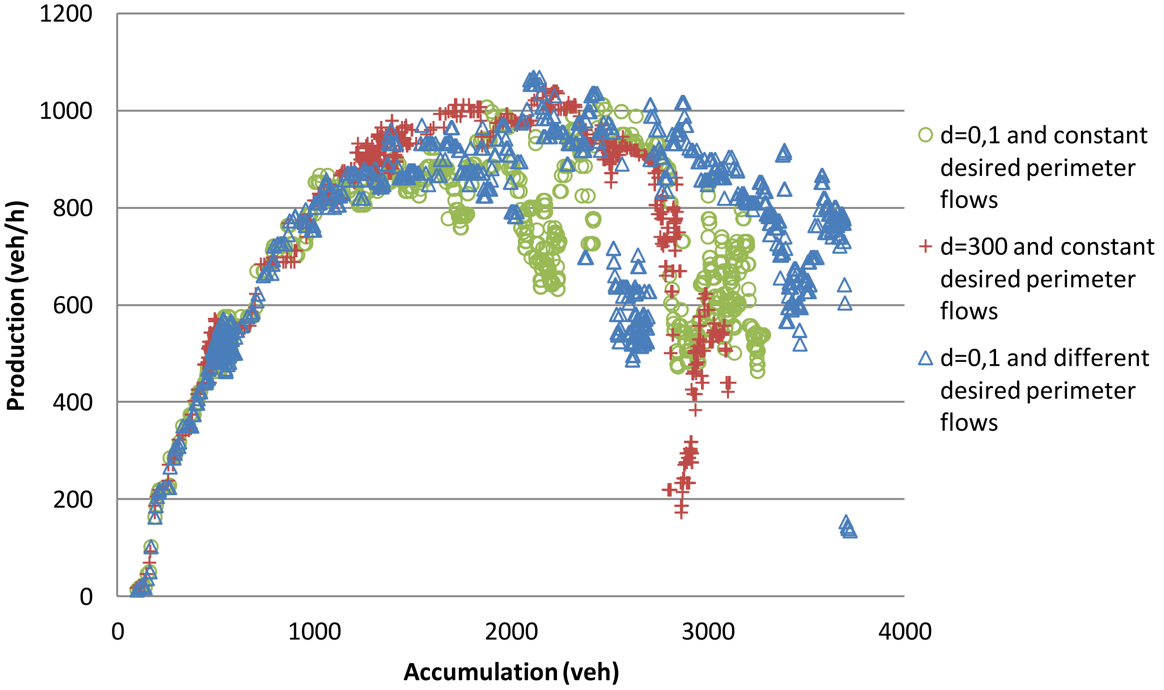


Figure 5-59: Comparison of the running medians of the extra simulations with the reference simulation (d=0.1 and constant desired perimeter flows)

Optimizing internal flows

The results on performance on total delay of the extra simulations are shown in figure 5-60.

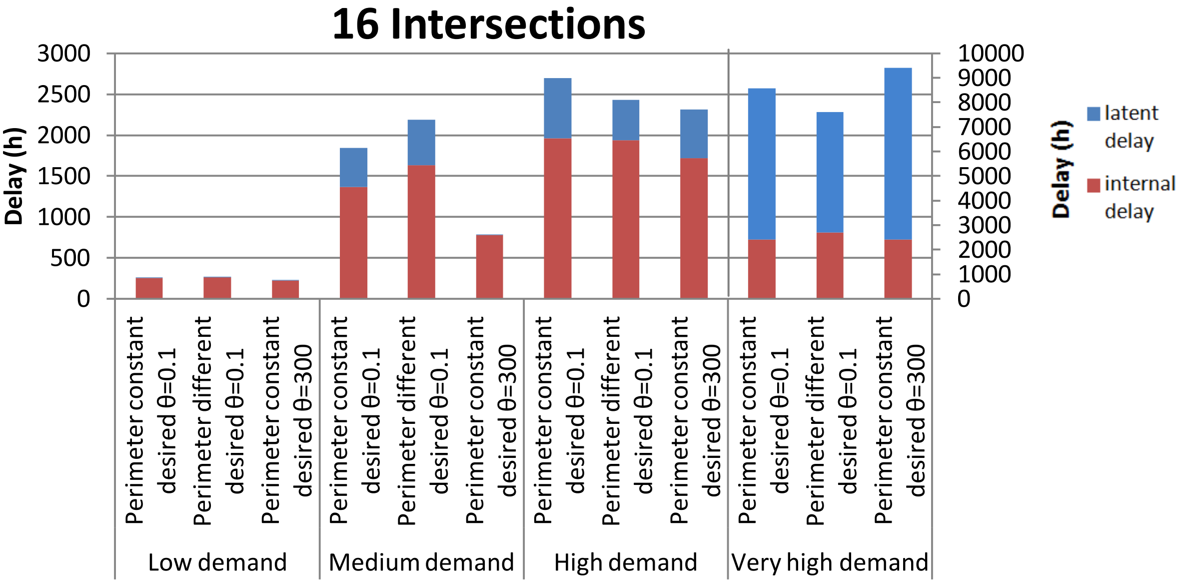


Figure 5-60: Total delay extra simulations divided in internal and latent delay

It is clear that at low, medium and high demand, the change of maximum deviation factor to 300 has a positive effect on total delay. That can be explained by the fact that vehicles are allowed to leave the subnetwork earlier and will thus not be blocked and gain delay. When a very high demand pattern has been applied, latent delay increases for simulations with a maximum deviation factor of 300. This can be explained by the fact that a gridlock did occur earlier in the simulation due to a specific traffic state.

The change of desired perimeter flow for different kind of intersections does influence the performance on total delay. However, no clear pattern between the different applied demand patterns can be noticed. The decision of the main controller on setting up certain desirable perimeter flow values is of high influence.

In figure 5-61 the results on inflow outflow and internal production have been visualised. All specific values on total delay and production (of figures 5-59 and 5-60) can be found in appendix A.6.

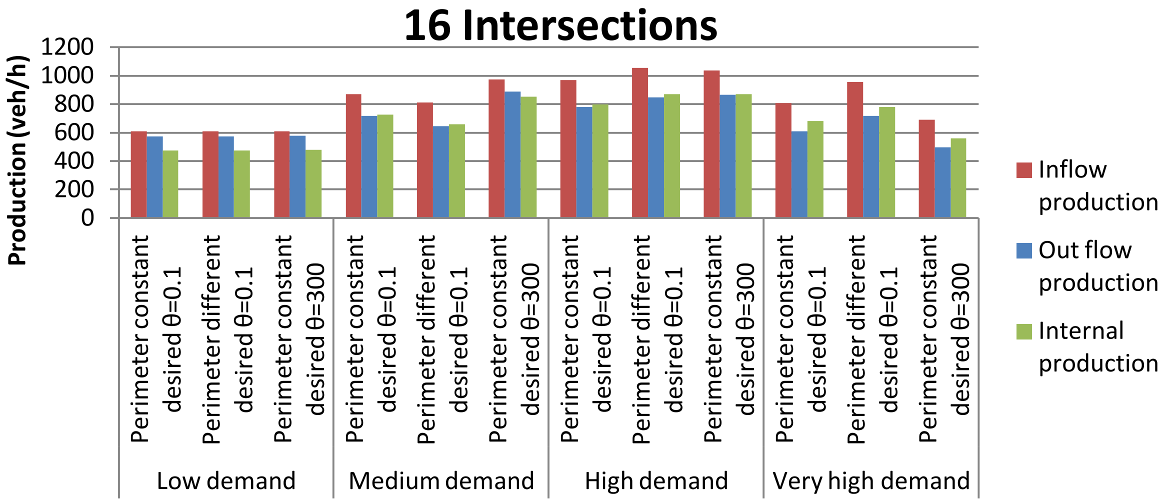


Figure 5-61: Production results of extra simulations

At low demand pattern, no difference has occurred in the extra simulations. When applying a maximum deviation factor of 300, the subnetwork flow controller is able to handle a higher production (all forms) when applying a medium or high demand pattern. At very high demand, the occurrence of an early gridlock is visible again on the production performance.

Different desired perimeter flows for different kind of intersections does increase production (high and very high demand), but does also decrease production (medium demand). This shows again that the decision of the main controller on setting up certain values for desired perimeter flows have a high influence on the performance of the subnetwork flow controller but that a clear pattern cannot be noticed.

In figure 5-62 till figure 5-65, results on the cumulative internal production are shown of the extra simulations compared to the performance of the simulation where constant desired perimeter flows and a maximum deviation factor of 0.1 has been applied.

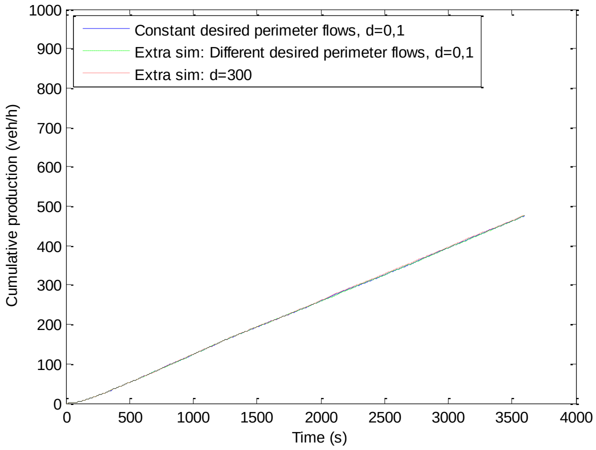


Figure 5-62: Low demand results on cumulative production

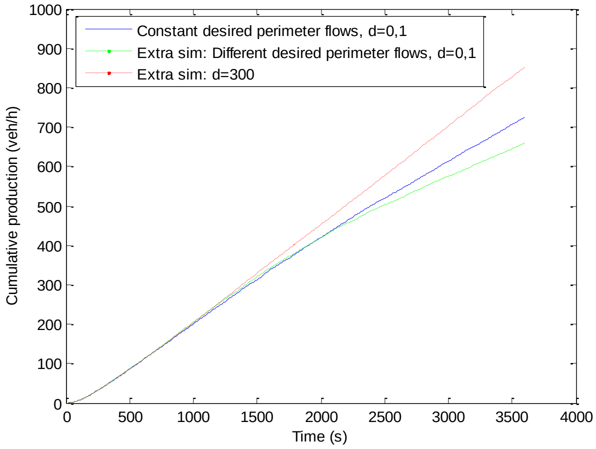


Figure 5-63: Medium demand results on cumulative production

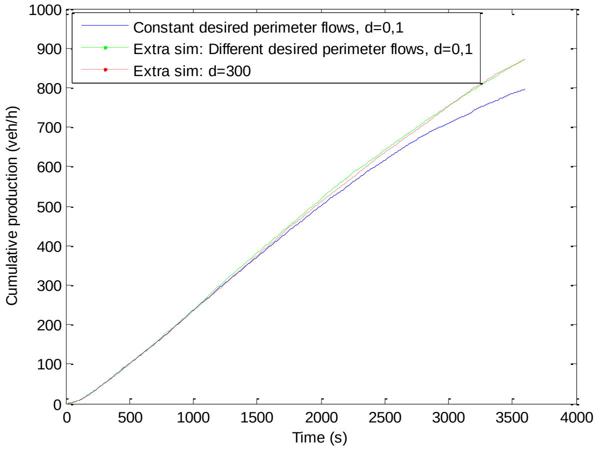


Figure 5-64: High demand results on cumulative production

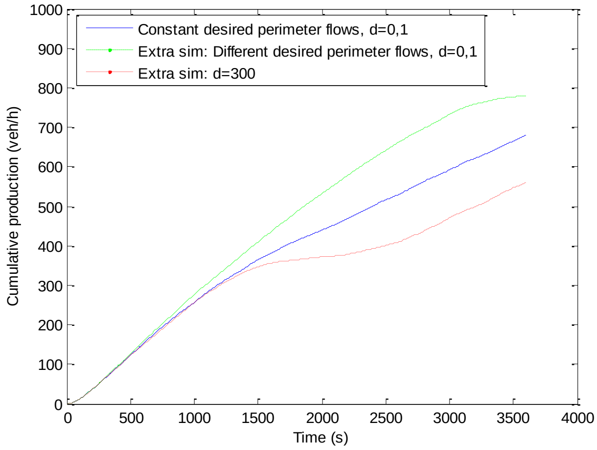


Figure 5-65: Very high demand results on cumulative production

When applying a low demand pattern, no differences can be noticed (figure 5-63). By increasing demand, the change of maximum deviation factor turned out to be negative on the internal cumulative production performance. At medium demand, the subnetwork flow controller with a θ of 300 performs better. This can again be explained by the higher allowed deviation to the desired perimeter flow which allows vehicle to leave the subnetwork earlier and thus cause a higher internal cumulative production due to extra space. The gridlock effect can be seen again in figure 5-65.

The change of desired perimeter flows in the extra simulations does again show no clear pattern in results on internal cumulative production. But changing the desired perimeter flows does influence the performance of the subnetwork flow controller according to these results. Again, the set up of specific values of desired perimeter flows by the main controller are of high influence on the performance of the controller.

Deriving desirable perimeter flows

All figures showing the deviation on cumulative number of vehicles which left the subnetwork can be found in appendix A.7. A description of the results will be given split in a perimeter link which is located at an intersection with two adjacent intersections and a perimeter link located at an intersection with three adjacent intersections.

Intersection with two adjacent intersections:

The extra simulations do not show any differences when a low demand pattern has been applied. It means that the subnetwork flow controller controls the traffic in the subnetwork the same for all investigated algorithm parameters. When a medium demand pattern is applied in the simulations, the change to different desired perimeter flows shows a positive result (8% deviation) with respect to the simulation with constant desired perimeter flows (36% deviation). At high demand however, the subnetwork flow controller with different desired perimeter flows show a negative result on the final deviation of number of vehicles which left the subnetwork with respect to the simulation with constant desired perimeter flows (28% and 8% respectively). When a very high demand is applied, no differences can be noticed again. Again, it can be concluded that the value of desired perimeter flow is of high influence on the performance of the subnetwork flow controller. Demand and desired perimeter flow are dependent on each other.

The change of maximum deviation factor θ to 300 has no influence on the deviation of cumulative number of vehicles which left the subnetwork for all demand patterns at perimeter links at intersections with two adjacent intersections. It was expected that the change of maximum deviation factor was of influence on the perimeter flows. But so far, the change in value is not of influence at all. More simulations might be needed in order to see changes in results. These results may have been caused by coincidence and thus a lack of number of simulations.

Intersection with three adjacent intersections:

Changing to different desired perimeter flows for intersections with three adjacent intersections shows large differences when a low, medium or high demand pattern is applied. The final deviation on cumulative number of vehicles which left the subnetwork for simulations with constant desired perimeter flows is approximately 6%, 8% and 8% for low, medium and high demand. While the final deviation on number of vehicles which left the subnetwork with different desired perimeter flows is approximately 35%, 65% and 54% for low, medium and high demand. When a very high demand pattern is applied, the final deviation is the same. The only difference is that in the extra simulation, the deviation is a positive one and in the other a negative one. This shows that a gridlock did not occur at the intersection with three adjacent intersections. The subnetwork flow controller was still able to let vehicles leave the subnetwork.

The results of the extra simulation with a changed θ show at intersections with three adjacent intersections that only when a medium demand pattern has been applied difference on the cumulative number of vehicles which left the subnetwork can be noticed. The difference is that an applied maximum deviation factor θ of 300 results in a larger deviation (43% while the simulation with an applied maximum deviation factor θ of 0.1 has a deviation of 8%). This is a result which can be expected, but could also be expected for all other applied demand patterns. When applying a larger maximum deviation factor θ, deviation should be larger due to the fact that the subnetwork flow controller allows more vehicles to leave the subnetwork when there is a exceed in demand. But again, more simulations are needed in order to investigate the influence of change in maximum deviation factor θ on the performance of the subnetwork flow controller.

6 Conclusions and recommendations

A subnetwork flow controller has been designed in this thesis which had to contribute to three main objectives; maintaining a constant shaped MFD, optimizing internal flows and providing desirable perimeter flows. Literature survey has been used in order to choose a certain control approach which represented the basis of the subnetwork flow controller. The subnetwork flow controller algorithm has been set up and performance on all three objectives has been tested in the microscopic simulation program VISSIM. In paragraph 6.1 conclusions will be given on several aspects of this thesis. First an overall conclusion will be made on the main goal of this thesis. After that some conclusions are made upon subnetwork application. Finally conclusions will be made upon the performance of the subnetwork flow controller split up in the three main objectives. From these conclusions, several recommendations are drawn in paragraph 6.2. These recommendations will hold recommendations on applying the subnetwork flow controller. And finally, some feature research topics will be handled in paragraph 6.3.

6.1 Conclusions

The main goal of this thesis was to design the subnetwork flow controller. Research questions have been set up to cope with this main goal. The research goals will be recalled and answered.

6.1.1 Design subnetwork flow controller

"On which criteria and objectives (input) should the subnetwork flow controller be designed to?

- *What will the constraints (MFD and perimeter traffic flows) given by the main controller look like where the subnetwork flow controller should contribute to?*
- *What information of the current traffic state and flows of the subnetwork should be available for the subnetwork flow controller?"*

Three main objectives have been set up for the subnetwork flow controller; maintaining a constant shaped MFD, optimizing internal flows and providing desirable perimeter flows which are set up by the main controller. In this thesis it has been chosen to let the main controller set up specific perimeter traffic flows only. A desired shape of the MFD has been chosen accordingly the literature survey and not by the main controller. It is assumed that the main controller only desires the constant shape of the MFD. This desired constant shape of the MFD, where average production (veh/h) is plotted against the accumulation (veh) in the subnetwork, consists of a free flow and a congestion branch. The point on the MFD where production is highest is called the sweet spot of the MFD.

The desired perimeter flows given by the main controller have been set up as an hourly flow for each individual perimeter link in the subnetwork. Deviation of this desired perimeter flow is allowed by setting up the maximum deviation factor θ. In order to determine the deviation on the desired perimeter flows, information on the current state of the subnetwork had to be available. Internal flows, perimeter flows and different kind of productions (inflow, outflow an internal) are determined within the simulations with the provided traffic information by the data collection points in VISSIM. These data collection points also provided information on accumulation in the subnetwork. And at last, the delay of the subnetwork has been split up in internal delay and latent delay in order to test the performance of the subnetwork flow controller on optimizing internal flows.

"Which approach of traffic controlling exists in subnetwork traffic control and which kind of approach should be taken for the subnetwork flow controller which uses MFD's and provides desirable traffic flows?"
Literature survey provided five different control approaches in subnetwork traffic control:

- Fixed-time control strategies
- Coordinated fixed-time control strategies
- Traffic responsive control strategies
- Coordinated traffic responsive control strategies
- Integrated urban-freeway traffic control strategies

By investigating all different approaches, it was concluded that a coordinated traffic responsive control strategy is the best approach for the subnetwork flow controller in this thesis. This is based on the conclusions of the literature survey on the influences of the shape of the MFD. A MFD with less scatter can be obtained if homogeneity of traffic conditions can be provided within the subnetwork. By using a coordinated traffic responsive control strategy, several intersection controllers can be connected and divide traffic over the subnetwork.

Within all investigated coordinated traffic responsive control strategies, it was concluded that the back pressure controller provided the best basis for the subnetwork flow controller in this thesis. The back pressure controller is able to balance the queues in the subnetwork and thus provide homogeneity in traffic conditions. Therewith, the back pressure control algorithm turned out to be less complex to work with compared to other existing subnetwork controllers.

"Which DTM measures should be controlled by the controller in order to control traffic flows in a subnetwork?"
Different DTM measures could be controlled by a subnetwork flow controller: traffic signals, ramp metering signals and dynamic route information panels. In this thesis only traffic signals have been controlled by the subnetwork flow controller due to the urban scope of the applied subnetwork. Dynamic route information panels have not been included in order to decrease complexity for now.

"What should be the control signals (output) of the subnetwork flow controller in order to operate those DTM measures?"
Based on the back pressure algorithm, the subnetwork flow controller decides which traffic phase, which consists of several traffic streams, has to get right-of-way in the next time slot of the algorithm. This decision will be taken by calculating a pressure for every available traffic phase based on queue lengths. Traffic signals operate with green, yellow and red times. By controlling the detectors in VISSIM (occupying them or not), the traffic signals can be set to green, yellow and

red. The durations of green, yellow and red time are determined by the time step taken in the subnetwork flow controller algorithm.

6.1.2 Network application

"Which kind of subnetwork should be chosen, which has the desirable size to get and maintain a constant-shaped MFD, to perform the simulation on?"

Simulations have been performed with a vehicle-actuated controller and a basic back pressure controller in order to decide which size of subnetwork should be chosen in order to maintain a constant shaped MFD. In order to decide if a controller is able to maintain a constant shaped MFD (independent of applied demand pattern) the scatter of the MFD had to be evaluated. When a MFD of a certain subnetwork has less scatter, the ability of the controller of maintaining a constant shaped MFD can be noticed better. For deciding on which subnetwork size is desirable, the scatter of each MFD has been evaluated by determining the standard deviation of the absolute deviation of data points with respect to the running median. Subnetworks consisting of four, eight and sixteen intersections have been set up to perform the simulation on. It turned out that the standard deviation of the scatter of the MFD's of simulations with a subnetwork size of sixteen intersections is less than other subnetwork layouts. Different demand patterns have been used. According to the literature survey, the shape of the MFD should be independent of demand. This was indeed the result of the simulations with a subnetwork layout consisting of sixteen intersections. For testing the subnetwork flow controller, a subnetwork layout consisting of sixteen intersections is therefore used only.

A standard intersection layout consisting of twelve traffic streams has been used in this thesis. Using this layout provides the desired results of all applied subnetwork controllers.

6.1.3 Performance subnetwork flow controller

"Which objectives or criteria should be taken into account to evaluate the performance of the subnetwork flow controller?"

As mentioned before, three main objectives have been set up to evaluate the performance of the subnetwork flow controller. The results of the vehicle-actuated controller and back pressure controller are reference results for the designed subnetwork flow controller. The size of scatter of the MFD and independency of the MFD on applied demand patterns form the criteria of a constant shaped MFD. Optimizing the internal flows by the controllers have been evaluated on determining the total delay of the subnetwork and the average internal production. The deviations of the perimeter flows with respect to the desired perimeter flows have been evaluated to test the last objective of the subnetwork flow controller.

"What are the performances of the subnetwork flow controller with respect to other existing subnetwork controllers?"

The conclusions on the performance of the subnetwork flow controller have been split up in the three main objectives.

First objective: maintaining a constant shaped MFD

Concluding form the simulation results, it seems that the subnetwork flow controller is not able to maintain a constant shaped MFD. Moreover, demand seems of influence on the shape of the MFD. Due to this non constant shape of the MFD, evaluating the scatter by determining the standard deviation of the absolute scatter deviation to the running median became meaningless. Some recommendations will be given on this topic in paragraph 6.2. Demand is however not the only factor which might be of influence on the shape of the MFD. The desired perimeter flow and maximum deviation factor θ are parameters of the subnetwork flow controller which might influence the shape of the MFD as well.

It turned out that a constant shaped MFD cannot be maintained when different desired perimeter flows are set up by the main controller (a lower desired perimeter flow when the demand is lower and a higher desired perimeter flow when the demand is higher). Furthermore, a problem has been detected in the set up of the desired perimeter flows due to the different origin-destination demand pairs for perimeter links at intersection with two or three adjacent intersections. Therefore, extra simulations have been performed with different applied desired perimeter flows for perimeter links at intersections with two and three adjacent intersections. It turned out that a non constant shaped MFD was the result again. It can be concluded that setting up certain desired perimeter flows is of high influence on the performance of maintaining a constant shaped MFD by the subnetwork flow controller and thus a restriction on the desired perimeter values is needed in that case. Some recommendations will be given on this topic in paragraph 6.2.1.

Different applied maximum deviation factors θ of [0,1] did not influence the shape of the MFD. Due to a mismatch between desired perimeter flow and measured perimeter flow, extra simulations have been performed with a maximum deviation factor θ of 300. The shape and scatter of the MFD did change, but the significance of this result cannot be described due to a lack of simulations. Some recommendations will be given on this topic in paragraph 6.2.1.

Due to the influences of the desired perimeter flows and the maximum deviation factor and a lack of simulations it cannot be concluded that the MFD provided by the subnetwork flow controller is not independent of demand.

Second objective: optimizing internal flows

In comparison with the performance of the vehicle-actuated controller and back pressure controller, the subnetwork flow controller generates higher delay values. This can be explained by the fact that the subnetwork flow controller is holding back traffic in order to provide the desirable perimeter flows when there is an exceed of demand. This causes a higher internal delay when a medium, high or very high demand pattern has been applied. Latent delay increases as well due to the fact that vehicles are not able to enter the subnetwork due to blocking of the input locations and gridlocks. Again no differences where noticed in the different applied maximum deviation factors. When a maximum deviation factor θ of 300 was applied, it turned out that the delay decreased. This is explained by the fact that with the same desired perimeter flows more vehicles are allowed to exit the subnetwork. A change to different desired perimeter flows for perimeter links at intersections with two or three adjacent intersections did not result in an obvious pattern in the results on total delay. Therefore, nothing can be said of restrictions on setting up desired perimeter flows yet.

With increasing demand, the subnetwork flow controller is able to control the traffic better than the vehicle-actuated controller with respect to the internal production. It means that the subnetwork flow controller is able to delay the introducing of the gridlock effect. The back pressure controller performs however better than the subnetwork flow controller. This is caused by the fact that the subnetwork flow controller has to provide some desirable perimeter flows and thus blocks traffic from leaving the subnetwork when the perimeter flow is too high. This results in a lower internal production. The extra simulations with a different maximum deviation factor resulted in a higher production (inflow, outflow and internal) while the simulations with different desired perimeter flows for different kind of perimeter links resulted in no obvious pattern in the results again. It seems that a maximum deviation factor θ of 300 is desirable, but there is no reference information on other values of θ except [0,1] . Due to a lack of simulations, nothing can be said on restrictions on setting up desired perimeter flows and optimal maximum deviation factor θ yet.

Third objective: providing desired perimeter flows

As said before, demand is of influence on setting up desired perimeter flows. In practice, a main controller would not set up the same value of desired perimeter flow for each perimeter link. It might imaginable that for each intersection perimeter link a different value of desired perimeter flow would be set up. But, it is also possible that the main controller sets up desired perimeter flows which do not match the demand pattern at all. Therefore restrictions are needed on setting up desired perimeter flows.

The results on deviation cumulative number of vehicles which left the subnetwork showed that nothing can be said on the optimal value of θ and which restrictions have to be set up on desired perimeter flows. It can however be said that under certain circumstances (certain demand patterns, maximum deviation factors and desired perimeter flows) the subnetwork flow controller is able to provide the desired perimeter flows with a deviation not larger as 10%.

Overall performance of subnetwork flow controller

The subnetwork flow controller as designed in this thesis has been proven to work properly; it is able to control traffic in a subnetwork. When the subnetwork flow controller provides the desired perimeter flows, a constant shaped MFD cannot be maintained. This is however influenced by the set up of the desired perimeter flows and maximum deviation factor θ. With certain applied values of these two factors, a constant shaped MFD is the result. However, the subnetwork flow controller is holding traffic which is resulting in an increase in delay and thus less optimal internal flows.

Concluding, the subnetwork flow controller is able to contribute to two main objectives (under certain values of θ and desired perimeter flows):

- Maintaining a constant shaped MFD
- Provide desirable perimeter flows

When optimizing the internal flows, perimeter flows cannot be controlled anymore. This is shown in the results of the back pressure controller.

6.2 Recommendations

Some recommendations are given in order to evaluate the designed subnetwork flow controller performance.

Applying subnetwork flow controller in practice

Due to the fact that the subnetwork flow controller as designed in this thesis is able to maintain a constant shaped MFD (under certain circumstances) while it provides the desirable perimeter flows, it can be expected that the controller can be applied in practice. The subnetwork flow controller has been applied in a hierarchical structure in this thesis. The main controller desires a constant shape of the MFD in order to maintain a desired traffic state in the subnetwork and provides desired perimeter flows to which the subnetwork flow controller has to contribute. However, it turned out that in order to make the subnetwork flow controller suitable in a hierarchical control structure restrictions are needed first on setting up the desired perimeter flows and the maximum allowed deviation factor θ of the algorithm.

It has been shown in the simulation results that the values of desired perimeter flows are of influence on the shape of the MFD. Furthermore, total delay decreased and internal production increased when desired perimeter values have been chosen which matched the demand pattern better. The subnetwork flow controller was however still able to provide the desirable perimeter flows under two constraints. The first constraint holds a minimum demand for certain desired perimeter flows (high desired perimeter flow cannot be provided if there is insufficient demand). The second constraint is that a gridlock needs to be prevented otherwise traffic is not able to reach the perimeter links anymore.

Restrictions on desired perimeter flow

It is recommended to set up restrictions on choosing the desirable perimeter flows. The simulation results do not provide a specific pattern. Extra simulations are needed in order to clear the effect of setting up different desirable perimeter flows.

Maximum deviation factor θ

Extra simulations are also needed in order to set up an optimal maximum deviation factor θ. In this thesis an effort has been made to derive the most optimal value of θ. A lack of simulations however caused that this effort has not been reached.

Demand patterns

The demand is of influence on the performance of the subnetwork flow controller as well. An evenly spread demand pattern has been used in all simulations. The effect of a heterogeneous divided demand pattern has not been investigated. It is therefore recommended to perform extra simulation with more kinds of different demand patterns. When an inhomogeneous demand pattern will be applied, it can be expected that the subnetwork flow controller has more effort in order to divide the traffic load over the subnetwork. The result is that, despite the control of the subnetwork flow controller, traffic will not be divided total homogenous over the subnetwork. It can be expected that the shape of the MFD will consist of more scatter compared when applying a homogeneous divided demand pattern. Moreover, due to different origin-destination pairs it is more difficult to set up values for the desired perimeter flows. This will result in more influence of the desired perimeter flow on the MFD which is of influence in the ability of maintaining a constant shape.

Demand has been set constant during the entire simulation time. It is also recommended to perform simulations with a demand pattern where demand increases and decreases. This will provide more information on the performance of the subnetwork flow controller. If it turns out that the subnetwork flow controller is able to control traffic with all kind of demand patterns, the subnetwork flow controller can be applied at all times (peak hours and off-peak hours for example).

Moreover, the same simulation seed number has been used within VISSIM during all simulations. This simulation seed is of influence on the input demand dynamics of the subnetwork and thus on the traffic state of the subnetwork. This might affect the shape of the MFD, performance on optimizing internal flows and deriving the desired perimeter flows. Gridlocks may occur earlier due to the different traffic state of the network. When a gridlock does occur for example five minutes earlier within the simulation, the expectation is that a total different performance of the subnetwork flow controller will be the result. It is therefore recommended to perform more simulations in which different simulation seeds will be applied in order to investigate the influence of the input demand dynamics.

Time slot length in subnetwork flow controller algorithm

A specific time slot length (twelve seconds) has been used in the subnetwork flow algorithm. No other values have been investigated. It is recommended to perform simulations with different kind of time slot lengths. This might increase or decrease the performance of the subnetwork flow controller on optimizing the internal flows.

Simulation time

A simulation time of 3600 seconds has been handled during the simulations. The subnetwork flow controller was executed after 228 seconds in order to load the subnetwork with a sufficient number of vehicles in order to provide the desirable perimeter flows. In order to evaluate the performance of the subnetwork flow controller on providing the desired perimeter flows, graphs have been made in which the deviation of cumulative number of vehicles which did left the subnetwork at a specific perimeter link was compared with the desired number of vehicles which should have left the subnetwork. It was shown that at some applied demand patterns stability in simulation results on deviation of cumulative number vehicles which left the subnetwork cannot be estimated. Therefore, it is recommended to increase the simulation time in order to judge the simulation results on stability. It can be expected that when the simulation time will be tripled, patterns in simulation results will occur.

Location of data collection points

Data collection points are located just downstream of each intersection. The effect is that some traffic is not counted as internal traffic when these vehicles use one intersection only. But those vehicles are controlled by the subnetwork flow controller as well. Different placement of the data collection points will influence the results of the simulations. It is therefore recommended to place more data collection points at different places and evaluate the difference in results in order to define the optimal locations to place the data collection points.

6.3 Future research topics

Some topics need to be investigated in the future which are not handled or turned out to be insufficient in this thesis.

Applying of clearance times

Due to the set up of a constant time slot length in the subnetwork flow controller algorithm, it is not able to take into account clearance times. It is recommended to perform future research on taken into account clearance times. Other simulation programs might be needed. So far, it was not known how to introduce clearance time in the subnetwork flow controller algorithm in Matlab, VISSIM, COM interface, VRIGen or TRAFCOD.

Measuring way of queue length

A difference in measuring queue length has been applied comparing the vehicle-actuated controller and the back pressure or subnetwork flow controller. While the vehicle-actuated controller uses queue detector loops to determine the presence of a queue, the back pressure and subnetwork flow controller make use of queue counters in VISSIM. The queue length is an important traffic measurement which has been used the subnetwork flow controller algorithm. Due to the fact that vehicles at the end of a queue are still in queue position while the front of the queue has been gone a long time ago, the queue length has not been determined very accurately. Predictions of the queue length might be useful in order to get more accurate queue lengths. It is therefore recommended to perform some future research on this topic.

Applying heterogeneous subnetworks

In this thesis highly strong homogeneous subnetworks have been used. The same speed was allowed on all links and only one type of road (urban road) has been applied. Therewith, no underlying network has been applied in order to keep the computation effort of VISSIM not too high. The question arises if a subnetwork flow controller is able to create homogeneity in traffic conditions and thus balance the queues in a more heterogeneous subnetwork.

Applying multiple kinds of DTM measures

The only applied DTM measure in this thesis is the traffic signal. Other DTM measures could be controller by the subnetwork flow controller has well. This might result in better homogeneity of traffic conditions due to the fact that there are more control options for the subnetwork flow controller. Therefore, when a highway is part of the subnetwork layout, ramp metering signals might be necessary to control traffic in the subnetwork.

Partitioning subnetworks

No literature survey has been performed specifically on partitioning of an urban road network in several subnetworks. In this thesis a reservoir based partitioning has been applied. It might be possible that the subnetwork flow controller is more suitable in a different way of partitioning the urban road network. Future research is proposed on this topic.

MFD overruling principle

The standard deviation of the scatter of the MFD has been determined in this thesis in order to evaluate the scatter size and constant shape of MFD. This way of determining the scatter size can also be handled within the MFD overruling principle which has been introduced in paragraph 3.5. When specific restrictions on the allowable deviation of scatter size of the MFD are introduced in the control algorithm, an overruling principle by the MFD could be applied in the subnetwork flow controller algorithm. It turned out that the subnetwork flow controller is not able to control internal flows very well when providing the desirable perimeter flows. When the shape of the MFD is not constant anymore, moreover scatter size has been increased significantly, the overruling principle by the MFD should be able to stop providing the desirable perimeter flows. When a constant shaped MFD with less scatter than a certain maximum deviation on the standard deviation of scatter has been recovered, the subnetwork flow controller can start controlling the perimeter flows again. This overruling principle might provide better homogeneity of traffic conditions due to better independency of demands and thus increasing chances on constant shaped MFD's.

Evaluating scatter size

A drawback of evaluating the scatter size of the MFD's performed in this thesis is that the absolute scatter deviation had been determined vertically. This was of influence on the high accumulation data points in certain MFD's. Absolute scatter deviation increased and therewith the standard deviation while the scatter seems low when evaluating the high accumulation data points of certain MFD's visually. It might be preferable to evaluate the scatter size of high accumulation data points horizontally. Moreover, it might be desirable to determine the absolute scatter deviation based on the tangents of a fit line of the MFD. Therefore, future research is proposed on evaluating the scatter size of the MFD's.

List of symbols

Symbol	**Unit**	**Explanation**
R	-	Road network
J_i	-	Set of intersections of road network
M_i	-	Set of traffic movements of intersection
ξ_i	veh/hour	Flow rate of traffic movement M_i
P_{all}	-	Set of all different available phases consisting of different traffic Movements
P_{out}	-	Set of phases which contain a perimeter traffic movement
P_{notout}	-	Set of phases which do not contain a perimeter traffic movement
p_i	-	Phase i
S_i	veh^2/hour	Pressure of phase i
P^*	-	Activated phase p_i
S^*	veh^2/hour	Pressure of activated phase P*
L	-	Link
L_{out}	-	Perimeter link
M_{out}	-	Perimeter traffic movement
L_a	-	Upstream link
L_b	-	Downstream link
W_{ab}	veh	Difference queue length upstream and queue length downstream of a traffic movement
Q_a	veh	Upstream queue length
Q_b	veh	Downstream queue length
ξ_{out}	veh/hour	Perimeter flow rate
$\xi_{desired}$	veh/hour	Desired perimeter flow rate set up by main controller
ξ_{outd}	veh/hour	Difference desired perimeter flow rate and actual perimeter flow rate
θ	-	Maximum deviation factor set up by main controller
k	-	Time slot number in algorithm
$z_i(k)$	-	Disturbances on traffic conditions in time step k
γ	-	Switch between "old and new" back pressure algorithm
T	sec	Total execution time of algorithm
t	sec	Time
T_k	sec	Time slot of execution controller algorithm

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Appendix

A.1 Backpressure algorithm

The back pressure algorithm has been applied original to communication and power networks. Wongpiromsarn et al. (2012) have proposed a distributed algorithm for controlling traffic signals based upon this back pressure algorithm. The algorithm they have set up requires minimal tuning and scales well with changing size of the network while ensuring satisfactory performances. It turned out that the most attractive performance of their back pressure algorithm is a maximum network throughput without requiring any knowledge about travel arrival rates.

The proposed algorithm, with a back pressure basis, determines the signals at each intersection independently from the other intersections. Due to the fact that they applied their controller in a distributed way, it can be applied to a large network.

The back pressure algorithm, applied on traffic signals, is based upon the different phases which exist for a single intersection. A phase consists of multiple traffic movements which can have right-of-way simultaneously.

The back pressure algorithm uses the queue lengths in order to compute a certain pressure of each traffic phase. By subtracting the downstream queue of the upstream queue of each traffic movement of the controlled intersection and multiplying this result by the flow rate (rate at which vehicles can pass the stop line of a specific traffic movement), the pressures are determined of each traffic movement. Adding up the pressures of traffic movements, which are part of a particularly phase, results in a total pressure of each phase. When the pressure of a phase exceeds the pressure of the current activated phase, this phase will be served next. When multiple phases have pressures higher than the current activated phase, the controller will pick the highest. If two phases have an equal pressure, the controller will pick one arbitrarily. These calculations will be made every time step in the algorithm.

In order to get more insight in this traffic signal control principle, a mathematical description is provided.

Mathematical description back pressure algorithm

A road network (R) is defined as a collection of set of links (L) and intersections (J) (Wongpiromsarn et al. 2012). R can then be written as R = (L,J) where $L = \{L_1,\ldots,L_n\}$ with n the total number of links of intersection $J = \{J_1,\ldots,J_m\}$ with m the total number of signalised intersections in the network. Each intersection J_i ,with $i \in \{1,\ldots, m\}$, can be described as $J_i = (M_i,P_i,Z_i)$ where $M_i \subseteq L^2$ represents a set of all possible traffic movements through J_i, $P_i \subseteq 2^{M_i}$ represents a set of all possible phases of J_i and Z_i is an finite set of traffic states. Z_i captures aspects of influence on the traffic state of the intersection, such as possible weather conditions, etc. Each traffic movement through intersection J_i is defined as a pair $(L_a,L_b) \in L^2$. A vehicle enters intersection through L_a and exits through L_b. Each phase $p_i \in P_{all}$, where P_{all} represents all possible phases of P_i, defines a combination of traffic movements simultaneously receiving right-of-way.

The traffic controller operates at a time slot $T_k \in \mathbb{R}^+$ with $k \in \{1,\ldots, N\}$ and $N \in \mathbb{N}^+$ representing the total number of time slots . For each $a \in \{1,\ldots,n\}$ and $i \in \{1,\ldots, m\}$ the number of queued vehicles on L_a are represented by $Q_a(k) \in \mathbb{N}_0$ and the traffic state around J_i by $z_i(k) \in Z_i$ at the beginning of timeslot T_k. The rate $\xi_i(p,L_a,L_b,z_i(k))$ (number of vehicles per unit time) represents the rate at which vehicles can go from L_a to L_b through intersection J_i under traffic state z if phase p is activated. $\xi_i(p,L_a,L_b,z_i(k)) = 0$ when $(L_a,L_b) \notin p$, it means that in phase p_i the traffic movement (L_a,L_b) does not have right-of-way and thus the traffic flow rate $\xi_i(p,L_a,L_b,z_i(k))$ will be zero. When the number of vehicles want to travel from L_a to L_b is very high (captured in traffic state z), saturated flow can be assumed. For calculating the pressures of each phase p_i, traffic flow rates ξ_i are taken into account when each traffic stream has right-of-way.

At each time slot T_k, each local controller C_i computes the phase $p^* \in P_{all}$ to be activated at intersection J_i during time slot T_k. P^* represents the current activated phase with S^* representing the pressure of that particular phase. The algorithm is described as follows:

Algorithm: computation of phase p^* to be activated during time slot T_k at intersection J_i.
Input: $z_i(k)$, $Q_a(k)$ for all $a \in \{1,\ldots,n\}$ and $Q_b(k)$ for all $b \in \{1,\ldots,n\}$ such that $(L_a,L_b) \in M_i$. ξ_i of each $L_a \in L$. Furthermore, S^* of the activated phase P^*.
Output: $p^* \in P$ to be activated during time slot T_k

```
Foreach $(L_a,L_b) \in M_i$ do
    $W_{ab} \leftarrow Q_a(k) - Q_b(k)$;
Foreach $p_i \in P_{all}$ do;
    $S_i \leftarrow \Sigma_{(L_a,L_b) \in p_i} W_{ab}\xi_i(p,L_a,L_b,z_i(k))$;
    If $S_i > S^*$ then
        $P^* \leftarrow p_i$;
        $S^* = S_i$;
```

A.2 Total delay: internal and latent delay

Demand pattern	Controller	Latent delay (h)	Internal delay (h)
Low demand	Vehicle-actuated	0,438	137,378
	Back pressure	0,475	224,982
	Subnetwork flow θ=0.1	0,487	254,909
	Subnetwork flow θ=0.5	0,480	252,143
	Subnetwork flow θ=1.0	0,480	247,468
Medium demand	Vehicle-actuated	21,650	498,345
	Back pressure	1,620	742,418
	Subnetwork flow θ=0.1	480,662	1364,025
	Subnetwork flow θ=0.5	474,549	1312,296
	Subnetwork flow θ=1.0	498,199	1283,605
High demand	Vehicle-actuated	1249,564	1547,677
	Back pressure	380,830	1692,653
	Subnetwork flow θ=0.1	738,344	1958,297
	Subnetwork flow θ=0.5	564,933	1814,516
	Subnetwork flow θ=1.0	572,481	1832,722
Very high demand	Vehicle-actuated	6317,186	2174,063
	Back pressure	6226,311	2261,717
	Subnetwork flow θ=0.1	6166,612	2414,524
	Subnetwork flow θ=0.5	5990,573	2457,779
	Subnetwork flow θ=1.0	6142,314	2405,546

Table A-1: Overview internal and latent delay all kind of controllers

A.3 Production: inflow, outflow and internal

Demand pattern	Controller	Inflow production (veh/h)	Outflow production (veh/h)	Internal production (veh/h)
Low demand	Vehicle-actuated	609,563	583,000	480,708
	Back pressure	609,563	576,813	477,000
	Subnetwork flow θ=0.1	610,250	574,438	475,229
	Subnetwork flow θ=0.5	610,250	575,375	475,771
	Subnetwork flow θ=1.0	610,250	575,313	477,438
Medium demand	Vehicle-actuated	968,250	901,563	866,125
	Back pressure	972,500	890,875	853,188
	Subnetwork flow θ=0.1	869,250	718,750	724,854
	Subnetwork flow θ=0.5	864,688	728,063	733,438
	Subnetwork flow θ=1.0	863,625	729,000	731,875
High demand	Vehicle-actuated	895,563	713,688	714,896
	Back pressure	1075,250	899,625	910,250
	Subnetwork flow θ=0.1	966,563	781,625	795,729
	Subnetwork flow θ=0.5	1033,313	857,625	887,396
	Subnetwork flow θ=1.0	1046,625	864,563	898,125
Very high demand	Vehicle-actuated	775,063	583,500	629,854
	Back pressure	836,875	653,313	721,479
	Subnetwork flow θ=0.1	809,000	610,938	679,354
	Subnetwork flow θ=0.5	729,688	539,063	601,896
	Subnetwork flow θ=1.0	712,313	527,063	583,375

Table A-2: Overview inflow, outflow and internal production different kind of controllers

A.4 Deviation cumulative number of vehicles

A.4.1 Intersection with two adjacent intersections

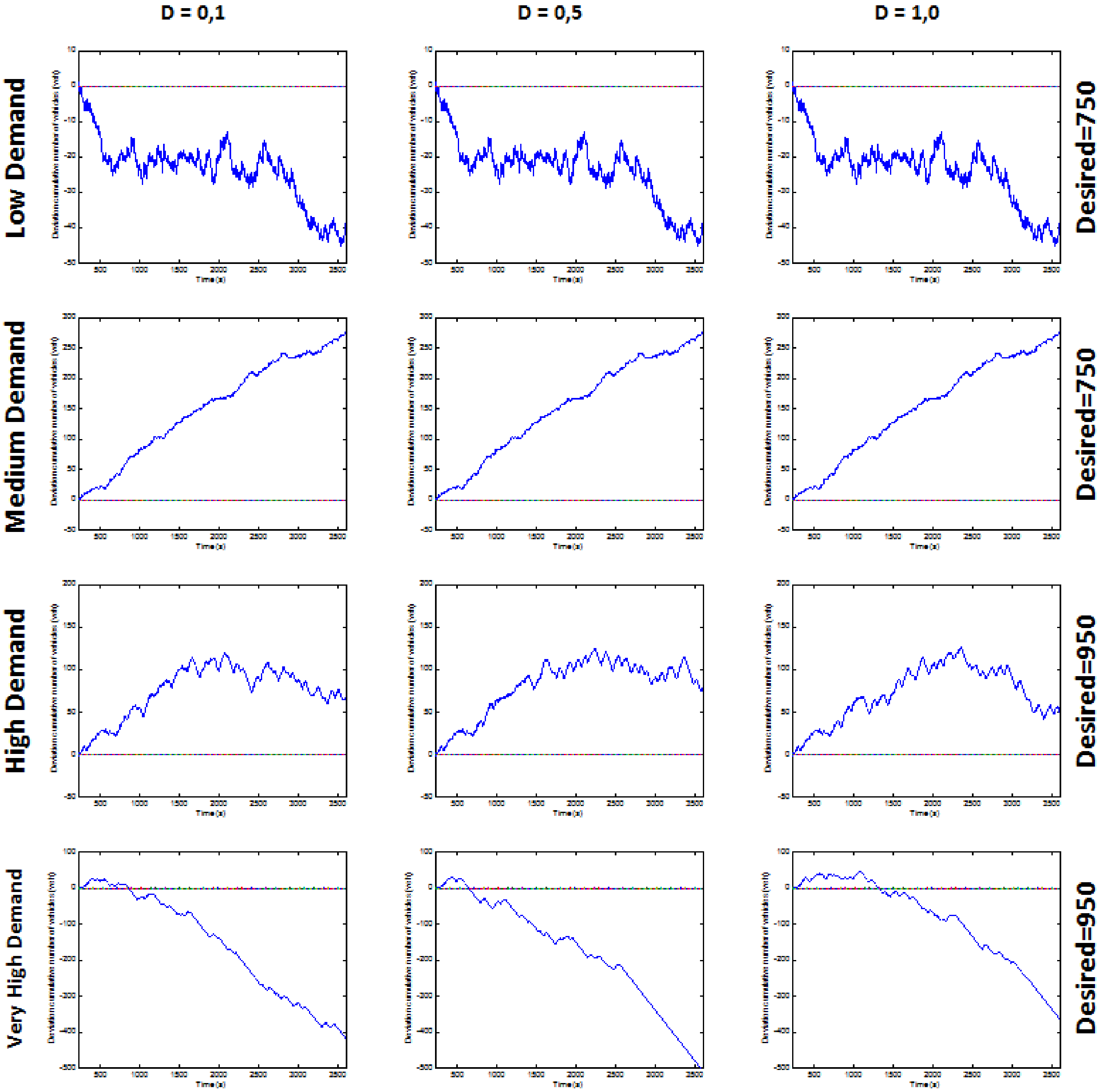

Figure A-1: Results different applied maximum deviation factors on deviation cumulative number of vehicles at perimeter link over time at intersection with two adjacent intersections

A.4.2 Intersection with three adjacent intersections

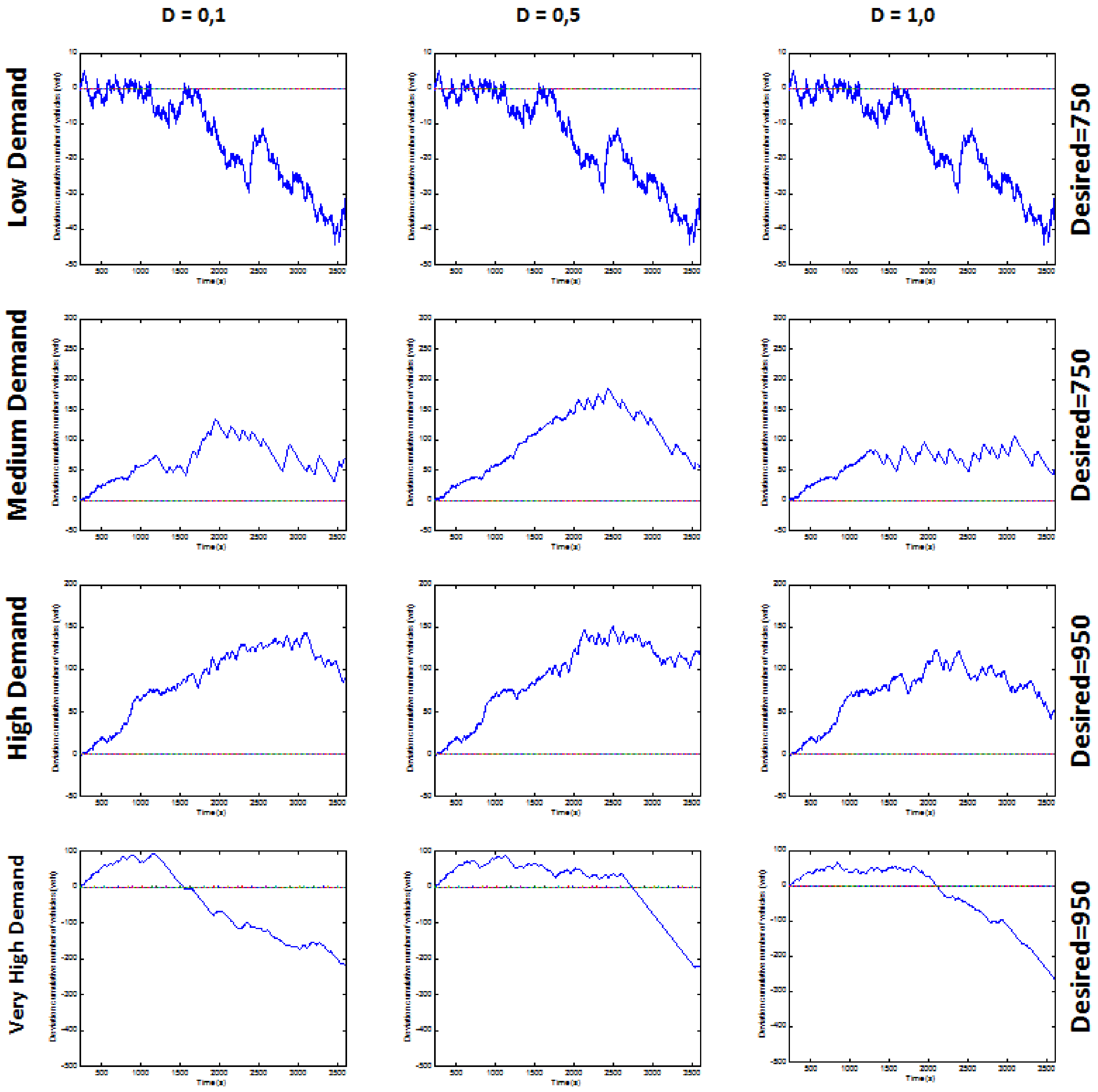

Figure A-2: Results different applied maximum deviation factors on deviation cumulative number of vehicles at perimeter link over time at intersection with three adjacent intersections

A.5 Extra simulation results: MFD scatter

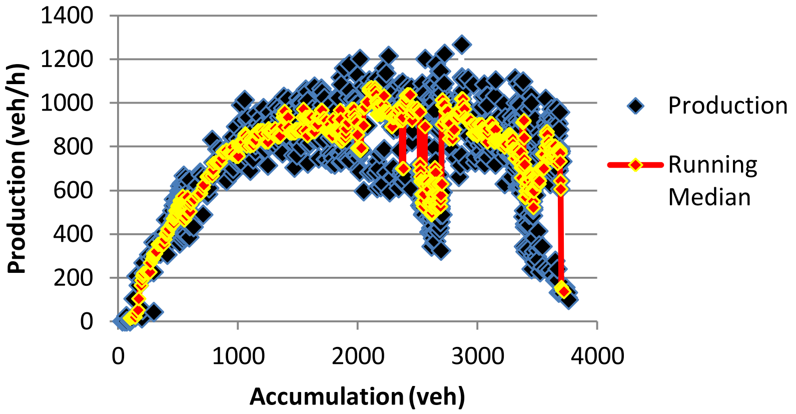

Figure A-3: Running median of MFD with an applied maximum deviation factor of 0,1 and different desired perimeter flows for intersections with two and three adjacent intersections

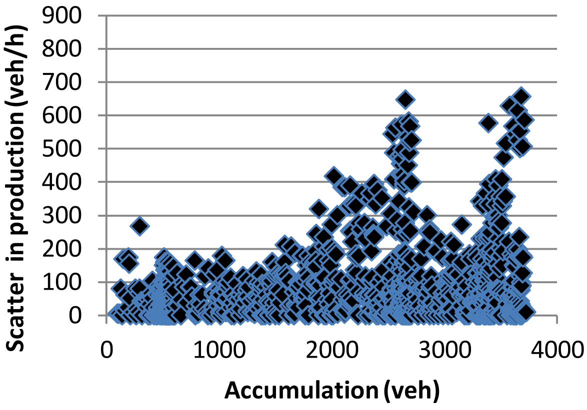

Figure A-4: Absolute scatter deviation of MFD with an applied maximum deviation factor of 0,1 and different desired perimeter flows for intersections with two and three adjacent intersections

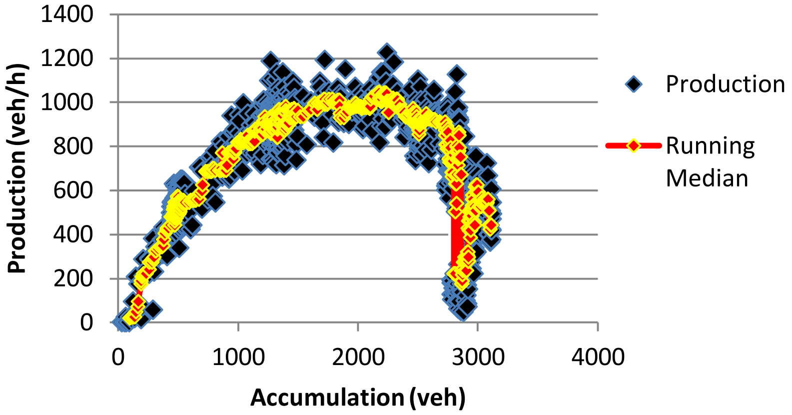

Figure A-5: Running median of MFD with an applied maximum deviation factor of 300 and the same desired perimeter flows for intersections with two and three adjacent intersections

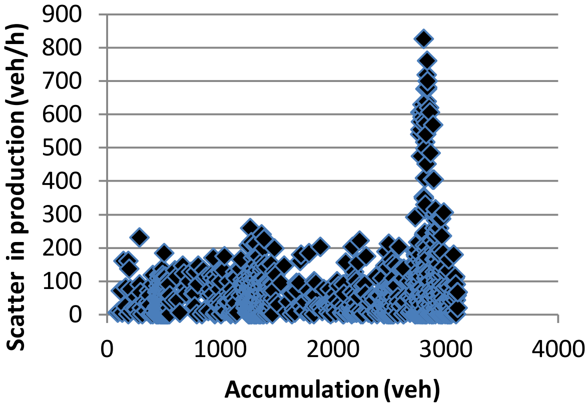

Figure A-6: Absolute scatter deviation of MFD with an applied maximum deviation factor of 300 and the same desired perimeter flows for intersections with two and three adjacent intersections

A.6 Extra simulation results: delay and production

		Latent delay (h)	Internal delay (h)
Low demand	Perimeter constant desired θ=0.1	0,487	254,909
	Perimeter different desired θ=0.1	0,482	258,076
	Perimeter constant desired θ=300	0,475	224,982
Medium demand	Perimeter constant desired θ=0.1	480,662	1364,025
	Perimeter different desired θ=0.1	557,680	1628,624
	Perimeter constant desired θ=300	1,647	775,872
High demand	Perimeter constant desired θ=0.1	738,344	1958,297
	Perimeter different desired θ=0.1	494,320	1940,007
	Perimeter constant desired θ=300	593,649	1715,972
Very high demand	Perimeter constant desired θ=0.1	6166,612	2414,524
	Perimeter different desired θ=0.1	4922,046	2693,856
	Perimeter constant desired θ=300	7016,846	2403,456

Table A-3: Overview internal and latent delay extra simulations

		Inflow production (veh/h)	Outflow production (veh/h)	Internal production (veh/h)
Low demand	Perimeter constant desired θ=0.1	610,250	574,438	475,229
	Perimeter different desired θ=0.1	610,250	573,750	475,854
	Perimeter constant desired θ=300	609,563	576,813	477,000
Medium demand	Perimeter constant desired θ=0.1	869,250	718,750	724,854
	Perimeter different desired θ=0.1	810,688	643,438	659,375
	Perimeter constant desired θ=300	972,000	886,188	851,167
High demand	Perimeter constant desired θ=0.1	966,563	781,625	795,729
	Perimeter different desired θ=0.1	1054,688	846,750	871,625
	Perimeter constant desired θ=300	1036,000	863,813	870,563
Very high demand	Perimeter constant desired θ=0.1	809,000	610,938	679,354
	Perimeter different desired θ=0.1	954,375	718,938	779,604
	Perimeter constant desired θ=300	690,813	497,938	559,938

Table A-4: Overview inflow, outflow and internal production extra simulations

A.7 Extra simulations: Deviation cumulative number of vehicles

A.6.1 Intersection with two adjacent intersections

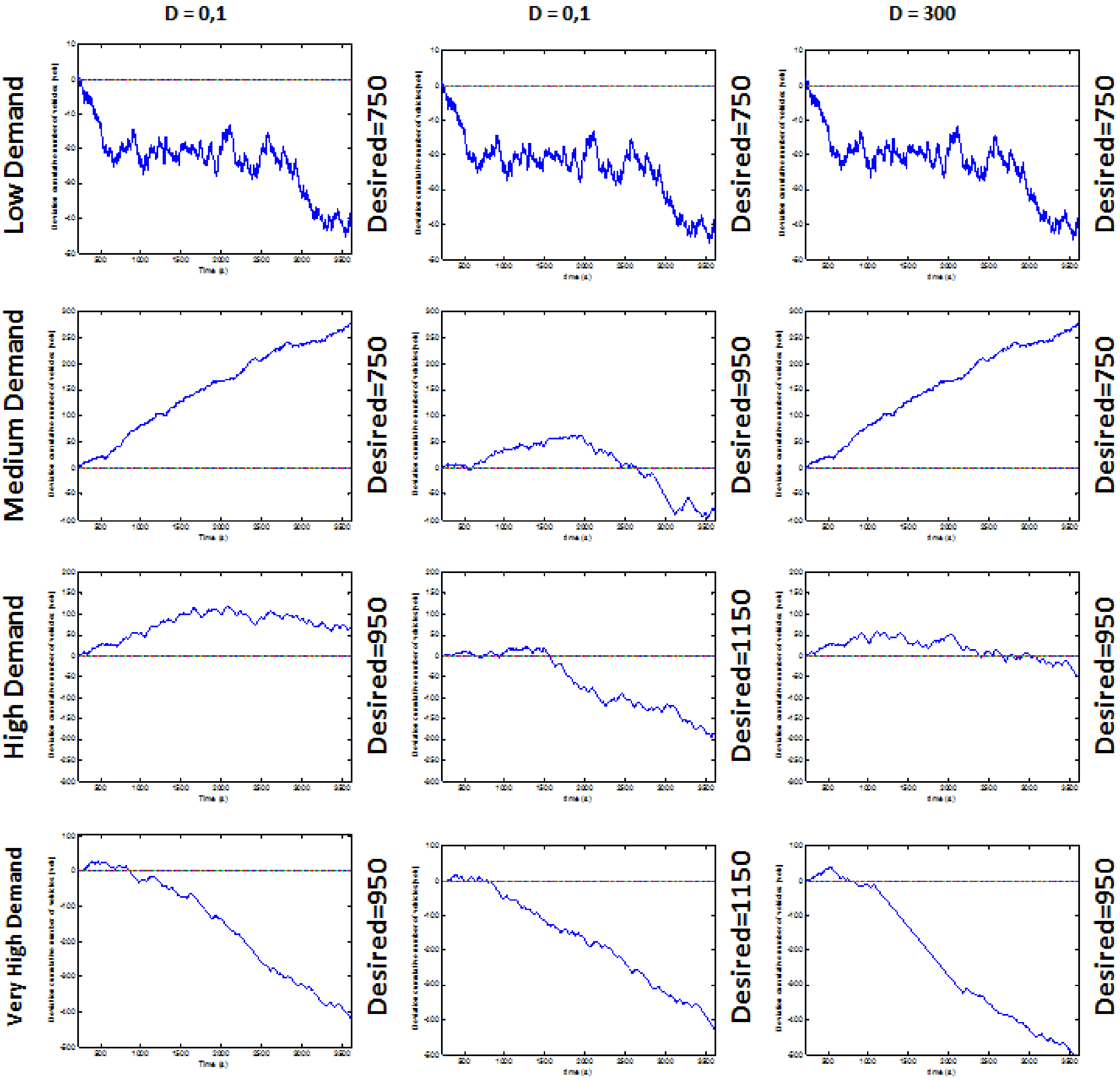

Figure A-7: Extra simulation results on deviation cumulative number of vehicles at perimeter link over time at intersection with two adjacent intersections

A.6.2 Intersection with three adjacent intersections

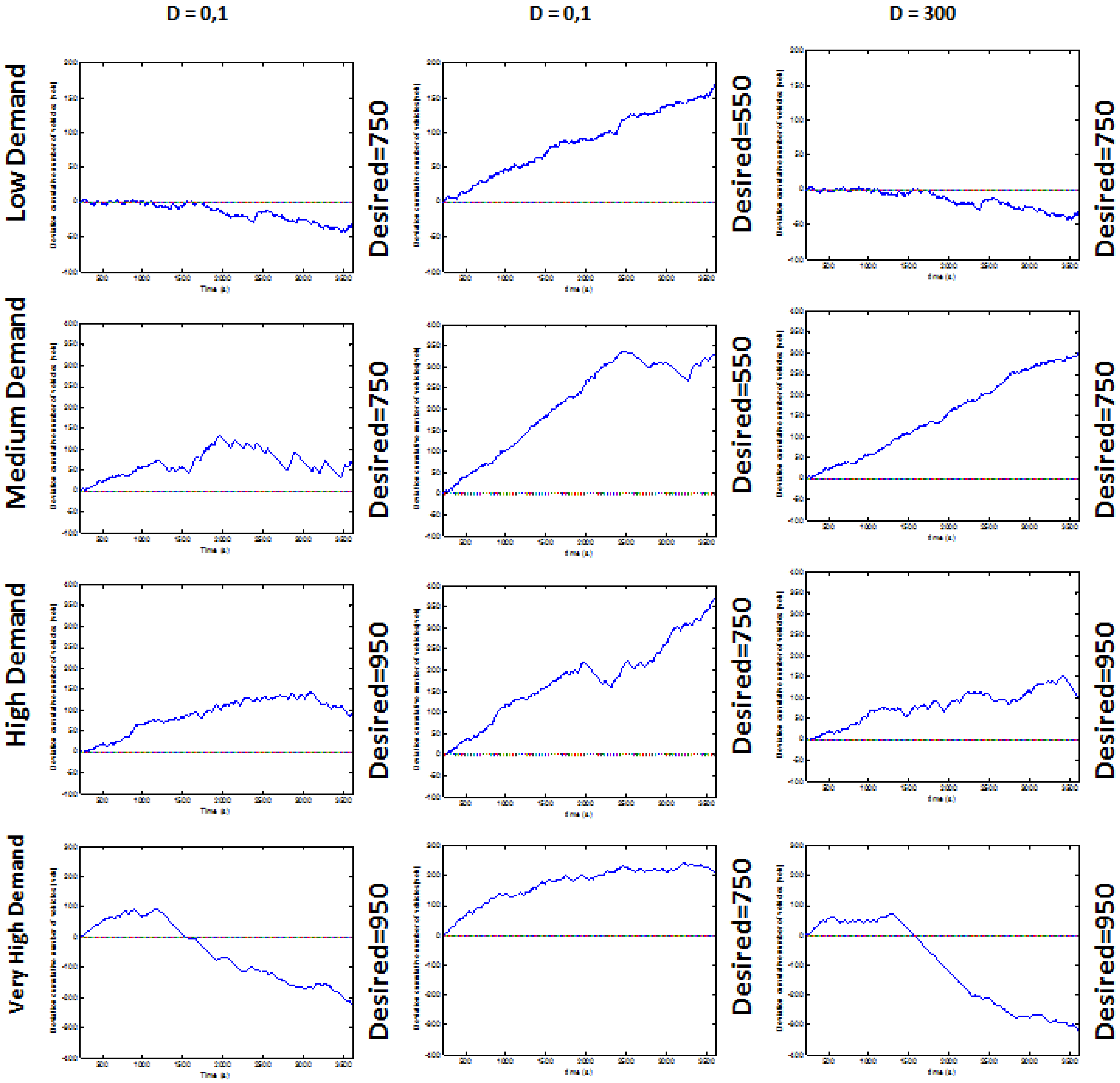

Figure A-8: Extra simulation results on deviation cumulative number of vehicles at perimeter link over time at intersection with three adjacent intersections