

Distribution of traffic over buffer space by using controlled intersections

Master of Science Thesis

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Preface

This thesis marks the end of my graduation work, which completes my Master of Science program Transport and Planning, offered at Delft University of Technology. This thesis project is performed in cooperation with Vialis, within the business unit Information Technology and Mobility.

The subject of this thesis is the distribution of traffic over buffer space in a road network. This distribution is performed using traffic lights at controlled intersections. A control algorithm is developed to distribute the traffic in several bottleneck situations. The algorithm is programmed in MATLAB and simulated with VISSIM.

During my graduation process some people have been of great help, for which I am grateful. First of all I would like to thank the members of my graduation committee. Henk, thanks for guiding me in the right directions during this research via the continuous feedback you gave me and via your attention for detail. Your advice has been of great help. Willem, I really appreciate your views and comments from the world outside the walls of the university, and would like to thank you for giving me the opportunity to perform my graduation project at Vialis. Serge, thanks for the help with finding a nice and challenging graduation topic and for the comments during the meetings. Paul and Cees, thanks for taking place in the committee and for the comments. Secondly I would like to thank Ramon Landman for the help to get the COM Interface up and running. Thirdly my colleagues at Vialis should be mentioned for creating a nice working atmosphere.

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Mark Buitenhuis
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Summary

Congestion on the road is a widely recognized problem. To improve traffic conditions on the road, several methods have been developed over the years. Dynamic traffic management is one of them and has proven to be effective. It aims at making better use of the existing network capacity and at managing traffic flows. In order to further improve the effectiveness of the individual measures, research into coordination of individual traffic management measures (i.e. integrated network management) has recently been increased. Effectiveness can be improved since (i) the counteracting of measures against each other can be reduced and (ii) the strengths of the individual measures can be combined. To show the benefits of integrated network management in a real world situation, a well performed field operational test is needed. In the Netherlands this was a reason to launch the Field Operational Test Integrated Network Management Amsterdam, in Dutch the Praktijkproef Amsterdam.

Part of the Praktijkproef Amsterdam was the development of a controller that can control bottleneck situations which occur in the neighbourhood of a junction of a freeway and an urban arterial. Bottleneck situations that can occur are: (i) spillback on the urban arterial causing blocking back on the urban arterial, (ii) spillback from the off-ramp towards the freeway causing congestion on the freeway, (iii) spillback from the on-ramp towards the urban arterial causing blocking back on the urban arterial. These three situations capture all possible bottleneck situations that can occur in this type of network. In the Praktijkproef Amsterdam a certain controller was developed which can only handle the third situation. Therefore, in this research a controller is developed that is able to control all three situations. Hence, the objective of this research is a controller that deals with bottleneck situations occurring in the neighbourhood of a junction of a freeway and an urban arterial; in order to reach its goals, the controller should distribute traffic over the available buffer space in the network, by using traffic lights at controlled intersections. In the first situation the bottleneck needs to be detected and controlled (detection is input for control), in the second and third situation the queue at the ramp needs to be controlled.

The research consists of three phases: (i) a literature survey that studies the state-of-the-art related to the controller to be developed, (ii) the development and programming (in MATLAB) of different controller variants and (iii) the simulation (in VISSIM) of the variants. The literature survey showed that controllers that are capable of controlling the three bottleneck situations mentioned, do not exist at the moment.

Several controller variants are developed to distribute traffic over the buffers in one of the bottleneck situations. Distribution is based on changing the signal settings of the traffic lights: an increase in green time results in a decrease in queue length, and vice versa. Signal settings are changed based on calculated desired flows for the buffers.

For the first situation three detection variants are developed: detection based on (i) a crisp critical queue length value, (ii) differences in queue lengths between two time periods, (iii) fuzzy logic with queue lengths and flows as input values. Furthermore three controller variants are developed: controllers that distribute the surplus of traffic over (i) one up- or downstream

buffer based on prespecified preferences of using up- or downstream buffers, (ii) one up- or three downstream buffers also based on these prespecified preferences of using up- or downstream buffers, (iii) one up- and one downstream buffer based on relative buffer space.

For the second situation the queue at the off-ramp is managed by increasing the outflow at the ramp, based on a target outflow. Due to this increase spillback should be prevented. Two controller variants are developed: a controller which increases the outflow by distributing traffic over (i) the first downstream buffer, (ii) three downstream buffers based on turn fractions.

For the third situation the queue at the on-ramp is managed by reducing the inflow into the ramp, based on a target inflow. This should lead to the prevention of spillback at the ramp. Three controller variants are developed: controllers that reduce the inflow by distribution traffic over the (i) first upstream buffer, (ii) three upstream buffers based on turn fractions, (iii) three upstream buffers based on relative queue lengths. The ST1Light (developed in the Praktijkproef Amsterdam) is the fourth variant in this bottleneck situation, the ST1Light calculates the amount of buffers needed to reach the target inflow.

Table 0.1 presents the percentage change in total travel time of all controller variants. In the first situation congestion on the urban arterial is reduced by preventing spillback. A fuzzy logic approach using flow and queue length as inputs in order to detect bottleneck situations, shows best results in combination with the controllers: the smooth approach of the fuzzy detection results in more smooth control actions and therefore less variation in queue lengths at the bottleneck. The controller that prefers to use downstream buffers shows largest improvements in network performance (-3.3% in total travel time). The controller that uses both up- and downstream buffers has the strongest effect on reducing the queue at the bottleneck situation, but due to the upstream buffering total travel time increases (+1.7% in total travel time).

In the second situation congestion at the freeway is prevented, by preventing spillback from the ramp towards the freeway. Both designed controllers prevent spillback towards the freeway, hence preventing congestion and the capacity drop at the freeway. There is no trade-off shown at the urban arterial. This results in large improvements in the overall network performance. If more downstream buffers are used, the traffic is flushed further into the network and it reaches the network boundaries faster, hence resulting in shorter travel times and larger improvements in overall network performance (-38.7% in total travel time).

In the third situation spillback from the on-ramp towards the urban arterial is prevented by the developed controllers. If more buffer capacity is used, the network performance shows larger reductions due to the buffering of traffic. Therefore the controller which only uses the first upstream buffers, shows best results in network performance (-1.1% in total travel time). If no control is used, the network performance is better (-3.8% in total travel time), but in that case spillback from the on-ramp is not prevented. If no spillback occurs, the metering time of ramp metering installations will increase and traffic safety in the network will improve since the conflict area at the urban arterial of the on-ramp intersection is not occupied anymore.

Table 0.1 Overview of percentage change in total travel time of all controller variants.

Performance indicator	Controller					
Situation 1*	Base	Control 1.1	Control 1.2	Control 1.3	(* with fuzzy bottleneck detection)	
Total travel time	0.0%	-1.9%	-3.3%	+1.7%		
Situation 2	Base	Control 2.1	Control 2.2			
Total travel time	0.0%	-38.4%	-38.7%			
Situation 3	Base	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1Light
Total travel time	0.0%	-3.8%	-1.1%	+1.1%	+1.9%	+1.6%

It can be concluded that if buffers downstream of the bottleneck can be used, the controllers show positive results regarding the network performance; and if buffers upstream are used,

delays for traffic upstream of the bottleneck increase. The latter results in a decrease in network performance.

First of all it is recommended to implement bottleneck detection on urban arterials, based on a fuzzy logic approach. Bottleneck detection is not a part of current intersection control systems, and can be added to those systems. In order to control the bottleneck situations, the developed controller that prefers to use downstream buffers can be coupled to a current control system. Secondly it is recommended to prevent spillback at the off-ramp by setting a target outflow. The controller that only uses the first downstream buffer can be combined with current active systems. Thirdly it is recommended to prevent spillback at the on-ramp by setting a target inflow. It is recommended to use the first and second upstream buffers to buffer traffic. Furthermore it is recommended to switch off the controller if spillback occurs to conflict areas of the intersections, since the latter leads to large increases in travel times at the urban arterial.

Future research should focus on further tuning (e.g. fuzzy parameters) and testing (e.g. different traffic conditions, increased network size) of the control algorithms, and on combining the controller with current used systems in the field. Furthermore a supervisor could be created that can deal with multiple active bottleneck situations.

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List of symbols

General

Variable	Unit	Description
k	-	index of period
T	s	length of control period
m	-	index of traffic stream
n	-	index of intersection
x	-	index of 1 st downstream buffer
\hat{x}	-	index of 2 nd downstream buffer
\ddot{x}	-	index of 3 rd downstream buffer
\bar{x}	-	index of 1 st upstream buffer
$\hat{\bar{x}}$	-	index of 2 nd upstream buffer
$\ddot{\bar{x}}$	-	index of 3 rd upstream buffer
l_m^n	m	queue length of stream m at intersection n
$l_{m,desired}^n$	m	desired queue length for stream m at intersection n
$l_{m,min}^n$	m	minimum queue length for stream m at intersection n
$l_{m,diff}^n$	m	critical queue length difference for stream m at intersection n
l_{veh}	m	average vehicle length including spacing when vehicles are standing still
p_m^n	m	traffic surplus in traffic stream m at intersection n
s_m^n	m	space in traffic stream m at intersection n
s_{rel}^n	-	relative space in buffer n
q_m^n	veh/h	flow for traffic stream m at intersection n
B_m^n	1/0	bottleneck status of stream m at intersection n
J_m^n	1/0	permission status of buffer m at intersection n
mf	-	membership function for fuzzy logic process
β	-	tuning parameter to check ratio of space and surplus
$\gamma_{m,\dot{m}}$	-	turn fraction, denotes the fraction of traffic traveling from stream m towards stream \dot{m}
$\delta_{\bar{m},m}$	-	origin-fraction, denotes the fraction of all traffic in stream m originating from stream \bar{m}

Freeway ramps

Variable	Unit	Description
q_{off}	veh/h	flow at off-ramp
$q_{target-off}$	veh/h	target outflow at off-ramp
$q_{off-plus}$	veh/h	extra outflow at off-ramp
q_{on}	veh/h	flow at on-ramp
$q_{target-on}$	veh/h	target inflow at on-ramp
q_{on-min}	veh/h	reduction in inflow at on-ramp

VRIs

Variable	Unit	Description
C	s	cycle time
t_{yellow}	s	yellow time
$t_{clearance}$	s	clearance time
g_m^n	s	green time of traffic stream m at intersection n
g_{ph}^n	s	green time of phase ph at intersection n
g_{min}	s	minimum green time
g_{max}	s	maximum green time
$g_{remaining}$	s	remaining green time for non-buffers
g_{ph}^n	s	green time of phase ph at intersection n
ph^n	-	phases at intersection n
ph_m^n	-	phase of traffic stream m at intersection n
no_ph^n	-	number of phases at intersection n
u_m^n	veh/h	saturation flow of traffic stream m at intersection n

Abbreviations

Abbreviation	Description
VRI	traffic control installation (in Dutch: VerkeersRegelInstallatie)
TDI	ramp metering installation (in Dutch: ToeritDoseerInstallatie)

Chapter 1. Introduction

This first chapter gives an introduction to the research. Section 1.1 presents the context of the research in the traffic and transportation engineering field. The problem at hand is presented in section 1.2. Section 1.3 discusses the scope of the research, i.e. the focus of this research. Subsequently section 1.4 presents the research objective and research questions that will be answered in order to reach the objective. In section 1.5 the approach to reach this objective is described. Section 1.6 presents the scientific and practical relevance of the research. The outline of the report is discussed in section 1.7. The chapter concludes with section 1.8, which gives a summary of this first chapter.

1.1 Research context

For several decades the level of mobility in the Netherlands is growing (SWOV, 2013). However, every year 65 million hours on Dutch roads are spent in congestion (TrafficQuest, 2012). This leads to environmental, societal, economic and safety related problems (KiM, 2013). Research of Van Mourik (2008) shows that economic costs of congestion in the Netherlands are estimated at 2.5-3.6 billion Euros a year, these are for example costs caused by loss hours and by dealing with unpredictability in travel times. Total costs associated with congestion in the Netherlands are estimated at 20 billion Euros a year, which includes also costs due to road crashes and CO₂ emissions.

To reduce the amount of congestion on the Dutch roads, several methods and measures can be applied. The most basic notion is the difference between affecting the demand side, or affecting the supply side of traffic. The demand side consists of people and goods that want or need transport. The supply side consists of the networks and services that make this transport possible.

In the past years numerous measures are designed to influence one or both sides of the transport market, which is illustrated by two examples. The need for commuting can be reduced by working at home or by encouraging people to live relatively close to their working place, this influences the demand side. The capacity of the freeway can be temporarily increased by opening plus lanes and peak lanes, this influences the supply side. Research has discussed the effectiveness of those types of measures. One of the conclusions (Hoogendoorn et al., 2011) shows it is more effective to make better use of the existing network capacity than creating extra capacity in the network (e.g. via the construction of new roads). This effectiveness is based on the costs of the measures as well as on the needed public space of the measures.

An effective measure is therefore dynamic traffic management. Dynamic traffic management aims at making better use of the existing road network capacity and at managing traffic flows

(TNO, 2014). Dynamic traffic management focuses on the supply side of the transport market: the demand exists (i.e. the demand is taken for granted) and with dynamic traffic management the traffic on the road can be influenced by dynamic measures. Examples of dynamic traffic management measures are ramp metering installations, peak hour lanes, dynamic route information panels, variable message signs, etc. By implementing dynamic traffic management, and therefore making more efficient use of the existing infrastructure, the need for building new roads is reduced. These measures are inexpensive compared to the construction of new roads. Research of Middelham (2006) showed that dynamic traffic management is a solution direction that effectively reduces congestion.

Individual dynamic traffic management measures can solve the local problem, but might cause at the same time congestion at another location in the network. For example a dynamic route information panel that manoeuvres traffic away from a congested freeway corridor, towards another corridor: the congestion might be replaced towards the other corridor.

To counteract this type of problems, research to coordination of individual measures has recently been increased. This coordination of measures is called integrated network management. The coordination (or combination) of the measures can increase the effectiveness of the measures, because: (i) the counteracting of measures against each other can be reduced and (ii) the strengths of the individual measures can be combined. Examples of integrated network management are the coordination of signal control with ramp metering installations, or the coordination of different ramp metering installations.

To show the benefits of integrated network management in a real world situation, a well performed field operation test is needed. In the Netherlands this was a reason to launch the Field Operational Test Integrated Network Management Amsterdam, in Dutch the *Praktijkproef Amsterdam*, in short PPA (Hoogendoorn et al., 2013; Mak, 2013). Ex-ante studies of Rijkswaterstaat (2009) showed positive expected effects of the test. The *Praktijkproef Amsterdam* is a cooperation between the municipality of Amsterdam, Delft University of Technology and different market parties, and Vialis was one of them. The *Praktijkproef Amsterdam* started in 2009 with a Proof of Concept and is at the moment of writing still going on.

The *Praktijkproef Amsterdam* focuses on the road network of Amsterdam, which consists of a freeway ring road and urban arterials. The control approach is implemented in different phases. The first phase focuses on one part of the freeway and one urban arterial. The ramps of the freeway are equipped with ramp metering installations, the intersections of the urban arterial are controlled by traffic lights. Subsequent phases focus on larger parts of the network. In the second phase all urban arterials are considered, in the third phase the entire ring road network is considered. In the last two phases the roadside measures will be combined with in-car measures.

1.2 Problem analysis

Part of the first phase of the *Praktijkproef Amsterdam* was the development of a controller that can control bottleneck situations which occur in the neighbourhood of a junction of a freeway and an urban arterial. The bottleneck situations that can occur are: (i) spillback on the urban arterial causing blocking back on the urban arterial, (ii) spillback from the off-ramp towards the freeway causing congestion on the freeway, (iii) spillback from the on-ramp towards the urban arterial causing blocking back on the urban arterial. The controller should buffer traffic in order to prevent, or remove, the spillback that arises in the bottleneck situations. To be able to buffer traffic, the controller to develop will control traffic lights at the urban arterial. The traffic lights are the actuators of the controller to develop.

In the *Praktijkproef Amsterdam* a certain controller was developed, as described by Taale (2014). However, it was only capable of controlling the third bottleneck situation. A control algorithm for the other situations was not designed, developed and simulated.

Therefore, in this research a controller is developed that is able to control all three bottleneck situations. To the author's best knowledge, such a controller does not exist yet.

1.3 Research scope

The scope of this research is a controller which can deal with three different bottleneck situations that can occur around a junction between a freeway and an urban arterial. The on-ramp is equipped with a ramp metering installation, the urban arterial is equipped with traffic lights. The controller can use traffic lights as actuators. Note these actuators are at the urban arterial: using traffic management measures at the freeway is out of the scope of this research.

The bottleneck situations are shown in Figure 1.1. In the first situation a bottleneck occurs on the urban arterial. A bottleneck in this situation is defined as a situation in which traffic is unnecessarily hindered at the urban arterial, e.g. traffic turning right has to wait for a queue of ongoing traffic. In this situation ramp metering is not active.

The second situation deals with a bottleneck that occurs at the off-ramp of the freeway. A bottleneck situation occurs if the queue at the off-ramp spills back towards the freeway, resulting in congestion on the freeway. In this second situation the ramp metering installation is switched off.

In the third situation congestion occurs at the freeway, this congestion is counteracted by the use of a ramp metering installation. Due to the use of the ramp metering installation a queue arises at the on-ramp which spills back to the urban arterial, resulting in the third type of bottleneck situation.

In the first situation the bottleneck situation needs to be detected and controlled. In the second and third situation the queue at the ramp needs to be managed. Note that it is not necessary to detect the congestion at the freeway, i.e. this is out of the research scope.

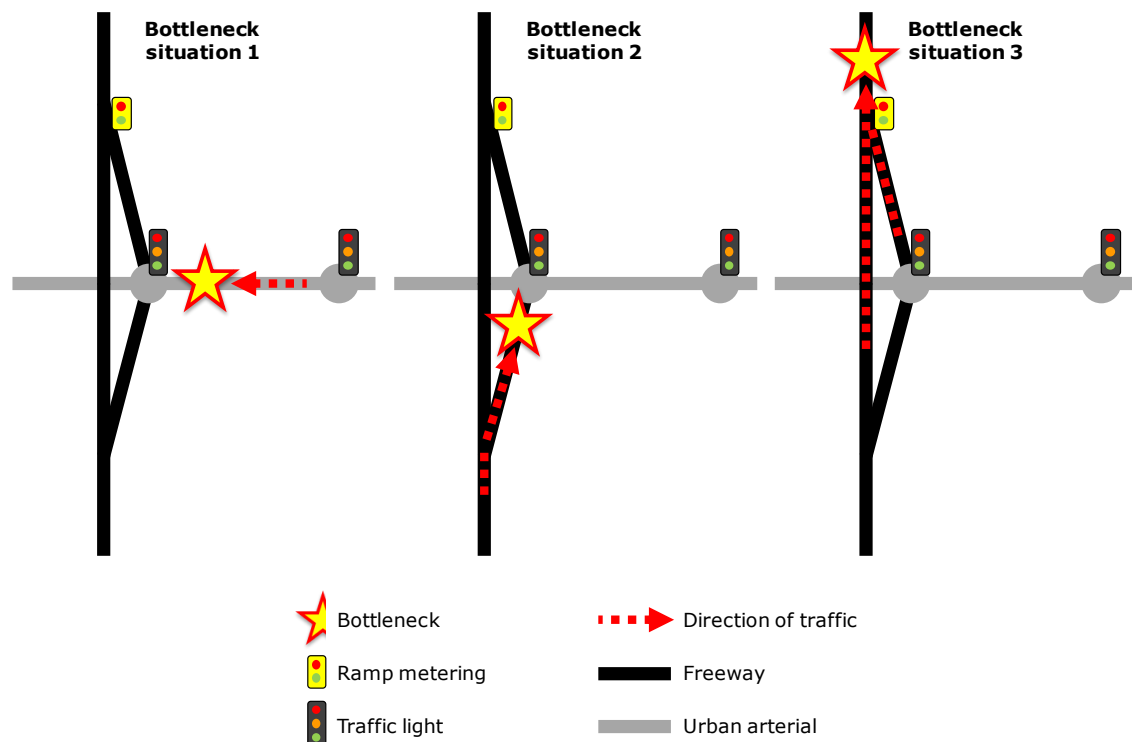


Figure 1.1 Schematic representation of three bottleneck situations with which the controller should deal.

These three situations capture all possible bottleneck situations that can occur in this type of network. This type of network (i.e. junction of a freeway and an urban arterial) is similar to the network used in the first phase of the Praktijkproef Amsterdam.

Within the Praktijkproef Amsterdam a controller was developed that can deal with the third situation, as described by Taale (2014). This controller is called the Supervisor Trajectory 1 Light, in short ST1Light.

1.4 Research objective and research questions

The objective of this research is a controller that deals with bottleneck situations occurring in the neighbourhood of a junction of a freeway and an urban arterial. In order to reach its goals, the controller should distribute traffic over the available buffer space in the network, by using traffic lights at controlled intersections.

To be able to reach the objective, research questions are established. The main question deals with the central part of the research: the functionality of the controller. The functionality of the controller are the actions the controller should take to distribute the traffic (e.g. the use of algorithms). Below, the main question is stated.

- How should a controller function that distributes road traffic over buffer space in a network (with a junction of a freeway and an urban arterial) by using the controlled intersections, and how does this controller perform?

Sub-questions deal with the core concepts of the main question. In order to answer the main question, the sub-questions will be answered first. Below, the sub-questions are shown. By answering these questions the research objective can be reached.

- I. How can the controller detect a bottleneck situation on the urban arterial?
- II. How can the controller deal with a bottleneck situation on the urban arterial?
- III. How can the controller deal with a bottleneck situation on the freeway?
- IV. How does the controller need to distribute the traffic among the available buffers to deal with a certain bottleneck situation?
- V. What is the effectiveness of the controller in relation to the goals of the controller?

The first sub-question deals with the detection of the bottleneck situation. The strategy how to deal with the consequences of this bottleneck is captured by the second sub-question. The strategy how to deal with the consequences of a bottleneck on the freeway is the subject of the third sub-question. Note that the bottleneck situation at the freeway does not have to be detected: a bottleneck exists and the controller should deal with it. The fourth sub-question discusses the algorithm of the designed strategies. The last sub-question deals with the impact assessment of the developed controller.

1.5 Research approach

The approach used in this research consists of three phases: (i) a literature study, (ii) the controller development, and (iii) the simulation of the controller.

In the first phase literature about the research subject is studied. The aim of this study is to create a clear theoretical research framework. Such a framework is created by getting to know

what is already available in the field, to notice gaps of knowledge, to see scientific and practical relevance, and to get to grips with regularly used definitions and terms. With this framework it is clear what should be studied and why this should be studied.

The second phase deals with the development of the controller. In this phase different control algorithms are developed. These different algorithms lead to several variants to control the bottleneck situations, described in the research scope.

In the third phase the controllers, i.e. the control algorithms, are tested in scenarios by using simulation software. The results of the simulations are used for the conclusions of the research. The conclusions are based on performance indicators which are defined before the start of the simulations.

1.6 Scientific and practical relevance

Integrated network management is a promising state-of-the-art solution to reduce congestion. However, there is a lack of practical experience. The Praktijkproef Amsterdam aims at gaining this experience. Part of the Praktijkproef Amsterdam is the controller that deals with consequences of bottlenecks arising in the neighbourhood of a junction of a freeway and an urban arterial. Within the Praktijkproef Amsterdam a controller is developed that can control one out of three possible bottleneck situations. This research aims at designing a controller that can control all three situations.

By performing research on the controller and by designing and testing the controller, this research can contribute to the scientific and practical research around the Praktijkproef Amsterdam. Furthermore conclusions can be used for other integrated network management studies. Practical relevance lies in the reduction of congestion and blockages, due to the prevention of spillback, which can be achieved. This can lead to reduction in environmental, societal, economic and safety related problems. If the controller reaches its goals, Vialis can benefit by using the research recommendations and the controller for other projects.

1.7 Report outline

In this first chapter the introduction of the research is presented. The problem is stated, the research objective and questions are defined and the approach to reach the objective is discussed. Chapter 2 discusses the literature related to the different parts of the research, i.e. literature regarding intersection control, freeway control and integrated network management. The chapter shows the state-of-the-art and discusses this in relation to the research. Chapter 3 explains the development and specifications of the algorithms of the controller. Different types of controllers are developed, these are called the controller variants. The chapter gives an overview of the controller variants and presents the functional specification of the algorithms. In the next chapter, chapter 4, the design of the simulation environment is discussed. This chapter shows the different software programs used, and the relation between them. Furthermore this chapter shows the scenarios in which the controller is simulated, and the software settings used to get a representative situation. Chapter 5 presents the simulation results and discusses these results, based on performance indicators. In the last chapter, chapter 6, conclusions are drawn based on the results. Furthermore recommendations for practical implementation and for future research topics are presented in this last chapter.

1.8 Summary

This first chapter showed an introduction to the problem that is dealt with during this research. Based on this problem statement the research objective was stated: a controller that deals with bottleneck situations occurring in the neighbourhood of a junction of a freeway and an

urban arterial; in order to reach its goals, the controller should distribute traffic over the available buffer space in the network, by using traffic lights at controlled intersections.

Three bottleneck situations were defined: (i) spillback on the urban arterial causing blocking back on the urban arterial, (ii) spillback from the off-ramp towards the freeway causing congestion on the freeway, (iii) spillback from the on-ramp towards the urban arterial causing blocking back on the urban arterial. In the third situation there is an active ramp metering installation installed at the on-ramp. These three situations capture all possible bottleneck situations that can occur in this type of network.

Several controller variants will be developed to control the three bottleneck situations, these controller variants are tested by using simulation software. These tests result in an impact assessment of the controllers on the bottleneck situations. The next chapter presents the literature survey regarding the controllers.

Chapter 2. Literature survey

In order to get a clear view on what the controller should be able to do, a literature survey is performed. The controller uses intersection control combined with freeway control, i.e. integrated network management, to control bottleneck situations using buffering. These three types of control (i.e. intersection control, freeway control, integrated network management) are the core aspects of the controller. In this chapter literature about those types of control is presented.

First traffic theory phenomena related to the research are described in section 2.1, these give an understanding of the phenomena that should be dealt with by the controllers. Section 2.2 presents literature about intersection control at urban arterials. It describes the history regarding intersection control and the current state-of-the-art. Section 2.3 discusses research regarding intersection control combined with bottleneck detection, this combination is needed for the first bottleneck situation. This is followed by studies regarding freeway control in section 2.4. The section focuses on freeway control that has direct effect on the urban arterial, since other types of freeway control are out of the research scope. In section 2.5 literature about integrated network management is discussed. Section 2.6 discusses the literature findings. The chapter concludes with a summary of the survey and an overview of relevant literature for each bottleneck situation.

2.1 Traffic theory phenomena

This section presents important traffic theory phenomena for this research. First the capacity drop at freeways is discussed, followed by spillback and gridlock effects. The rationale of these phenomena and the possible negative effects of them on traffic performance are presented.

2.1.1 Capacity drop

A macroscopic relation exists between the flow q (unit: vehicles per hour, veh/h), speed u (unit: kilometre per hour, km/h) and density k (unit: vehicles per kilometre, veh/km) on a freeway. The most simple version of this relation says the flow equals the product of the density and the speed ($q = k \cdot u$).

The versions of this equation vary for example in the way the functions are derived and in their mathematical properties. An important difference is the occurrence of the capacity drop in these equations. The capacity drop shows the fact that capacity in free flow conditions is larger than capacity in congested conditions. Capacity in free flow is called free flow capacity, capacity in congested conditions is called queue discharge capacity. The free flow capacity is approximately 10-15% higher compared to the queue discharge capacity, according to Hall &

Agyemang-Duah (1991). Recent studies of Yuan et al. (2014) show the capacity drop ranges between 3-18%.

The capacity drop reduces throughput at the freeway, hence resulting in a decrease of network performance. By postponing or preventing the capacity drop, the throughput at the freeway can be maintained at a high level for a longer time. Therefore, in order to improve the network performance, it is important to prevent or postpone the capacity drop via traffic management measures.

Several theories exist that explain the reason for the capacity drop (Van Lint et al., 2012). One theory relates the capacity drop to driver behaviour before and after congestion: a driver would drive slower after congestion than before and keeps larger following distance. Another theory relates it to differences in vehicle heterogeneity, for example differences in acceleration between cars and trucks. A third theory relates it to lane changing behaviour.

Figure 2.1 schematically shows the fundamental relation of Wu (2002) in the flow-density plane, this figure clearly indicates the capacity drop. In the figure q_{c1} is the free flow capacity, q_{c2} is the queue discharge capacity, k_c is the critical density and k_j is the jam density. Critical density is the point at which the capacity drop can occur. Jam density is the density when all vehicles are standing still.

The curve on the left of k_c denotes the free flow state, this part of the diagram is called the free flow branch. The line on the right of k_c denotes the congested state, this part is called the congested branch. The figure shows that the flow increases until congestion is reached. In free flow the speed decreases with increasing density, due to overtaking opportunities, resulting in a curved line. In congestion it is assumed every vehicle has a constant time headway, resulting in a straight line. Exact values of the parameters differ per road and per road type.

In Wu's original fundamental diagram, the densities corresponding with q_{c1} and q_{c2} are not the same. In that case there is not 'one' critical density: there is a critical region in which it is possible that traffic is in the free flow or in the congested state. Since the main point is to show the existence of the capacity drop, this overlapping area is not shown in here, for simplification reasons.

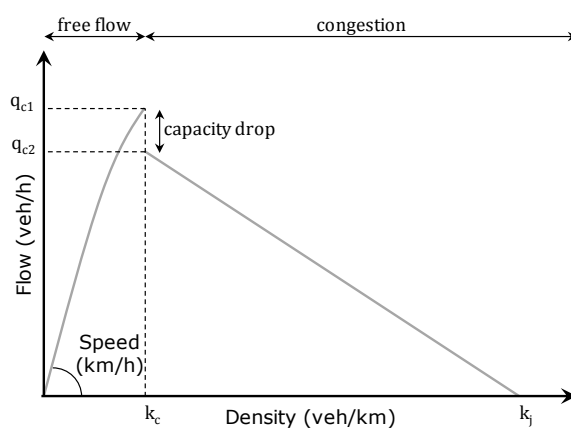


Figure 2.1 Schematic fundamental diagram showing the relation between flow q , density k and speed u . The curve on the left of k_c denotes the free flow state, the line on the right of k_c denotes the congested state.

Detailed information about the derivation of the equations of Wu are out of the scope of this research. Main point is the existence of the capacity drop in the fundamental diagram and the need to postpone or even prevent it: by postponing it, a higher throughput can be achieved for a longer time.

2.1.2 Spillback

Spillback occurs if a queue takes up such an amount of space that it hinders traffic flows that do not have to pass the bottleneck. This results in congestion on other roads. Eventually this can lead to severe congestion in a large part of the network, called the gridlock process (Daganzo, 2007). Spillback can occur at several levels and places. For example at a freeway network and at an urban network. But also from a freeway towards an urban arterial, or vice versa.

Due to spillback (or even worse: gridlock), traffic that should not be hindered by a bottleneck also gets delayed. Therefore the bottleneck does not only affect the traffic that has to pass the bottleneck, but also the traffic in a larger part of the network. This results in negative effects on the network performance. By preventing spillback delays are restricted to the bottleneck only, therefore extra delays can be prevented and the network performance can be increased.

2.2 Intersection control

Traffic lights are used at intersections to improve safety and to reduce delays (Akçelik, 1998; Muller et al., 2011). A branch of an intersection can consist of multiple traffic streams. Conflicting streams are streams that use a common part of the intersection, called the conflict area. During a cycle all conflicting streams should get a green period (i.e. a green phase), this way all streams get permission to use the conflict area and a safe crossing is provided. Non-conflicting streams can get green periods in the same phase. The realization order of green phases is called the phase structure.

Different strategies to control intersections exist. With an optimal control strategy the total time spent in a network can be minimized and safe crossings can be provided. This section provides an overview of currently used systems. Basis of this overview is research by Taale (1999), Papageorgiou et al. (2003), Van Katwijk (2008) and Van Eijk (2014).

In the first place intersection control can be divided into local control and coordinated control. Local control is control for one intersection. Coordinated control controls a larger part of the network, i.e. multiple intersections. Secondly controllers can be classified according to the way they handle traffic. The main difference is between fixed time control and traffic responsive control. With fixed time control the signal settings are fixed for a certain time of the day. Traffic responsive control responds to the real-time traffic situation.

In the following paragraphs, currently used systems are classified into four sections: local fixed time, local traffic responsive, coordinated fixed time and coordinated traffic responsive. Thereafter research to future control approaches is discussed: those approaches are tested via simulation, but are not (yet) deployed in reality. This gives an overview of developments over the years regarding intersection control.

2.2.1 Local fixed time control

Local fixed time controllers control one intersection and have prespecified signal times, these are the least complex controllers. The signal times can be prespecified for different time periods, e.g. the morning and evening peak. The different control systems vary in the method of calculating the signal times.

Webster

One of the first people that dealt with the design of traffic controllers was Webster (Webster, 1958; Webster & Cobbe, 1966). He used computer simulation to derive a formula to estimate delays at an intersection. Based on this delay an optimum cycle time and optimal green times could be calculated for one intersection. The research of Webster is still in use for the design of fixed time controllers.

SIGSET

SIGSET (Allsop, 1971) is a system that calculates the green times and cycle time, based on a prespecified number of phases. Webster's delay-formula is used as an optimization objective. With this formula SIGSET minimizes the total delay at an intersection, given the demands at a traffic stream.

2.2.2 Local traffic responsive control

Fixed time controllers do not incorporate the fluctuations in traffic demand at an intersection, since they are programmed based on average flows. This leads to signal settings which are not modified for all moments of the day, resulting in unnecessary delays etc. To overcome these problems, signal times of traffic responsive controllers are based on the actual traffic situation. Local traffic responsive control deals with one intersection. The controllers differ in the way they handle, i.e. respond to, the traffic situation.

Vehicle-Actuated control

Vehicle-Actuated control (Wilson & De Groot, 2006) uses a fixed phase structure, but the duration of green times depends on the presence of traffic and therefore the traffic demand. Presence is measured via loop detectors, cameras and pushbuttons. If there is no traffic at a stream, this stream can be skipped in the cycle, resulting in more green time for other streams. If a queue is not dissolved, it is possible to extend the green time of that stream.

MOVA

MOVA (Microprocessor Optimized Vehicle Actuation) (Vincent & Young, 1986) is developed to overcome problems regarding aging vehicle-actuated control. MOVA is a controller that can work in two modes: uncongested and congested mode. In the uncongested mode MOVA checks whether there is a benefit from extending the green time for a certain phase. If there is no benefit the green time stays the same, else it is extended until the next time step and the check is repeated. In congested mode the controller determines the ideal signal times to maximize the intersection throughput.

CRONOS

CRONOS (ContROI of Networks by Optimization of Switchovers) (Boillot et al., 1992) uses an approach in which a phase is the smallest possible entry. With a traffic prediction model departures are modelled. Furthermore a rolling time horizon is used. CRONOS optimizes the signal settings until the highest performance is reached. Cycle time and phase structure are not prespecified. This results in a more flexible approach compared to fixed-structures. However, complexity also increases.

SPPORT

SPPORT (Signal Priority Procedure for Optimization in Real Time) (Dion & Hellinga, 2002) makes use of an heuristic rule-based optimization procedure. This procedure is developed as a response to optimization procedures which take much computation effort for networks with high variations in demand. Signals are switched based on rules. The rules are derived from the observation that signals often switch after certain discrete traffic events.

2.2.3 Coordinated fixed time control

A widely used approach in the field to coordinate traffic signals at successive intersections is the creation of a green wave. In a green wave vehicles do not have to stop at any successive signal, within a given speed limit. This can result in smaller delays. To be able to realize a green wave multiple intersections should be handled at once. Coordinated fixed time control handles multiple intersections at once. Signal times are predefined and are therefore not varied based on the traffic situation. The controllers vary in their objective.

MAXBAND

MAXBAND (Little, 1966) specifies the offsets (phase differences between cycles for successive intersections) for succeeding intersections in order to create a green wave. The signal times are fixed. MAXBAND places the red phases in order to maximize the bandwidths of the green wave (i.e. the length of the green wave).

PASSER

PASSER (Progression Analysis and Signal System Evaluation Routine) (Venglar et al., 2000) also tries to maximize the bandwidths of the green wave. The PASSER algorithm optimizes the bandwidths of the green wave over the set of possible phase sequences.

TRANSYT

TRANSYT (TRAffic Network StudY Tool) (Hale, 2006) is a model that optimizes its objective function, by making small changes to decision variables. The objective function can consist of e.g. a weighted sum of the number of stops and amount of delay. The decision variables are e.g. the cycle time, offset and green time. All considered intersections in the network have the same cycle or half-cycle time. TRANSYT is very well known in the field and frequently used.

2.2.4 Coordinated traffic responsive control

Controllers mentioned in the previous section can realize a green wave, with related positive effects, but do not vary signal times based on the traffic situation. Section 2.2.2 explained benefits of traffic responsive control. Coordinated traffic responsive control can realize a green wave and can react on the real-time traffic situation. These controllers are potentially more efficient than the previous ones, but are also more complex (and therefore costly).

TOPTRAC

TOPTRAC (Trend OPTimizing TRAffic Control) (TPA, 2002) is developed by TPA, currently it is deployed and further developed by Vialis. TOPTRAC combines real-time data with a traffic model to come up with control actions. The data that is used consist of the number of vehicles for all traffic directions in the last two cycle periods. The model is a real-time version of TRANSYT. To be able to define a set of control actions (e.g. new green times, new cycle times) for multiple intersections, a prespecified optimization objective (e.g. total delay or total number of stops) is minimized. TOPTRAC is used in multiple cities in the Netherlands.

SCATS

SCATS (Sydney Coordinated Adaptive Traffic System) (Lowrie, 1982) is a controller which uses a hierarchical control structure. Three levels are used: a central computer, regional computers and local controllers. The central computer monitors the system performance. The regional computer executes traffic responsive control with maximum freedom, as long as it is consistent with the coordination of successive intersections. SCATS can be rather easily expanded due to this structure. SCATS can optimize to strategic desires, minimum stops, minimum delay or maximum throughput. SCATS is implemented in multiple cities around the world, for example in Australia.

SCOOT

SCOOT (Split, Cycle, and Offset Optimization Technique) (Hunt et al., 1982) is considered to be the traffic responsive version of TRANSYT, and is also widely used. SCOOT uses detectors upstream of the stop line to measure vehicles and predict arrival patterns. With this arrival pattern and prespecified departure profiles calculations are made in order to get the number of delayed vehicles and the length of the queues. In a centralized structure, a model is used to process the measured and calculated values and to optimize the objective function by making small changes in cycle time, offset and green times. If changes are beneficial, they are communicated to the local controllers. Furthermore SCOOT uses a gating mechanism. With gating queues are relocated, from sensitive areas in the network to less sensitive and more

acceptable areas (Wood, 1993; SCOOT-UTC, 2013). SCOOT was tested in the nineties in Nijmegen, but thereafter not used anymore in the Netherlands. SCOOT is used in several cities around the world, for example in Great Britain.

UTOPIA

UTOPIA (Urban Traffic OPTimization by Integrated Automation) (Mauro & Taranto, 1989) is developed to give priority to public transport, and as well to optimize signal settings for other traffic. The system uses two levels: the intersection level and the network level. At the network level, data is gathered and boundary conditions are established to optimize the objective function. These boundaries are communicated to the intersection level. At this level the intersection is optimized, also by looking to neighbouring intersections. UTOPIA is used in Italy. UTOPIA was tested in the nineties in Eindhoven, but thereafter not used anymore in the Netherlands.

TUC

TUC (Traffic-responsive Urban Control) (Dinopoulou et al., 2006) is developed in order to be used for large scale networks. TUC uses a store-and-forward based approach to model traffic flows. TUC can be used for large networks due to a model simplification: the model assumes an average flow at a traffic stream during a cycle time, instead of using the saturation flow during green time and using a flow of zero during red time. This opens the way to the application of a number of highly efficient optimization and control methods (Van Katwijk, 2008). The objective of the used model is to minimize the risk of spillback and oversaturation at intersections. This objective is reached by adapting green times. TUC is implemented in Greece.

Other systems

Several other coordinated traffic responsive control systems exist, such as MOTION (Bielefeldt & Busch, 1994), OPAC (Gartner, 1983), PROLYN (Henry & Farges, 1989) and RHODES (Mirchandani & Head, 2001). It is out of the scope of this research to discuss all these systems in detail. Therefore the best known systems (in the world and in the Netherlands) are chosen, and presented in the previous sections.

2.2.5 Current research to future control approaches

Previous sections described control approaches that are used in the field (note there are large differences in the number of deployments per control approach). Although differences in efficiency exist, previous mentioned control approaches show positive results in under saturated conditions. Approaches that take into account the actual traffic situation show best results. However, all approaches show deterioration in saturated conditions, therefore it is still a largely studied area. This section describes some of the approaches that are part of current research to future control approaches. These approaches are tested via simulation, but are (to the author's best knowledge) not used in the field.

Model predictive control

Model predictive control, as proposed by Van den Berg et al. (2007), takes into account the current and future traffic situation in order to come up with ideal signal times. The future situation is predicted with a traffic simulation model. In this model the effects of a proposed control action on the objective can be checked. The objective can be specified via the model. Model predictive control shows better results in saturated conditions than e.g. SCOOT and SCATS. However, a lot of computational effort is required to achieve these results. This especially is a problem if large real-time networks are used.

Agent-based control

With agent-based control methods, as proposed by Wang (2005) and Van Katwijk (2008), agents (e.g. controlled intersections) try to optimize their own part of a larger network.

Multiple agents can be combined to be able to reach a network optimum. These agents are used instead of control algorithms. Agent-based control should result in easy (and therefore cheap) implementation. The objective of the agents can be specified in the method.

Back-pressure control

Back-pressure control, as proposed by Varaiya (2013), is based on the queue lengths at controlled intersections. Back-pressure aims at activating the signal phase with the highest weight, this weight is the product of: (i) the saturation flow at the stream and (ii) the difference in queue length between the up- and downstream streams (Van Kampen, 2015). Several variants exist on this basic idea. Back-pressure control should improve network stability and the control should have low complexity. The objective of back-pressure control can be for example the maximization of network throughput, but other objectives are also possible.

2.3 Intersection control with bottleneck detection

Previous control approaches deal with intersection control on urban arterials. However, those approaches are not created for: (i) detecting bottleneck situations and (ii) reacting on these detected situations. This intersection control with bottleneck detection is needed in this research, however, it is an area with no studies available. Studies regarding the detection of bottlenecks situations (without a combination with control) are available, although it is still an area with little research. The latter is presented in this section.

Long et al. (2008) use one crisp value to detect bottleneck situations on arterials. Long et al. (2008) use average journey time of a vehicle as a critical value. When the average journey time exceeds a certain value, it is defined as a bottleneck situation.

Other research focuses on freeway bottleneck situation detection. Chen et al. (2004) and Bai et al. (2011) use approaches that can be used on urban arterials. Chen et al. (2004) check the differences in speed between the current and previous time step, to define a bottleneck situation. If this difference exceeds a certain value, it is defined as a bottleneck situation. Bai et al. (2011) use a similar approach, but they use occupancies instead of speed. Both approaches show positive results.

2.4 Freeway control

Numerous methods exist to control freeways. For example variable message signs, dynamic route information panels, ramp metering, automatic incident detection, peak lanes, plus lanes, pre and on trip travel advice, etc. The measures themselves and the effects of the measures are a widely studied area. In this literature survey, only freeway control measures that have a direct relation with intersection control are discussed. The other measures are irrelevant, since those are out of the scope of this research (recall section 1.3). Therefore, the measures that are presented are off-ramp and on-ramp control.

2.4.1 Off-ramp control

The off-ramp is the road via which the freeway can be exited and the urban arterial can be entered. For the freeway side of the off-ramp no control measures exist. At the side of the urban arterial a controlled intersection can be realized to control the flow from the off-ramp towards the arterial. The control of off-ramps is an area with almost no studies available.

Newel (1999) recognizes the problem of a queue spilling back from the ramp towards the freeway, but only describes the traffic flow at the freeway and does not come up with a solution.

Tian et al. (2002) develop a strategy to integrate intersection control and on-ramp control. If there is an incident at the freeway and the traffic demand towards the off-ramp increases, the model gets a message and increases green times for the off-ramp. The on-ramp is controlled by using different metering rates for the ramp metering installation. This results in different outflows at the on-ramp which should prevent spillback from the on-ramp towards the arterial. Lim et al. (2011) performed a study into off-ramp control to prevent spillback from the ramp towards the freeway. Via a model (binary mixed integer linear programming), ideal signal timings were calculated. The green times at the off-ramp were changed based on the saturation of the off-ramp. This resulted in a prevention of the capacity drop at the freeway and a minimization of the average delay time.

2.4.2 On-ramp control

The on-ramp is the road via which the freeway can be entered. Controlling this ramp can be realized via the inflow side and the outflow side. Control of the outflow of an on-ramp happens via ramp metering installations, these are traffic lights at the on-ramp which regulate the inflow towards the freeway. For example by letting one vehicle pass every five seconds. This is a widely studied area. The control of the inflow towards an on-ramp is an area less studied. In the ensuing literature regarding these two types of control is presented.

Ramp metering has proven to be an effective solution in increasing capacity on the freeway and in reducing delays (Middelham & Taale, 2006; Papageorgiou & Papamichail, 2007). The metering strategy determines when the metering should start, and when it is started what the metering rate should be. Several algorithms exist that determine the strategy. Two well known algorithms are the demand-capacity algorithm (Masher et al., 1975) and the ALINEA algorithm (Papageorgiou et al., 1991). The demand-capacity algorithm is a feed forward system (open loop) and determines the metering rate based on the capacity of the freeway and the flow at the ramp. ALINEA is a feedback system (closed loop), it determines the metering rate based on occupancies. The demand-capacity algorithm proves to be rather stochastic in congested conditions since it does not have a feedback loop, ALINEA shows better results.

Problems with ramp metering occur if the storage space at the ramp becomes filled. To prevent spillback the ramp meter can be switched off, resulting in the flushing of traffic towards the freeway and consequently in congestion on the freeway. To increase the effectiveness of ramp meters the queue at the ramp should be controlled.

As was shown in previous section, Tian et al. (2002) control the queue at the on-ramp by using different metering rates for the ramp metering installation.

Most studies focus on the coordination of multiple ramp metering installations to increase total storage space (Yuan et al., 2009). The coordination of ramp metering installations is also a part of the *Praktijkproef Amsterdam* (Hoogendoorn et al., 2013).

Another solution is to use the urban arterial as storage space for the on-ramp. In the *FileProof A10* project (Rijkswaterstaat, 2010) the use of upstream intersections as storage space is mentioned, however, it is not further elaborated. Other research regarding this solution was not available.

2.5 Integrated network management

Previous sections showed individual traffic management measures. In the past years it became clear that coordination of the individual traffic management measures was a promising new solution to further reduce congestion. Coordination of different measures leads to integrated network management. With this integrated network management the effectiveness of individual measures can be further improved. The coordination (or combination) of the measures can increase the effectiveness of the measures, because: (i) the counteracting of measures against each other can be reduced and (ii) the strengths of the individual measures can be combined. Several studies opt for this integrated or coordinated kind of traffic management and control (Papageorgiou, 1995; Tian et al., 2002; Papageorgiou et al., 2007;

Hoogendoorn & Bertini, 2012; TrafficQuest, 2012; Van Katwijk & Taale, 2012; Hoogendoorn, 2013).

Various simulation studies show integrated network management is a promising solution. For example an older study of Diakaki et al. (1997), which studies the effects of integrated network management on a freeway corridor in Glasgow. And a more recent one by Van den Berg et al. (2007), in which model predictive control is used. There is however a lack of practical experience via field operational tests. In the nineties there were some tests with integrating freeway control with urban arterial control. Two of those tests were in the United States of America. One test in California (MacCarley et al., 2000) was never fully completed due to several management issues. Another test in Minneapolis (Booz-Allen & Hamilton Associates, 2000) was completed, but, before and after studies were of low quality due to changing traffic patterns over time. To show the benefits of integrated network management in a real world situation, a well performed field operation test is needed.

As mentioned in section 1.1, this was a reason to launch the Field Operational Test Integrated Network Management Amsterdam, the *Praktijkproef Amsterdam*, in short PPA (Hoogendoorn et al., 2013; Mak, 2013). Ex-ante studies of Rijkswaterstaat (2009) show positive expected effects of the test.

The control approach of the *Praktijkproef Amsterdam* is based on solution directions of integrated network management as described by Landman et al. (2010). These solution directions are translated into the following four principles, as described by Hoogendoorn et al. (2013): (i) use spare capacity in the network optimally, given the prevailing traffic conditions; (ii) prevent the capacity drop from occurring as long as possible; (iii) traffic flows in the network should not be unnecessarily hindered; (iv) a bottleneck needs to be resolved at the level at which it manifests itself.

Integrated network management is a promising solution to improve traffic conditions by combining existing traffic management measures.

2.6 Literature discussion

The controller that is developed in this research, needs to be able to control the three bottleneck situations that can occur in the neighbourhood of a junction of a freeway and an urban arterial (recall the description of the situations in section 1.3). The controller should: (i) detect and control spillback on the urban arterial, (ii) prevent spillback from the off-ramp towards the freeway, and (iii) prevent spillback from the on-ramp towards the urban arterial. If these situations are controlled, spillback at the urban arterial and ramps is prevented. The latter should result in postponing or preventing the capacity drop at the freeway. In order to reach these goals, intersection control can be used.

In section 2.2 it became clear several control approaches exist for intersection control. However, a controller that takes action when a bottleneck occurs does not exist yet, as was shown in section 2.3. Section 2.4 showed the control of queues at off-ramps as well as on-ramps is an area in which little research is available. Instead, most studies focus on ramp metering installations and the control of those installations. All three sections showed that the controller that should be developed, does not exist at this moment. Section 2.5 presented integrated network management as a promising solution to tackle traffic problems.

Coordination of intersection control and freeway control is one type of this solution. This coordination basically deals with preventing spillback due to the buffering of traffic. Buffering means traffic with destination A is temporarily stored at location not-A in a network. By temporarily storing traffic, spillback (and therefore the three bottleneck situations) can be dealt with. Queues that are too long can be prevented by reducing inflow into the queued region, or by increasing outflow from the queued region. Inflow can be reduced by temporarily storing traffic that wants to use a queued road. This way the inflow towards the queued road is limited. Outflow can be improved by giving priority to traffic leaving the queued road. Giving

priority can result in buffering traffic on other traffic streams. As a result of both methods the queue on the road stays equal or reduces, thereby preventing spillback towards other roads.

2.7 Summary

This chapter presented a literature survey about the research. Literature was studied regarding intersection control, freeway control and integrated network management. The scope of this research is to develop a controller that can handle three bottleneck situations occurring in the neighbourhood of a junction between a freeway and an urban arterial. The three situations basically deal with preventing spillback. The controller should use controlled intersections as actuators. The survey showed that controllers that are capable of controlling the three bottleneck situations do not exist at the moment. Table 2.1 shows all the relevant findings in literature, ordered per bottleneck situation.

Table 2.1 Overview of relevant findings in literature, ordered per bottleneck situation.

Bottleneck situation	Relevant findings
Situation 1 (spillback at urban arterial)	<ul style="list-style-type: none"> • Real time traffic situations should be taken into account to deal with fluctuations in traffic demand • Most controllers do not perform well in saturated conditions • Small changes in cycle time, offset and green times result in more smooth control • Coordinated traffic responsive control shows best results but asks much computational effort • Model predictive control deals best with saturated conditions but is complex and takes much computational effort • Control tailored for bottleneck situations is not found in literature • Bottleneck detection based on a crisp value shows positive results • Bottleneck detection on freeways for a difference between time steps shows positive results
Situation 2 (spillback from off-ramp towards freeway)	<ul style="list-style-type: none"> • Increasing green times at the intersection decreases the queue at the ramp and can prevent spillback • Off-ramp control is an area with little studies available
Situation 3 (spillback from on-ramp towards urban arterial)	<ul style="list-style-type: none"> • Ramp metering is an effective solution to prevent the capacity drop at the freeway • Adapting the metering rate is an often used approach to control the queue at the ramp • Coordination of multiple ramp meters is a solution which increases total storage space • Controlling the inflow towards the on-ramp is an area with little studies available

This overview shows most studies do not focus on the controller to develop within this research. Studies focus for example on controlling intersections with optimization of total delays, instead of controlling spillback in a bottleneck situation. Studies for on-ramps concentrate on for example controlling the outflow at the on-ramp, instead of dealing with the inflow towards the on-ramp. Furthermore the survey showed the coordination of different traffic management measures, i.e. integrated network management, is a promising solution to increase the effectiveness of individual traffic management measures. However, a low amount of experience exists in this field of study. It can be concluded that this research deals with a rather unexplored field of study. These findings will be used in the next chapters.

Chapter 3. Controller development

Previous chapters showed the motivation for this research and the related state-of-the-art. In this third chapter the development of the controller is presented: the rationale and the functional specifications of the controller variants are presented. The chapter starts with section 3.1 in which the design process is described. It discusses the different steps that are taken during the process and gives insight in the design choices. Section 3.2 shows the overall design of the controller: it shows the place of the different variants in relation to the overall controller. The next three sections present the controller variants per bottleneck situation (recall the description of the situations in section 1.3). Section 3.3 shows the first situation, section 3.4 the second, and the third situation is shown in section 3.5. The chapter ends with a summary of the control approaches of the presented variants.

A list of all symbols which are used in this chapter, is included at the start of this report (see page xix).

3.1 Design process and scope

For all three bottleneck situations a controller will be designed. The literature survey showed increasing complexity in controllers is accompanied by increasing computational efforts. Therefore, to come up with the best controller, different variants will be designed which increase in complexity. The functional specifications of the variants are presented in the upcoming sections. In the sections the unique parts of each variant are described. Parts of the variants that are similar to each other, are only presented once.

In order to create a working controller within a limited amount of time, the design process is restricted by some boundaries. These boundaries are design choices and are explained in the ensuing.

First of all designing a controller based on a traffic model is outside the boundaries of this research, although this might lead to good results, this would take too much time due to complexity. Therefore model predictive control is not an option to use in the control algorithms. An advantage of this boundary is that the controller design will be less complex and therefore might be more generic.

Secondly the ramp metering algorithm will not be part of the research. There are several types of algorithms, but they are outside the research scope since this could be a study in itself. The ramp meter that is used needs to solve the congestion on the freeway and should create spillback from the on-ramp towards the urban arterial. To be able to isolate the effects of the controller on the spillback, the spillback should not be reduced by the ramp meter. The latter could be the case if an algorithm like ALINEA is implemented: this algorithm acts based on the

situation on the freeway, if the situation improves the flow at the ramp meter is increased. Therefore a ramp meter with fixed signal settings, i.e. fixed cycle time and green time, is used. The signal settings result in the prevention of congestion on the freeway. Due to the reduced outflow at the ramp, spillback occurs. The settings are based on literature and will be explained in more detail in the simulation design (section 4.1.5).

Thirdly the traffic composition that is dealt with, is based on cars, vans and lorries. Public transport, pedestrians and cyclists are outside the research scope. Those road users often have dedicated roads, and are therefore no part of the buffering of traffic.

Fourthly the bottlenecks that are dealt with described in section 1.3 are taken into account. Queues or congestion due to incidents and accidents are not part of this research, since this would lead to a different type of research.

Fifthly the controller can use traffic lights as actuators, traffic management measures dealing with other actuators are outside the research scope. Therefore controllers that use intersection control are part of the research, controllers that use for example variable message signs are outside the research scope.

3.2 Overall control design

The controller design consists of multiple parts, all are programmed in the programming environment. Figure 3.1 presents a schematic overview of the overall design. The figure shows the controller consists of a monitoring and a control part. Both parts consist of several sub-parts, all are programmed in MATLAB (this will be explained in more detail in the next chapter). The programmed code and algorithms are too extensive to include in the report, but can be requested at the author.

The monitoring deals with: (i) updating the data measurements which are needed for the input of the controller and for the assessment of the controller and (ii) the bottleneck detection on the urban arterial. For the detection of bottleneck situations on the urban arterials several detection variants are developed. The output of the monitoring is input for the control part.

The control deals with the control of the three bottleneck situations that can occur in the network. For all three bottleneck situations multiple control variants are developed to deal with the situation. The output of the control variants are new signal settings for the VRIs (i.e. traffic control installation).

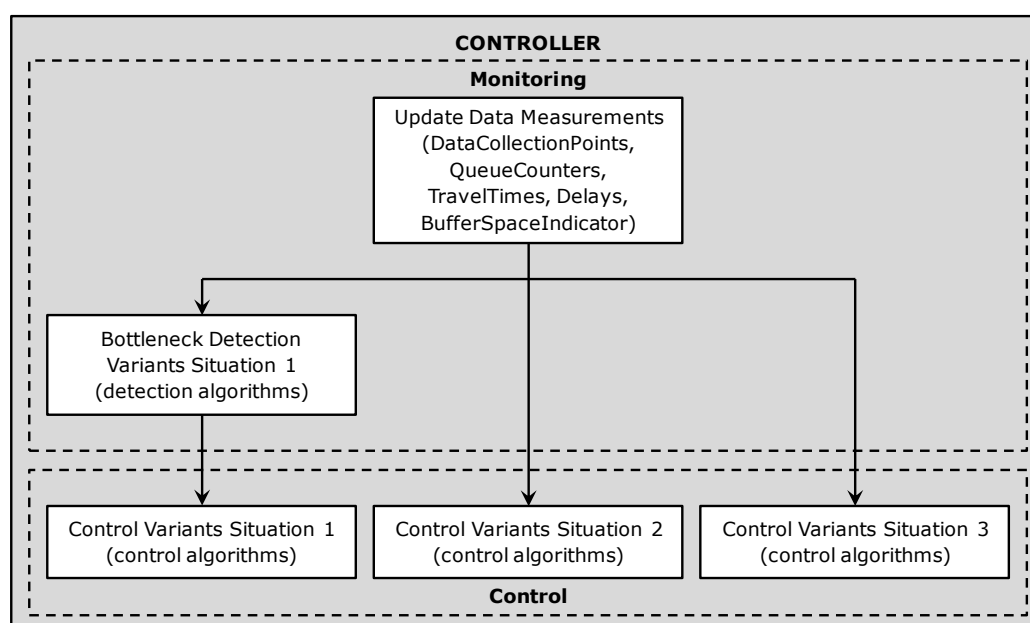


Figure 3.1 Overview of the overall design of the controller. The controller consists of a monitoring and control part, in those parts the different variants are located.

The developed variants (i.e. detection and control variants) all run after each control period with index k . Furthermore the update period of the data measurements (i.e. the monitoring period) is similar to the control period: therefore the measurements of one control period do not have to be recalculated, the latter would be the case if the monitoring period would be e.g. smaller compared to the control period. The control period is equal to the cycle time of the VRIs. This choice is made to be able to finish all calculated signal settings, if for example the control period is shorter compared to the cycle time, the calculated settings for the next cycle cannot be finished.

3.3 Situation 1

In the first situation a bottleneck situation occurs at the urban arterial. A bottleneck situation is defined as a situation in which spillback occurs for a traffic stream m at intersection n . Figure 3.2 gives a schematic representation of this first situation. In Figure 3.2 the first downstream buffer is intersection 2, the first upstream buffer is intersection 1. The frame in the figure shows the up- and downstream traffic streams of the bottleneck. Those streams are the streams from which the traffic is arriving (i.e. upstream) and to which the traffic is departing (i.e. downstream).

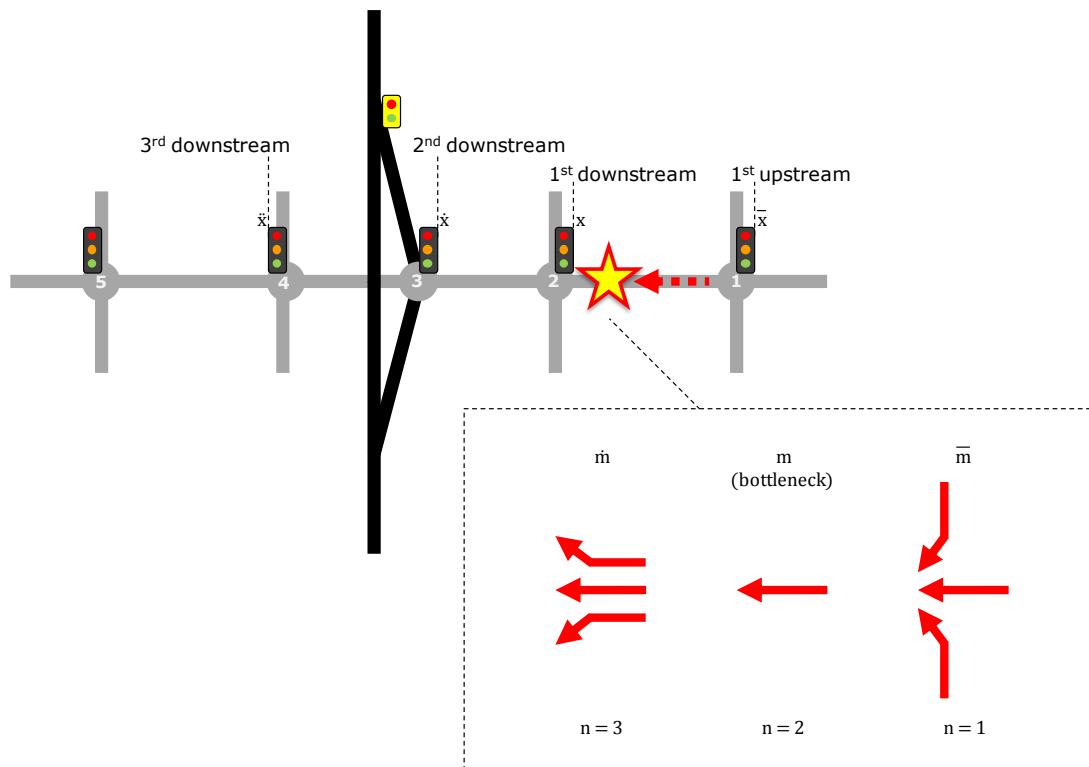


Figure 3.2 Schematic representation of the first bottleneck situation. The frame denotes the up- and downstream traffic streams of the bottleneck.

First the bottleneck situation needs to be detected. Three variants to detect the situation are designed. Secondly the situation should be controlled. Controlling the situation means the queue length is reduced in order to prevent spillback. To reach this, three variants are designed. These variants are presented in the following: for each variant a short introduction is given, followed by the functional specification (i.e. the designed algorithm).

3.3.1 Detection variant 1

The first variant detects bottleneck situations in a rigid way, the detection is based on one critical value per traffic stream. This critical value is the measured queue length at the signal heads. With this queue length it is possible to check for spillback.

Step 1: Target of the algorithm

The target of the algorithm is to detect a bottleneck situation on an urban arterial. The bottleneck situation causes blocking back.

Step 2: Derive queue lengths

The queue lengths l (unit: meters, m) are derived for every traffic stream m at intersection n . The queue is counted from the location of the queue counter upstream to the last vehicle that is in the queue. Queue lengths are chosen as inputs since these have a direct relation on the occurrence of spillback.

Different types of queue length can be used. The ones that give the most useful information are: (i) the maximum queue length of every stream during a cycle time and (ii) the queue length directly after endgreen of the particular stream.

With the two queue types, two different types of problems can be checked. With the maximum queue length blocking back can be checked: if the queue length exceeds the length of the queuing area, another traffic stream is hindered by the queue. With the queue length directly after endgreen, it can be checked if all vehicles could be flushed during the green time: if the queue is larger than zero, not all vehicles were flushed. Figure 3.3 shows these different queuing processes. In this figure the queue length over time is presented. The desired queue is the queue length at which blocking back is prevented.

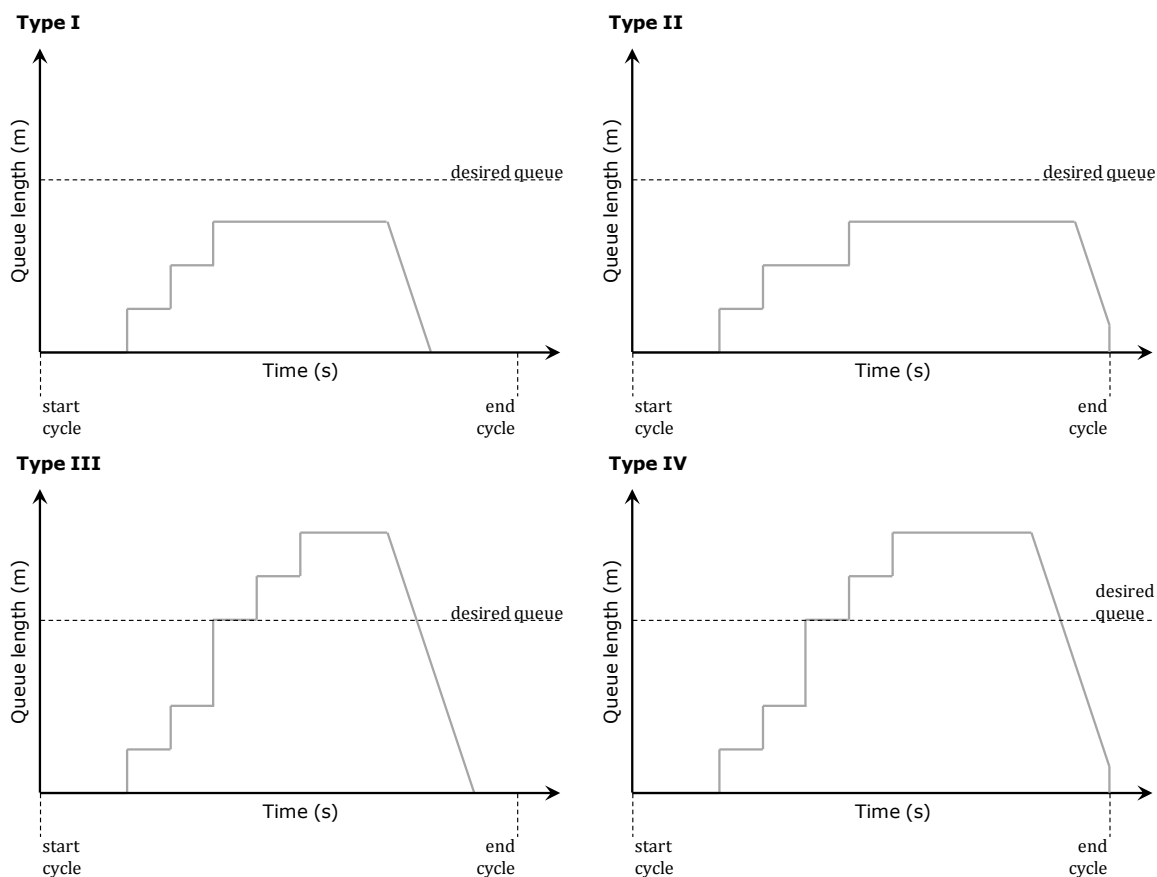


Figure 3.3 Schematic representation of four different queuing processes that can occur at a traffic light.

Type I does not cause a problem. Type II might cause a problem in the next cycle. Type III causes blocking back during the cycle. Type IV causes blocking back during the cycle and might cause a problem in the next cycle. This shows the maximum queue length always addresses a problem, the queue length after endgreen might address a problem. Therefore the maximum queue length is used for the measurements. In VISSIM it is possible to derive the maximum queue length of one control period k by properly setting up the measurement preferences.

for every k
get $l_m^n(k)$ 3.1

Step 3: Check for bottleneck situations

The queue lengths are compared to a desired queue length $l_{m,desired}^n$. The desired queue is the queue length at which spillback is prevented. The desired queue length is predefined per traffic stream. It is equal to the length of the queuing area of the traffic stream minus 10 meters: if the queue stays under this length, there is no spillback. The 10 meters reduction is a margin. If the queue length exceeds the desired queue length, there is a bottleneck situation and the bottleneck status B is set to 1. Else there is no bottleneck situation and B is set to 0.

if $l_m^n(k) > l_{m,desired}^n$
 $B_m^n(k) = 1$
else $B_m^n(k) = 0$ 3.2

Step 4: Output of the algorithm

The bottleneck statuses are stored in a database.

3.3.2 Detection variant 2

The second variant uses differences in queue length as a critical value to detect bottleneck situations. First it is checked if the queue length is below a certain minimum or above a certain maximum. This is needed to ensure a bottleneck situation is detected if the queue length is above the maximum, but has a small difference. And to ensure no bottleneck situation is detected if the difference is large, but the queue length is still under the minimum.

If the queue length is below the minimum, there is no bottleneck situation, if the queue length is above the desired value there is a queue. Else the difference will be checked. If the difference in queue length on a traffic stream between the current and the previous period, exceeds a critical value, it is defined as a bottleneck situation. Using the difference as a critical value should lead to a more fluent detection, compared to the previous variant. A fluent detection might be easier to deal with by the controller.

Step 1 (target of the algorithm) and **step 2** (derive queue lengths) are similar to those steps in the previous variant.

Step 3: Check for bottleneck situations

The queue lengths are compared to a minimum queue length $l_{m,min}^n$. The minimum queue length is predefined and is based on the queue length in calm traffic conditions. The minimum queue length is set at half of the queuing area.

If the queue length is smaller than the minimum queue value, there is no bottleneck situation and B is set to 0.

if $l_m^n(k) < l_{m,min}^n$
 $B_m^n(k) = 0$ 3.3

Else the queue lengths are compared to the desired queue length $l_{m,desired}^n$. If the queue length exceeds the desired value, there is a bottleneck situation and B is set to 1.

$$\begin{aligned} &\text{if } l_m^n(k) > l_{m,desired}^n \\ &B_m^n(k) = 1 \end{aligned} \quad 3.4$$

Else the difference in queue length between the queue length at period k and at period $k - 1$ is compared to a critical difference value $l_{m,diff}^n$. The critical difference is set at 30 m. This difference value is set at a value smaller than the difference between the minimum and maximum queue, in order to have a margin to use. The critical difference is a tuning parameter and can be tuned later on.

If the difference exceeds the critical value, there is a bottleneck situation and B is set to 1. Else there is no bottleneck situation and B is set to 0.

$$\begin{aligned} &\text{if } l_m^n(k) - l_m^n(k - 1) > l_{m,diff}^n \\ &B_m^n(k) = 1 \\ &\text{else } B_m^n(k) = 0 \end{aligned} \quad 3.5$$

If the difference becomes negative, there is no bottleneck situation and B is set to 0, since the queue is becoming shorter.

Step 4 (the output of the algorithm) is similar to the previous variant.

3.3.3 Detection variant 3

Choices that have to be made in traffic engineering are often based on fuzzy input, i.e. input that is uncertain, subjective and ambiguous, as described by Teodorovic (1992). It can be useful to use fuzzy logic to handle these inputs. With fuzzy logic, fuzzy boundaries in combination with expert knowledge is used to make a choice and generate an output value. Instead of sharp switching between modes (i.e. yes or no bottleneck) based on breakpoints, logic flows smoothly from regions where the system's behaviour is dominated by either one rule or another (The Mathworks, 2014b). Chou & Teng (2002) and Rahman & Ratrout (2009) show promising results for the use of fuzzy logic in combination with traffic signal control. This third detection variant uses fuzzy logic to detect bottlenecks.

One of the advantages of fuzzy logic is the possibility to fuse multiple inputs to one output value. In order to increase the reliability of the detection, two inputs are chosen: queue length and flow. Both can give information about a possible bottleneck situation.

The fuzzy logic process (i.e. fuzzification, apply fuzzy rules, fuzzy set operations, defuzzification) is performed via the Fuzzy Logic Toolbox, which is an add-on for MATLAB. This toolbox offers two types of fuzzy logic processes: Mamdani (Mamdani & Assilian, 1975) and Sugeno (1985). With Sugeno the output membership functions are either linear or constant, with Mamdani these functions can be all types of functions. Since the latter is needed, Mamdani is used. Furthermore Mamdani is chosen since it is the most used type and it is intuitive to use, as described by The MathWorks (2014a).

Step 1 (target of the algorithm) and **step 2** (derive queue lengths) are similar to those steps in detection variant 1.

Step 3: Derive flows

The flows q (unit: vehicles per hour, veh/h) are derived for every traffic stream m at intersection n . Flows are used as inputs since these give a good view on the throughput at the buffer. The flow is the inflow into the buffer. The used flow is the summation of flows in the control interval, i.e. the total flow in the control interval.

$$\begin{aligned} &\text{for every } k \\ &\text{get } q_m^n(k) \end{aligned} \quad 3.6$$

Step 4: Fuzzification

The flows and queue lengths are translated into fuzzy values via membership functions mf . Flows for double lanes are multiplied by a factor 1/2 to be able to use the same input membership functions. Queue lengths at double lanes do not differ from queue lengths at single lanes, therefore there is no need to multiply them with a factor.

Membership functions show the degree of membership, varying between 0 and 1, of each input value (i.e. flow q and queue length l) to certain linguistic variables (e.g. low, medium, high). The membership functions are based on expert opinions (i.e. Delft University of Technology and Vialis). The membership functions are depicted in Figure 3.4.

The membership functions show straight lines, horizontal as well as oblique. The horizontal parts are chosen for input values at which no doubt exists regarding the membership of the value. For example a queue larger than 100 m is always long, since it exceeds the queuing area. The oblique lines are chosen for parts at which the membership of the input values is not that clear. For example a flow of 250 veh/h is not high, but it still can be low and medium.

The same functions are used for all buffers in order to reduce the complexity of the controller and since all buffers in this research show large similarities. In reality numerous types of buffers (i.e. different expected queue lengths and flows at these buffers) exist, therefore in reality multiple membership functions would be needed.

If the input values exceed the largest value showed in the figure (respectively 600 veh/h, 150 m), the values get a degree of membership of 1 for the right (respectively high, long) function. These values are not shown in order to get clear figures.

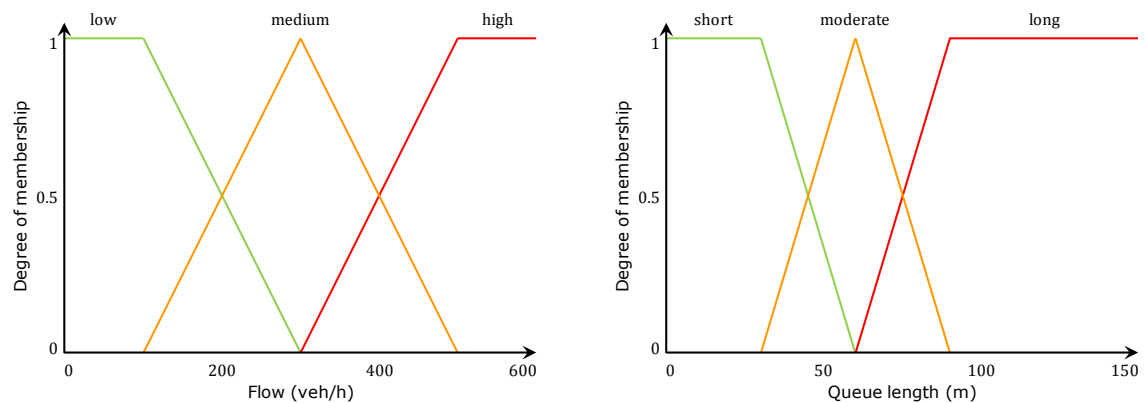


Figure 3.4 Membership functions of input values flow (left) and queue length (right). The x-axes represent the input values. The y-axis represents the degree of membership to the membership functions.

Step 5: Apply fuzzy rules

Fuzzy rules are applied on the output of the fuzzification process. The rules combine the linguistic input values of the queue lengths and flows, the result is a linguistic value for the output membership function. Table 3.1 shows the rules. The rules are in the form: IF flow is [value] AND queue is [value] THEN output membership function is [value].

Table 3.1 Fuzzy rules to combine the input of the membership functions.

Flow / Queue	Short	Moderate	Long
Low	No	Yes	Yes
Medium	No	No	Yes
High	No	No	Yes

The rules are based on expert opinions. The table shows that: (i) if the queue is short, the output function of no-bottleneck is selected and (ii) if the queue is long, the output function of bottleneck is selected. These situations are clear. However, the situation with a moderate queue is more difficult. Therefore the flow gives extra information. If the queue is moderate

and there is a low flow, there might be a bottleneck situation, because there should be at least a medium flow if there is a moderate queue.

Step 6: Fuzzy set operations

The fuzzified input values are evaluated for all nine rules. Fuzzy set operations are used to be able to evaluate the values. Those operations are settings for the different steps in the process. Table 3.2 shows the used settings. The settings for these operations are equal to the most used settings in fuzzy logic, according to Hellmann (2001) and Bilkent University (2010).

Table 3.2 Fuzzy set operation settings.

Fuzzy set operation	Setting
And method	Min
Implication	Min
Aggregation	Max
Defuzzification	Centroid

The following explanation of the terms is based on The MathWorks (2014b). The input values are evaluated for all nine rules; therefore only the rules for which both inputs are available, are used. The *and method* says the minimum value of the two input values to each rule should be chosen. This minimum value is used for the selected output function. *Implication* deals with this output function, minimum means the output fuzzy set of the function is truncated above the input value. *Aggregation* deals with the combination of the different outcomes of each rule, maximum means the different outcomes are all placed in the same plane, without summing up. In the *defuzzification* process the aggregated output fuzzy set is translated into a crisp output value. The centroid method, i.e. the centre of gravity method, is used to generate one output value. This method returns the centre of area under the curve.

Step 7: Defuzzification

The fuzzified values are defuzzified in this step via output membership functions. The values for the two membership functions are known, i.e. these are the degree of membership values from the fuzzification process. Which function should be used is known due to the fuzzy rules and fuzzy set operations. The output membership functions are depicted in Figure 3.5.

The horizontal parts of the functions are chosen in order to create clear bottleneck statuses (i.e. high or low value for bottleneck status) for fuzzified values with high degrees of membership for one of the two functions. The oblique parts are chosen since most values result in semi-bottleneck situations, i.e. it is not always clear if a set of input values should result in a true or false bottleneck status.

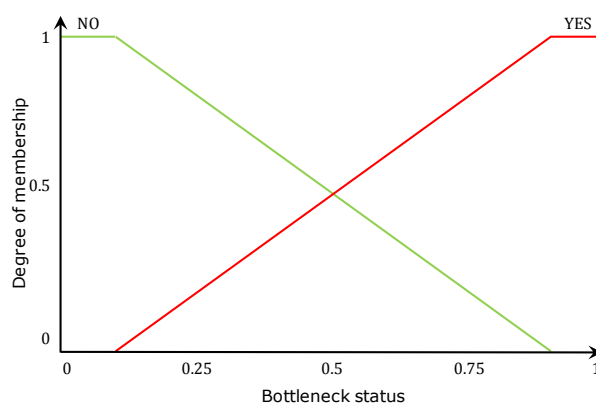


Figure 3.5 Output membership functions. The x-axis represents the bottleneck status, which follows from the fuzzy process. The y-axis represents the degree of membership to the membership functions.

Step 8: Derive bottleneck status

Via the output membership functions and the centre of gravity method the corresponding bottleneck status B can be derived. The value of B varies between 0 and 1. Figure 3.6 shows the output surface of the fuzzy logic process. It shows the relation between the input values flow and queue length, and the output value bottleneck.

The surface of the figure is based on the input values, the shape of the membership functions, the fuzzy operation settings and the fuzzy rules. Due to the shape of the output membership functions and the use of the centroid method to determine the output value, the surface does not reach bottleneck values of 0 and 1. Furthermore the figure indicates that a long and short queue result in respectively a high and low bottleneck value. Due to the used fuzzy rules, the flow has low influence on the bottleneck value outcome if a queue is long or short. For moderate queues, the surface shows the influence of the use of flow as an input value. This can be explained again by looking at the fuzzy rules: for a short and long queue the flow value has no influence on the output of the rules, for a moderate queue the flow value determines the output of the rules.

The bumps in the surface are due to the shape of the input membership functions. This can be explained with an example: say the queue length is fixed at 20 m and the flow is increasing from 0 veh/h to 150 veh/h; due to the increase in flow, the flow becomes a member of multiple input functions (recall Figure 3.4); two of the fuzzy rules (recall Table 3.1) are activated due to the multiple inputs, both rules denote the output no-function should be used; the fuzzy set operations say the minimum input value to the rules needs to be chosen to be used for the output function; therefore if the flow increases to e.g. 150 veh/h the degree of membership of the output function decreases; due to the lower degree of membership of the no-function and the use of the centroid method, the resulting bottleneck status increases, since the centre of gravity of the area under the graph shifts to the right. All the bumps can be explained in a similar way: changing input values result in changes in activated rules, resulting in changes in the output functions, resulting in changes in bottleneck statuses, and therefore in changes in the surface of Figure 3.6.

Since B should be either 0 or 1, the value derived from the fuzzy logic process is translated into either a 0 or a 1.

$$\begin{aligned} &\text{if } B \leq 0.5 \\ &B_m^n(k) = 0 \\ &\text{else } B_m^n(k) = 1 \end{aligned} \quad 3.7$$

Step 9 (the output of the algorithm) is similar to step 4 of detection variant 1.

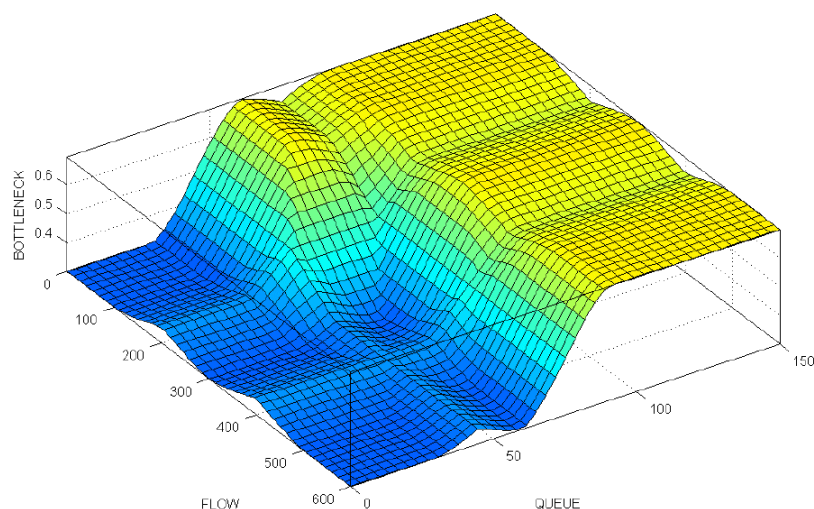


Figure 3.6 Output surface of the fuzzy logic process. Showing the relation between the input values flow (veh/h) and queue (m), and the output value bottleneck.

3.3.4 Control variant 1.1

With the previous variants bottleneck situations on the urban arterial can be detected. This control variant controls the situation, i.e. solves the bottleneck situation or reduces the queue length of it. In this variant the queue at the bottleneck situation is reduced by using the first upstream or first downstream buffer, the choice which of the two should be used is based on a tuning parameter.

Only the first up- and downstream buffers are used, in order to try to solve the problem on a local level: more buffers would result in using a larger part of the network. The usage of the buffers is not combined (i.e. up- or downstream is used) to be able to give priority to only use the downstream buffer. Giving this priority can be realized via the tuning parameter. In order to achieve the largest improvements in the performance indicators (e.g. total delay, see section 4.2), the controller tries to get traffic as soon as possible out of the network. By only using the downstream buffer, this might be realized in a more effective way, compared to using upstream buffers. This is because downstream results in an increase of outflow, and upstream results in a decrease in inflow. To check the effects of this rationale, this variant uses up- or downstream. In other variants a combination of both is developed.

Step 1: Target of the algorithm

The target is to reduce the queue length of a bottleneck situation on an urban arterial, in order to get rid of spillback. This algorithm uses the bottleneck statuses from the detection variants as input. If a bottleneck situation is detected, the algorithm is activated.

Step 2 (derive queue lengths) and **step 3** (derive flows) are similar to those steps in detection variant 3.

Step 4: Calculate traffic surplus in bottleneck stream

In order to know the amount of traffic that causes the spillback, the surplus p (unit: meters, m) of traffic in the bottleneck traffic stream m is calculated. Therefore the desired queue $l_{m,desired}^n$ is extracted from the queue l_m^n . The surplus p is the amount of traffic that leads to spillback.

$$p_m^n(k) = l_m^n(k) - l_{m,desired}^n \quad 3.8$$

Figure 3.7 gives a schematic representation of the surplus, maximal queue and the desired queue. The figure shows the queuing process over time.

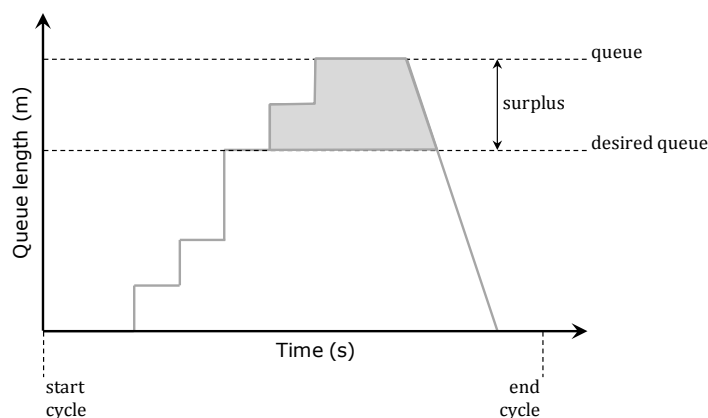


Figure 3.7 Schematic representation of maximal queue, desired queue and the resulting traffic surplus for one traffic stream.

If the bottleneck stream is at a two-lane link, the surplus should be multiplied with a factor 2, to deal with the multiple lanes. If the surplus becomes negative, it is set to 0.

Step 5: Check streams for permission to buffer

All traffic streams m are checked for permission J to be used as a buffer. The default setting for all streams is permission to use, $J = 1$. The user can change this permission, $J = 0$. This results in a set of buffers with permission to use \hat{J} .

$$\text{get } \hat{J} \quad 3.9$$

If a buffer has no permission to be used, the space s in the buffer is set to zero: there is no buffer space, but the buffer is still to be used as a part of the network.

$$s_m^n = 0, \quad \forall m \notin \hat{J} \quad 3.10$$

Step 6: Calculate space in streams

The space s (unit: meters, m) in the buffers is calculated. Therefore the queue l_m^n is subtracted from the desired queue $l_{m,desired}^n$.

$$s_m^n(k) = l_{m,desired}^n - l_m^n(k) \quad 3.11$$

If the bottleneck stream is at a two-lane link, the space should be multiplied with a factor 2, to deal with the multiple lanes. If the space becomes negative, it is set to 0.

Step 7: Check with tuning parameter and calculate new flows

The surplus p is compared to the space s in the downstream buffer \hat{n} to which the traffic flows. The space in the downstream buffer is a summation of the space in the streams to which traffic is flowing from the bottleneck stream. The ratio of the space and surplus is compared to beta β , a tuning parameter. Figure 3.2 gives an illustration of the downstream buffer. The downstream buffer to which the traffic flows in this figure, is the buffer at intersection 3. $\gamma_{m,\hat{m}}$ is the turn fraction from m towards \hat{m} . Turn fractions are calculated via the origin-destination matrices of the traffic.

$$\left(\sum_{\gamma_{m,\hat{m}} > 0} s_m^{\hat{n}}(k) \right) / p_m^n(k) > \beta \quad 3.12$$

β can be tuned by the user, by setting β the preference of using up- or downstream buffers can be set. If β is set to 1, the space should equal the surplus to use downstream buffers. If β is lower than 1, downstream buffers can be used even if the surplus is larger than the space, resulting in more usage of the downstream buffers. If β is higher than 1, downstream buffers can only be used if the space is larger than the surplus, resulting in less usage of the downstream buffers and more usage of the upstream buffers.

The default setting for β is based on the time of the day. In the peak periods, i.e. morning and evening peaks, the value of β will be set at 0.75. With this value downstream buffers can be used, even if the surplus will not completely fit. The rationale of this choice: the network is busy since it is a peak period, so the requirement to fit the complete surplus would often not be satisfied, resulting in the usage of upstream buffers. This then would not correspond with the rationale of letting traffic leaving the network as soon as possible.

In off-peak periods β is set to 1, therefore the surplus should fit in order to use the downstream buffers. The rationale of this choice: the network is not busy, therefore the requirement to fit the complete surplus can be made.

If the ratio of the two is larger than the critical value β , the outflow from the first downstream buffer, i.e. the bottleneck stream (recall Figure 3.2), is increased by adding the surplus p to the current flow q . This is a simple feedback strategy. In order to translate the surplus' unit from m to veh/h, a calculation is made using the length of the control period T (unit: seconds,

s) and the average vehicle length l_{veh} (unit: meters, m). The average vehicle length is calculated in VISSIM and is set at 6.5 m.

$$q_m^n(k+1) = q_m^n(k) + \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \quad 3.13$$

Else the inflow towards the bottleneck stream is decreased by distracting a fraction of the surplus p from the flow q of the upstream intersection \bar{n} . This fraction is calculated based on the origin-fractions δ of the buffer. An origin-fraction denotes where the traffic is coming from, e.g. 10% of the traffic comes from stream 06. Figure 3.8 shows the difference between a turn fraction γ and an origin-fraction δ . A larger origin-fraction of a stream, will result in a larger part of the surplus that is subtracted from the flow at that stream, since more traffic is coming from that stream compared to other upstream streams. Origin-fractions are calculated via the origin-destination matrices of the traffic.

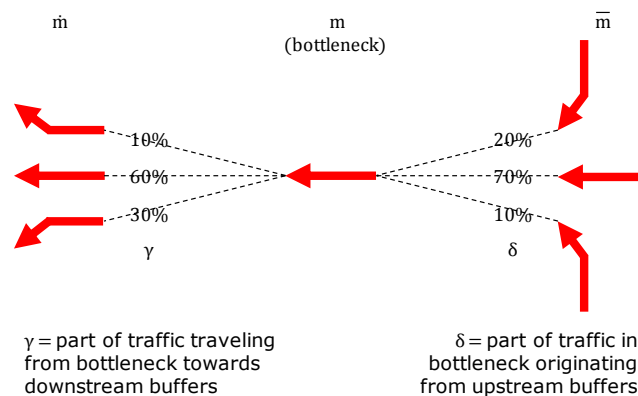


Figure 3.8 Schematic representation of the turn fraction γ and the origin-fraction δ . The percentages in the figure are examples.

The flow is decreased (via a feedback strategy) for the first upstream buffer, i.e. traffic streams \bar{m} from which traffic is flowing towards the bottleneck stream, as shown in Figure 3.2. Not all traffic in the upstream buffer is travelling towards the bottleneck stream, therefore, to reach the right amount of traffic the buffer rate should be raised. This can be done by using the turn fraction γ of traffic traveling from the upstream buffer towards the bottleneck stream. The surplus is divided by using this turn fraction.

$$q_{\bar{m}}^n(k+1) = q_{\bar{m}}^n(k) - \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.14$$

If the flow becomes negative, it is set to 0.

Step 8: Translate flows to green times

The calculated flow q is translated into a green time g (unit: second, s) by dividing the flow q by the capacity u (unit: vehicles per hour, veh/h) of the traffic stream m and multiplying it by the cycle time C (unit: seconds, s).

$$g_m^n(k+1) = \frac{q_m^n(k+1)}{u_m^n} \cdot C \quad 3.15$$

The capacity of the stream can be calculated based on realized flows and known green times and cycle times. The capacity of a 1x1 stream is 2300 veh/h. This capacity is calculated via measured flows in VISSIM with data collection points located just after the stopping line of a traffic light.

Step 9: Check for boundary problems

The boundaries are calculated based on the default settings of the VRIs, explained in the next paragraph. The calculated green time g is compared to the maximum green time g_{max} . If the new green time exceeds the maximum green time, the maximum green time is used.

$$\begin{aligned} \text{if } g_m^n(k+1) > g_{max} \\ g_m^n(k+1) &= g_{max} \end{aligned} \quad 3.16$$

Else the calculated green time g is compared to the minimum green time g_{min} . If the new green time is smaller than the minimum green time, the minimum green time is used.

$$\begin{aligned} \text{if } g_m^n(k+1) < g_{min} \\ g_m^n(k+1) &= g_{min} \end{aligned} \quad 3.17$$

Else the calculated green time is used. If an increase in green time is desired, and the calculated green time is smaller than the default green time, the default green time is used, in order not to worsen the situation. This situation might appear if the current flow is small due to blockages, because the new flow is calculated based on this current flow.

Step 10: Calculate new signal times for the VRIs

In the previous steps, green times are calculated. Those green times belong to a phase. All streams in the phase will get the calculated green time, since they are controlled by the same traffic light. If the new green time for stream 02 at intersection 2 is calculated, the green time for phase 1 is calculated. Figure 3.9 visualizes the calculated and conflicting phases for the use of an upstream or downstream buffer.

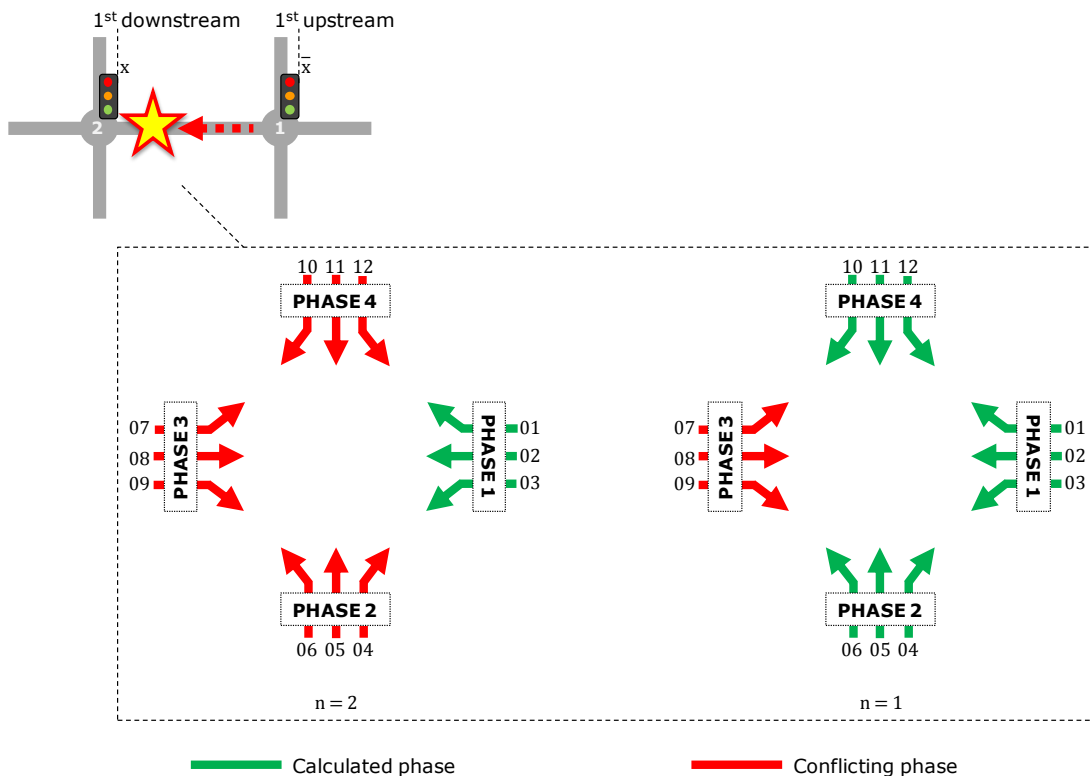


Figure 3.9 Calculated and conflicting phases for a downstream (left, $n = 2$) or an upstream (right, $n = 1$) buffer.

Default settings for all VRIs are used. These settings are based on expert opinions, i.e. opinions in the field, of Vialis.

The realized flow during one cycle depends on the green time and the length of the cycle, recall equation 3.15. Therefore, in order to translate the calculated flow to a green time, the cycle time should be a fixed value. If the increase in green time would be added to the cycle time, the calculated flow would not be reached, resulting in a new calculation, etc. This would result in an iterative process, this is undesired since this would result in time consuming calculations. Besides that, a varying cycle time leads to several sets of combinations for the green and cycle time (multiple solutions are possible). The latter is undesirable since this would lead to an extra decision step: the ideal combination should be chosen for all VRIs. Furthermore, the calculated flow can only be reached if the cycle time is finished, because the flow is calculated based on that same cycle time. Therefore, the control interval should equal the cycle time: a varying control interval could lead to unfinished cycles.

The cycle time is fixed at 120 s. The yellow time is 3 seconds, the clearance time 2 seconds. The minimum green time is 7 seconds. The default settings for the VRI result in a minimum green time and a maximum green time per phase of the VRI: cycle time minus yellow time, clearance time and minimum green time. The default green times are equal for all phases at one intersection.

The complexity of the controller is reduced by assigning all streams of one branch to one phase. This results in four phases (three phases for the off/on-ramp intersection). The choice to reduce the complexity is made to be able to get a good insight in the working of the controller: it is important to know the expected result of the controller, in order to know if the controller improves the traffic condition, or if some other factor improves the traffic condition. Therefore the choice is made to use four phases with a fixed order, instead of twelve phases and a variable order. The latter means each control interval the ideal order should be recalculated.

Figure 3.10 shows the relation between streams and phases, and gives an example of the settings within one cycle time for one VRI.

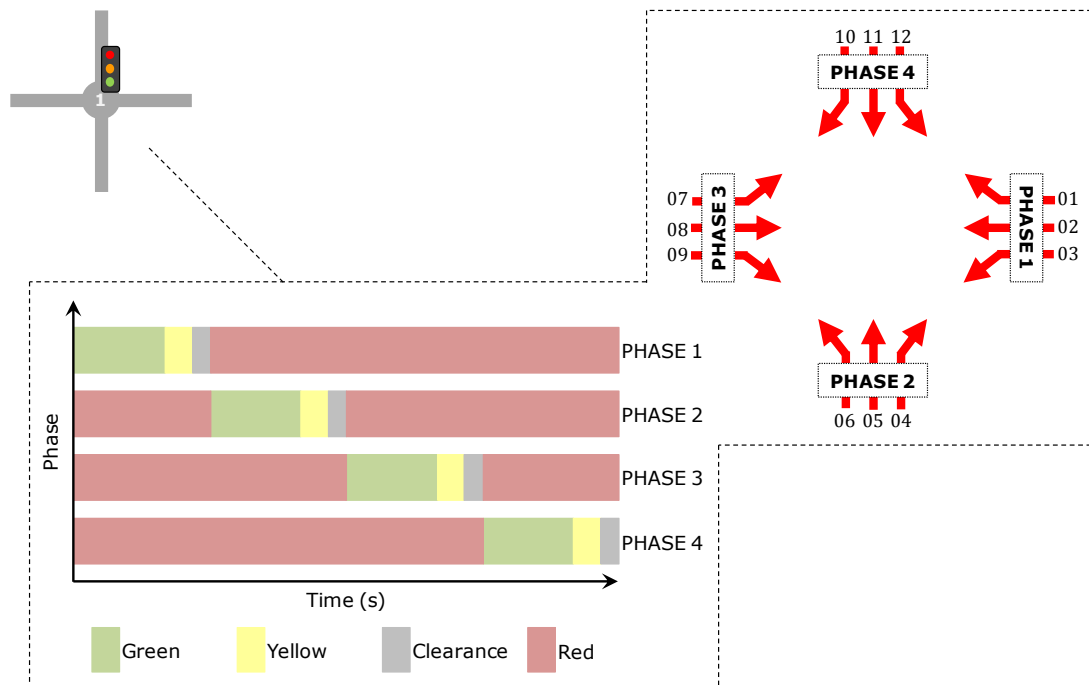


Figure 3.10 Example of a phase diagram for one intersection, which shows the relation between: (i) streams and phases and (ii) settings within one cycle time.

The new green time(s) for the phases of the buffer(s) is/are calculated. The new green times for the other phase(s) need to be calculated. Two different types of starting points for the calculation exist: (i) type A in which downstream buffers are used and (ii) type B in which upstream buffers are used.

- Type A: an increase of green time is needed for downstream buffers, resulting in decreased green time for conflicting directions.
- Type B: a decrease of green time is needed for upstream buffers, resulting in a possibility for increased green time for conflicting directions.

Type A: use downstream buffer

For type A the green time g_m^n for the phase ph_m^n of the downstream buffer is calculated. Figure 3.9 shows an example of the conflicting phases, those conflicting phases will get a reduction in green time. The new green times for those groups are calculated: the remaining green time is distributed over the other phases.

The remaining green time $g_{remaining}$ is calculated based on the cycle time C , the yellow time t_{yellow} , the clearance time $t_{clearance}$ and the amount of phases no_ph^n at intersection n . The remaining green time is the time that remains after distraction from the cycle time of: (i) the yellow, clearance and minimum green times and (ii) the previously calculated green time.

$$g_{remaining} = C - t_{yellow} \cdot no_ph^n - t_{clearance} \cdot no_ph^n - g_{min} \cdot (no_ph^n - 1) - g_m^n(k) \quad 3.18$$

The remaining green time is distributed over the other phases, based on the relative flow of the phases: a high flow will result in more green time.

The maximum flow per phase is used to calculate this relative flow: the streams in one phase will get the same green time since they are controlled by the same traffic light, so the maximum flow denotes the desired green time for that phase.

The relative flow is the maximum flow of the streams assigned to the branch for which the green time is calculated, divided by the sum of maximum flows in all branches for which the green time needs to be calculated.

$$g_{ph}^n(k+1) = g_{min} + g_{remaining} \cdot \frac{\max_{m \in ph} \{q_m^n(k)\}}{\sum_{ph \in ph_m^n} \max_{m \in ph} \{q_m^n(k)\}}, \quad \forall ph^n \neq ph_m^n \quad 3.19$$

For example (see Figure 3.9), the green time for phase 2 needs to be calculated: the relative flow is the maximum flow of the streams assigned to phase 2, divided by the sum of maximum flows for the streams assigned to phase 2, 3 and 4.

Type B: use upstream buffer

For this type the green times $g_m^{\bar{n}}$ for the phases $ph_m^{\bar{n}}$ of the upstream buffer are calculated. Figure 3.9 shows that there is one conflicting phase, that conflicting phase will get an increase in green time. The new green time is calculated: the remaining green time is the new green time of the phase.

The remaining green time $g_{remaining}$ is calculated based on the cycle time C , the yellow time t_{yellow} , the clearance time $t_{clearance}$ and the amount of phases no_ph^n at intersection n . The remaining green time is the time that remains after distraction from the cycle time of: (i) the yellow and clearance times and (ii) the summation of the previously calculated green times. The remaining green time is the new green time of the one conflicting phase.

$$g_{ph}^{\bar{n}}(k+1) = C - t_{yellow} \cdot no_ph^{\bar{n}} - t_{clearance} \cdot no_ph^{\bar{n}} - \sum_{\gamma_{\bar{n},m}} g_m^{\bar{n}}(k), \quad \forall ph^{\bar{n}} \neq ph_m^{\bar{n}} \quad 3.20$$

Step 11: Output of the algorithm

The output of the algorithm are new signal settings for the VRIs. CCOL (i.e. an application to program VRIs) is used to control the VRIs, in section 4.1 this link will be explained in more detail. The new green times of the phases are communicated to the CCOL controller. If no new green times are calculated, default settings are used.

3.3.5 Control variant 1.2

This variant uses three downstream buffers (see Figure 3.2 for location of those buffers), to encounter the effect of relocating the bottleneck situation, something what might happen in control variant 1.1, since only one downstream buffer is used. By using three buffers, the traffic can flow further into the network. Due to turn fractions more buffers are not used: due to turn fractions the traffic flowing from the bottleneck stream towards the fourth downstream buffer might be almost zero. Therefore, to keep the algorithm as simple as possible, but not stupid, three buffers are used.

The difference between this variant and the first control variant is the amount of buffers used for the calculation of new flows, this is dealt with in step 7. The other steps are similar.

Step 7: Check with tuning parameter and calculate new flows

The check is similar to variant 1.1: the space in the downstream buffer is checked, because this buffer is needed to let traffic flow towards the other buffers. So a check of the space in e.g. the third downstream buffer is not useful since the traffic first needs to travel through the first buffer.

If the ratio of the two is larger than the critical value β , the outflow from the three downstream buffers is increased by adding the surplus p to the current flow q . The flow of the first downstream buffer n is increased with the surplus.

$$q_m^n(k+1) = q_m^n(k) + \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \quad 3.21$$

The flows of the second downstream buffer \bar{n} are increased with the surplus multiplied by the fraction γ of traffic flowing from the bottleneck stream towards the downstream buffer.

$$q_m^{\bar{n}}(k+1) = q_m^{\bar{n}}(k) + \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \cdot \gamma_{m,\bar{n}}, \quad \forall \gamma_{m,\bar{n}} > 0 \quad 3.22$$

The flows of the third downstream buffer $\bar{\bar{n}}$ are increased with the surplus multiplied by the fraction γ of traffic flowing from the bottleneck stream towards the downstream buffer.

$$q_m^{\bar{\bar{n}}}(k+1) = q_m^{\bar{\bar{n}}}(k) + \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \cdot \gamma_{m,\bar{\bar{n}}}, \quad \forall \gamma_{m,\bar{\bar{n}}} > 0 \quad 3.23$$

Else the inflow towards the bottleneck stream is decreased, similar to variant 1.1 (recall equation 3.14).

3.3.6 Control variant 1.3

This variant uses the up- and downstream buffer to distribute traffic. The traffic is distributed based on the relative space in the buffers. Both buffers are used in order to see the effect of using both up- and downstream buffer, and to solve the problem on a local level.

The difference between this variant and the first control variant is the amount of buffers used for the calculation of new flows, this is dealt with in step 7. The other steps are similar.

Step 7: Calculate new flows

The surplus p is distributed over the first upstream buffer \bar{n} and downstream buffer n based on the relative space s_{rel} in the buffers. The relative space is the space in the buffer compared to the sum of the space in the up- and downstream buffer.

The relative space $s_{rel}^{\bar{n}}$ in the downstream buffer n is calculated, this buffer is the destination of the traffic in the bottleneck stream.

$$s_{rel}^{\bar{n}}(k) = \left(\sum_{\gamma_{m,\bar{n}} > 0} s_{m,\bar{n}}^{\bar{n}}(k) \right) / \left(\left(\sum_{\gamma_{m,\bar{n}} > 0} s_{m,\bar{n}}^{\bar{n}}(k) \right) + \left(\sum_{\gamma_{\bar{m},m} > 0} s_{\bar{m},m}^{\bar{n}}(k) \right) \right) \quad 3.24$$

The relative space $s_{rel}^{\bar{n}}$ in the upstream buffer \bar{n} is calculated, this buffer is the origin of the traffic in the bottleneck stream.

$$s_{rel}^{\bar{n}}(k) = \left(\sum_{\gamma_{\bar{m},m} > 0} s_{\bar{m},m}^{\bar{n}}(k) \right) / \left(\left(\sum_{\gamma_{m,\bar{n}} > 0} s_{m,\bar{n}}^{\bar{n}}(k) \right) + \left(\sum_{\gamma_{\bar{m},m} > 0} s_{\bar{m},m}^{\bar{n}}(k) \right) \right) \quad 3.25$$

The flow in the downstream buffer n is increased, i.e. the outflow from the bottleneck stream: the surplus times the relative flow is added to the current flow.

$$q_m^n(k+1) = q_m^n(k) + \frac{p_m^n(k) \cdot 3600}{l_{veh} \cdot T} \cdot s_{rel}^{\bar{n}}(k) \quad 3.26$$

The flow in the upstream buffer \bar{n} is decreased, i.e. the inflow in the bottleneck stream: the surplus times the relative space is distracted from the current flow. Furthermore the surplus is multiplied by the origin-fraction and divided by the turn fraction, this is similar to variant 1.1 (recall equation 3.14).

$$q_{\bar{m}}^{\bar{n}}(k+1) = q_{\bar{m}}^{\bar{n}}(k) - \frac{p_{\bar{m}}^{\bar{n}}(k) \cdot 3600}{l_{veh} \cdot T} \cdot s_{rel}^{\bar{n}}(k) \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.27$$

A high relative space will result in a larger change in new flow.

3.4 Situation 2

In the second situation a queue at the off-ramp spills back towards the freeway, resulting in congestion on the freeway. In Figure 3.11 this situation is presented. The figure shows the bottleneck streams m at intersection n and its downstream buffers. Upstream buffers do not exist in this situation, since these are located at the freeway (which is out of the research scope). The frame denotes the streams at the off-ramp, it shows the off-ramp consists of two traffic streams, i.e. a left and right turning one. These are controlled by the same traffic light and are therefore part of the same signal phase.

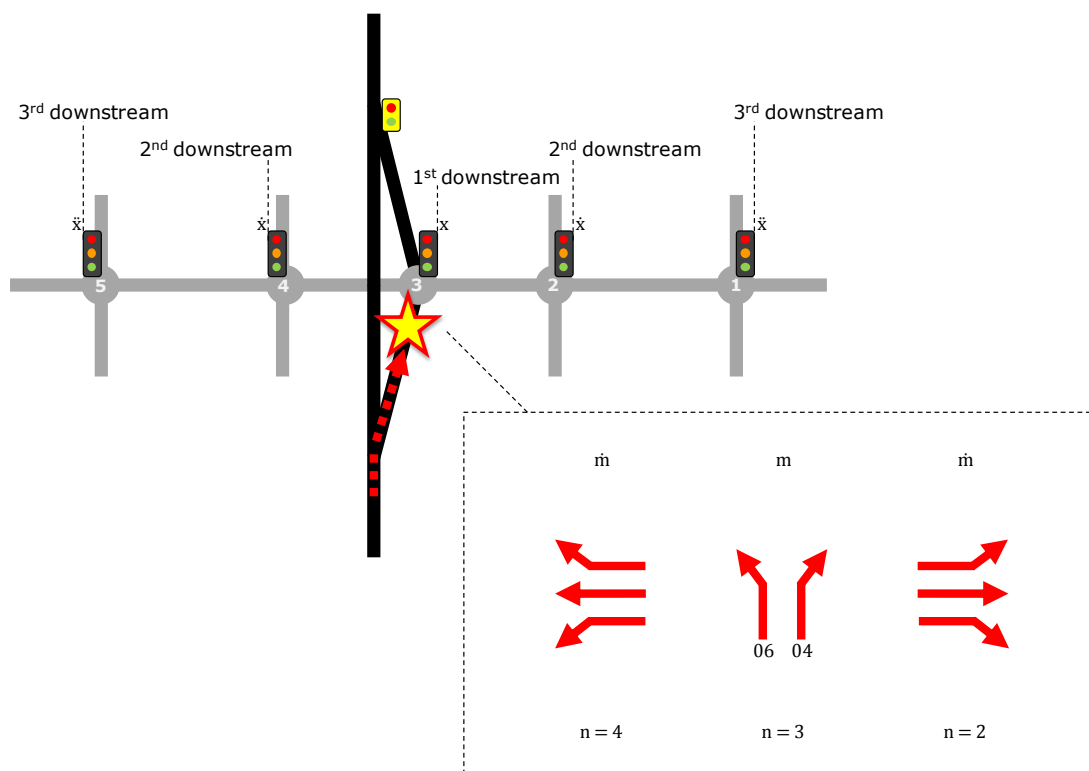


Figure 3.11 Schematic representation of the second bottleneck situation. The frame denotes the downstream traffic streams of the bottleneck.

In this situation the queue length at the off-ramp needs to be kept under the length of the off-ramp, in order to prevent spillback. Two control variants are designed to deal with this situation. The functional specifications of the variants are presented in the ensuing.

The notation below for the off-ramp is situation specific, i.e. the flows are shown with the intersection number (3) and the stream number (04 or 06). This should make the calculation more understandable for the reader compared to using generic notation. The location of the streams is shown in Figure 3.11.

3.4.1 Control variant 2.1

The first control variant for the second situation tries to solve the problem by using only the first downstream intersection, thus solving it locally.

Step 1: Target of the algorithm

The target is to prevent spillback from a queue at the off-ramp towards the freeway.

Step 2 (derive flows) is similar to step 3 in detection variant 3.

Step 3: Determine target outflow

To keep the queue at the off-ramp on a constant level, the inflow should equal the outflow. In order to prevent spillback, the inflow should be the inflow in uncongested conditions. (in congested conditions the inflow will be lower due to blockages). Therefore, the target outflow $q_{target-off}$ is determined based on the origin-destination matrix of this situation. The target flow is set for the complete off-ramp, i.e. both off-ramp streams, since an individual target would result in fixed signal times (the flow would always be changed to the target, resulting in fixed green times). The latter is undesirable since this is less flexible and therefore the green times are not adapted based on the current situation, hence resulting in unnecessary delays.

Step 4: Calculate extra outflow

To reach the target outflow, the difference between the current flow and the target is checked. The flow at the off-ramp q_{off} is a summation of the flows at the off-ramp traffic streams (i.e. in this case 04 and 06, see Figure 3.11).

$$q_{off}(k) = q_{04}^3(k) + q_{06}^3(k) \quad 3.28$$

The extra outflow $q_{off-plus}$ is calculated by subtracting the current flow at the off-ramp q_{off} from the target outflow $q_{target-off}$.

$$q_{off-plus}(k) = q_{target-off} - q_{off}(k) \quad 3.29$$

If the extra outflow becomes negative, it is set to 0 and no further action needs to be taken.

Step 5: Calculate new flows

If the extra outflow is larger than zero, new flows for the first downstream buffer (i.e. the off-ramp itself) are calculated. The flows are calculated for the two streams at the off-ramp (i.e. 04 and 06).

The streams at the off-ramp are part of the same phase. Individual new green times are not an option: both streams get the same new green time. Therefore the maximum of the two is taken. The outflow of the streams is increased with the extra outflow $q_{off-plus}$.

$$q_{off}^n(k+1) = \max\{q_m^n(k) + q_{off-plus}(k)\}, \quad \forall m \in offramp \quad 3.30$$

The extra outflow is not multiplied with the fraction of traffic flowing from the off-ramp towards the particular stream. This choice is made because it is possible that the queuing area of one of the streams blocks the other one. Due to this blocking the desired flow at one of the streams would not be achieved, and therefore the target outflow is not reached (after all this is a summation of both of the outflows). If the target is not reached, spillback from the ramp towards the freeway can occur with resulting congestion on the freeway. Therefore, to decrease the chance on spillback, both streams get the complete extra outflow.

Step 6 (translate flows to green times), **step 7** (check for boundary problems), **step 8** (calculate new signal times for the VRIs) and **step 9** (output of the algorithm) are similar to those steps in control variant 1.1 (respectively steps 8, 9, 10 and 11).

3.4.2 Control variant 2.2

The second control variant uses three downstream buffers instead of one, following the same rationale as control variant 1.2 (see page 32).

The difference between this variant and previous one is in step 5, the calculation of flows. The other steps are similar.

Step 5: Calculate new flows

The flow of the first downstream buffer n is increased with the extra outflow.

$$q_{off}^n(k+1) = \max\{q_m^n(k) + q_{off-plus}(k)\}, \quad \forall m \in offramp \quad 3.31$$

The flows of the second downstream buffers i are increased with the extra outflow multiplied by the fraction γ of traffic flowing from the off-ramp towards the downstream buffers.

$$q_m^i(k+1) = q_m^i(k) + q_{off-plus}(k) \cdot \gamma_{m,i}, \quad \forall \gamma_{m,i} > 0 \quad 3.32$$

The flows of the third downstream buffers \bar{n} are increased with the extra outflow multiplied by the fraction γ of traffic flowing from the off-ramp towards the downstream buffers.

$$q_{\bar{n}}^{\bar{n}}(k+1) = q_{\bar{n}}^{\bar{n}}(k) + q_{off-plus}(k) \cdot \gamma_{m,\bar{m}}, \quad \forall \gamma_{m,\bar{m}} > 0 \quad 3.33$$

3.5 Situation 3

In the third bottleneck situation congestion on the freeway is solved by activating a ramp metering installation. Due to limited inflow towards the freeway, a queue occurs at the on-ramp. After a while this queue spills back to the urban arterial. Figure 3.12 shows this bottleneck situation. In this situation, the bottleneck is at the on-ramp, therefore the stream m which denotes the bottleneck situation is the stream at the on-ramp. The first upstream buffer is the buffer at intersection 3.

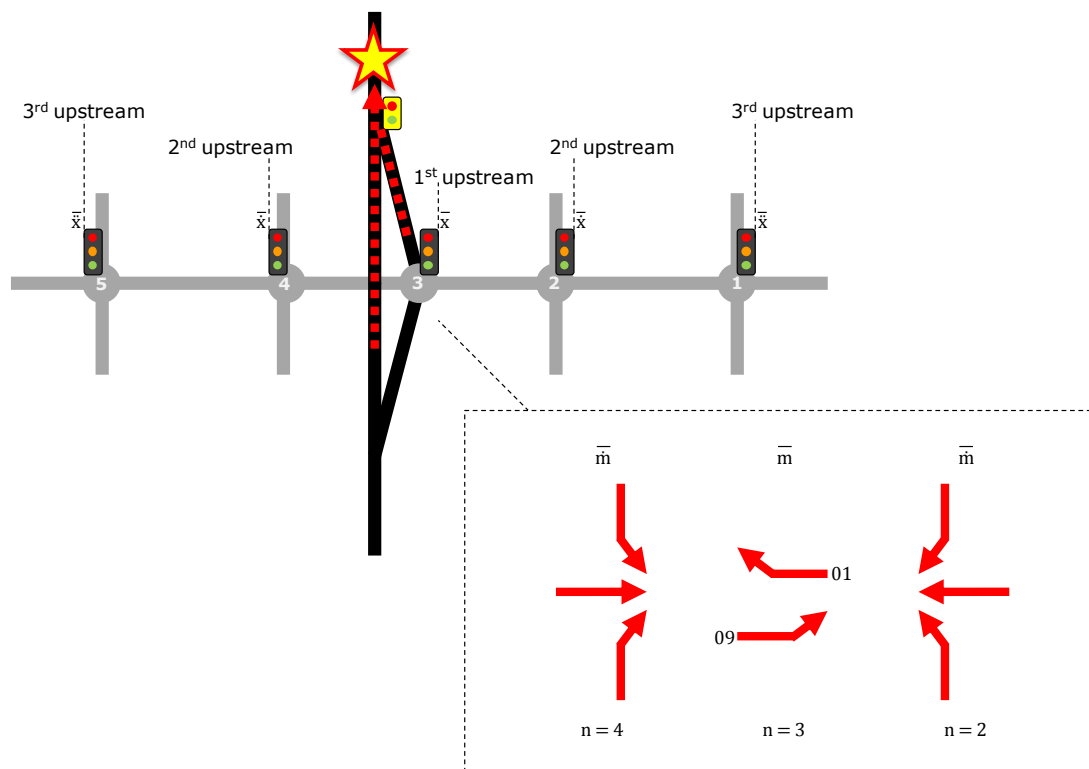


Figure 3.12 Schematic representation of the third bottleneck situation. The frame denotes the upstream traffic streams of the bottleneck.

To prevent spillback the queue at the on-ramp should be kept smaller than the length of the on-ramp. Three control variants are designed and presented in the ensuing. Furthermore the ST1Light is discussed.

The notation below for the on-ramp is situation specific, i.e. the flows are shown with the intersection number (3) and the stream number (01 or 09). This should make the calculation more understandable for the reader compared to using generic notation. The location of the streams is shown in Figure 3.12.

3.5.1 Control variant 3.1

The first control variant to control this situation uses the first upstream buffer, in order to solve the problem as local as possible.

Step 1: Target of the algorithm

The target of this algorithm is to prevent spillback from the on-ramp towards the urban arterial.

Step 2 (derive flows) is similar to step 3 in detection variant 3.

Step 3: Determine target inflow

In order to keep the queue length at the on-ramp smaller than the length of the on-ramp, the inflow should equal the outflow. The outflow at the on-ramp is determined by the ramp metering installation. Therefore target inflow $q_{target-on}$ is equal to the flow at the ramp meter.

Step 4: Calculate reduction in inflow

The difference between the current flow towards the on-ramp and the target flow is checked. The flow towards the on-ramp is a summation of the flows at the on-ramp traffic streams (i.e. in this case 01 and 09, see Figure 3.12).

$$q_{on}(k) = q_{01}^3(k) + q_{09}^3(k) \quad 3.34$$

The reduction in inflow q_{on-min} is calculated by subtracting the target inflow $q_{target-on}$ from the current flow at the on-ramp q_{on} .

$$q_{on-min}(k) = q_{on}(k) - q_{target-on} \quad 3.35$$

Step 5: Calculate new flows

If the reduction is positive, new flows for the first upstream buffer \bar{n} are calculated. The inflow q is reduced with the reduction in inflow, multiplied by the origin-fraction δ and divided by the turn fraction γ . The latter is similar to variant 1.1 (recall equation 3.14).

$$q_{\bar{m}}^{\bar{n}}(k+1) = q_{\bar{m}}^{\bar{n}}(k) - q_{on-min}(k) \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.36$$

If the new calculated flow of one of the two streams is negative the buffer target cannot be reached. Therefore, in this case the negative flow is added to the other stream. If the other stream also becomes negative the maximum buffer capacity is reached and negative flows are set to 0.

Else, if the reduction is negative, the flow from the first upstream buffer towards the on-ramp can be set at the target flow $q_{target-on}$. The target flow is distributed based on the origin-fraction.

$$q_{\bar{m}}^{\bar{n}}(k+1) = q_{target-on} \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.37$$

Step 6 (translate flows to green times), **step 7** (check for boundary problems), **step 8** (calculate new signal times for the VRIs) and **step 9** (output of the algorithm) are similar to those steps in control variant 1.1 (respectively steps 8, 9, 10 and 11).

3.5.2 Control variant 3.2

In the second control variant three upstream buffers are used in order to realize a larger buffer capacity.

This variant differs from the previous one in step 5, calculation of new flows. The other steps are similar.

Step 5: Calculate new flows

The calculation of new flows for the first upstream buffer is similar to equations 3.36 and 3.37 of previous variant.

If the reduction is positive, the flows of the second upstream buffer \bar{n} and third upstream buffer \bar{n} are reduced with the reduction in inflow, multiplied by the origin-fraction and divided by the turn fraction.

$$q_{\bar{m}}^{\bar{n}}(k+1) = q_{\bar{m}}^{\bar{n}}(k) - q_{on-min}(k) \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.38$$

$$q_{\bar{m}}^{\bar{n}}(k+1) = q_{\bar{m}}^{\bar{n}}(k) - q_{on-min}(k) \cdot \delta_{\bar{m},m} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.39$$

If the reduction is negative, the same formulas as above are applied. This results in an increase in flow. This differs from the approach at the first upstream buffer: at that buffer the flow was set at the target inflow. At the second and third upstream buffer this target is not set, since it is expected this would result in much unnecessary reduction in flow due to the turn fractions: the majority of traffic in those buffers might not have the direction of the on-ramp, and therefore should not be hindered. Therefore an increase in flow is accepted for those buffers.

3.5.3 Control variant 3.3

The third control variant distributes traffic over three upstream buffers, based on the relative queue lengths in the first upstream buffers. A large queue length means less space, and therefore that buffer will be used less compared to a buffer with more space. The relative queue at the first buffer is chosen since that is the buffer which receives the traffic. If the queue in that buffer is long, the inflow into that buffer should be limited.

This variant differs to the previous variant in step 5, the calculation of new flows. Furthermore the queue length is needed, this is derived according to step 2 of detection variant 1.

Step 5: Calculate new flows

If the reduction is positive, the flows of the first upstream buffer are reduced with the reduction in inflow multiplied by the relative queue length in the buffers. A large queue corresponds with a smaller part of the reduction.

$$q_{01}^3(k+1) = q_{01}^3(k) - q_{on-min}(k) \cdot \frac{l_{09}^3(k)}{l_{01}^3(k) + l_{09}^3(k)} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.40$$

$$q_{09}^3(k+1) = q_{09}^3(k) - q_{on-min}(k) \cdot \frac{l_{01}^3(k)}{l_{01}^3(k) + l_{09}^3(k)} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.41$$

If one of the flows becomes negative, the same procedure as was explained in control variant 3.1 is applied.

If the reduction in inflow is negative, the flow from the upstream buffers towards the on-ramp is set at the target flow $q_{target-on}$. The target flow is distributed over the upstream buffer, based on queue lengths. If the queue at one of the two buffers is longer compared to the other, it gets a higher flow. This should keep both queues at equal length.

$$q_{01}^3(k+1) = q_{target-on} \cdot \frac{l_{01}^3(k)}{l_{01}^3(k) + l_{09}^3(k)} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.42$$

$$q_{09}^3(k+1) = q_{target-on} \cdot \frac{l_{09}^3(k)}{l_{01}^3(k) + l_{09}^3(k)} \cdot \gamma_{\bar{m},m}^{-1}, \quad \forall \gamma_{\bar{m},m} > 0 \quad 3.43$$

The calculation of flows for the second and third upstream buffer is also based on the relative queue of the first upstream buffer, since this is the most important buffer because it directly leads to the on-ramp. The equations are almost similar to equations 3.38 and 3.39, with the difference that the origin-fraction δ is replaced by the relative queue length as in equations

3.40 and 3.41. If the reduction is negative, the same procedure as was applied in variant 3.2 is used.

3.5.4 ST1Light

The last variant is the controller designed in the Praktijkproef Amsterdam to control the third bottleneck situation. It is called the ST1Light. A full functional specification of the algorithm is given by Taale (2014). This section shows the rationale of the variant.

Step 1. Determine the set of available buffers, based on the maximum buffer space and the current traffic demand in the buffer. If the buffer is filled or the demand is too low, the buffer is not available.

Step 2. Determine whether the usage of buffers is needed, based on the space at the on-ramp. The boundary value (i.e. percentage of on-ramp that is filled) to start using buffers is a tuning parameter.

Step 3. Determine the amount of traffic that needs to be buffered, based on the metering rate of the ramp metering installation and the current flow. The surplus of traffic will be distributed over the available buffers.

Step 4. Distribute the traffic over the buffers based on a uniform distribution. The buffers are used proportionally, taking into account the maximal buffer space. If a buffer is filled, a new buffer is activated.

Step 5. Translate the amount of traffic that needs to be buffered to flows and check the boundaries of the VRIs. If new calculated flows are outside the boundaries, the desired flow will not be reached. In order to reach the flow, the difference between the calculated and realized flow is distributed over the other buffers.

Step 6. Translate the calculated flows to delta green times. The delta green time is the difference between current green time and the calculated green time. If the delta green time is too large it is applied divided over a prespecified amount of cycles.

3.6 Summary

The third chapter discussed the development of the controller, it showed functional specifications of the algorithms. Several variants of the control algorithm were presented, divided per bottleneck situation they should deal with. Traffic is distributed by changing the signal settings at the intersections.

In the first situation the bottleneck situation is detected and controlled. For the detection three variants are developed: detection based on (i) a crisp critical queue length value, (ii) differences in queue lengths between two time periods, (iii) fuzzy logic with queue lengths and flows as input values. The detection variants are combined with controller variants in order to see the impact of the detection strategies. For the controller three variants are developed: controllers that distribute the surplus of traffic over (i) one up- or downstream buffer based on prespecified preferences, (ii) one up- or three downstream buffers based on prespecified preferences, (iii) one up- and downstream buffer based on relative space in the buffer. For the first two control variants it is possible to specify the preference of using up- or downstream buffers, by setting a tuning parameter. Using multiple downstream buffers could prevent the replacement of the bottleneck to the first downstream buffer.

In the second situation the queue at the off-ramp is managed by increasing the outflow at the ramp, based on a target outflow. Due to this increase in flow, spillback should be prevented. Two variants of the controller are developed: a controller which increases the outflow by distributing traffic over (i) the first downstream buffer, and (ii) three downstream buffers.

In the third situation the queue at the on-ramp is managed by reducing the inflow into the on-ramp, based on a target inflow. The reduction in inflow is achieved by buffering traffic. This should lead to the prevention of spillback at the ramp. Three controller variants are developed: controllers that reduce the inflow by distribution traffic over the (i) first upstream buffer, (ii) three upstream buffers based on turn fractions, and (iii) three upstream buffers based on

relative queue lengths. The ST1Light is used as the fourth controller, the ST1Light calculates the amount of buffers needed to reach the target inflow.

Table 3.3 gives an overview of the designed controller variants, ordered per situation they should deal with.

Table 3.3 Overview of designed controller variants, the table shows the main differences in approach.

Bottleneck situation	Variants			
Situation 1 Target: detect bottleneck situation and reduce queue length at the bottleneck situation.	Detection 1 Detection based on a crisp queue length value.	Detection 2 Detection based on differences in queue length between current and previous period.	Detection 3 Detection based on fuzzy logic with input values flow and queue length.	
	Control 1.1 Distribute traffic over one up- or downstream buffer. Decision based on a preference for using up- or downstream.	Control 1.2 Distribute traffic over one up- or three downstream buffers. Decision based on a preference for using up- or downstream.	Control 1.3 Distribute traffic over one up- and downstream buffer, based on relative space.	
Situation 2 Target: control queue length at off-ramp.	Control 2.1 Increase outflow at the ramp. Use one downstream buffer.	Control 2.2 Increase outflow at the ramp. Use three downstream buffers.		
Situation 3 Target: control queue length at on-ramp.	Control 3.1 Reduce inflow towards the ramp. Use one upstream buffer. Distribute traffic based on turn fractions.	Control 3.2 Reduce inflow towards the ramp. Use three upstream buffers. Distribute traffic based on turn fractions.	Control 3.3 Reduce inflow towards the ramp. Use three upstream buffers. Distribute traffic based on relative queue lengths.	ST1Light Reduce inflow towards the ramp. Calculate amount of needed buffers and use a new buffer if the buffer is filled.

In the table the approach differences between the versions are shown. These variants will be tested via simulation. The next chapter will present the design of this simulation.

Chapter 4. Simulation design

The developed controllers of the previous chapter will be tested via simulation. This chapter explains the design of the simulation. Section 4.1 presents the experimental set up and the degrees of freedom in the simulation. The used software programs, the test network and the base situations (i.e. bottleneck situations) are shown. To compare the different controllers to each other, performance indicators are needed. Section 4.2 presents these indicators and explains why these are chosen. In section 4.3 an overview of the used simulation parameters is given, these parameters came up in the controller development in the previous paragraph. The chapter concludes with a summary.

4.1 Experimental set up

The simulation exists of: (i) the network, (ii) traffic demand and (iii) control of the traffic in the network. These three parts can be changed in the simulation and are the degrees of freedom. Multiple controllers are designed. In order to test the effects of the controllers, the network and the traffic patterns and demands should be fixed. If the latter two would be changed too, it would be hard to say if the realized changes in performance are due to the controller or due to changes in the network or the traffic demands. Therefore, only the controller will be varied. In this section the interaction between the network, the traffic and the controller is presented. This is the simulation framework. Hereafter the road network and the base (traffic) situations are shown.

4.1.1 Simulation framework

The simulation framework presents the used software programs and their role. Figure 4.1 gives a schematic overview of the framework.

MATLAB (The MathWorks, 2014c) is the core of the simulation framework. In MATLAB simulation settings are specified, control algorithms are programmed and data is stored and processed: in MATLAB the controller (recall Figure 3.1) is programmed. The programmed code and algorithms are too extensive to include in this report, but can be requested at the author. Via MATLAB the correct (i.e. the one that should be tested) control variant should be specified. MATLAB is chosen for its capability to control VISSIM via the COM Interface and for its analytical tools.

VISSIM (PTV Group, 2014) is the test environment in the framework. VISSIM is a multi-modal microscopic traffic flow simulation software package. In VISSIM the network and the traffic demand is programmed. The network consists of the roads, detectors and actuators. The detectors are for example QueueCounters and DataCollectionPoints (recall the overall design of the controller in Figure 3.1). The detectors gather data like queue length, flow, travel times,

delays, etc. The actuators are the VRIs. Traffic demand in VISSIM is set via origin-destination matrices, these matrices can be specified for time periods. The origin and destination zones are created in the network. VISSIM is chosen because it is a test environment which can be influenced via a program like MATLAB, and because it shows good capabilities of modelling traffic according to Van Lint et al. (2012).

The COM Interface is the communication tool between MATLAB and VISSIM: via the COM Interface data is exchanged. If, for example, queue counters should generate output, the queue counters should be switched on via MATLAB.

The VRIs are controlled via CCOL (Vialis, 2014), an application for the programming of VRIs. In CCOL the phase-structure of the VRIs is specified, including the minimum green time and the clearance times. New green times can be communicated to the VRIs via CCOL. CCOL is chosen for its capabilities to control the VRIs in a comprehensible manner.

Note that MATLAB and VISSIM are also chosen since both programs are used in the Praktijkproef Amsterdam to test the ST1Light.

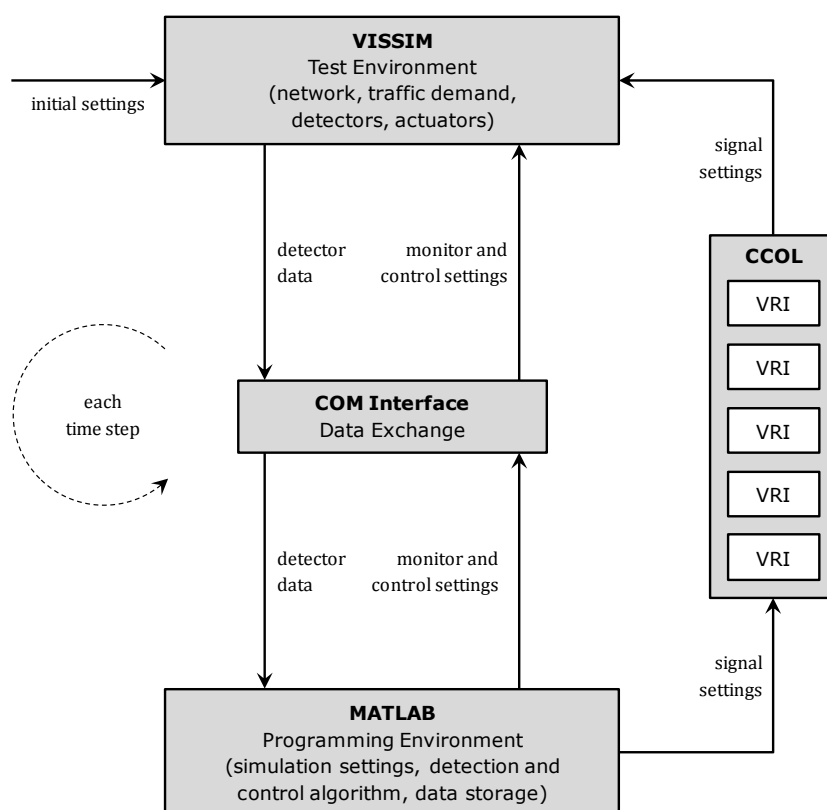


Figure 4.1 Schematic overview of the simulation framework. MATLAB is the programming environment. In VISSIM the test environment is set up. Via the COM Interface, MATLAB and VISSIM exchange data. The VRIs are controlled via CCOL. CCOL gets its settings via MATLAB.

4.1.2 Example of a simulation run

In order to clarify the communication between the different software programs, a typical simulation run (step by step) is presented below. For each step of the simulation run a description is given including the program in which the action should be started. For example the start of the simulation of one control period is performed in MATLAB, but the simulation itself runs in VISSIM. The steps are categorized based on offline (i.e. before or after the simulation) or online (i.e. during the simulation) execution.

Preparations (offline)

Step 1. Create the road network, including detectors and actuators. Specify the traffic demand patterns via origin-destination matrices. VISSIM

Step 2.	Specify the phase-structure and VRI default settings.	CCOL
Step 3.	Program the detection and control algorithms, i.e. the controller variants.	MATLAB
Step 4.	Specify the input settings, for example which control variant should be used.	MATLAB
Step 5.	Initiate data modules, for example DataCollectionPoints and QueueCounters.	MATLAB
Step 6	Load the network, input settings, etc. and start the online simulation.	VISSIM

Simulation (online)

Step 7.	Run the simulation for one control period.	VISSIM
Step 8.	Update and process the monitoring data of the simulation run.	MATLAB
Step 9.	Run the control algorithm and calculate new green times for the VRIs.	MATLAB
Step 10.	Write new green times into a *.txt-file and place it into the directory of the CCOL controller.	MATLAB
Step 11.	Load the new green times in the VRI.	CCOL
Step 12.	<u>If</u> the last control step is reached close the simulation and go to step 13. <u>Else</u> go to step 7 and run the simulation for the next control period.	MATLAB

Process results (offline)

Step 13.	Process all collected data and save the results.	MATLAB
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4.1.3 Lane change settings

VISSIM uses car following models (i.e. the Wiedemann approach) and lane change models to model driving behaviour. The default settings of VISSIM result in a rather terrible modelling of the capacity drop and the merging behaviour on freeways: the capacity drop does not exist or is very small; the merging behaviour results in congestion even with demand much lower than capacity.

In order to improve the modelling, default parameter settings of the lane change model are changed. These changes are adapted from the research of Legius (2014). The modelling of the merging behaviour is improved by reducing the safety distance reduction factor. The modelling of the capacity drop is improved by reducing the maximum acceleration of the vehicles. Appendix A shows the old and new settings.

4.1.4 Road network

The road network in which the controller is tested, should give the possibility to show the working of the controller. Therefore the network first of all needs to consist of a junction between a freeway and an urban arterial. Secondly the on-ramp and off-ramp of the freeway should have such a length that spillback can occur. Thirdly, enough intersections need to exist to be able to buffer traffic.

Furthermore it is important that the network is controllable: it should be possible to argue the changes in traffic conditions, based on the actions the control algorithm. If this is possible it can be checked if the rationale of the controller works as intended. With a large uncontrollable network (for example the complete network used in the Praktijkproef Amsterdam), it is impossible to know if changes in traffic conditions are due to the controller, or due to some other 'randomness'.

Based on these requirements the network shown in Figure 4.2 is created. In the figure the shape and dimensions of the road network are shown. The dimensions are based on Google Earth measurements in real world conditions.

The freeway consists of 1x2-lanes, the urban arterial consists of 2x2-lanes. The on-ramp and off-ramp both consist of 1 lane. The off-ramp has a length of 375 m, and is located at 1430 m from the start of the freeway. The on-ramp is 200 m long and located at 2300 m from the start of the freeway. The length of the freeway is 2600 m.

The queuing area at the urban arterial in East-West direction (and vice versa) is 100 m, in North-South (and vice versa) it is 70 m. Ongoing directions at the urban arterial have a 2-lane queuing area, turning directions have a 1-lane queuing area.

Intersections 1, 2, 4 and 5 have four phases. All phases consist of three streams. Phase 1 consists of stream 01, 02 and 03; phase 2 of stream 04, 05, 06; phase 3 of stream 07, 08, 09; phase 4 of stream 10, 11, 12. Intersection 3 has three phases due to the on and off-ramp, all three phases consist of two streams. Phase 1 consists of stream 01 and 02; phase 2 of stream 04 and 06; phase 3 of stream 08 and 09. Recall Figure 3.10 for a schematic representation of these phases and the phase structure.

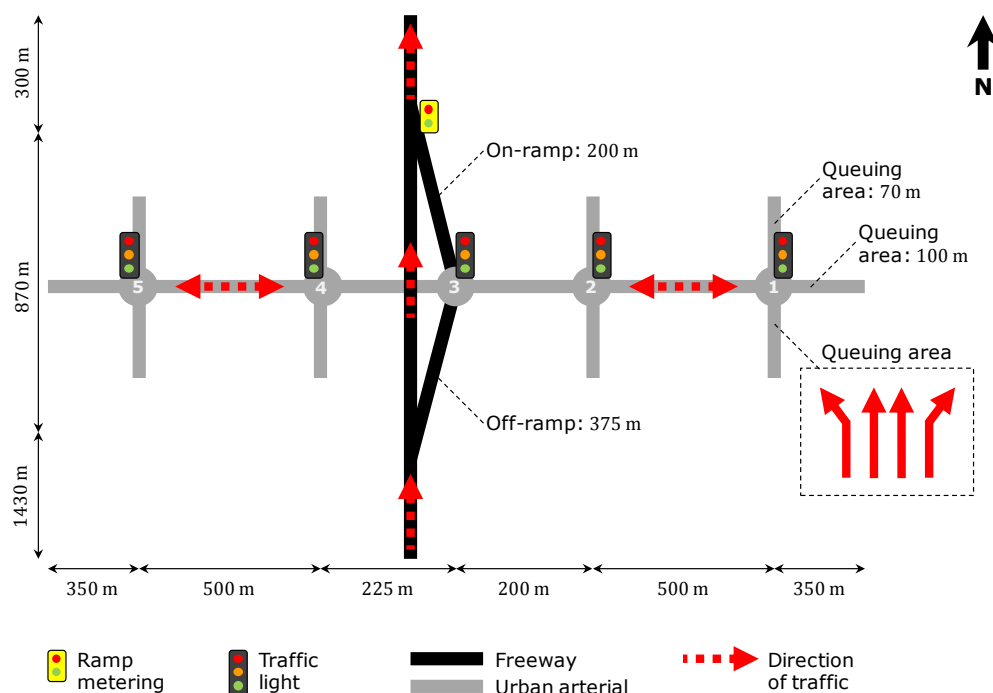


Figure 4.2 Schematic representation of the simulation network. The freeway consists of 1x2-lanes, the urban arterial of 2x2-lanes. The queuing area for ongoing traffic consists of 2 lanes, the area for turning traffic consists of 1 lane (shown in the frame).

4.1.5 Base situations

The traffic demand in VISSIM is set via origin-destination matrices. These can be specified for different time periods. First, in order to let traffic spread over the network, a warming-up period is included, this takes 10 minutes. Secondly the situation specific period is active, this takes 1 hour. With this situation specific origin-destination matrices, the three bottleneck situations are created (recall Figure 1.1). Thirdly a cooling-down period is included, which takes 10 minutes, this period is included to let massive congestion solve and let vehicles leave the network. The warming-up and cooling-down periods are equal for all three situations.

This section shows how the situation specific matrices are derived. All (i.e. warming-up, situation specific, cooling-down) used origin-destination matrices are presented in Appendix B.

Situation 1

In the first situation spillback should occur on the urban arterial. The bottleneck situation is created at the second intersection, in order to have up- and downstream buffers to use. Based on the capacity, cycle time and green time of the traffic stream (recall equation 3.15), the amount of traffic that should lead to a bottleneck situation, is calculated. This amount is realized by using different origin-destination pairs. Different pairs are used in order to create the bottleneck only at the second intersection, and not as well at the third, fourth, etc. intersection.

Situation 2

The second situation is a queue spilling back from the off-ramp towards the freeway. Similar to previous variant, based on equation 3.15, the amount of traffic that should lead to a bottleneck situation is calculated. This traffic is added travelling from the freeway towards the urban arterial, and results in a higher inflow into the off-ramp compared to the outflow at the off-ramp, resulting in an increasing queue at the off-ramp. Note that the amount of traffic travelling at the freeway should not lead to congestion by itself. The congestion is caused by the spillback.

Situation 3

In the third situation first of all congestion needs to occur on the freeway at the location of the on-ramp. Therefore the amount of traffic travelling at the freeway should not lead to congestion by itself, the congestion should arise if the traffic from the on-ramp is added. Secondly, due to the use of a ramp metering installation, the congestion should be solved and the queue at the on-ramp should spill back towards the urban arterial.

The traffic demand at the freeway is based on capacities of two-lane freeways. The algorithm of the ramp meter is out of the scope of this research, therefore a fixed-time meter will be used. The settings of the ramp metering installation are based on research to impacts of fixed-time ramp metering through microsimulation, by Poorjafari & Yue (2013). The green time is 2 s, the cycle time is 8 s. This results in one vehicle per green time. In order to create spillback at the on-ramp, the inflow into the on-ramp should be higher compared to the outflow at the ramp meter. The outflow at the ramp metering can be calculated based on the signal times (recall equation 3.15).

The ramp metering installation is switched off in the cooling-down period, in order to flush the traffic at the on-ramp towards the freeway. Due to the switching off, possible queues at the ramp can dissolve and all vehicles can leave the network.

4.2 Performance indicators

In this section the performance indicators to compare the different controller variants are presented. First the verification of the controllers is described, followed by the impact assessment of the controllers.

To know if the controllers function as intended, i.e. if they function in a technical perspective, the controllers are verified. For this verification no specific performance indicators are needed. Verification can be carried out based on detector data. By pausing the simulation and stepping through the algorithm in MATLAB it can be checked whether the calculations are performed correctly. Furthermore detector data can be visualized in figures in order to show the verification results.

To ensure all controllers need to deal with the same (situation specific) traffic demand, the numbers of vehicles in the network, the numbers of vehicles that have left the network, and the number of vehicles that still have to enter the network after the simulation, are checked. These should be the same for the controller variants in one situation.

In order to compare the impact of the developed controllers, i.e. impact assessment, performance indicators are needed. The impact assessment deals with: (i) a controlled part, i.e. the urban arterial (ii) an uncontrolled part, i.e. the freeway, and (iii) the total network. The effects on these three parts are made visible through performance indicators. These are presented in this section. Indicators that are frequently found in literature are used in this research, as well as indicators that are specific for this research.

In literature numerous impact studies regarding traffic signal control are presented. Akçelik (1998) describes delays as indicators. Van den Berg et al. (2007) describe total time spent by all vehicles in the network, this is a regularly used indicator. Taale et al. (1998) use travel

times to evaluate SCOOT. Al-Mudhaffar (2006) uses total delay and travel times to evaluate systems like SCOOT, SCATS and UTOPIA.

Besides these regularly used indicators, some other indicators are used which are specific for this research. The occurrence of spillback at the urban arterial and the freeway ramps is checked via the maximal queue lengths over time. The effects of the controllers on the traffic situation at the freeway is checked via speedcontourplots and slanted cumulative curves of the freeway. Furthermore traffic safety and comfort at the urban arterial is checked via the occupancy of the conflict area of intersections: if the conflict area is occupied, dangerous traffic situations might occur. Therefore, if the conflict area stays clear due to the controllers, traffic safety and comfort in the network increase.

The indicators to show the impact on the **urban arterial** are:

- maximum queue length (m) per control period for all traffic streams, to show the occurrence of spillback;
- travel times (s) from East towards West, to show the effect on travel times of traffic travelling through the bottleneck;
- travel times (s) from West towards East, to show the effect on travel times of traffic that does not have to pass the bottleneck;
- occupancy of conflict area at intersections via maximum queue lengths, to check the effect on traffic safety and comfort in the network.

The indicators to show the impacts on the **freeway** are:

- maximum queue length (m) per control period at ramps, to show the occurrence of spillback;
- travel times (s) on the freeway, to show the effect on travel times at the freeway;
- speedcontourplots, to visualize the effect of congestion at the freeway;
- slanted cumulative curves, to check the effect on the capacity drop at the freeway.

The performance indicators to indicate the **network performance** are:

- total distance travelled (km);
- total travel time (h);
- total delay time (h), i.e. the difference between the ideal travel time (without stops) and the realized travel time;
- total stopped delay (h), i.e. the delay gained due to speed of the vehicles being zero.

With the presented indicators the impact of the controller variants and the differences between the variants is clearly shown. All indicators give different insight into the working and effect of the controller. Therefore the performance indicators are not ordered based on importance: not all indicators can be compared to each other, and some authorities might have other preferences than others.

4.3 Simulation parameters

The control algorithm presented in the previous chapter showed some parameters that should be determined before the simulation. These parameters are: the length of the control period, the desired queue length at traffic streams, the minimum queue length at traffic streams, the critical difference in queue length between two time periods, the fuzzy membership input and output functions, the turn fractions, the origin-fractions, the average vehicle length, the stream capacity, the length of the cycle time, the minimum green time, the clearance time, the yellow time and the default green time.

An overview of the values of these parameters is shown in Table 4.1. The rationale behind the values of these parameters is already shown in the previous chapter, at the place the parameters first occurred. Therefore the table only shows the values used for the parameters.

Table 4.1 Overview of prespecified simulation parameters.

Simulation parameter	Symbol	Value
Control period	T	120 s
Desired queue	$l_{desired}$	90 m or 60 m
Minimum queue	l_{min}	45 m
Difference in queue	l_{diff}	30 m
Fuzzy membership functions	mf	multiple
Turn fraction	γ	calculated via origin-destination matrices
Origin-fraction	δ	calculated via origin-destination matrices
Average vehicle length	l_{veh}	6.5 m
Stream capacity	u	2300 veh/h
Cycle time	C	120 s
Minimum green time	g_{min}	7 s
Clearance time	$t_{clearance}$	2 s
Yellow time	t_{yellow}	3 s
Default green	g	equal for all phases

4.4 Summary

This chapter presented the simulation design to test the developed controllers. In simulation three degrees of freedom exist: (i) the network, (ii) traffic demand and (iii) control of the traffic in the network. To be able to clearly see the effects of the controller, the network and the traffic demand are fixed and therefore not varied.

The simulation framework showed MATLAB is the core of the simulations. MATLAB is the programming environment to control the situation. VISSIM is the test environment in which the traffic movements are simulated. MATLAB and VISSIM communicate via the COM Interface. The VRIs in VISSIM are controlled via CCOL. The default settings of the VRIs are local fixed time control.

The road network in which the controllers are simulated consists of a junction of a freeway and an urban arterial, there is one off-ramp and one on-ramp. The urban arterial has five controlled intersections, the ramps are located at the central intersection. To create the bottleneck situations, traffic demands for the base situations were calculated and applied via origin-destination matrices.

In order to compare the multiple controllers, performance indicators were presented. Indicators are derived for the total network, the controlled part (i.e. the urban arterial) and the uncontrolled part (i.e. the freeway). The urban arterial is assessed on maximum queue lengths, travel times and the occupancy of conflict areas. The freeway is assessed based on maximum queue lengths at the ramps, speedcontourplots, slanted cumulative curves and travel times. To be able to see the effects on the total network, the total travel time, total delay time, total distance travelled and total stopped delay will be used.

The developed controllers are tested in the simulation design that is presented in this chapter. The results of the simulation runs are presented in the next chapter.

Chapter 5. Results and discussion

The controllers that are developed in chapter 3 (recall the overview of the control approaches in Table 3.3) are tested with the designed simulation of chapter 4 (recall the framework in Figure 4.1). This fifth chapter presents and discusses the results of the simulation runs. Section 5.1 shows the verification of the developed controllers, the section shows if the controllers function in a technical perspective. Sections 5.2, 5.3 and 5.4 respectively show the impact assessment of bottleneck situations 1, 2 and 3. Each impact assessment first shows the network performance of the different controllers, this performance is explained based on detailed figures and numbers of the impact on the freeway and the urban arterial. Section 5.5 presents a discussion regarding the results, the section shows limitations of the research which should be taken into account if conclusions are drawn. The last section of the chapter gives a summary regarding the results of the simulation runs.

5.1 Verification

The algorithms of the controller variants are verified in order to check if the controllers function in a technical perspective.

First the calculations that should be made are verified. By pausing the simulation and stepping through the algorithms it can be concluded that the calculations that should be made during the simulation, are made.

Secondly the working of the controller is verified: do the calculations result in the expected traffic behaviour. Verification results for one controller variant are shown. Verification results for other variants would show more or less the same figures, and are therefore not included in the report. Figure 5.1 presents these verification results of control variant 1.2 with detection variant 3 in a figure. In the top part of the figure the measured queue length at the bottleneck is shown, the queue length also presents indirectly the space in the bottleneck (i.e. a large queue results in less space). If the queue is larger than 100 m the queue exceeds the length of the queuing area. In the middle part of the figure the calculated green time for the bottleneck is presented. This green time is calculated based on the current flow and the queue length in the bottleneck (recall the controller development in chapter 3). The bottom part of the figure shows the realized flow at the bottleneck. These results show that if the queue becomes larger than approximately 90 m, new green times are calculated. These green times result in an increase in flow at the bottleneck. These results show the space in the buffer (bottleneck in this case) is increased due to increased green times.

Thirdly the number of vehicles in the network, the number of vehicles that have left the network and the latent demand (i.e. the number of vehicles that still needs to enter the network after the total simulation time) are checked per bottleneck situation. In each situation

the number of vehicles in the network and the number of vehicles that have left the network should be equal since the demand pattern is equal. The latent demand in all situations should be zero. If the latent demand is not zero, this means some vehicles could not enter the network. The latter could result in a buffer outside the network that distorts the total network performance: vehicles could not enter the network and are therefore not taken along the total delay etc., but due to the lower amount of traffic in the network delays of other vehicles might decrease, hence resulting in distorted network performance. The network performance of the variants shows the number of vehicles in the network and the number of vehicles that have left the network, are approximately equal for all controllers in one bottleneck situation. The latent demand for all controllers is zero. The exact values are presented in Appendix C.

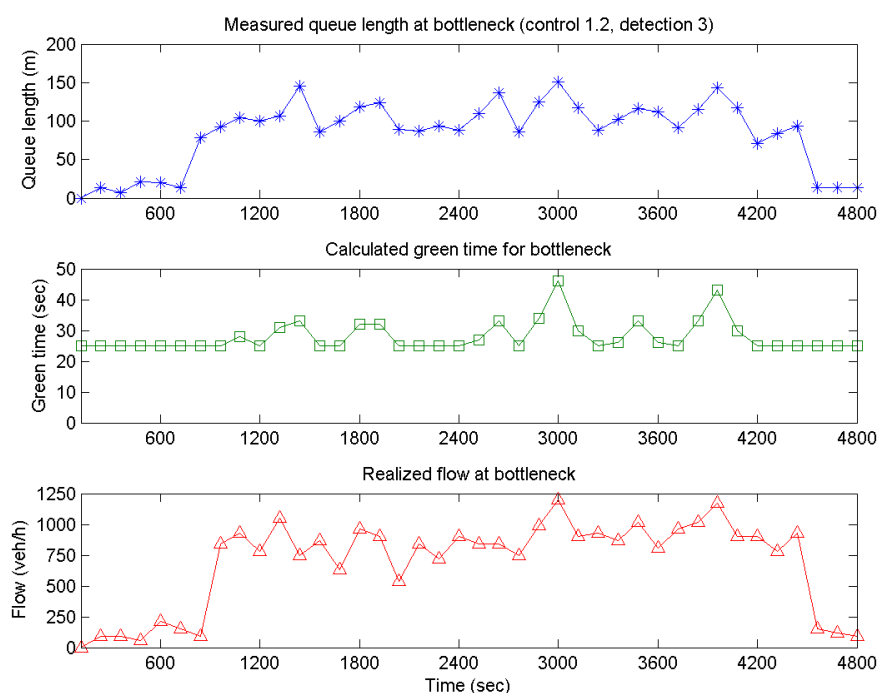


Figure 5.1 Verification results for control variant 1.2 with detection variant 3. At the top the measured queue is presented, in the middle the calculated green times and at the bottom the realized flow.

5.2 Impact assessment situation 1

For the first situation detection and control variants are designed. Detection is needed to control the situation. In order to measure the impact of the detection variant, all three control variants are simulated with all three detection variants. This results in nine different 'variants'. First the results of the detection are shown. Thereafter the controllers in combination with the detection, i.e. the bottleneck controllers, are shown.

5.2.1 Bottleneck detection

The three detection variants have no effect on the traffic conditions, since they only detect bottleneck situations. Figure 5.2 presents the queue length at the buffer (or stream) at which a bottleneck situation is created, in combination with the bottleneck detection (i.e. true or false) of the three variants.

The figure shows the first variant only detects a bottleneck situation if the queue is larger than the desired queue. The second variant also detects a bottleneck situation if the difference between the current and previous queue exceeds the critical value. This results in an earlier

detection of an upcoming bottleneck situation: the first variant detects a bottleneck situation at 960 s, the second at 840 s. The third variant uses both queue lengths and flows at the stream as inputs to the detection process, this results in more bottleneck detections. Figure 5.3 presents the flow and queue length related to the detection of variant 3. This shows the influence of the use of an extra input value, in this case the flow. The first and second variant do not detect bottleneck situations at 1560 s, 2160 s, 2400 s and 2760 s; the third variant does detect bottleneck situations at these points in time due to relative low flows at these times.

Appendix D presents these figures for the stream downstream of the bottleneck stream. This shows similar results: the third variant detects more bottleneck situations due to the use of more input values.

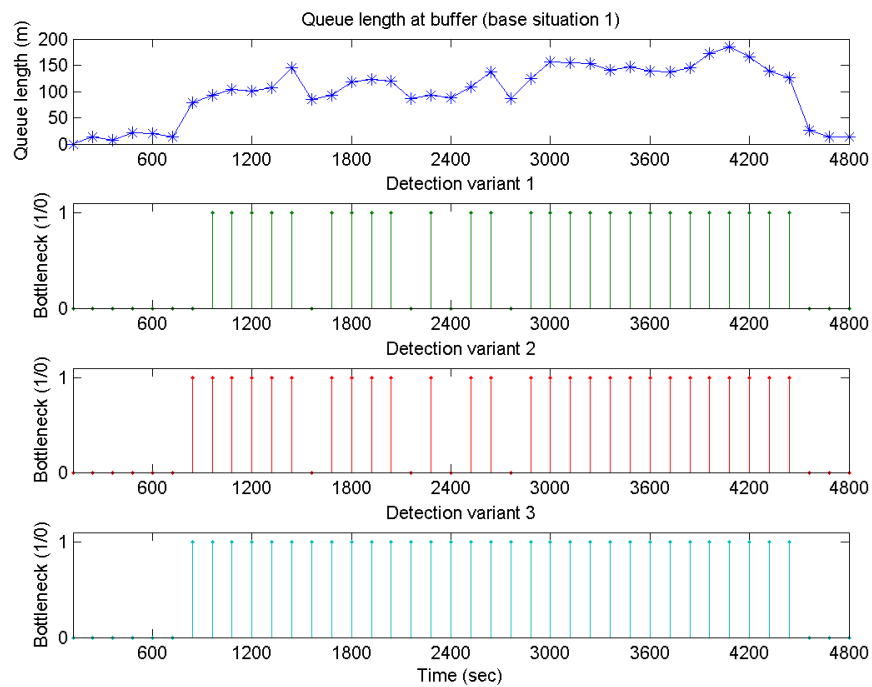


Figure 5.2 Queue length at the bottleneck stream and related detection status (i.e. true or false) of the three detection variants.

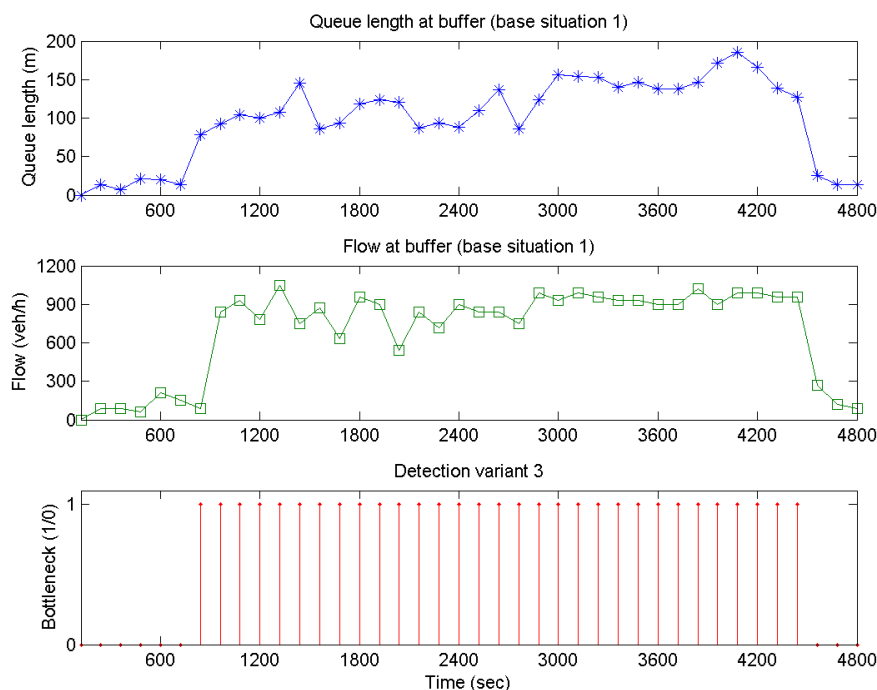


Figure 5.3 Queue length and flow at the bottleneck stream and related detection status of the third detection variant (i.e. fuzzy logic approach).

5.2.2 Bottleneck control

This section presents results regarding the controllers in situation 1. First the network performance is discussed. Followed by the effect of the different detection variants on the controllers. Thereafter the effect of the controllers on the urban arterial is shown.

Network performance

Nine controllers are simulated in the first situation. The network performance of these controllers is shown in Table 5.1. The table presents the total distance travelled, total travel time, total delay time and total stopped delay for the base situation and each variant. Percentage changes in network performance are included in Appendix D.

The table makes clear control variants 1.1 and 1.2 show better network performance compared to variant 1.3. Controller 1.1 shows a reduction in total travel time of approximately 5 hours compared to the base situation. Controller 1.2 shows an even larger reduction in total travel time compared to the base situation: between approximately 7 (-2.8%) and 9 (-3.3%) hours, depending on the used detection variant. Controller 1.3 shows no improvement in total travel time compared to the base situation. The controller shows an increase in total travel time between approximately 3 (+0.9%) and 5 (+1.7%) hours, depending on the used detection strategy. The differences in total travel time correspond with the differences in total delay and total stopped delay. The total distance travelled is approximately equal for all controllers, except for controller 1.3 with detection variant 3. The latter shows a decrease of approximately 3 km in total distance.

The differences in network performance can be explained by looking at the buffer strategy of the controllers. The first two controllers try to get the traffic as fast as possible out of the network, by giving preference to the usage of downstream buffers. The third controller spreads the traffic over the up- and downstream buffer. The latter means the third controller decreases green time upstream and increases green time downstream. The reduction in green time upstream results in an increase in delay for traffic in that buffer. This explains why the network performance of the third controller is worse compared to the other two. The performance of the second controller is better than the first one, since it uses more downstream buffers.

Therefore more downstream buffers will get an increase in green time, resulting in better network performance.

Table 5.1 Network performance of the controllers in situation 1.

Performance indicator	Controller			
Detection 1	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled (km)	12748.9	12748.9	12748.8	12748.3
Total travel time (h)	270.6	265.5	263.0	273.0
Total delay time (h)	116.5	111.4	108.9	118.9
Total stopped delay (h)	94.9	90.6	88.4	96.9
Detection 2	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled (km)	12748.9	12748.9	12748.8	12748.3
Total travel time (h)	270.6	265.5	262.9	274.2
Total delay time (h)	116.5	111.4	108.8	120.1
Total stopped delay (h)	94.9	90.6	88.3	98.2
Detection 3	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled (km)	12748.9	12748.9	12748.8	12745.9
Total travel time (h)	270.6	265.5	261.6	275.1
Total delay time (h)	116.5	111.4	107.5	121.0
Total stopped delay (h)	94.9	90.5	87.3	99.3

Influence of detection variants on controllers

Furthermore, Table 5.1 shows the detection variants have influence on the controller performance. The third detection variant detects more bottlenecks due to the usage of more input variables (recall section 5.2.1), and therefore the controller is switched on more often. More detected bottleneck situations result in a better network performance for the first two controllers. For the last controller the increase in detection has no positive effect on the performance: more detected bottleneck situations result in more delays due to the usage of upstream buffers, as explained in the previous.

Based on the network performance the third detection variant suits best for controllers 1.1 and 1.2. Controller 1.3 should be combined with detection variant 1. However, by looking at the maximum queue lengths at the bottleneck stream, it becomes clear controller 1.3 should also be used in combination with detection variant 3.

Figure 5.4 shows the queue length at the bottleneck stream by using detection variant 1. It shows high variations for the third controller. It seems that the controller effectively reduces the queue length at the bottleneck stream, but due to the rigid way of detecting bottleneck situations the variations are high. Figure 5.5 makes clear the more fluent approach of detection variant 2 has a positive effect on the third controller: the queues are shorter and the variation is lower. The queue length and variation in queue length improve further by using the third detection variant, shown in Figure 5.6. Due to the multiple inputs and the more fluent detection, the third controller performs better with regard to the queue length at the bottleneck situation.

The results of the controllers in combination with the third detection variant will be discussed in the ensuing, since the last detection variant gives best performances, i.e. best network performance for controller 1.1 and 1.2 and best control performance for controller 1.3. The results of controllers in combination with the other detection variants are included in Appendix D.

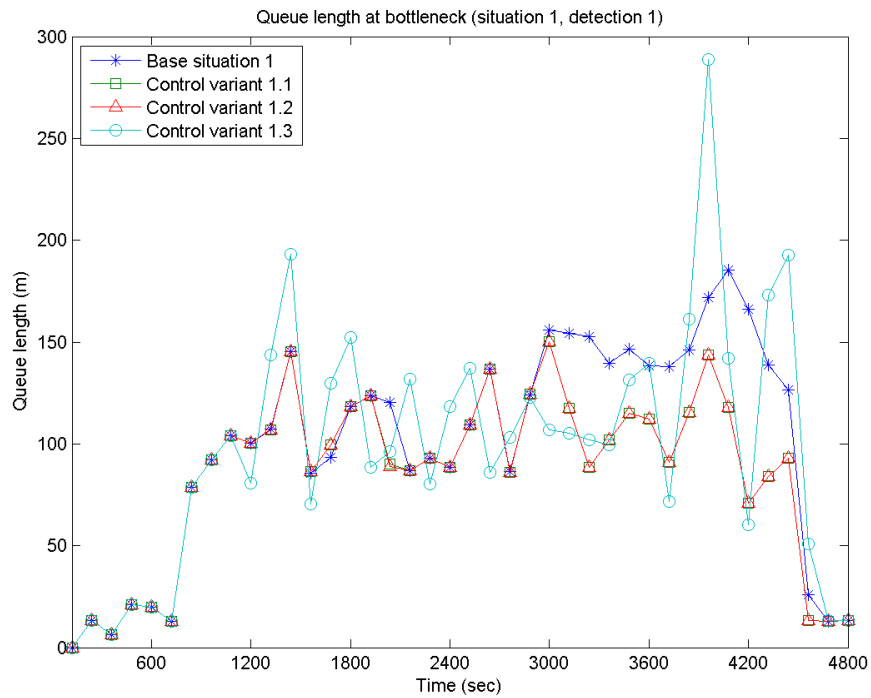


Figure 5.4 Queue length at the bottleneck stream in situation 1, using the controllers in combination with detection variant 1.

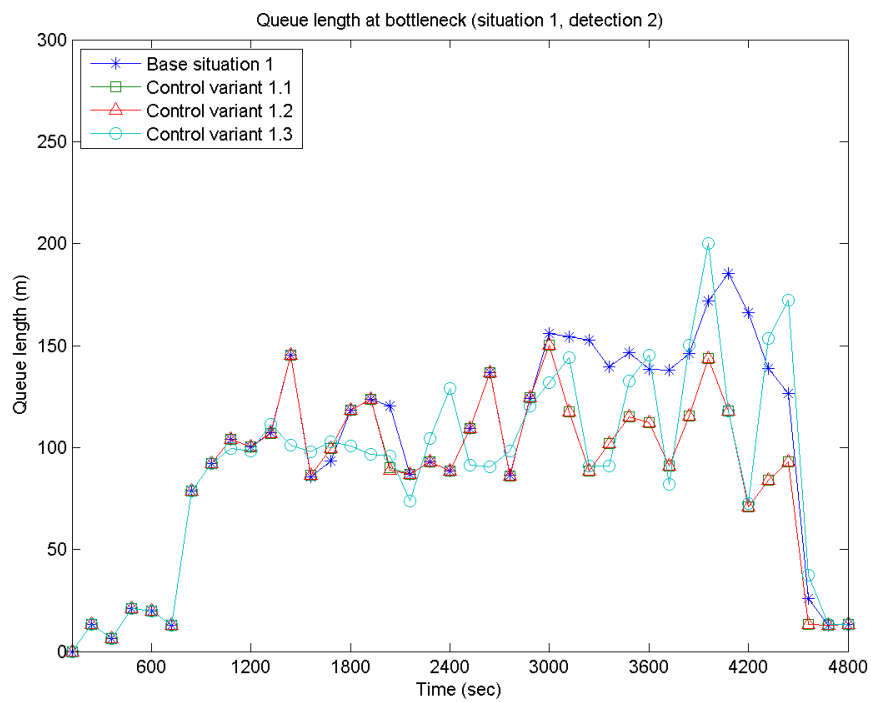


Figure 5.5 Queue length at the bottleneck stream in situation 1, using the controllers in combination with detection variant 2.

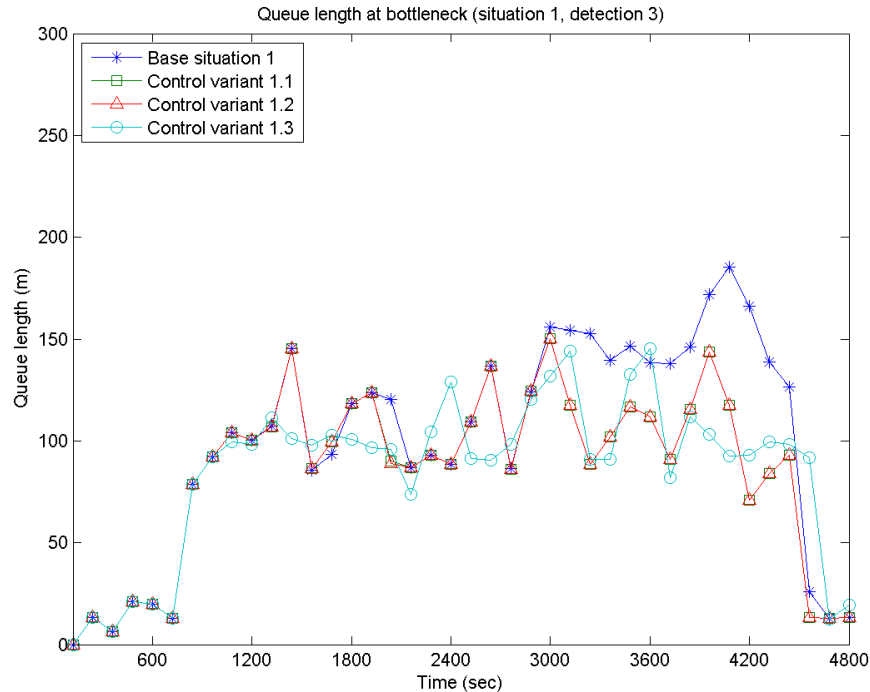


Figure 5.6 Queue length at the bottleneck stream in situation 1, using the controllers in combination with detection variant 3.

Effect on urban arterial

Figure 5.6 shows the effect of the controllers on the queue length at the bottleneck stream. It shows the queue in the base situation often results in spillback, this occurs if the queue length exceeds 100 m. Since variant 1.2 only differs from variant 1.1 in using more downstream buffers, control variant 1.1 and 1.2 show equal effects on the bottleneck stream.

The results show the third controller performs best with regard to reducing the queue at the bottleneck stream: despite some peaks, the queue is managed around the spillback level, i.e. 100 m. These peaks can be due to fluctuations in traffic demand. Since the controller calculates new green times based on the current flow, it is possible the new green times are too low due to sudden increases in traffic demand.

The first and second controller only show good results if the queue is getting above 150 m, this can be seen at 3000 s. This can be explained by the method of calculating new flows. The controllers calculate new flows based on a summation of the current flow and the surplus of traffic. The effect of adding the surplus is larger, if the surplus becomes larger. The latter is the case if the queue becomes larger. This effect can be seen in the figure.

In Figure 5.7 the queue length downstream of the bottleneck stream is presented. This shows the queue length varies more than in the base situation, but is still below the spillback level. The queue due to control variant 1.3 sometimes is smaller compared to the base situation. This is the effect of the usage of upstream buffers, because due to upstream buffering the traffic is set on hold upstream.

Figure 5.8 shows the queue length upstream of the bottleneck stream. The main stream is shown in the figure, i.e. the upstream stream with direction East to West. Two side streams are also used as buffers, but since less traffic is travelling from those streams, these are less interesting to show. The figure shows that the first two control variants do not change the queue upstream of the bottleneck. This is due to the preference of using downstream buffers. The upstream queue caused by the third controller is larger compared to the base situation. This clearly shows the buffering of traffic. The queue at the bottleneck stream decreases (recall Figure 5.6) if the queue upstream increases. After 3000 s spillback occurs due to the buffering.

For the base situation as well as for all control variants there is no queue formed at the intersections that reaches the upstream intersection, and hence blocks the conflict area.

Figure 5.9 and Figure 5.10 show the effect of the controllers on the travel time on the urban arterial, respectively from East to West and from West to East. Traffic which is travelling from East to West is hindered by the bottleneck situation. Traffic in the opposite direction should not be hindered.

The travel times from East to West (Figure 5.9) show results corresponding with previously presented tables and figures. The travel times due to controllers 1.1 and 1.2 decrease, since the traffic is moved out of the network as fast as possible. Controller 1.2 shows slightly better results than controller 1.1 since it uses more downstream buffers. Controller 1.3 shows an increase in travel times due to the upstream buffering: especially if the queue at the buffers reaches high levels, after 3000 s, a clear increase in travel times is shown.

Travel times in the opposite direction (Figure 5.10) are improved for all control variants compared to the base situation. This is due to the vehicle dependent signal control that is activated if a buffer is used: the default settings for the VRIs are fixed settings, if a buffer is used the remaining green time is divided based on the current flows (i.e. vehicle dependent control). Control variant 1.1 only uses one up- or downstream buffer, and shows therefore the smallest improvement. Control variant 1.2 can use three downstream buffers. If all three are used, all three get vehicle dependent control. This results in large travel time improvements. The last controller, 1.3, improves the travel times mainly because it uses also the upstream buffer. At the upstream buffer the green time is decreased, in order to buffer. Therefore the opposite direction can get an increase in green time, this results in improvements in travel time on the West to East direction.

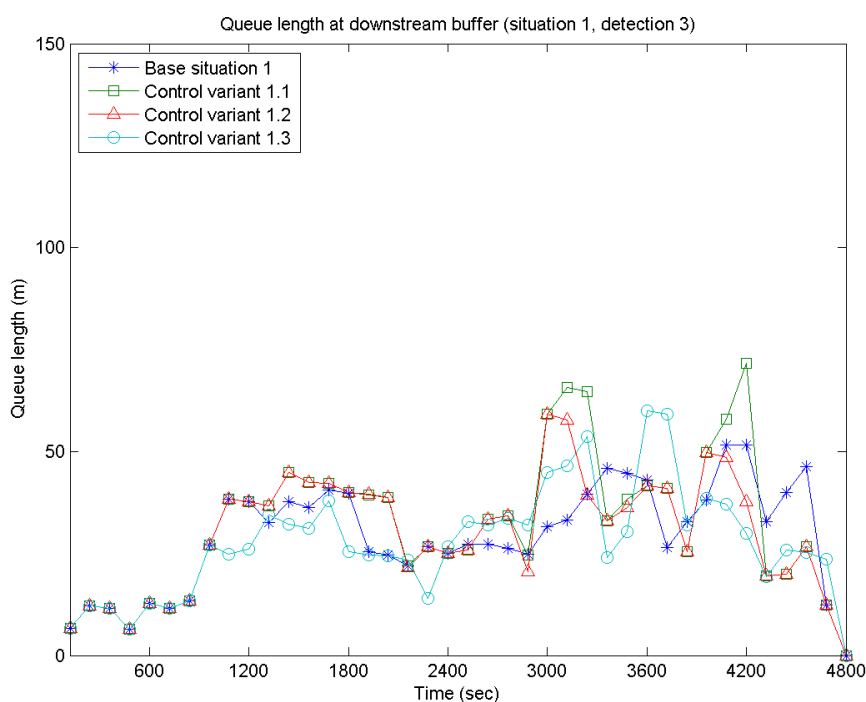


Figure 5.7 Queue length downstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 3.

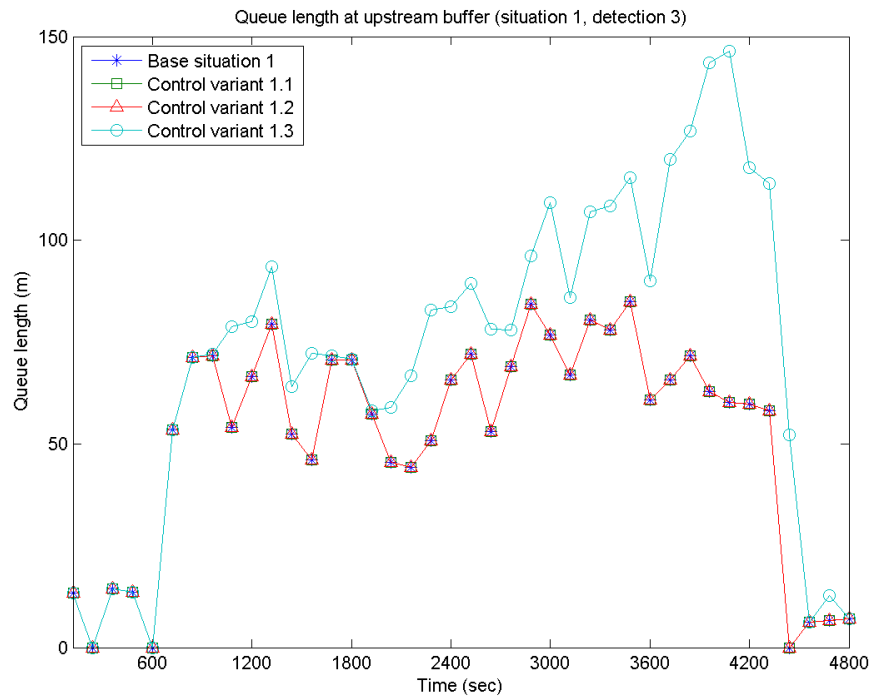


Figure 5.8 Queue length upstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 3.

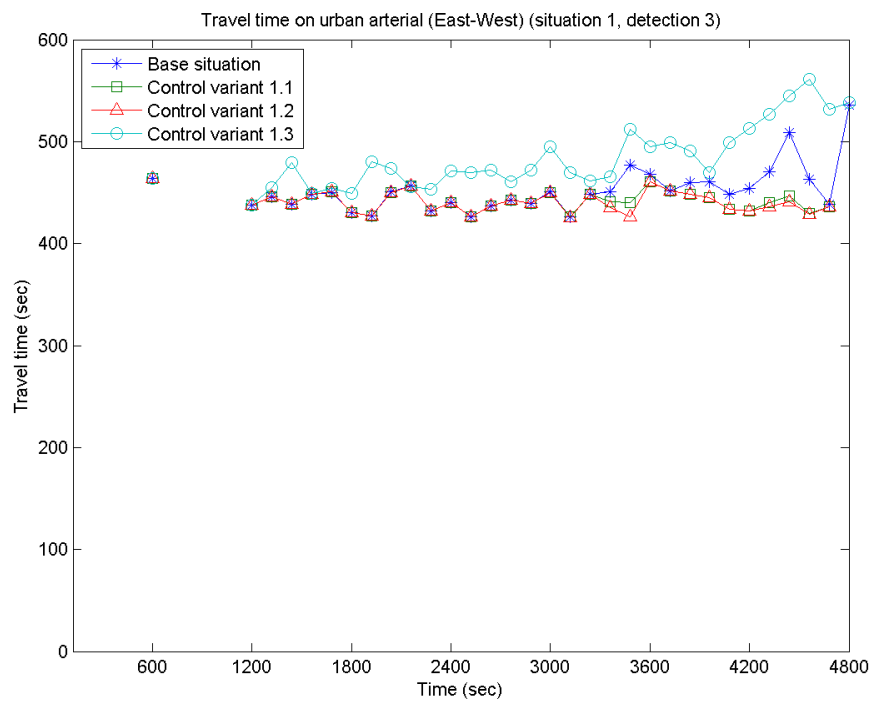


Figure 5.9 Travel time on the urban arterial from East to West in situation 1, using the controllers in combination with detection variant 3.

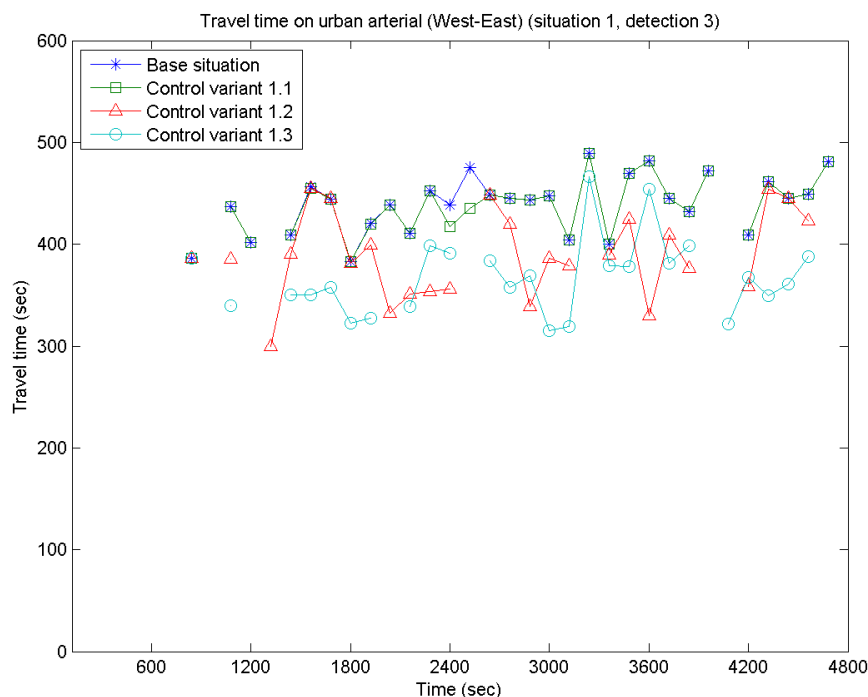


Figure 5.10 Travel time on the urban arterial from West to East in situation 1, using the controllers in combination with detection variant 3.

5.3 Impact assessment situation 2

This section discusses the impact assessment of situation 2. First the tuning of the outflow target is presented. This is followed by the network performance. Thereafter the effect on the queue length at the off-ramp is shown. The section ends with the impact on the freeway and the urban arterial.

Tuning outflow target

For the second situation the queue at the off-ramp is managed by setting the outflow at the ramp equal or higher to the inflow. The inflow based on the origin-destination matrix (recall Appendix B) is 1100 veh/h. Based on tuning results the target outflow should be set at 1400 veh/h. If the target is set below 1400 veh/h, spillback occurs (figure included in Appendix E). This is explained by two causes: (i) fluctuations in traffic demand and (ii) the lay-out of the ramp. First of all fluctuations in traffic demand exist which result in different flows compared to the origin-destination matrix. Second of all, the lay-out of the off-ramp (one-lane ramp splitting into two one-lane queuing areas) causes a difference between the actual target and the origin-destination matrix target. If the queue at one of the traffic lights (i.e. left or right) exceeds the length of the queuing area, the entrance to the other queuing area might be blocked. The latter can result in a queuing area which is not filled. With a non-filled queuing area, the calculated flow will not be reached during the green time, simply because the amount of waiting traffic is too low. Therefore the target outflow should be higher than the flow based on the origin-destination matrix.

Network performance

Table 5.2 shows the network performance of the variants controlling the second situation. The controllers clearly improve the traffic situation: in the controlled situation the total travel time decreases with approximately 150 hours (-38.7%). The other network performance indicators show corresponding numbers. Percentage change in network performance are included in Appendix E. The large improvement in network performance is due to the preventing of

spillback and hence preventing congestion on the freeway. Since large amounts of traffic travel at the freeway and no trade-off is shown at the urban arterial (explained in more detail in further sections), preventing congestion results in large overall improvements. The difference in total travel time between controller 2.1 and 2.2 is approximately 1 hour. This is due to the use of three downstream buffers in the second control variant. Therefore the traffic can leave the network faster, hence resulting in an improved travel time.

Table 5.2 Network performance of the controllers in situation 2.

Performance indicator	Controller		
	Base	Control 2.1	Control 2.2
Total distance travelled (km)	11386.9	11398.2	11398.7
Total travel time (h)	390.5	240.4	239.3
Total delay time (h)	253.1	102.7	101.6
Total stopped delay (h)	131.9	81.9	81.0

Queue length at off-ramp

Figure 5.11 shows the controllers prevent spillback from the off-ramp towards the freeway. In the base situation the queue spills back after 1200 s. The controllers prevent this by increasing the outflow at the ramp, presented in Figure 5.12.

The small differences in queue lengths (and corresponding flows) between controllers 2.1 and 2.2 are due to the usage of more downstream buffers by controller 2.2. The changes in signal settings of the downstream buffers influence the traffic travelling past the off-ramp intersections. This might lead to small differences in outflow due to differences in traffic patterns at the off-ramp intersection. However, these changes are very small. Figure 5.12 also shows that the target flow is not reached. First of all this is due to the traffic demand: the origin-destination matrix shows the demand is lower than the target. Secondly the queuing areas might be blocked due to the ramp lay-out (recall the explanation at the start of section 5.3).

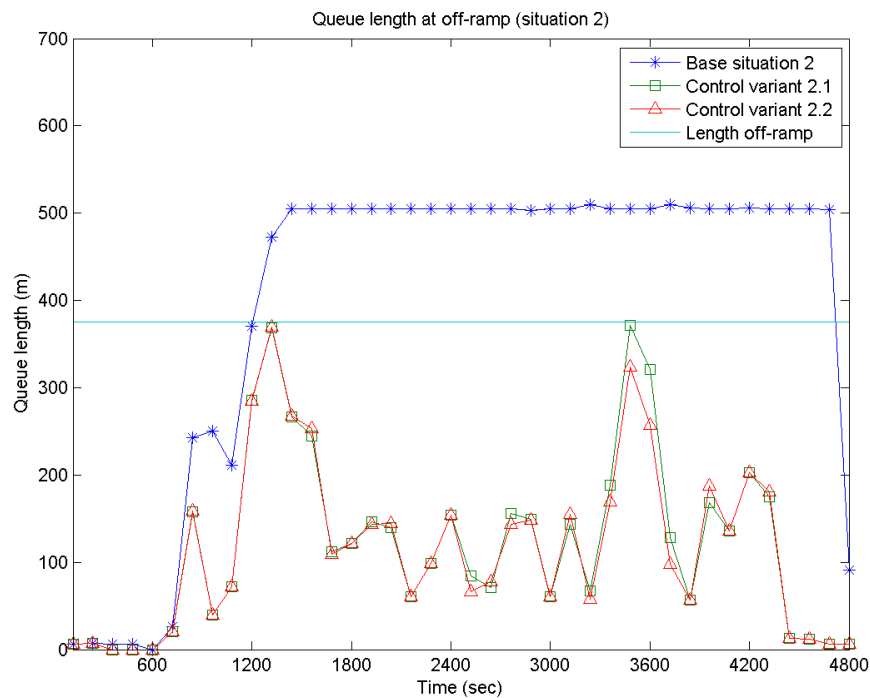


Figure 5.11 Queue length at the off-ramp for the base situation and the controllers in situation 2, compared to the off-ramp length.

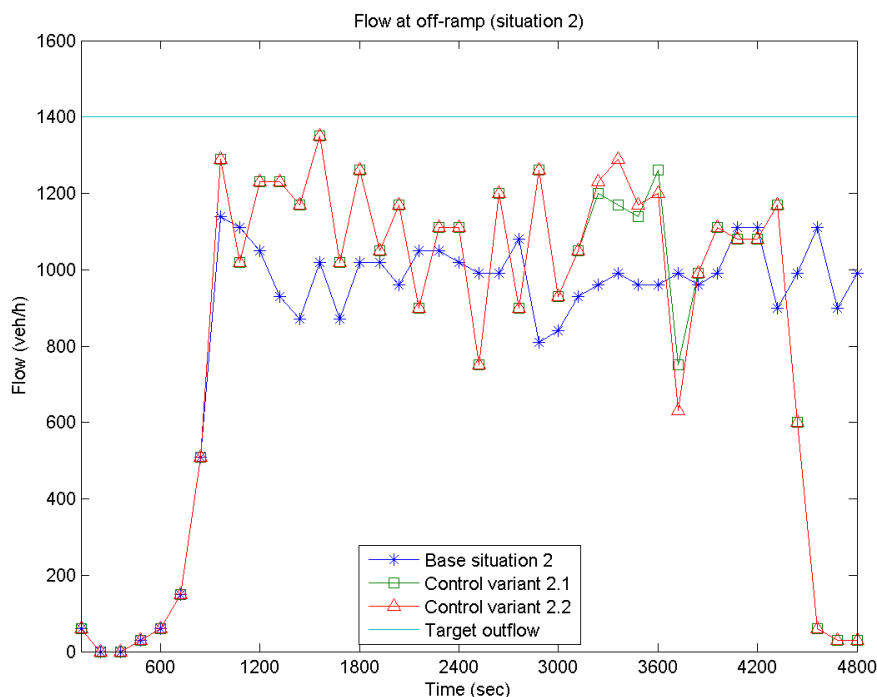


Figure 5.12 Flow at the off-ramp for the base situation and the controllers in situation 2, compared to the target outflow.

Effect on freeway

The queue length at the off-ramp showed spillback was prevented. Figure 5.13 presents the speedcontourplot of the freeway without the use of a controller. A speedcontourplot shows the average speed measured at multiple freeway locations over multiple time periods. Such a plot clearly visualizes the location and time congestion starts.

The figure shows a queue arising at the start of the off-ramp, at 1400 m, around 1200 s. Recall the moment spillback from the ramp towards the freeway occurred: 1200 s. Figure 5.14 shows the speedcontourplot if the best performing controller (based on the network performance), 2.2, is used. This shows the queue at the off-ramp is removed. Some minor speed reductions are shown. These are due to the queue at the off-ramp that almost reaches the freeway (at 1440 s and 3480 s), or due to merging behaviour. The speedcontourplot of controller 2.1 is almost the same and is included in Appendix E.

The speedcontourplots showed positive effects on the freeway. Through the use of slanted cumulative vehicle plots the effects on the capacity drop, and therefore the throughput at the freeway, can be shown.

Cumulative vehicle plots show the cumulative number of vehicles over time that have passed a certain location at the freeway. Cumulative plots never have a decreasing slope, since the number of vehicles will never decrease. If congestion occurs some vehicles will pass the location with delay, this is shown in the plot as a smaller slope.

In order to amplify the features of the curves a scaling rate q_0 is distracted from the curve, resulting in slanted cumulative curves. The rate is an estimation of the capacity of the road. If the location of the curve is chosen just after the bottleneck (in this case the off-ramp), the occurrence of the capacity drop can be visualized. Since the capacity drop is a reduction in capacity, the slanted cumulative curve will show a sudden change in slope if the capacity drop occurs. With this information the time the drop is postponed can be checked. If the capacity drop does not occur and the scaling rate is chosen properly, the curve should have a steady positive slope.

Figure 5.15 presents the slanted cumulative curve of the second situation, measured just after the beginning of the off-ramp. It clearly shows the capacity drop in the base situation at 1200

s. The sudden increase in the slope at 4000 s is due to the solving of the congestion at the end of the simulation (due to reducing traffic demand). In the controlled situations the capacity drop does not occur. This corresponds with the speedcontourplots.

Since the capacity drop does not occur in the controlled situations, the throughput at the freeway can be maintained at a high level, resulting in smaller travel times. This is shown in Figure 5.16. The figure shows large improvements in travel times for the controlled situations. The freeway travel times in the controlled situation equal the free flow travel time.

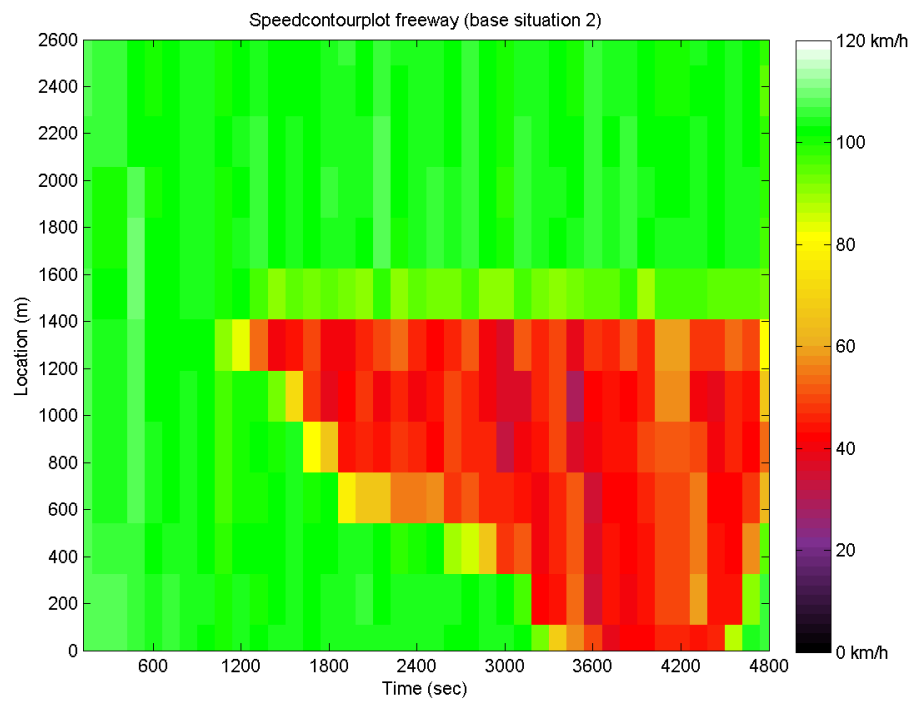


Figure 5.13 Speedcontourplot of the freeway in situation 2 without the use of a controller, the off-ramp is located at 1430 m.

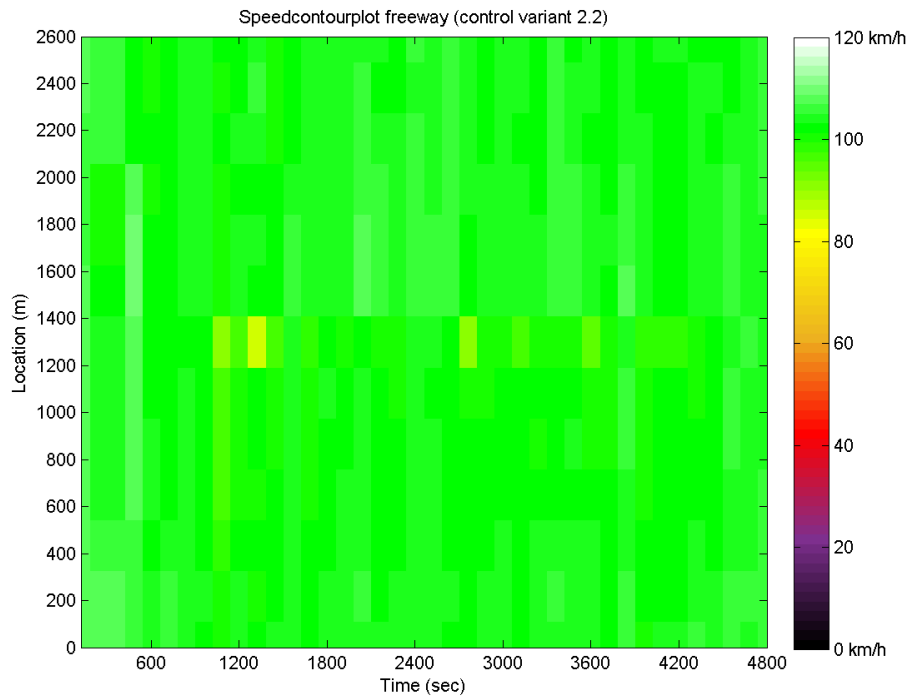


Figure 5.14 Speed contour plot of the freeway in situation 2 with the use of controller 2.2, the off-ramp is located at 1430 m.

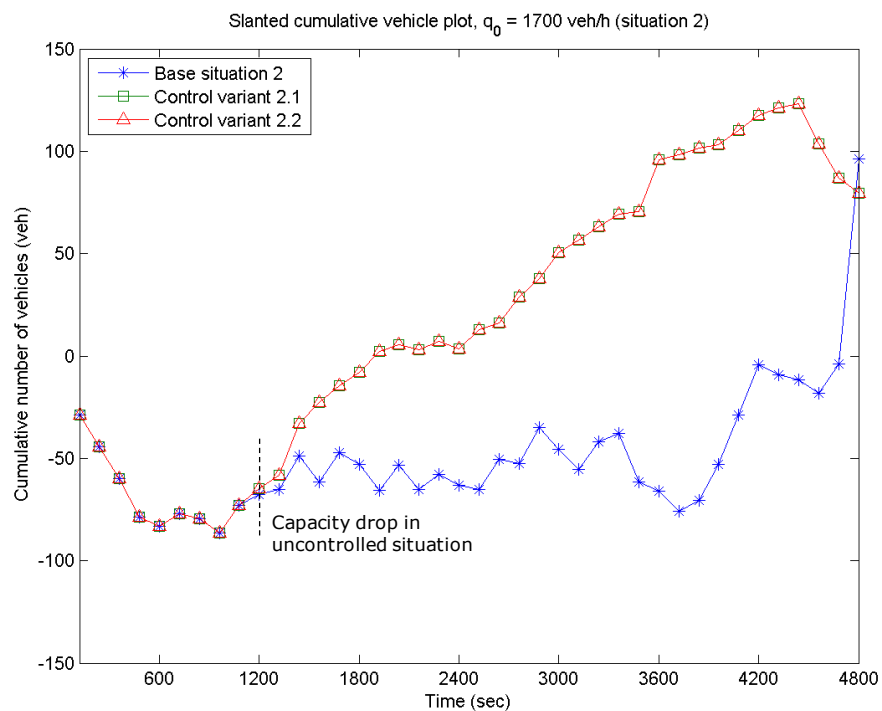


Figure 5.15 Slanted cumulative curve for the base situation and the controllers in situation 2, measured just after the beginning of the off-ramp. In the figure the moment the capacity drop occurs is indicated.

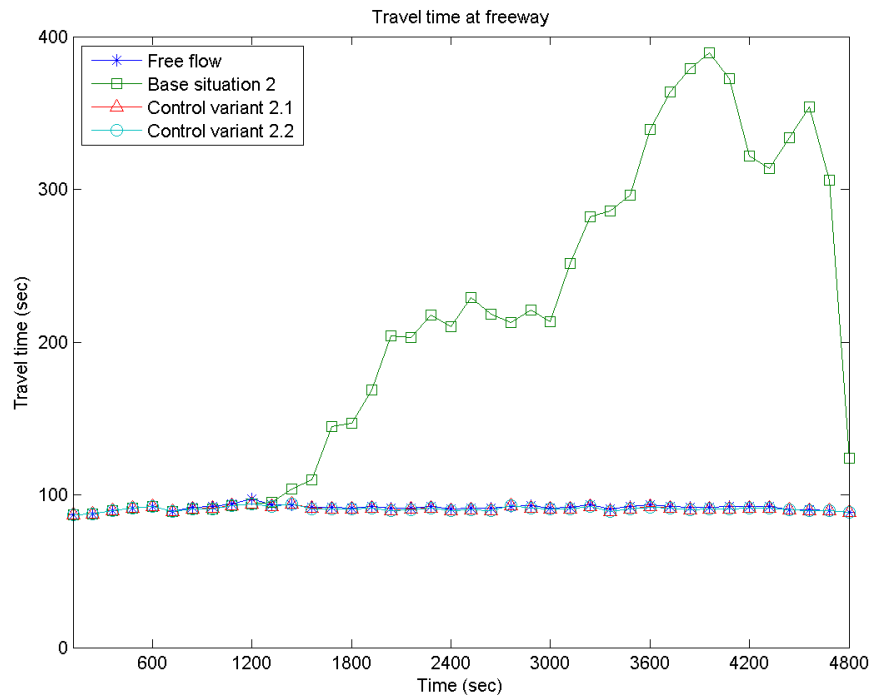


Figure 5.16 Travel time at the freeway for the base situation and the controllers in situation 2.

Effect on urban arterial

The previous figures showed great improvements regarding the freeway. A trade-off is possible at the urban arterial: the freeway conditions improve while the urban conditions decrease.

Figure 5.17 and Figure 5.18 show the travel times on the urban arterial, respectively from East to West and vice versa. The figures show there is no trade-off, this corresponds with the queue lengths. Although extra traffic is added at the urban arterial, a trade-off is not visible. This might be due to a too low traffic demand at the urban arterial. The travel times are even improved if control variant 2.2 is used, since this variant uses three downstream buffers. If these buffers are used a vehicle dependent control is actuated, resulting in better signal control. This results in improved travel times.

The queue lengths at the urban arterial do not increase due to the controllers. Since the queues do not increase there are also no queues at the intersections formed that reach the upstream intersection, and hence block the conflict area.

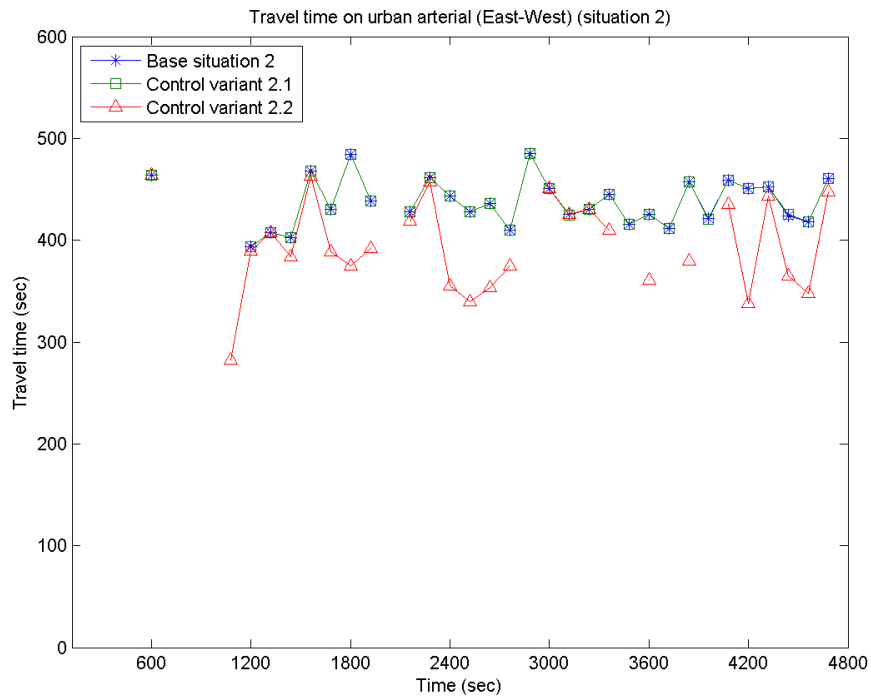


Figure 5.17 Travel time on the urban arterial from East to West for the base situation and the controllers in situation 2.

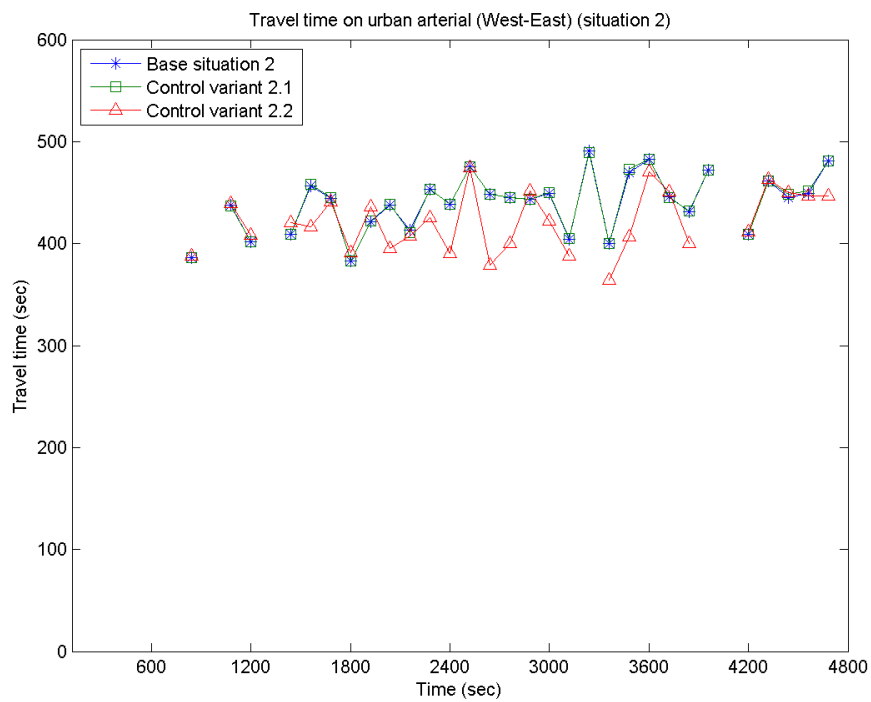


Figure 5.18 Travel time on the urban arterial from West to East for the base situation and the controllers in situation 2.

5.4 Impact assessment situation 3

In the third bottleneck situation all controllers are switched on after 1440 s, at this moment the queue at the on-ramp (i.e. 190 m) almost exceeds the length of the on-ramp (i.e. 200 m). In order to keep equal conditions for all controllers, the controllers are only switched off if the ramp metering installation is flushed at the end of the simulation. The latter is at 4320 s.

The impact assessment first shows the results of the tuning of the inflow target. Thereafter the network performance is shown. This is followed by the queue length at the on-ramp and the effects of the controllers on the freeway and urban arterial.

Tuning inflow target

In order to manage the queue at the on-ramp, the inflow towards the on-ramp is limited. The measured flow at the ramp metering installation is around 450 veh/h, this is the outflow of the on-ramp. By setting the target inflow at 450 veh/h, the queue length stays below the length of the on-ramp. A higher target inflow results in spillback, a figure that shows multiple target inflows is included in Appendix F.

Network performance

Table 5.3 presents the network performance of the controllers in the third situation. Percentage changes in network performance are included in Appendix F. The deployment of the ramp metering installation shows positive results on the network performance: due to the ramp meter the total travel time decreases with approximately 14 hours. The use of the controllers shows an increase in total travel time, total delay and total stopped delay, compared to the base situation with the ramp metering. Controllers 3.1, 3.2, 3.3 and the ST1Light show an increase in total travel time compared to the ramp meter situation of respectively 10 (+2.8%), 18 (+5.1%), 21 (+5.9%) and 20 (+5.6%) hours. Compared to the base situation without ramp metering, the first controller shows a decrease in total travel time of approximately 4 hours (-1.1%).

The changes in total delay and total stopped delay correspond with these changes. The total distance travelled in each situation also shows differences, these correspond with the number of vehicles that are still in the network at the end of the simulation (recall Appendix C). This increase in network performance is due to the buffering of traffic: the traffic is buffered in order to prevent spillback from the on-ramp towards the urban arterial and this buffering leads to increased delays for the vehicles in the buffers.

The difference between the controllers is due to the amount of used buffers. Controller 3.1 uses the least buffers and therefore shows less delays, the other two controllers and the ST1Light use more buffers and therefore show more delays. The differences between the last three controllers is due to differences in buffer strategy. These are shown in the following sections.

Table 5.3 Network performance of the controllers in situation 3.

Performance indicator	Controller					
	Base, no TDI	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1 Light
Total distance travelled (km)	15914.9	15892.4	15885.3	15882.6	15894.5	15887.0
Total travel time (h)	356.3	342.8	352.3	360.3	363.0	361.8
Total delay time (h)	179.5	166.4	175.9	184.0	186.7	185.5
Total stopped delay (h)	67.1	107.3	124.9	132.7	135.9	134.4

Buffering, and also the use of ramp metering installations, is the relocation of delays in a network: the delay at the freeway is reduced, the delay at the ramp and the urban arterial is increased. In the ideal situation the network performance improves, like the base situation with the ramp meter switched on compared to no ramp metering.

However, important to note is that the ramp meter is not switched off in situations in which spillback occurs. This would happen in real life, recall the problems with the metering time in the literature survey. Hence resulting in platoons entering the freeway, with resulting congestion. The latter would have a negative effect on the network performance. This however is not included in the simulation: the ramp meter stays active, even if spillback occurs.

Because of this possible switching off of the ramp meter, it is interesting to see the results in the ensuing regarding the occurrence of spillback: if spillback can be prevented, the metering time would increase. Therefore, although the network performance decreases, still positive results can be shown.

Queue length at on-ramp

Figure 5.19 shows the queue length at the on-ramp for the situations with an active ramp meter. Without ramp metering there is no queue, since the traffic can flow into the congested freeway. The figure shows that controllers 3.1, 3.2 and 3.3 keep the queue under the length of the ramp, the small differences are due to the buffer strategies. The ST1Light does not prevent spillback at all times. If the queue exceeds the length of the on-ramp, the ST1Light reduces the queue. But then again it becomes too large. The latter might be because the ST1Light uses the space at the on-ramp as a factor to check if buffering is needed (the parameter is set at 85%: it is allowed to have a queue at the ramp which is 85% of the length of the total ramp): if there is more space, the buffering rate can decrease. This might be the cause of the increasing queue lengths. Furthermore the parameters of the ST1Light might need extra calibration and tuning, for example the parameter that determines the desired queue at the ramp. The other control variants try to manage the queue at the on-ramp by ensuring the inflow towards the on-ramp (i.e. the target flow) equals the outflow at the on-ramp. Note these variants, contrary to the ST1Light, do not use the space at the on-ramp as a parameter, but use the target flow as an objective.

In the base situation the queue at the on-ramp reaches the conflict area of the freeway intersection if spillback from the on-ramp to the arterial occurs: after 1440 s this is the case, recall Figure 5.19. In the controlled situations this spillback is managed and the conflict area stays clear, this is shown in Figure 5.20 via print screens of the simulation. By using no controller the conflict area stays clear for 1680 s (35% of the time). By using controller 3.1, 3.2 and 3.3 the conflict area at the freeway intersection always stays clear for a total of 4800 s (100% of the time). Due to the use of the ST1Light spillback sometimes occurs and therefore the conflict area is not always clear. By using the ST1Light the conflict area is clear for 3960 s (82.5% of the time).

The queue at the on-ramp is reduced by reducing the inflow towards the ramp, shown in Figure 5.21. To create a more clear figure, the figure only shows the control variants, since these control the inflow and the others do not. The inflow for the base situations is shown in Appendix F. Furthermore the figure is zoomed in: it does not show the large increase in flows after 4320 s (this is the moment the ramp metering and hence the controller is switched off), since this is less interesting. The full figure is also included in Appendix F.

Figure 5.21 shows corresponding results with the queue at the ramp. Controllers 3.1, 3.2 and 3.3 manage the flow around the target, while the ST1Light fluctuates. The small variations can be explained by fluctuations in traffic demand. The large variations in the ST1Light are again due to the usage of the space at the on-ramp as a factor to determine the buffering rate, as described previously.

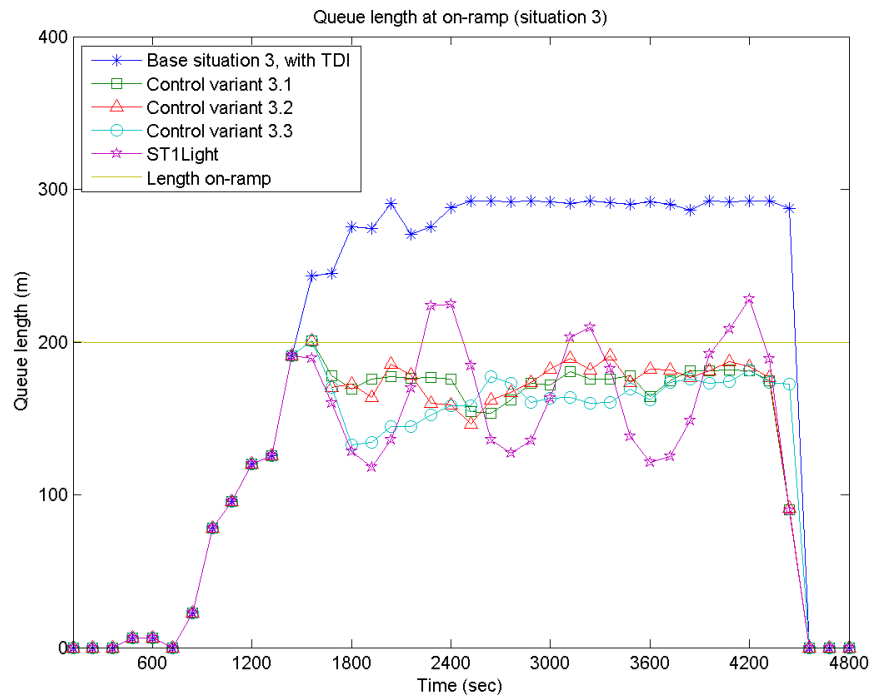


Figure 5.19 Queue length at the on-ramp in situation 3 for the base situation (with ramp meter) and the controllers, compared to the length of the on-ramp.

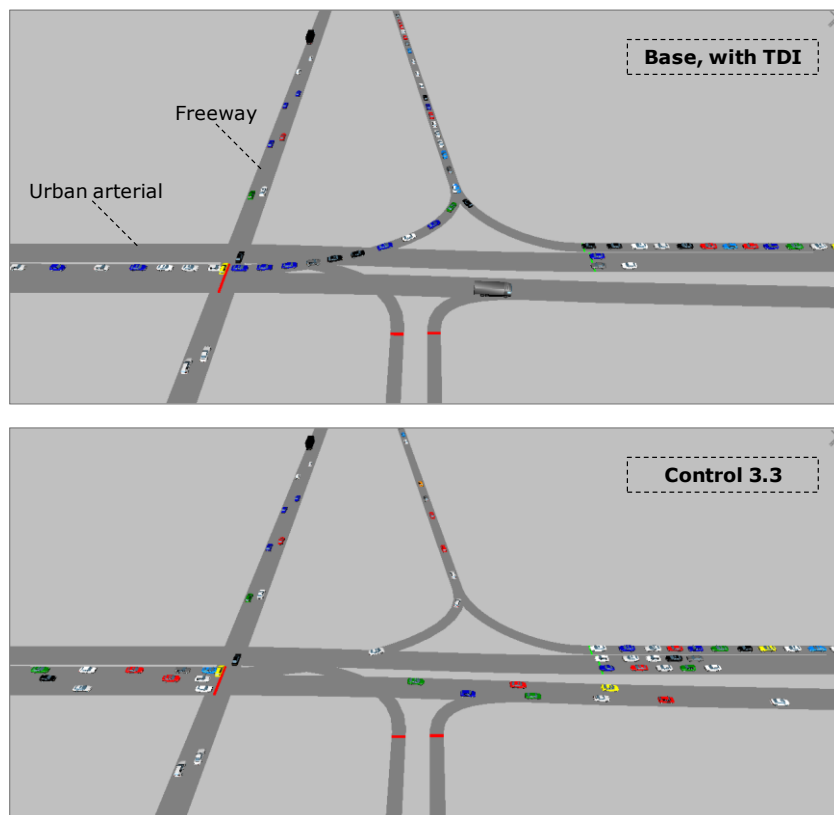


Figure 5.20 Print screens of the traffic situation in the VISSIM simulation, at 2640 s, for the base situation with the ramp meter active and for the situation with controller 3.3.

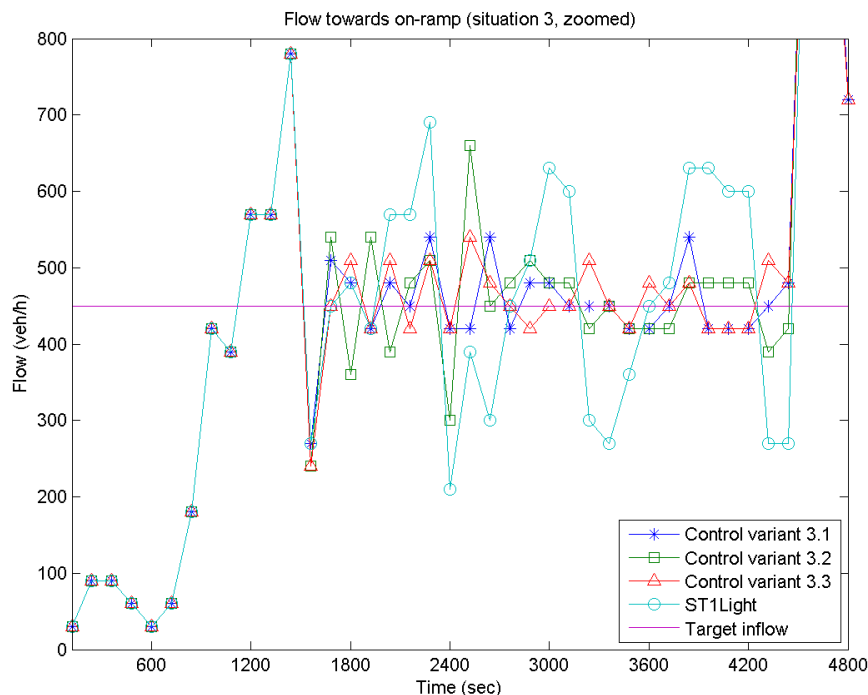


Figure 5.21 Inflow towards the on-ramp for the different controllers in situation 3, compared to the target inflow. The plot zooms in and therefore does not show the large flows after 4320 s, at that time the ramp meter is switched off and the traffic is flushed into the freeway.

Effect on freeway

The network performance showed the positive effect of the ramp meter. This is clearly shown in speedcontourplots of the freeway. Figure 5.22 shows the situation without activation of the ramp meter, Figure 5.23 shows the situation with usage of the ramp metering installation. In the first figure the start of congestion is just after the end of the on-ramp, at 2300 m, around 1080 s. In the second figure this congestion is mostly removed, despite some small decreases in speed. The latter might be due to merging behaviour, since the traffic demand at the freeway is still almost near capacity, congestion can simply occur. The speedcontourplots of the situation with the controllers are almost similar to Figure 5.23 and are therefore not shown here, but included in Appendix F. These plots also show some small congestion occurring due to the high traffic demand.

By setting the metering rate even stronger, i.e. longer cycle time with the same green time, the inflow towards the freeway would be reduced and the congestion would probably be totally gone. The latter however is not part of this research.

Similar to the impact assessment of situation 2, a slanted cumulative curve is produced, presented in Figure 5.24 (the cumulative curve is included in Appendix F). The slanted curve is produced just after the location of the on-ramp. The curve shows the capacity drop is postponed with 1680 s due to the use of the ramp meter and the controllers. Thereafter the capacity drop occurs, this again might be due to the high traffic demand and merging behaviour. The controllers show similar results, since they all deal with the same metering rate at the ramp meter.

The prevention of congestion on the freeway results in large improvements in travel times, presented in Figure 5.25. The figure indicates the travel times in the controlled situations are almost equal to free flow travel time. The improvements correspond with the speedcontourplots and the slanted cumulative curve.

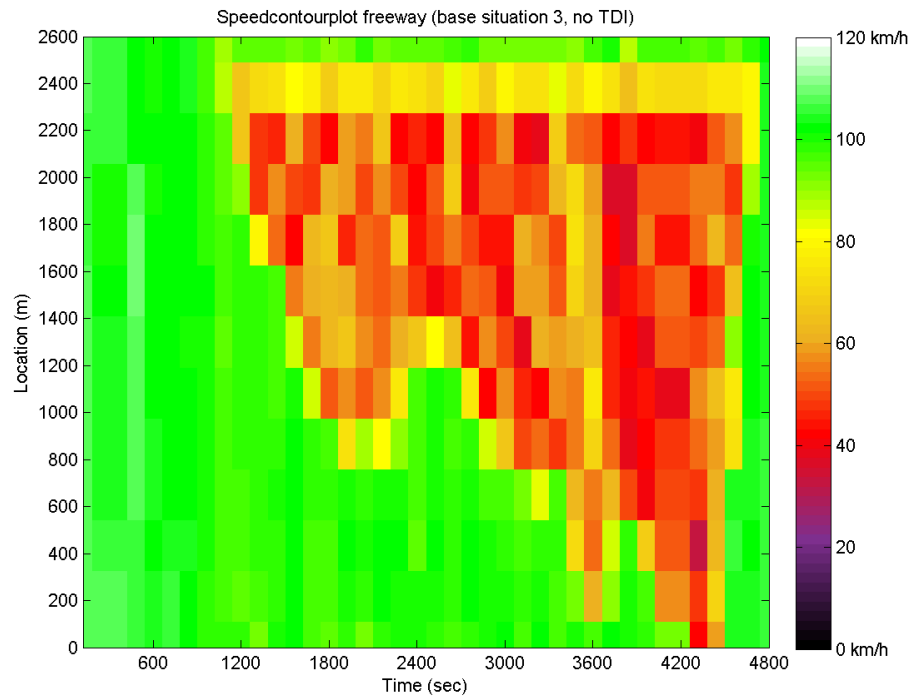


Figure 5.22 Speedcontourplot of the freeway in situation 3 without the use of ramp metering, the on-ramp is located at 2300 m.

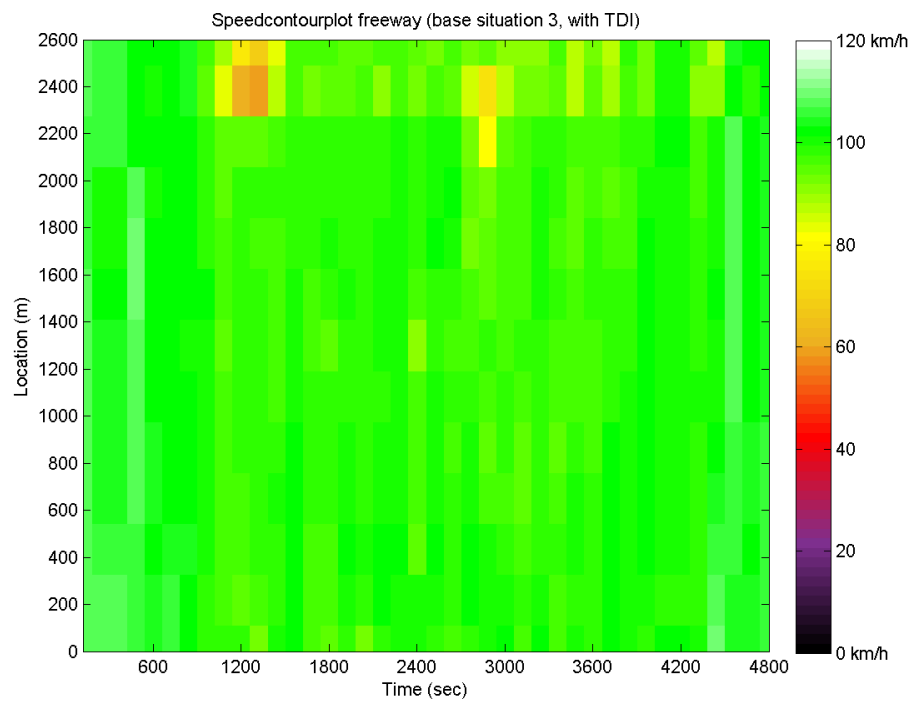


Figure 5.23 Speedcontourplot of the freeway in situation 3 with the use of ramp metering, the on-ramp is located at 2300 m.

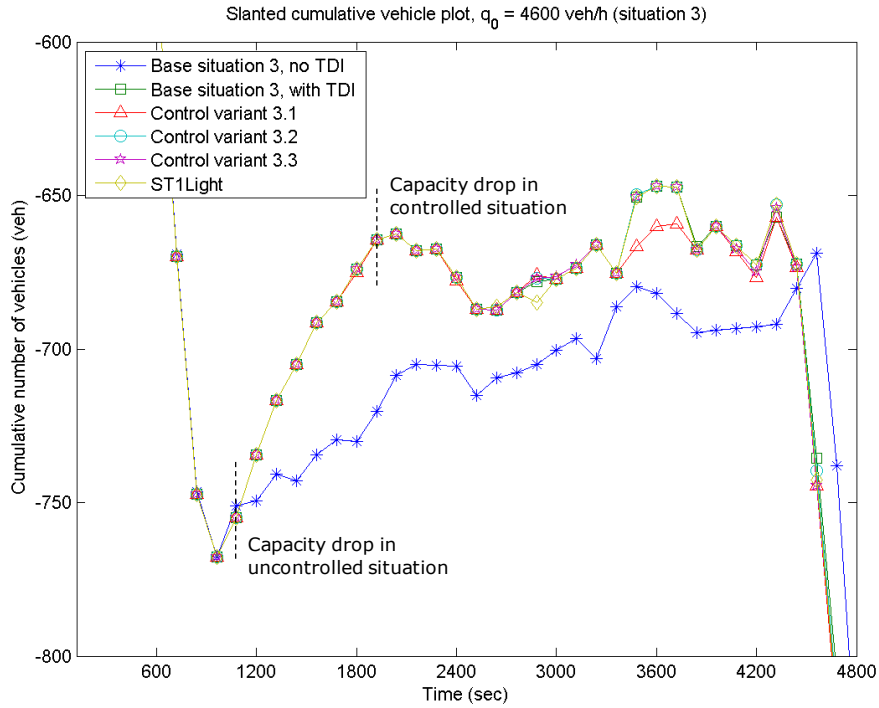


Figure 5.24 Slanted cumulative curve for the base situation (with ramp meter) and the controllers in situation 3, measured just after the end of the on-ramp. In the figure the moment the capacity drop occurs is indicated.

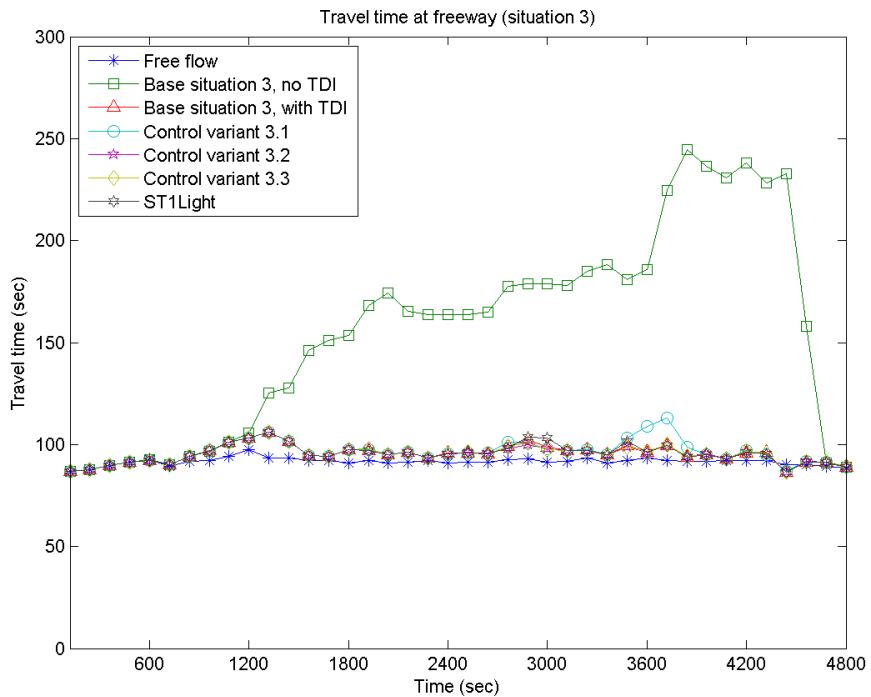


Figure 5.25 Travel time for the base situation and the controllers at the freeway in situation 3.

Effect on urban arterial

The network performance already showed the controllers do not improve the situation for the complete network. At the freeway the situation improves, the trade-off is made with the urban arterial at which the situation does not improve. Despite these overall performances, there are some positive results. This section shows these results.

Figure 5.26 and Figure 5.27 present the queue length at the first upstream buffers, respectively the East and the West buffer. The first upstream buffers are the streams at the intersection directly leading to the on-ramp. The queuing area is 100 m long. Spillback to the conflict area of the Western upstream intersections occurs if the queue exceeds 225 m. Spillback to the conflict area of the Eastern upstream intersections occurs if the queue exceeds 200 m. The length of the queue directly corresponds with the space in the buffer, therefore via the queue length the filling of the buffer can be checked.

Figure 5.26 shows the controllers cause the queue length at the first Eastern buffer to increase compared to the base situation, i.e. the buffer is filled due to the controllers. Controllers 3.2 and 3.3 fill the buffer the slowest, this is due to the use of three upstream buffers by these controllers. Therefore the inflow into the buffer is smaller compared to the other controllers. The first Western buffer, shown in Figure 5.27, also gets filled. The differences in queue lengths between the two buffers might be due to the lay-out of the network. Both figures show the buffers are filled, the time in which they are filled differs slightly per variant. The first Eastern buffer is filled after approximately 1800-2040 s, the exact moment differs per variant. The first Western buffer is filled after approximately 1680 s.

Spillback towards the upstream conflict area occurs at both buffers, this is indicated in the figures. At the Eastern buffer the conflict area gets occupied after 2520 s in the base situation, or if controller 3.1 or the ST1Light is used. Controllers 3.2 and 3.3 keep the conflict area clear until 3600 s. This is due to the usage of more buffers by controllers 3.2 and 3.3 compared to the other controllers. At the Western buffer the conflict area gets occupied after 2520 s for controllers 3.1 and 3.2, after 3000 s for controller 3.3 and the ST1Light, and after 3480 s for the base situation. The differences in queue lengths between the two buffers are due to the network lay-out and the buffer strategy.

Figure 5.28 and Figure 5.29 present the queues at the second upstream buffers, respectively on the East and West side. The queuing area is 100 m, spillback to the upstream intersection occurs if the queue reaches 500 m.

The queues in the situation without controllers is smaller, since there is no buffering and therefore the vehicles are queuing in front of the on-ramp. By using the controllers the second upstream buffers get also filled, except for controller 3.1 which uses only the first upstream buffers. The differences are due to the buffer strategies. Controller 3.3 tries to fill the buffers equally. This results in more equal queue lengths of both buffers (i.e. East and West) if the queues are compared to those due to controller 3.2. The latter does not take into account the equal filling of the buffers.

The queuing area of the second Eastern buffer is filled after approximately 3000 s. The area of the second Western buffer after approximately 2880 s. Thereafter the traffic demand is such that the queues are filling up a large part of the road. The conflict areas of the upstream intersections are not reached, these are located at 500 m upstream of these intersections.

The queues at the third upstream intersections do not exceed 50 m, due to the low traffic demand at these intersections. The figures regarding the filling of these buffers are therefore included in Appendix F and not presented here.

The travel times at the urban arterial show corresponding results with the queue lengths at the buffers: the travel times increase. Figure 5.30 and Figure 5.31 show the travel times at the arterial, respectively from East to West and vice versa. The figures show that the buffering leads to higher travel times at the arterial. These figures clearly indicate that if the buffers are filled (recall Figure 5.26 till Figure 5.29), travel times increase at the urban arterial.

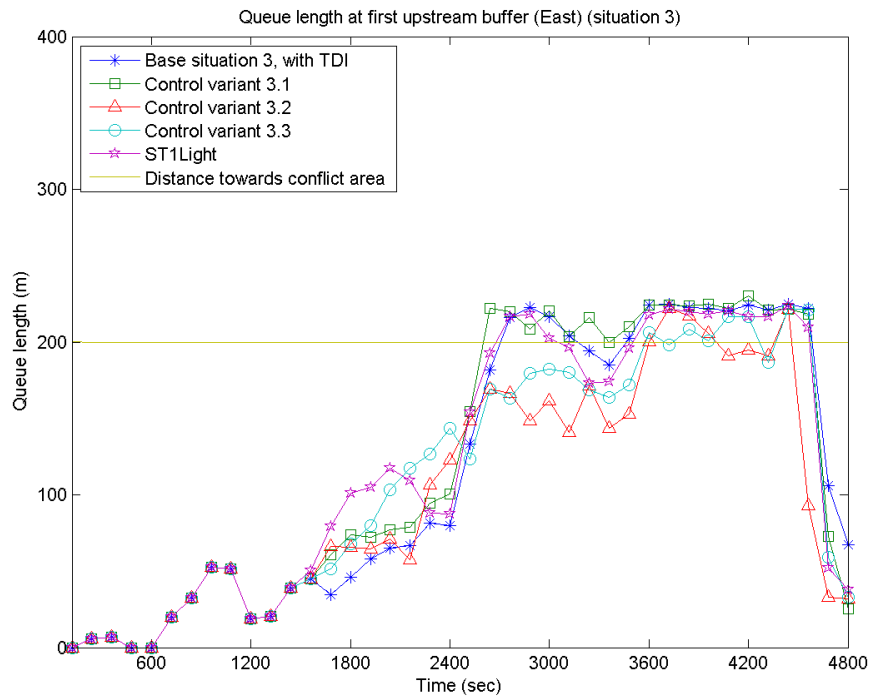


Figure 5.26 Queue length at the first upstream buffer (East) for the base situation (with ramp meter) and the controllers in situation 3.

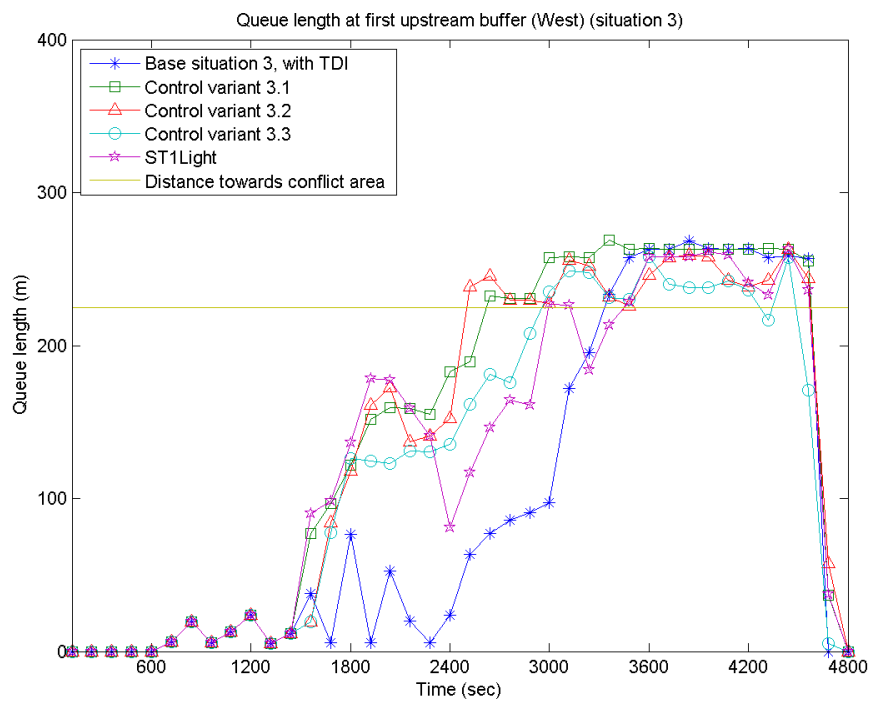


Figure 5.27 Queue length at the first upstream buffer (West) for the base situation (with ramp meter) and the controllers in situation 3.

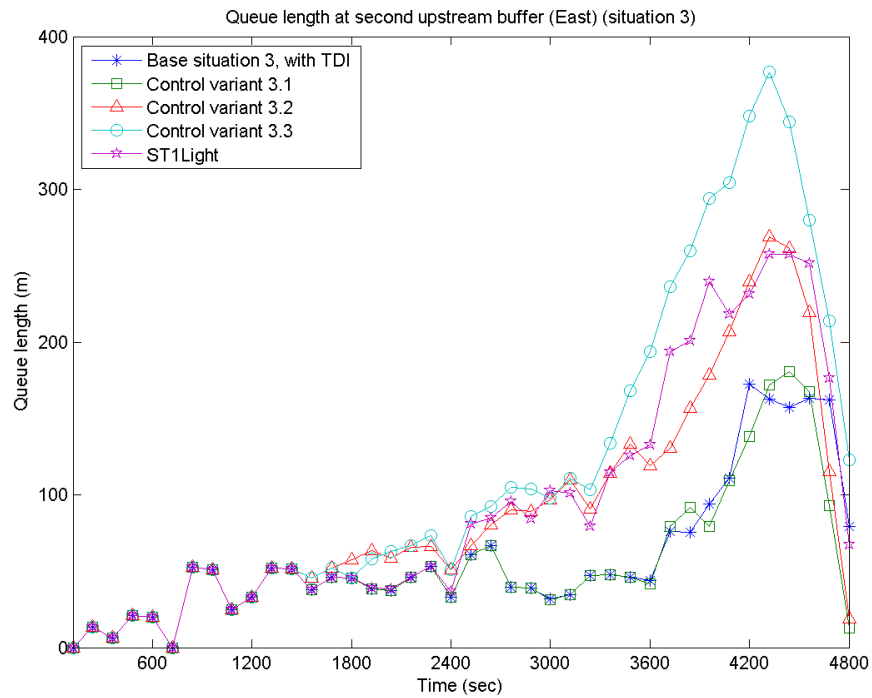


Figure 5.28 Queue length at the second upstream buffer (East) for the base situation (with ramp meter) and the controllers in situation 3.

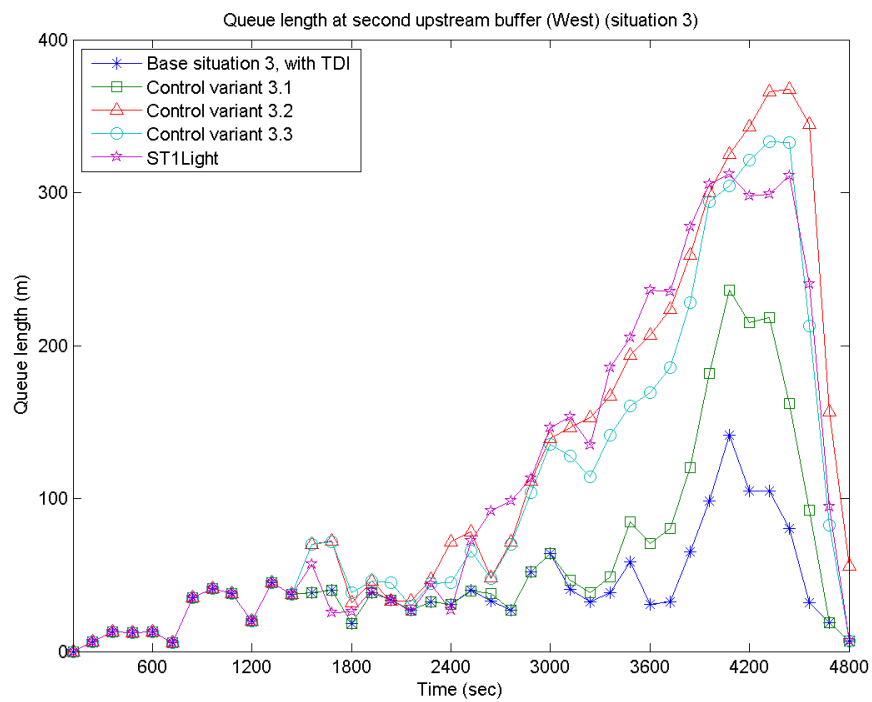


Figure 5.29 Queue length at the second upstream buffer (West) for the base situation (with ramp meter) and the controllers in situation 3.

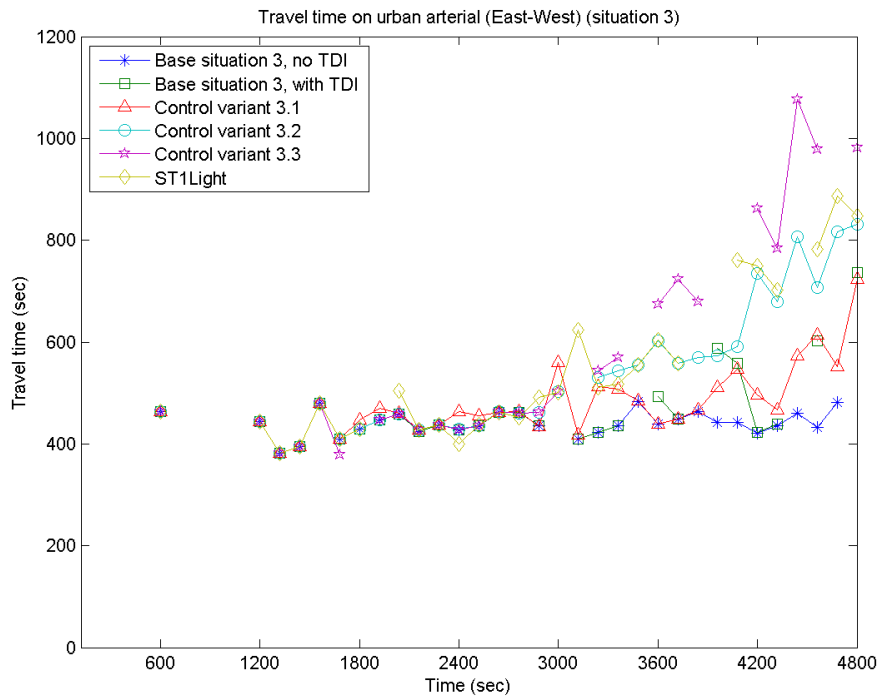


Figure 5.30 Travel time on the urban arterial from East to West for controlled and uncontrolled situations in situation 3.

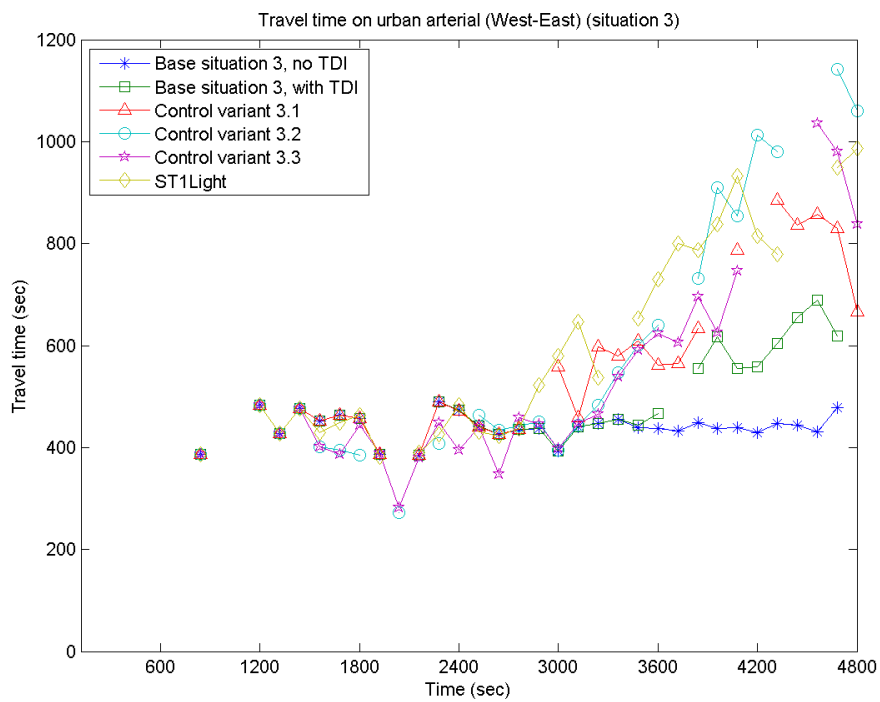


Figure 5.31 Travel time on the urban arterial from West to East for controlled and uncontrolled situations in situation 3.

5.5 Discussion

Previous sections showed the simulation results of the developed controllers. This section discusses the limitations of the research, which are for example due to the use of simulation tools. These need to be taken into account in order to draw conclusions and give recommendations.

Input data

The controllers use queue lengths as inputs for the algorithms. In the simulation these can be measured without an error-margin. In reality this is much harder. Within the Praktijkproef Amsterdam this was also a problem, for which Fileradar (a small company founded by two PhD students from Delft University of Technology) came up with a solution to give better estimates for queue lengths.

Another input are the origin-destination matrices. These are used to derive turn fractions. The matrices are known in the simulation. Again, in reality this is much harder.

Both types of input values are part of ongoing research. Through the enrichment of data via in-car measurements (i.e. floating car data), estimates for queue lengths might be improved. Furthermore origin-destination matrices might be improved due to the increasing data regarding trips of persons.

Dynamic cycle time

The developed controllers use a fixed cycle time that equals the control period and the monitoring period of the data measurements. In reality this might not be the case, and therefore the algorithm would have to be changed.

A change could be to update the control period to the calculated (ideal) cycle time after the calculation, hence the control period should still equal the cycle time, but the control period is not a fixed time period anymore. The monitoring period of the data measurements could in this case also be updated to the length of the cycle time.

If the monitoring period of the data measurements cannot be equal to the cycle time or control period, for any reason whatsoever, the data measurements should be recalculated. If for example the cycle time is 90 s and the monitoring period is 60 s, it might be the case that at a branch of an intersection a small maximum queue is measured during the monitoring period, because the branch's green period was in this monitoring period and therefore the queue could not grow to full size. In this case the data measurements could be recalculated by, for example, taking the maximum queue of the current and previous monitoring period.

Ramp metering algorithm

As indicated in the results, the ramp metering installation stays active if spillback occurs at the on-ramp. In reality this would not be the case. This needs to be taken into account when looking at the results of the situation without buffering and with ramp metering: in reality the ramp meter would be switched off if spillback occurs, hence resulting in platoons entering the freeway, with possible resulting congestion.

Furthermore the ramp metering installation does not use an algorithm that reacts on the traffic situation on the freeway. If such an algorithm would be used, e.g. ALINEA, the metering rate would change over time. The latter might be an advantage for the performance of the controller, since the target flow towards the on-ramp could be increased at some moments. This would result in less severe buffering.

Blockages at conflict area

In the simulation vehicles can drive through each other if vehicles are blocking the conflict area of an intersection. In reality blockages of conflict areas would lead to delays and unsafe traffic situations, hence resulting in changes in overall network performance. The latter however cannot be modelled in VISSIM.

Traffic conditions

The results showed there was no trade-off at the urban arterial in the second situation. To see the effects on the urban arterial, other traffic compositions should be used. With these changed traffic conditions, overall network performance would probably decrease compared to the simulated conditions due to the trade-off between improved conditions on the freeway, and decreased conditions on the urban arterial.

Furthermore the results showed the controllers in the third bottleneck situation have problems in dealing with severe traffic conditions on the urban arterial. The network performance decreases, although some promising results were shown. This also counts for the ST1Light, the developed controller for the Praktijkproef Amsterdam. Since the ST1Light showed positive results in reality, the last simulation situations might be too heavy.

5.6 Summary

The fifth chapter presented the results of the simulations, based on performance indicators for the overall network, the urban arterial and the freeway. Note that the urban arterial is the controlled part in the simulation, the freeway is the uncontrolled part. Furthermore this chapter showed the limitations of the research in the discussion.

For the first bottleneck situation, the fuzzy logic detection performs best regarding the detection and control. The fuzzy approach shows the least variations in bottleneck detection, this results in more smooth control: the controllers benefit from the fuzzy logic approach. Furthermore the fuzzy approach uses multiple input values (i.e. flows and queues) to detect bottleneck situations, this results in more reliable detection. The second controller shows the largest improvements in network performance and travel time on the urban arterial (-3.3% in total travel time). This is due to the preference of getting traffic fast out of the network, i.e. using downstream buffers. The third controller performs best with regard to reducing the queue length at the bottleneck stream. However, the controller does increase the travel time since it always used down- and upstream buffers, this results in a reduction of network performance (+1.7% in total travel time).

For the second bottleneck situation the queue is effectively managed by increasing the outflow at the off-ramp intersection. Since the off-ramp consists of one lane splitting into two separate queuing areas (i.e. right and left turning) and the traffic demand is high, blockages can occur. Therefore the target outflow is set higher than the inflow. Both controllers show large improvements in network performance. The controller that uses three downstream buffers shows the largest improvements (-38.7% in total travel time). Spillback at the off-ramp is prevented, therefore congestion at the freeway is prevented. The latter results in large improvements in freeway travel time. The travel time at the urban arterial does not decrease. This might be due to too low traffic demands at the arterial. With other traffic compositions a trade-off between the freeway and the urban arterial might be shown.

For the third bottleneck situation the developed controllers prevent spillback from the on-ramp towards the urban arterial. Furthermore the conflict area at the freeway intersection stays clear due to buffering: this improves traffic safety and comfort in the network. But due to the buffering, the delays at the urban arterial show large increases. This results in reduced network performance if the controllers are compared to the base situation with only ramp metering active. The first controller shows the least reduction in network performance, since it only uses the first upstream buffer. This controller shows an improvement in total travel time compared to the base situation without ramp metering (-1.1% in total travel time). The second and third controller both use three upstream buffers, and hence show more reduction in performance (respectively +1.1% and +1.9% in total travel time). The ST1Light also shows a decrease in network performance (+1.6% in total travel time). Due to the distribution based on relative queue lengths, the third controller distributes traffic more equally over the buffers. The ST1Light does not always prevent spillback: the queue length at the on-ramp shows large variations. The latter might be because the ST1Light uses the space at the on-ramp as a factor

to check if buffering is needed: if there is more space, the buffering rate can decrease. Furthermore the parameters of the ST1Light might need extra calibration and tuning. If the buffers are filled, travel times at the urban arterial show large increases, hence resulting in a decrease in network performance.

In reality ramp meters are often switched off if spillback towards the urban arterial occurs. If this situation would be simulated, the developed controllers for the third bottleneck situation would increase the metering time since spillback is prevented by the controllers. This should have positive results on the network performance. However, the latter is not tested via simulation.

Chapter 6. Conclusions and recommendations

The final chapter of this report presents the conclusions and recommendations of the research. These are based on the results and discussion, which are presented in the previous chapter. The conclusions of the research are given in section 6.1. In this section the research objective is recalled from the first chapter and the main findings of the research are presented, these findings are presented in a rather generic way. Detailed numbers regarding the impact assessment are shown in the answers to the research questions, which are presented after the main findings. Section 6.2 gives recommendations regarding practical implementation of the research. The chapter concludes with section 6.3, which presents future research topics that came up during this research. These topics could improve the design of the controller in the future.

6.1 Conclusions

The objective of the research was stated in the first chapter: a controller that deals with bottleneck situations occurring in the neighbourhood of a junction of a freeway and an urban arterial; in order to reach its goals, the controller should distribute traffic over the available buffer space in the network, by using traffic lights at controlled intersections. Three bottleneck situations were defined: (i) spillback on the urban arterial causing congestion on the urban arterial, (ii) spillback from the off-ramp towards the freeway causing congestion on the freeway, (iii) spillback from the on-ramp towards the urban arterial causing blocking back on the urban arterial. In order to control these three situations, three types of controllers were developed, each dealing with one of the situations. In the Praktijkproef Amsterdam a certain controller was developed which can only handle the third situation, this controller is called the ST1Light. It can be concluded that the controllers developed during this research, are able to solve (or prevent) spillback.

Table 6.1 gives an overview of the percentage change in total travel time for all controller variants. In the first situation congestion on the urban arterial is reduced by preventing spillback. In this situation first the bottleneck situation needs to be detected. A fuzzy logic approach using flow and queue length as inputs shows best results in combination with the controllers: the smooth approach of the fuzzy detection results in more smooth control actions and therefore less variations in queue lengths at the bottleneck. The controller that prefers to use downstream buffers to distribute the surplus of traffic shows largest improvements in network performance (-3.3% in total travel time). The controller that uses both up- and

downstream buffers has the strongest effect on reducing the queue at the bottleneck situation. Due to the usage of upstream buffers, the network performance decreases (+1.7% in total travel time).

In the second situation congestion at the freeway is prevented by preventing spillback from the ramp towards the freeway. Both designed controllers prevent spillback towards the freeway, hence preventing congestion and the capacity drop at the freeway. There is no trade-off with the urban arterial. This results in large improvements in overall network performance. If more downstream buffers are used, the traffic is flushed further into the network and it reaches the network boundaries faster, hence resulting in shorter travel times and improvements in overall network performance (-38.7% in total travel time). The latter is the case for the second controller.

In the third situation spillback from the on-ramp towards the urban arterial is prevented by the developed controllers. If more buffer capacity is used, the network performance shows larger reductions due to the buffering of traffic. Therefore the controller which only uses the first upstream buffers, shows best results in network performance (-1.1% in total travel time) compared to the base situation without ramp metering. If no control is used, the network performance is even better (-3.8% in total travel time), but in that case spillback is not prevented.

It can be concluded that if buffers downstream of the bottleneck stream can be used, the controllers show positive results regarding the network performance. If buffers upstream are used, delays for traffic upstream of the bottleneck increase. The latter results in a decrease in network performance.

Table 6.1 Overview of percentage change in total travel time of all controller variants.

Performance indicator	Controller					
Situation 1*	Base	Control 1.1	Control 1.2	Control 1.3	(* with fuzzy bottleneck detection)	
Total travel time	0.0%	-1.9%	-3.3%	+1.7%		
Situation 2	Base	Control 2.1	Control 2.2			
Total travel time	0.0%	-38.4%	-38.7%			
Situation 3	Base	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1Light
Total travel time	0.0%	-3.8%	-1.1%	+1.1%	+1.9%	+1.6%

Sub-question I: How can the controller detect a bottleneck situation on the urban arterial?

Via a fuzzy logic approach the best results regarding the detection of bottleneck situations are shown. Input values for the fuzzy logic process are flows and queue lengths at traffic streams. Output is the bottleneck status, i.e. true or false. Due to the fuzzy approach, the detection is more smooth and hence the bottleneck statuses show less variations over time. This results in better technical performance of the controllers, since on/off switching of the control results in more fluctuations in queue lengths. Furthermore the multiple inputs to the detection process might result in more reliable detection, and therefore more bottleneck situations can be detected. The latter results in improved network performance.

Sub-question II: How can the controller deal with a bottleneck situation on the urban arterial?

To control spillback on the urban arterial, the controller should reduce the queue length at the bottleneck. The queue can be reduced by increasing the outflow at the bottleneck situation, or by reducing the inflow into the bottleneck situation. A combination of both is also possible. The desired change in flow can be calculated based on the surplus of traffic in the bottleneck situation. This surplus is calculated based on the desired queue at the bottleneck situation. If this surplus is added to the outflow, and/or subtracted from the inflow, the queue decreases in the next period. The latter controls spillback on the arterial.

Sub-question III: How can the controller deal with a bottleneck situation on the freeway?

Two types of bottleneck situations on the freeway need to be dealt with by the controller: (i) a bottleneck situation that is caused by spillback from the off-ramp, and (ii) a bottleneck situation that is caused by a too high inflow from the on-ramp.

In the first situation the spillback needs to be prevented by managing the queue at the off-ramp. If the outflow at the ramp is equal or higher compared to the inflow, the queue length does not increase and spillback does not occur. Based on a target outflow, the flow at the ramp is changed. The target outflow depends on the lay-out of the off-ramp, if blockages can occur the target should be higher than the inflow.

In the second situation a ramp metering installation is switched on to reduce the inflow from the ramp towards the freeway, in order to prevent spillback from the ramp towards the urban arterial the queue at the ramp should be managed. The queue at the on-ramp is managed by reducing the inflow into the ramp, based on a target inflow. If the target inflow is equal to the outflow at the ramp, the queue at the ramp does not spill back towards the urban arterial. If the queue does not spill back, the ramp metering can stay active.

Sub-question IV: How does the controller need to distribute the traffic among the available buffers, to deal with a certain bottleneck situation?

If a bottleneck situation on the urban arterial is detected, distributing the surplus of traffic over both up- and downstream buffers based on relative space in the buffers, shows best results with regard to reducing the queue length at the bottleneck. Using the upstream buffer results in longer queues at the upstream buffer. Giving preference to using the downstream buffer solves this problem. Using the downstream buffer does not result in a replacement of the bottleneck. However if this is the case, multiple downstream buffers can be used.

Spillback from the off-ramp towards the freeway can be prevented by increasing the outflow at the ramp, based on a target outflow. Since the off-ramp consists of one lane splitting into two separate queuing areas (i.e. right and left turning) and the traffic demand is high, blockages can occur. Therefore the target outflow should be higher than the inflow. By increasing the outflow of the off-ramp intersection, spillback is prevented and hence congestion at the freeway is prevented.

Spillback from the on-ramp towards the urban arterial can be prevented by decreasing the inflow towards the ramp, based on a target inflow. The target inflow should be equal compared to the outflow at the ramp metering installation. Via buffering the inflow can be decreased. If the traffic is distributed amongst more upstream buffers, e.g. four instead of two, it takes longer until the buffers are filled. Distributing the traffic over the buffers based on relative queue lengths, results in more equal queue lengths at the buffers compared to distribution based on traffic fractions. Calculating the amount of needed buffers, i.e. the approach of the ST1Light, does not always prevent spillback at the ramp.

Sub-question V: What is the effectiveness of the controller in relation to the goals of the controller?

In the first situation, the controllers that prefer to use downstream buffers over upstream buffers show best results with regard to overall network performance and travel time reduction on the urban arterial. The usage of downstream buffers results in getting the traffic fast out of the network, with corresponding improvements in performance. The largest improvement in total travel time is approximately 9 hours (-3.3%), this is achieved by the variant which gives preference to using three downstream buffers. Using both up- and downstream buffers is the most effective strategy to reduce the queue lengths of the bottleneck: in this case the queue is managed around the spillback level, i.e. 100 m. But, due to the usage of upstream buffers, delays increase and hence overall network performance decreases: total travel time increases with approximately 5 hours (-1.7%).

In the second situation, all controllers prevent spillback from the off-ramp. Therefore congestion does not occur at the freeway and the capacity drop is prevented, with large improvements in overall network performance: total travel time improves with approximately

150 hours (-38.7%). This is achieved by the variant which uses three downstream buffers. A trade-off with the urban arterial is not shown in the results, this might be the case if the traffic demand at the arterial would be higher. Due to this trade-off the overall network performance would decrease.

In the third situation, all controllers except the ST1Light prevent spillback from the on-ramp. Due to the prevention of spillback, the conflict area at the freeway intersection stays clear for the complete simulation time (4800 s, 100% of the time) by using the developed controllers. The ST1Light keeps the conflict area clear for 3960 s (82.5% of the time). If no controller is used, the conflict area becomes occupied after 1680 s (35% of the time). Due to the use of the ramp meter, congestion at the freeway is prevented and the capacity drop is postponed by 1680 s. However, the buffering increases delays at the urban arterial. After approximately 1700 s the first upstream buffers are filled. After approximately 2900 s also the second upstream buffers are filled and travel times show large raises, hence resulting in a reduction in overall network performance. If only the first upstream buffers are used (so spillback is prevented), the total travel time increases with 10 hours (+2.8%) compared to the situation with only a ramp metering installation active. Compared to the base situation without ramp metering the total travel time decreases with 4 hours (-1.1%) by using this variant. A positive result of the buffering is that the controllers show good results for the first, approximately, ten minutes. Thereafter the traffic demand is too severe to show positive effects in overall network performance.

Main question: How should a controller function that distributes road traffic over buffer space in a network (with a junction of a freeway and an urban arterial) by using the controlled intersections, and how does this controller perform?

The controller has three separate parts, each part controls one of three possible bottleneck situations at the junction.

A bottleneck on the urban arterial is best detected based on fuzzy logic. The fuzzy approach uses queue lengths and flows at traffic streams as inputs. The queue at the bottleneck shows largest reductions if up- and downstream buffering is applied, in this case the queue is managed around the spillback level (i.e. 100 m). The network performance increases most if preference for downstream buffering is given, the improvement in total travel time is approximately 9 hours (-3.3%).

Spillback at the off-ramp can be managed by managing the queue at the ramp based on a target outflow. This target is reached by increasing outflow at the off-ramp intersection. Due to the prevention of spillback and hence the prevention of congestion at the freeway, the overall network performance shows large improvements: the total travel time improves with 150 hours (-38.7%).

Spillback at the on-ramp can be managed by setting a target for the inflow towards the ramp. This target is reached by buffering traffic at upstream buffers. Due to the buffering delays at the urban arterial increase. Distributing traffic based on relative queues at the buffers results in most equal queues at the buffers. If the least amount of buffers is used (so spillback is prevented), the total travel time increases with 10 hours (+2.8%) compared to the situation in which only a ramp metering installation is active, and the total travel time decreases with 4 hours (-1.1%) compared to the base situation without ramp metering. Due to the prevention of spillback at the on-ramp, the conflict area at the urban arterial of the freeway intersection stays clear.

6.2 Recommendations

This section presents recommendations regarding practical implementation of this research, based on the conclusions.

Bottleneck detection on urban arterials as was implemented in this research, is not a part of current intersection control systems. The fuzzy logic approach showed promising results: the smooth detection due to the multiple input values resulted in smooth control actions. This could be added to current control systems, to be able to act on bottlenecks. The control of the detected bottleneck situations could be based on one of the developed controllers, it is recommended to use the controller that prefers to use downstream buffers. This controller could be added to current active systems like TOPTRAC. Since the latter has shown positive results in reality and the controller has shown positive simulation results regarding controlling the bottleneck situation, this could give good results.

Preventing of spillback at the off-ramp by managing the queue via a target outflow, has shown good results. It is recommended to implement the controller that only uses the first downstream buffer, and to combine it with current active intersection control systems. The target outflow could for example overrule other control actions, in order to prevent spillback.

Spillback at the on-ramp can be prevented by setting a target inflow. This would increase metering time of ramp metering installations and would improve traffic safety in the network since the conflict area at the freeway intersection is not occupied. It is recommended to implement the target inflow and use the first and second upstream buffers to buffer traffic. Due to turn fractions almost no traffic is travelling from the third upstream buffer and it is therefore less useable to increase buffer capacity. Furthermore it is recommended to switch off the controller if spillback occurs to conflict areas of the buffers, since the latter leads to large increases in travel times at the urban arterial.

6.3 Future research topics

During the research some interesting topics came up that should deserve extra attention. These future research topics are shown below.

Tune the algorithm

Some parts of the algorithm can be tuned. For example the critical values regarding bottleneck detection, the fuzzy logic membership functions, the fuzzy logic input values and the preference value to determine whether up- or downstream buffers need to be used. These values are not changed in the simulation. It could be interesting to see the effects of tuning these parameters on the performance of the controller. For example using the saturation of an intersection as input value for the fuzzy logic approach instead of the flow.

Test the robustness

The controllers use origin-destination matrices, queue lengths and flows as inputs for the algorithms. In reality these are error-prone (note that the reliability can be increased due to the use of floating car data). To check the reliability of the controller on these input values, an error-margin could be implemented on the input data in the algorithm.

Change traffic conditions

The controller deals with fixed traffic conditions. It is interesting to see how the controller reacts on changes in traffic conditions. Furthermore it is possible that the chosen traffic situations in this research are too severe or too calm. If those situations would be altered, more strengths and weaknesses of the controller might become visible.

Implement a dynamic cycle time

The used cycle time is fixed and equal to the control and monitoring period. In reality this is not always the case, therefore it is interesting to change the controller in such a way it is able to deal with dynamic cycle times.

Implement a ramp metering algorithm

Fixed ramp metering settings are used in the simulation of this research. In reality a ramp metering algorithm is used that reacts on the traffic situation. It is interesting to check the effects of such an algorithm on the impact of the controller. A changing metering rate could result in positive effects on the impact of the controller, since the buffering rate can decrease at some moments.

Implement spillback prevention at upstream buffers

Previous sections showed the controller could increase metering time for a ramp metering installation, because spillback can be prevented. However, after some time spillback occurs at the first upstream buffers, at this moment the controller could be switched off or the buffering rate could be changed in order to prevent blockages of the conflict area. The latter is not studied in the research.

Deal with multiple bottlenecks

The developed controllers each deal with one specific bottleneck situation. In reality multiple bottlenecks can occur. To deal with multiple bottlenecks a supervisor should be created, that determines which controller should be activated. This choice could be made based on, for example, the minimization of an objective function or policy objectives.

Increase the network size

The used simulation network is rather small. A larger network brings more complexity to the simulation and can show new insights in the working of the controller. A larger network results for example in more buffers, which might result in more buffer capacity.

Merge with current used intersection control systems

As was shown in the previous sections: the controller could be combined with current used systems like TRANSYT, in order to further improve network performance. It is interesting to develop such a controller and test it via simulation.

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Appendices

In order to get a clear view on the appendices, all figures and tables in each appendix are grouped: first some explanatory text is presented which discusses the content of the appendix, followed by the figures and tables.

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Appendix A. Lane change settings

Figure A.1 shows the old and new lane change settings of VISSIM. With the new values the capacity drop and merging behaviour is modelled properly. The values are adapted from the research performed by Legius (2014).

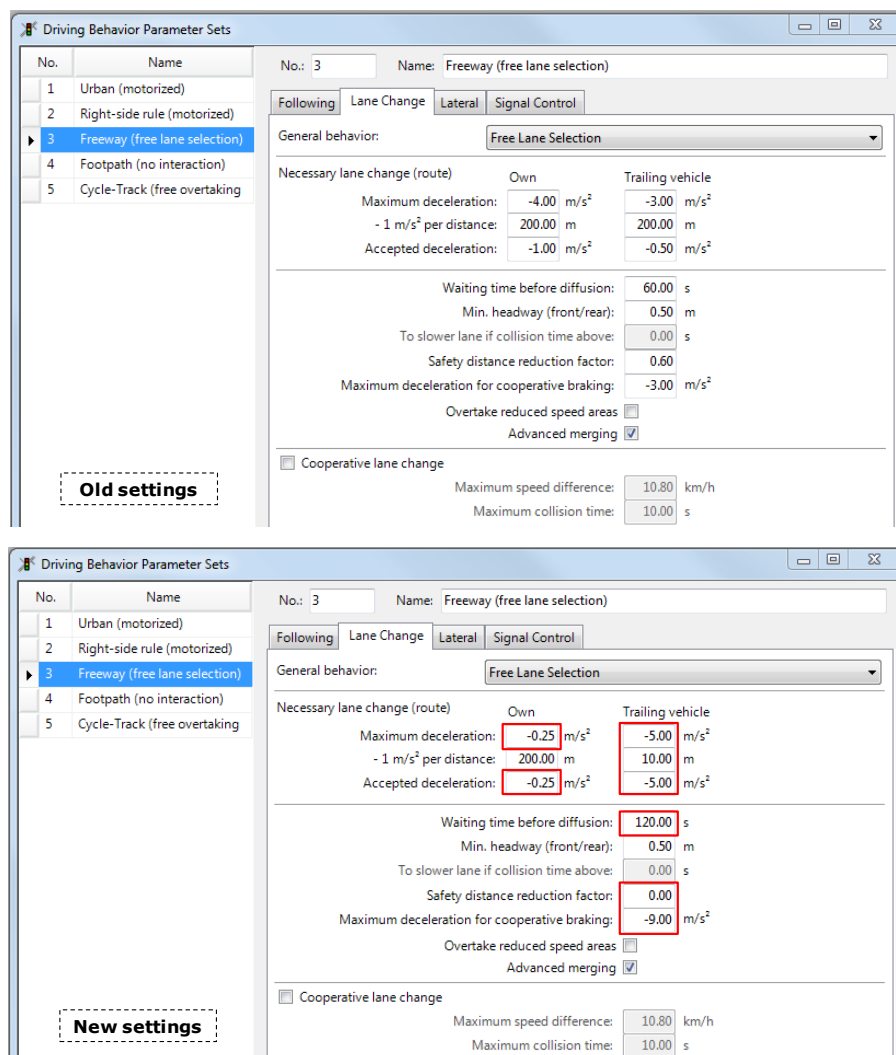


Figure A.1 Old and new lane change settings in VISSIM. The values within the red boxes are changed.

Appendix B. Origin-destination matrices

In this appendix figures and tables regarding the origin-destination matrices, which define the traffic demand in the modelled situations, are shown.

In the situation specific matrices extra traffic is added to create a bottleneck, the values that create the bottleneck situation are marked red. Furthermore extra traffic travelling at the urban arterial from East to West and vice versa is added, to be able to get extra travel time measurements for ongoing traffic and to see the effects on a possible trade-off at the arterial.

Origin and destination zones

Figure B.1 shows the used road network with the numbered origin and destination zones. Note that the freeway is one-way traffic.

Traffic demand over time

Figure B.2 gives a schematic representation of the traffic demand over time. This shows the relation between the warming-up, situation specific and cooling-down period.

Warming-up and cooling-down period

Table B.1 shows the matrix of the warming-up and cooling-down period. This matrix results in calm traffic conditions with no bottleneck situations.

Situation 1

Table B.2 shows the origin-destination matrix used to create the first bottleneck situation. Extra traffic is added in order to create a bottleneck at the second intersection.

Situation 2

In Table B.3 the matrix of the second situation is presented. This traffic demand results in a queue spilling back from the off-ramp towards the freeway.

Situation 3

Table B.4 shows the origin-destination matrix of the third situation. These origin-destination pairs result in congestion on the freeway if ramp metering is switched off. If ramp metering is switched on, congestion on the freeway is solved and spillback from the on-ramp towards the urban arterial occurs.

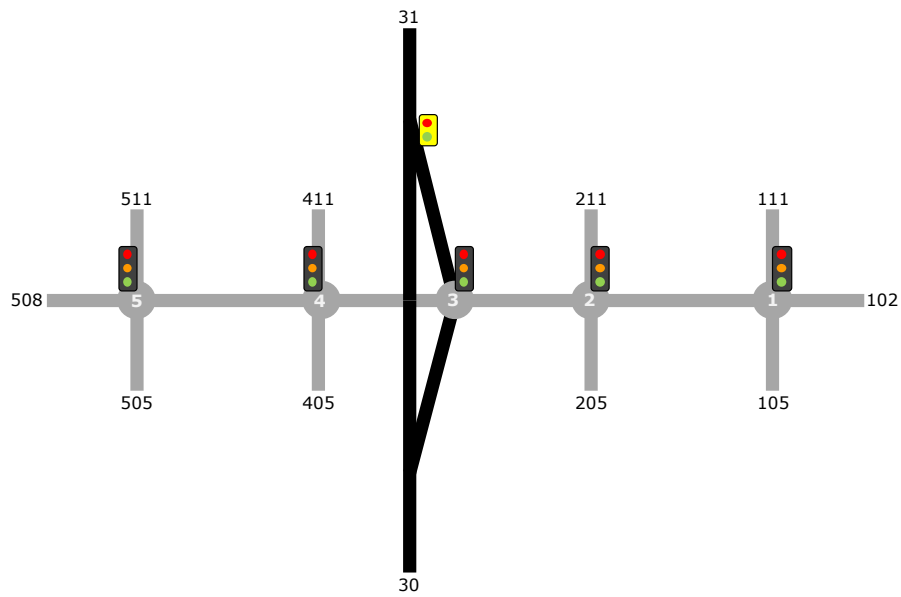


Figure B.1 Schematic representation of the origin-destination zones in the network. Note that the freeway is one-way traffic.

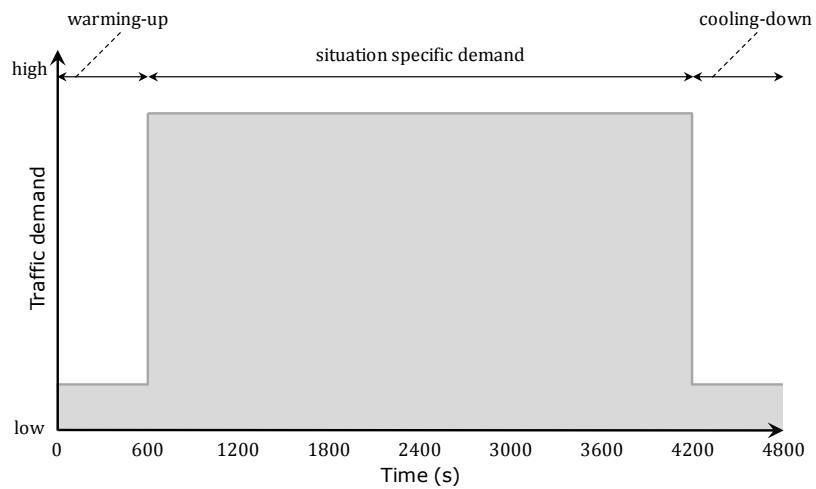


Figure B.2 Schematic representation of traffic demand over time. The first 600 s are a warming-up period, the last 600 s are a cooling-down period. The time in between is situation specific.

Table B.1 Origin-destination matrix of the warming-up (0-600 s) and cooling-down period (4200-4800 s).

		DESTINATION											Σ (veh/h)
		102	105	111	205	211	405	411	505	508	511	31	
ORIGIN	102	0	1	1	1	1	1	1	1	1	1	1	60
	105	1	0	1	1	1	1	1	1	1	1	1	60
	111	1	1	0	1	1	1	1	1	1	1	1	60
	205	1	1	1	0	1	1	1	1	1	1	1	60
	211	1	1	1	1	0	1	1	1	1	1	1	60
	405	1	1	1	1	1	0	1	1	1	1	1	60
	411	1	1	1	1	1	1	0	1	1	1	1	60
	505	1	1	1	1	1	1	1	0	1	1	1	60
	508	1	1	1	1	1	1	1	1	0	1	1	60
	511	1	1	1	1	1	1	1	1	1	0	1	60
	30	1	1	1	1	1	1	1	1	1	1	240	1500
	Σ (veh/h)	60	60	60	60	60	60	60	60	60	60	1500	

Table B.2 Origin-destination matrix of the first bottleneck situation (600-4200s). The red values indicate the values that result in the bottleneck situation.

		DESTINATION											Σ (veh/h)
		102	105	111	205	211	405	411	505	508	511	31	
ORIGIN	102	0	12	12	12	12	70	70	70	250	70	70	648
	105	12	0	12	36	12	24	24	24	24	24	24	216
	111	12	12	0	12	36	24	24	24	24	24	24	216
	205	12	12	12	0	12	12	12	12	12	12	12	120
	211	12	12	12	12	0	12	12	12	12	12	12	120
	405	12	12	12	12	12	0	12	12	12	12	12	120
	411	12	12	12	12	12	12	0	12	12	12	12	120
	505	12	12	12	12	12	12	12	0	12	12	12	120
	508	72	12	12	12	12	12	12	12	0	12	12	180
	511	12	12	12	12	12	12	12	12	12	0	12	120
	30	12	12	12	12	12	12	12	12	12	12	2880	3000
	Σ (veh/h)	180	120	120	144	144	202	20	20	382	302	3082	

Table B.3 Origin-destination matrix of the second bottleneck situation (600-4200s). The red values indicate the values that result in the bottleneck situation.

		DESTINATION											Σ (veh/h)
		102	105	111	205	211	405	411	505	508	511	31	
ORIGIN	102	0	12	12	12	12	12	12	12	72	12	12	180
	105	12	0	12	12	12	12	12	12	12	12	12	120
	111	12	12	0	12	12	12	12	12	12	12	12	120
	205	12	12	12	0	12	12	12	12	12	12	12	120
	211	12	12	12	12	0	12	12	12	12	12	12	120
	405	12	12	12	12	12	0	12	12	12	12	12	120
	411	12	12	12	12	12	12	0	12	12	12	12	120
	505	12	12	12	12	12	12	12	0	12	12	12	120
	508	72	12	12	12	12	12	12	12	0	12	12	120
	511	12	12	12	12	12	12	12	12	12	0	12	120
	30	110	110	110	110	110	110	110	110	110	110	1900	3000
	Σ (veh/h)	278	218	218	218	218	218	218	218	278	218	3000	

Table B.4 Origin-destination matrix of the third bottleneck situation (600-4200s). The red values indicate the values that result in the bottleneck situation.

		DESTINATION										Σ (veh/h)	
		102	105	111	205	211	405	411	505	508	511		31
ORIGIN	102	0	12	12	12	12	12	12	12	72	12	60	228
	105	12	0	12	12	12	12	12	12	12	12	60	168
	111	12	12	0	12	12	12	12	12	12	12	60	168
	205	12	12	12	0	12	12	12	12	12	12	60	168
	211	12	12	12	12	0	12	12	12	12	12	60	168
	405	12	12	12	12	12	0	12	12	12	12	60	168
	411	12	12	12	12	12	12	0	12	12	12	60	168
	505	12	12	12	12	12	12	12	0	12	12	60	168
	508	72	12	12	12	12	12	12	12	0	12	60	228
	511	12	12	12	12	12	12	12	12	12	0	60	168
	30	12	12	12	12	12	12	12	12	12	12	4250	4370
	Σ (veh/h)	180	120	120	120	120	120	120	120	180	120	4850	

Appendix C. Check for latent demand

The three tables in this appendix show for all simulated variants: (i) the number of vehicles that have left the network, (ii) the number of vehicles in the network and (iii) the latent demand. With these numbers a check for latent demand is made, the latent demand should be zero.

Situation 1

Table C.1 shows the checks for the first situation. It shows all numbers are approximately equal.

Situation 2

Table C.2 shows the numbers for the second situation. It shows the latent demands are all zero. The number of vehicles in the network in the base situation is larger, due to congestion that is not yet fully resolved.

Situation 3

Table C.3 shows the checks for the third and last situation. The latent demand is in all situations zero. The number of vehicles that is still in the network at the end of the simulation increases if buffering is applied.

Table C.1 Check for latent demand in the first bottleneck situation.

Performance indicator	Controller			
	Base	Control 1.1	Control 1.2	Control 1.3
Detection 1				
Vehicles that have left the network	5597	5597	5597	5597
Vehicles in the network	83	83	83	83
Latent demand	0	0	0	0
Detection 2				
Vehicles that have left the network	5597	5597	5597	5597
Vehicles in the network	83	83	83	83
Latent demand	0	0	0	0
Detection 3				
Vehicles that have left the network	5597	5597	5597	5594
Vehicles in the network	83	83	83	86
Latent demand	0	0	0	0

Table C.2 Check for latent demand in the second bottleneck situation.

Performance indicator	Controller		
	Base	Control 2.1	Control 2.2
Vehicles that have left the network	4908	4937	4936
Vehicles in the network	112	83	83
Latent demand	0	0	0

Table C.3 Check for latent demand in the third bottleneck situation.

Performance indicator	Controller					
	Base, no TDI	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1 Light
Vehicles that have left the network	6788	6766	6770	6741	6749	6755
Vehicles in the network	82	104	100	129	121	115
Latent demand	0	0	0	0	0	0

Appendix D. Extra results situation 1

In this appendix extra results of the first bottleneck situation are presented. First the percentage changes in network performance are shown. Furthermore these extra results consist of figures regarding bottleneck detection and regarding the combination of the controllers with detection variants 1 and 2. The latter shows worse results compared to the combination with detection variant 3, as was explained in chapter 5.

Percentage change in network performance

Table D.1 presents the percentage changes in network performance for the controllers, the base situation is the base for the calculations.

Bottleneck detection

Figure D.1 shows the detection statuses of the different detection variants for the stream downstream of the bottleneck stream. Note that spillback occurs if the queue exceeds 100 m. The figure shows the third variant detects most bottleneck situations due to the use of flows as second input value in the fuzzy logic process. The latter is shown in more detail in Figure D.2.

Queue lengths

Figure D.3 and Figure D.4 show the effect of the controllers in combination with detection variant 1 on the queue lengths at the down- and upstream buffers. Figure D.5 and Figure D.6 show these effects for the combination with detection variant 2. The figures show control variant 1.3 benefits from the use of a more fluent detection variant, like the fuzzy logic variant.

Travel times

Figure D.7 and Figure D.8 show the effects of the controllers in combination with detection variant 1 on the travel times on the urban arterial. Figure D.9 and Figure D.10 show these results for the combination with detection variant 2. These figures show the improved travel times for controller 1.3 by using a more fluent bottleneck detection.

Table D.1 Percentage change in network performance for the controllers in situation 1 (base = base situation).

Performance indicator	Controller			
Detection 1	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled	0.0%	0.0%	0.0%	0.0%
Total travel time	0.0%	-1.9%	-2.8%	+0.9%
Total delay time	0.0%	-4.4%	-6.5%	+2.1%
Total stopped delay	0.0%	-4.5%	-6.8%	+2.1%
Detection 2	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled	0.0%	0.0%	0.0%	0.0%
Total travel time	0.0%	-1.9%	-2.8%	+1.3%
Total delay time	0.0%	-4.4%	-6.6%	+3.1%
Total stopped delay	0.0%	-4.5%	-7.0%	+3.5%
Detection 3	Base	Control 1.1	Control 1.2	Control 1.3
Total distance travelled	0.0%	0.0%	0.0%	0.0%
Total travel time	0.0%	-1.9%	-3.3%	+1.7%
Total delay time	0.0%	-4.4%	-7.7%	+3.9%
Total stopped delay	0.0%	-4.6%	-8.0%	+4.6%

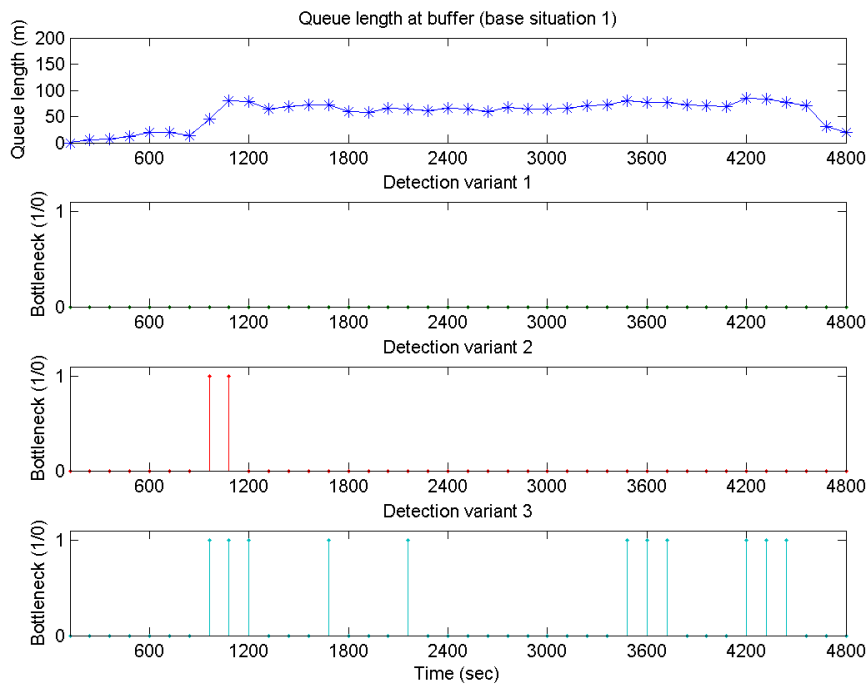


Figure D.1 Queue length downstream of the bottleneck stream and related detection status (i.e. true or false) of the three variants.

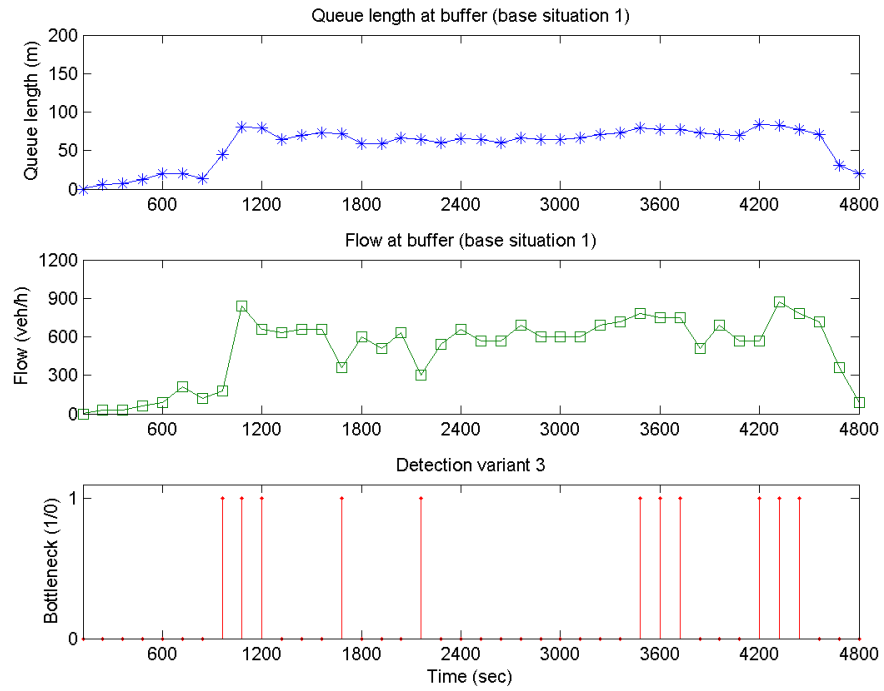


Figure D.2 Queue length and flow downstream of the bottleneck stream and related detection status of the third detection variant (i.e. fuzzy logic).

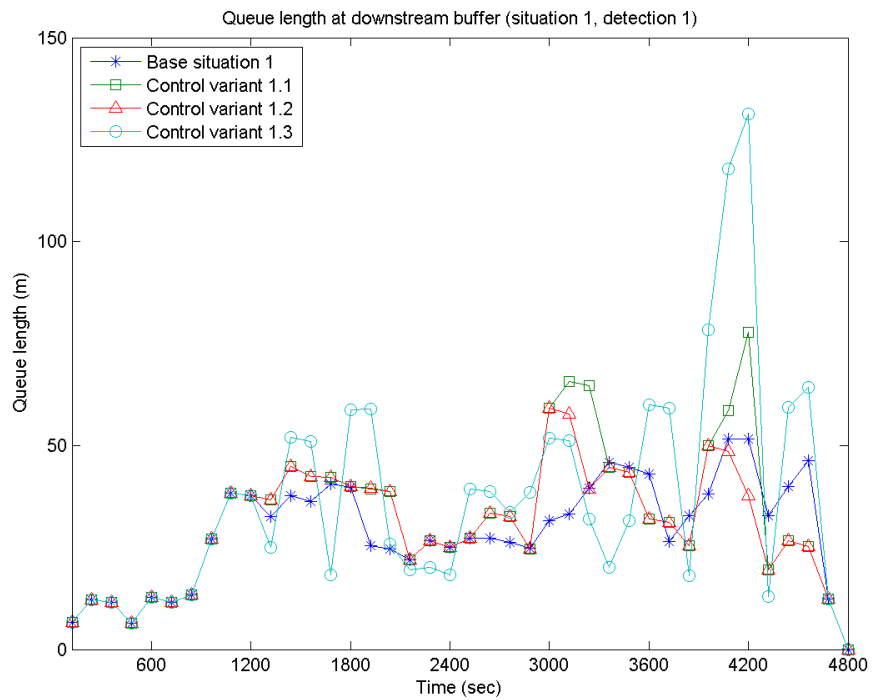


Figure D.3 Queue length downstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 1.

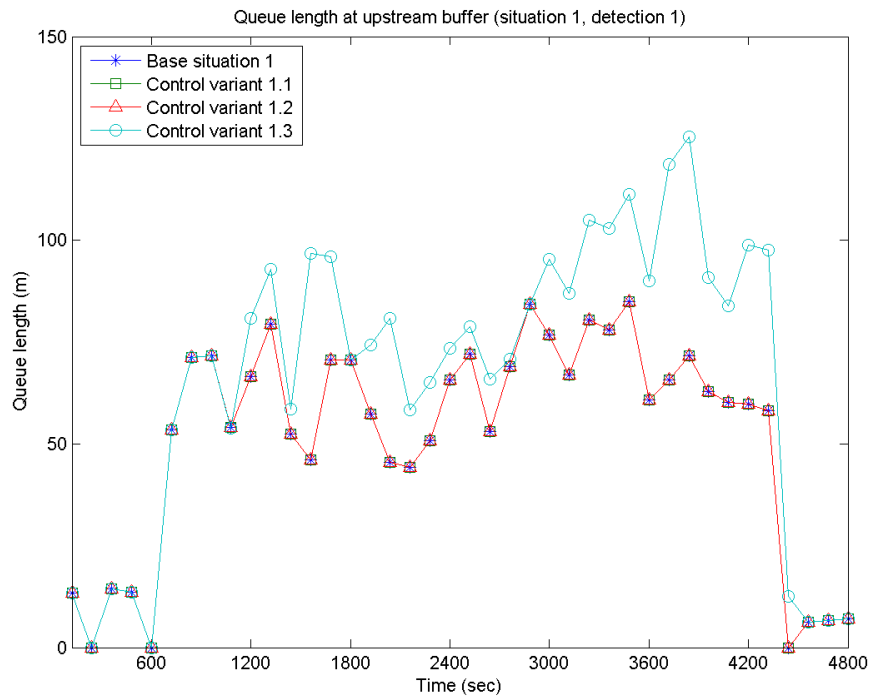


Figure D.4 Queue length upstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 1.

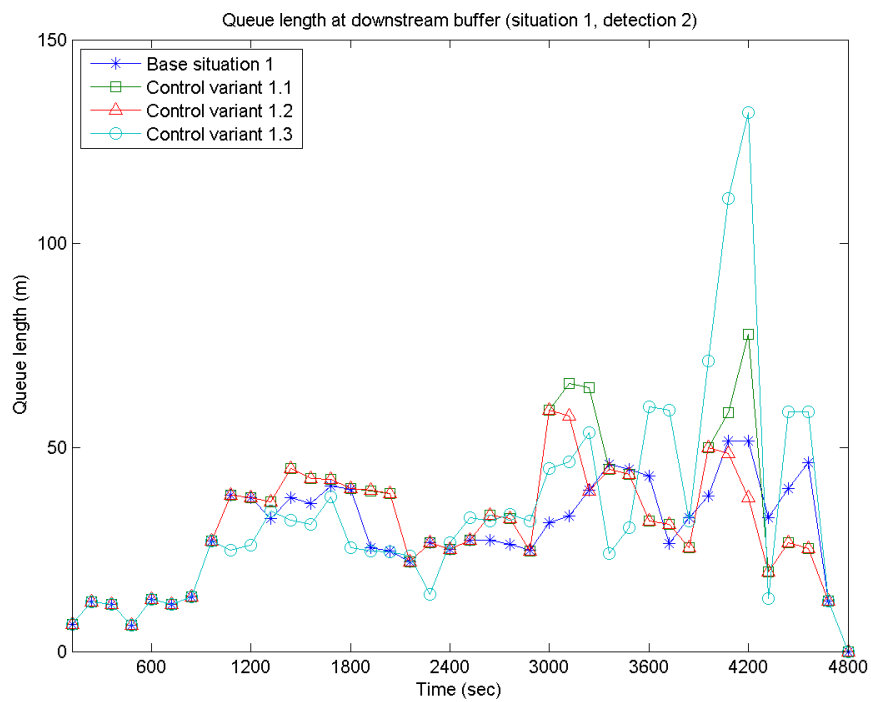


Figure D.5 Queue length downstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 2.

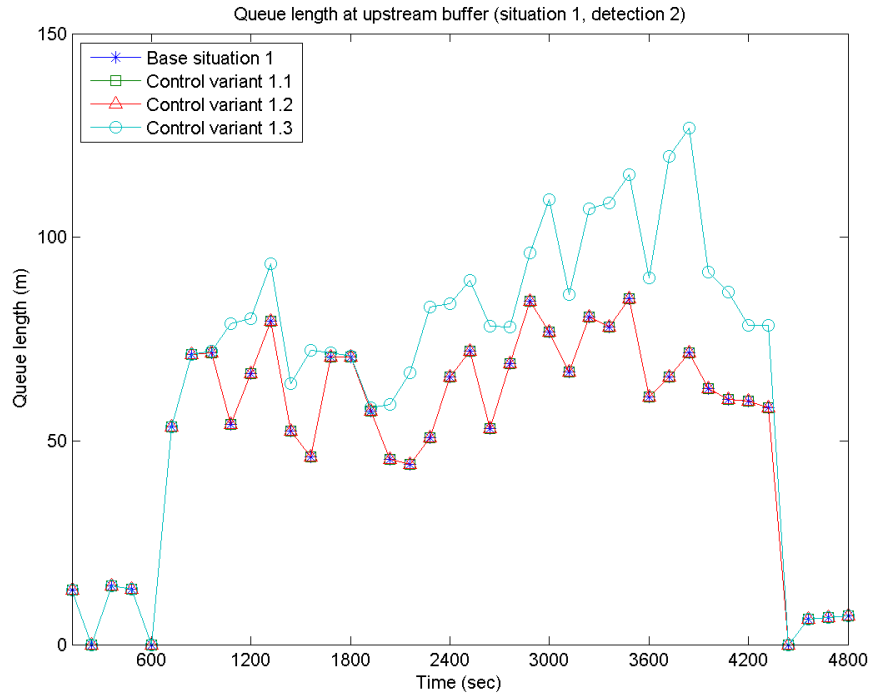


Figure D.6 Queue length upstream of the bottleneck stream in situation 1, using the controllers in combination with detection variant 2.

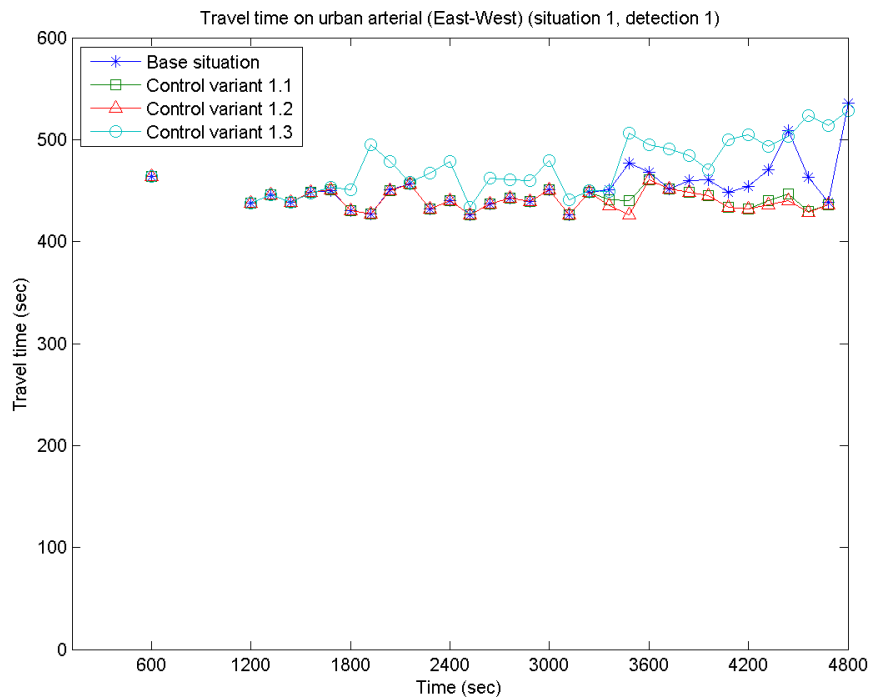


Figure D.7 Travel time on the urban arterial from East to West in situation 1, using the controllers in combination with detection variant 1.

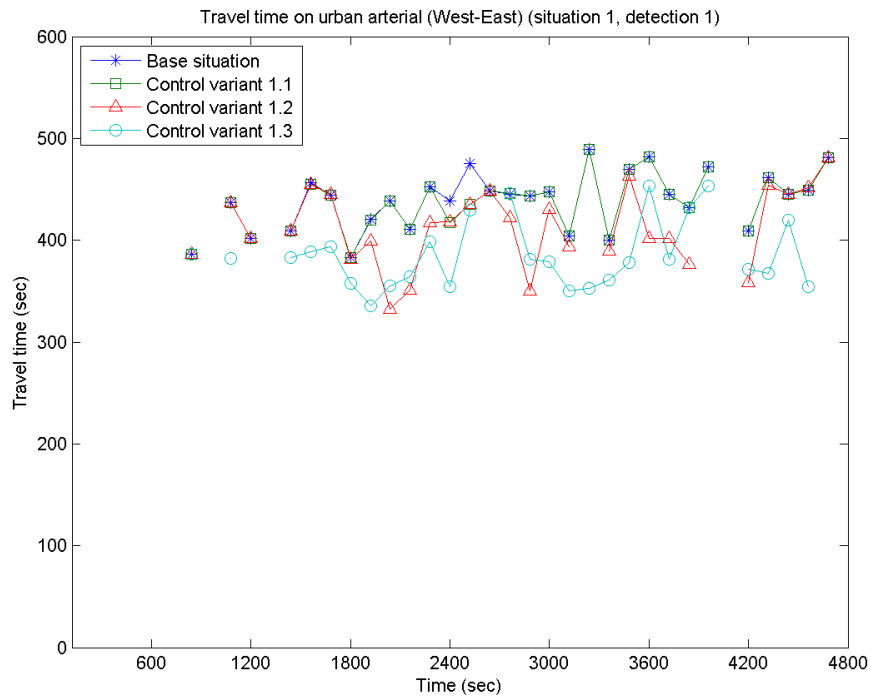


Figure D.8 Travel time on the urban arterial from West to East in situation 1, using the controllers in combination with detection variant 1.

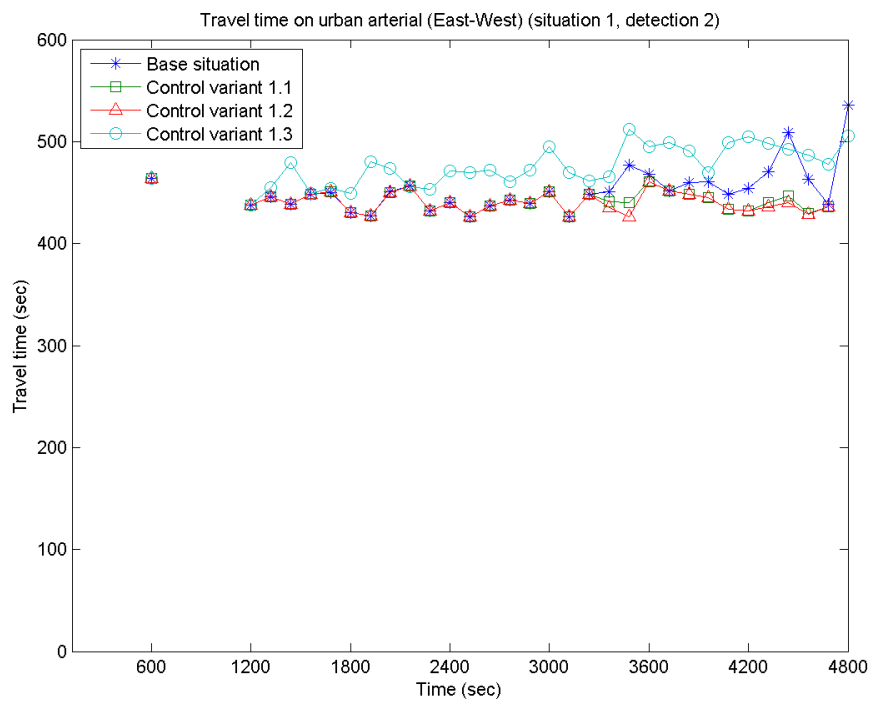


Figure D.9 Travel time on the urban arterial from East to West in situation 1, using the controllers in combination with detection variant 2.

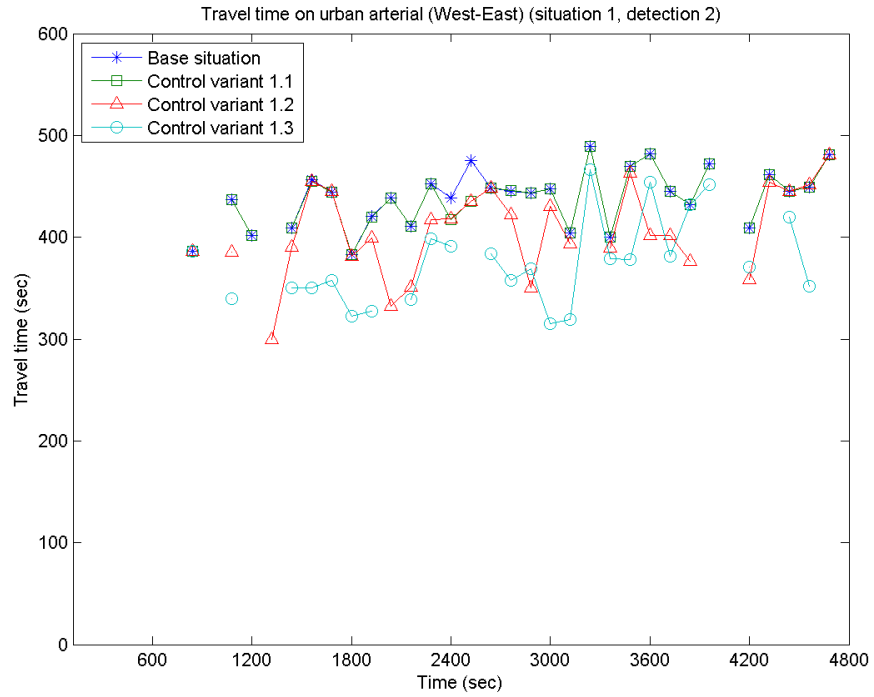


Figure D.10 Travel time on the urban arterial from West to East in situation 1, using the controllers in combination with detection variant 2.

Appendix E. Extra results situation 2

In this appendix extra results of the second bottleneck situation are presented. These results consist of a table with the percentage changes in network performance and figures regarding the tuning of the target outflow, a speedcontourplot of the first controller and the cumulative vehicle plot.

Percentage change in network performance

Table E.1 presents the percentage changes in network performance for the controllers in situation 2, the base situation is used as base.

Tuning the target outflow

Figure E.1 presents the tuning results for the outflow target. It shows spillback occurs if the target is set below 1400 veh/h.

Speedcontourplot

The speedcontourplot of situation 2 with the use of controller 2.1 is shown in Figure E.2. The plot shows congestion does not occur if the controller is used.

Cumulative vehicle plot

Figure E.3 presents the cumulative vehicle plot of situation 2. It shows the effect of congestion in the base situation on the arrival pattern of the vehicles.

Table E.1 Percentage change in network performance for the controllers in situation 2 (base = base situation).

Performance indicator	Controller		
	Base	Control 2.1	Control 2.2
Total distance travelled	0.0%	+0.1%	+0.1%
Total travel time	0.0%	-38.4%	-38.7%
Total delay time	0.0%	-59.4%	-59.9%
Total stopped delay	0.0%	-37.9%	-38.6%

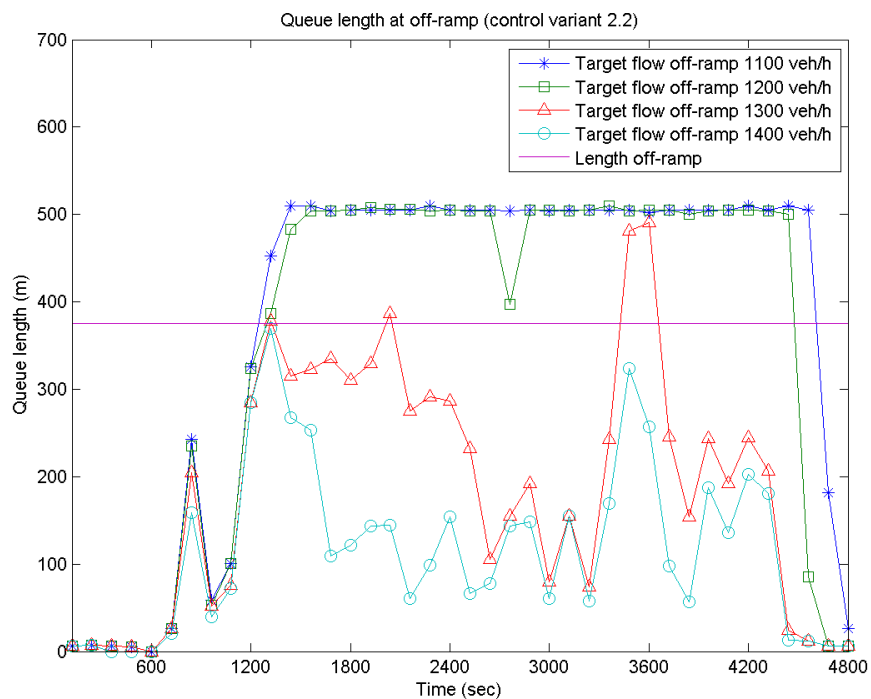


Figure E.1 Results of the tuning of the target outflow in situation 2. The maximum queue at the off-ramp is set at 500 m.

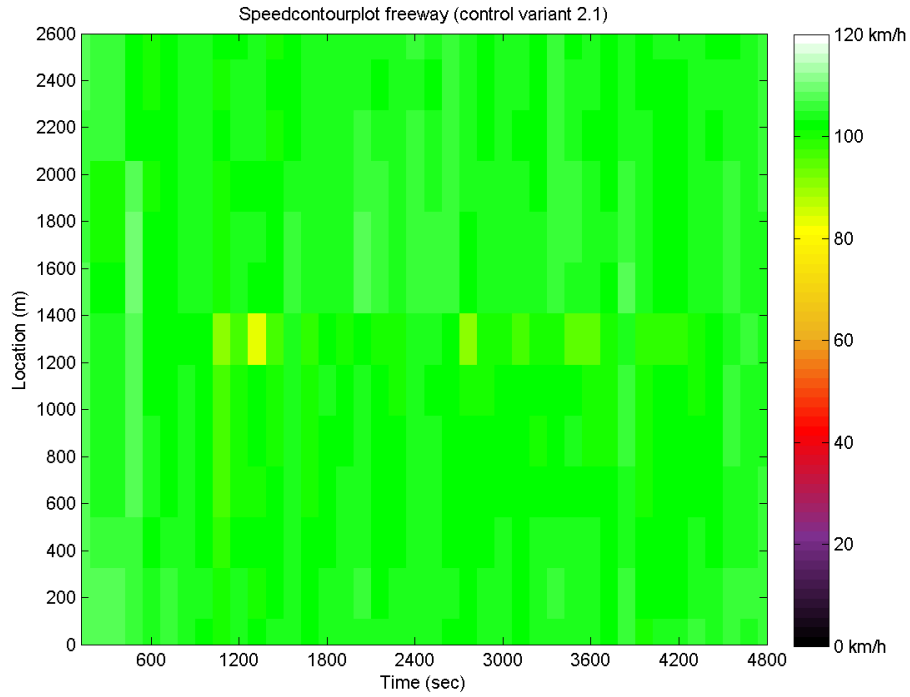


Figure E.2 Speed contour plot of the freeway with the use of controller 2.1, the off-ramp is located at 1430 m.

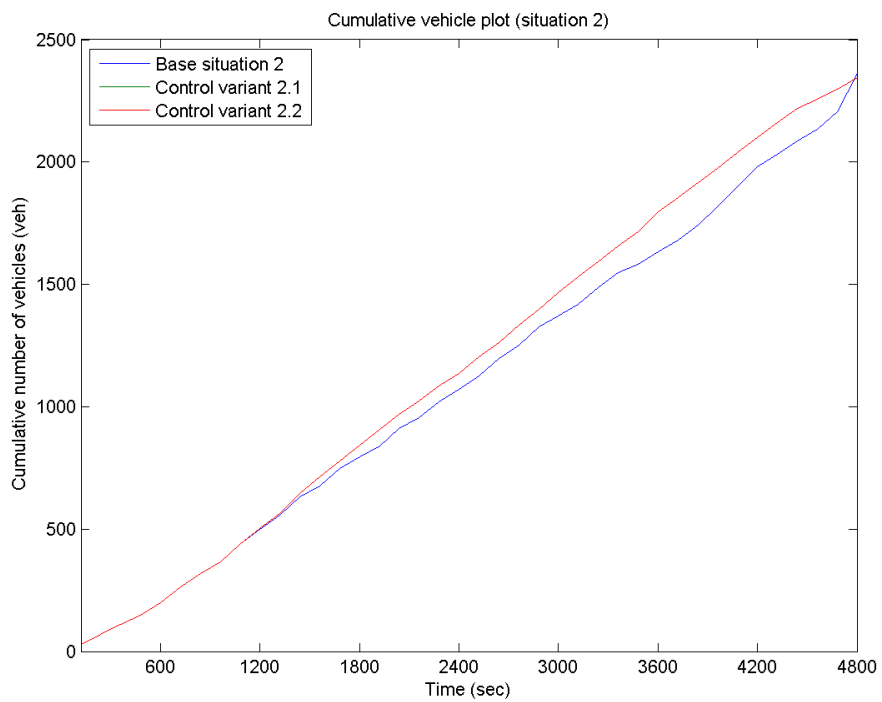


Figure E.3 Cumulative vehicle plot at the freeway for the base situation and controllers in situation 2.

Appendix F. Extra results situation 3

This appendix presents extra results regarding bottleneck situation 3. These results consist of two tables with the percentage changes in network performance, and of figures regarding the tuning of the inflow target and the resulting inflow towards the on-ramp. Furthermore speedcontourplots of controllers 3.1, 3.2, 3.3 and the ST1Light are presented, followed by the cumulative vehicle plot of the freeway and queue lengths at the third upstream buffers.

Percentage change in network performance

Table F.1 presents the percentage changes in network performance with the situation without ramp metering as base situation. Table F.2 also shows percentage changes in network performance, but uses the situation with active ramp metering as base situation.

Tuning the target inflow

Figure F.1 shows the results of different target inflows on the queue length at the on-ramp. The figure shows that a target flow larger than 450 veh/h results in spillback.

Inflow towards the on-ramp

Figure F.2 presents the inflow towards the on-ramp for the uncontrolled and the controlled situations, in bottleneck situation 3. Figure F.3 only shows the controlled situations.

Speedcontourplots

Figure F.4, Figure F.5, Figure F.6 and Figure F.7 show the speedcontourplots of the freeway by using respectively controller 3.1, 3.2, 3.3 and the ST1Light. The plots indicate congestion is solved due to the use of the ramp metering installation. Due to the high traffic demand, small drops in speed can occur.

Cumulative vehicle plot

Figure F.8 presents the cumulative vehicle plot of situation 3. It shows the effect of congestion in the base situation on the arrival pattern of the vehicles. These effects are amplified in the slanted cumulative curve.

Queue lengths

Figure F.9 and Figure F.10 show the queue length at the third upstream buffers, respectively East and West, with the use of the controllers. The figures indicate the queues are short and the queues stay under the length of the queuing area.

Table F.1 Percentage change in network performance for the controllers in situation 3 (base = base situation without ramp metering).

Performance indicator	Controller					
	Base, no TDI	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1 Light
Total distance travelled	0.0%	-0.1%	-0.2%	-0.2%	-0.1%	-0.2%
Total travel time	0.0%	-3.8%	-1.1%	+1.1%	+1.9%	+1.6%
Total delay time	0.0%	-7.3%	-2.0%	+2.5%	+4.0%	+3.3%
Total stopped delay	0.0%	+59.9%	+86.2%	+97.8%	+102.6%	+100.3%

Table F.2 Percentage change in network performance for the controllers in situation 3 (base = base situation with ramp metering active).

Performance indicator	Controller					
	Base, no TDI	Base, TDI	Control 3.1	Control 3.2	Control 3.3	ST1 Light
Total distance travelled	+0.1%	0.0%	0.0%	-0.1%	0.0%	0.0%
Total travel time	+3.9%	0.0%	+2.8%	+5.1%	+5.9%	+5.6%
Total delay time	+7.9%	0.0%	+5.8%	+10.6%	+12.2%	+11.5%
Total stopped delay	-37.5%	0.0%	+16.5%	+23.7%	+26.7%	+25.3%

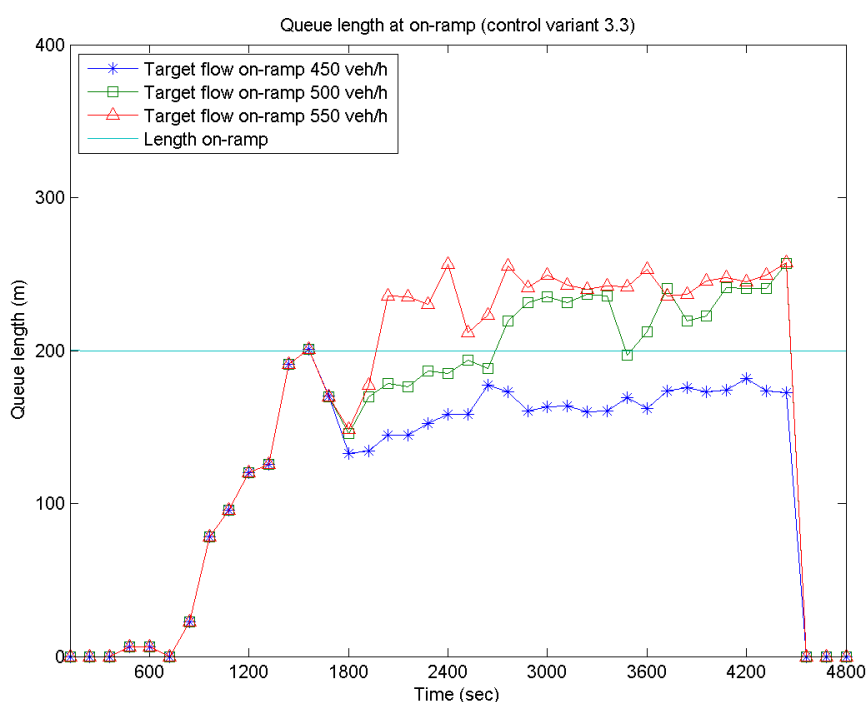


Figure F.1 Results of the tuning of the target inflow towards the on-ramp for controller 3.3, in situation 3.

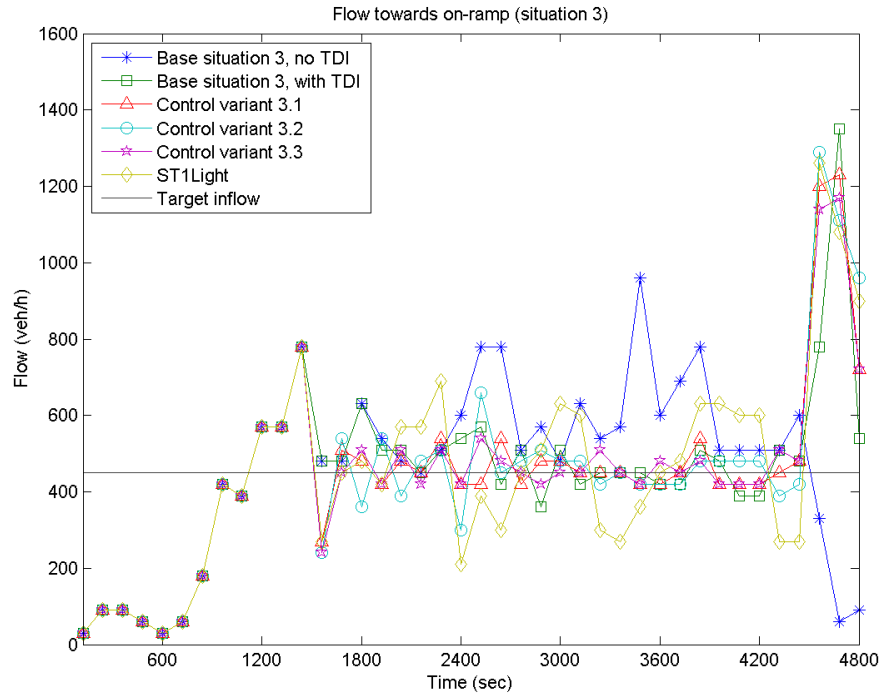


Figure F.2 Inflow towards the on-ramp for controlled and uncontrolled situations in situation 3, compared to the target inflow.

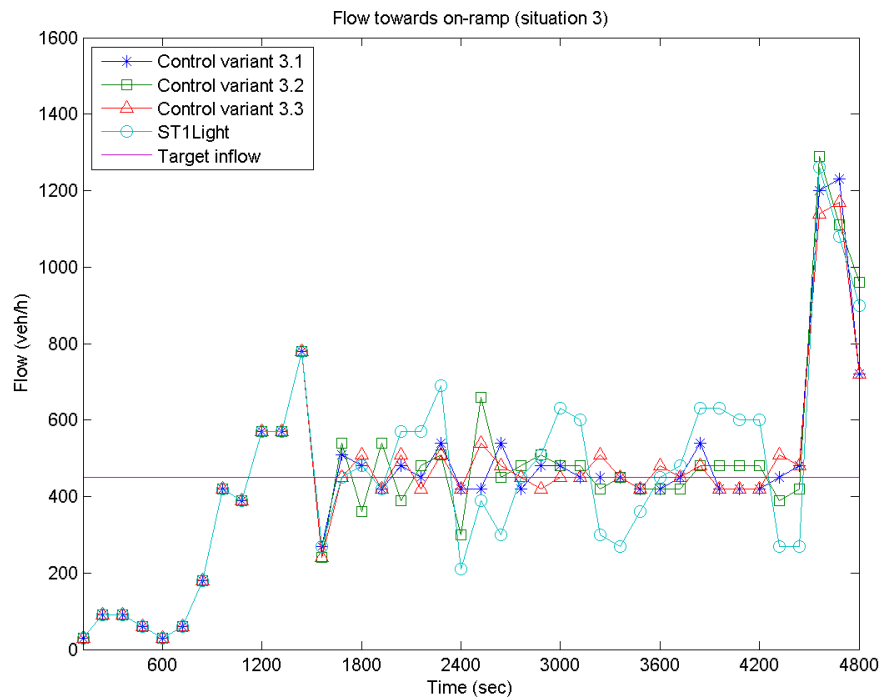


Figure F.3 Inflow towards the on-ramp for the different controllers in situation 3, compared to the target inflow.

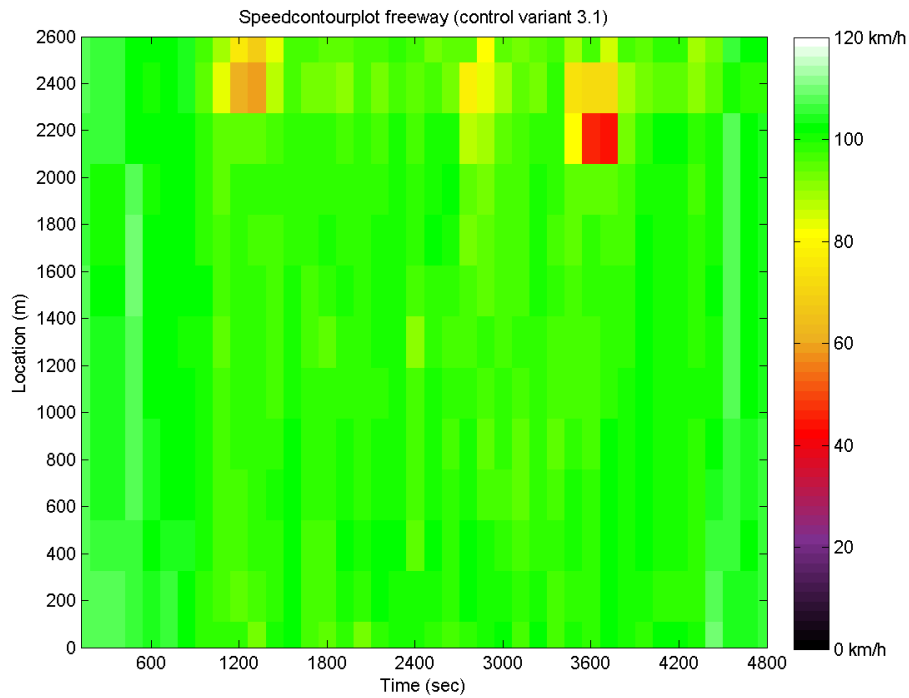


Figure F.4 Speedcontourplot of the freeway with the use of controller 3.1, the on-ramp is located at 2300 m.

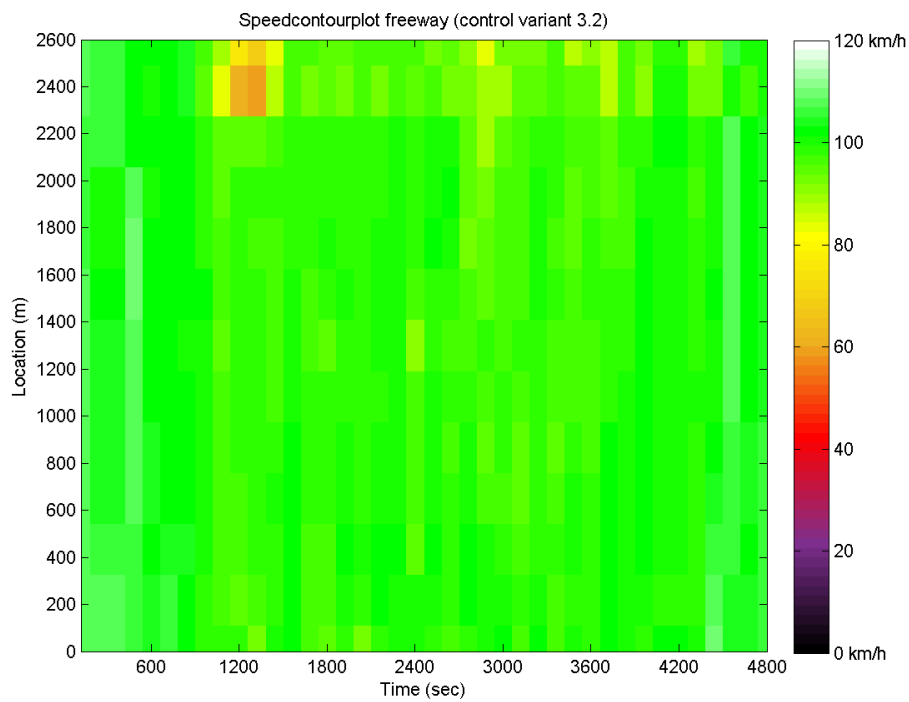


Figure F.5 Speedcontourplot of the freeway with the use of controller 3.2, the on-ramp is located at 2300 m.

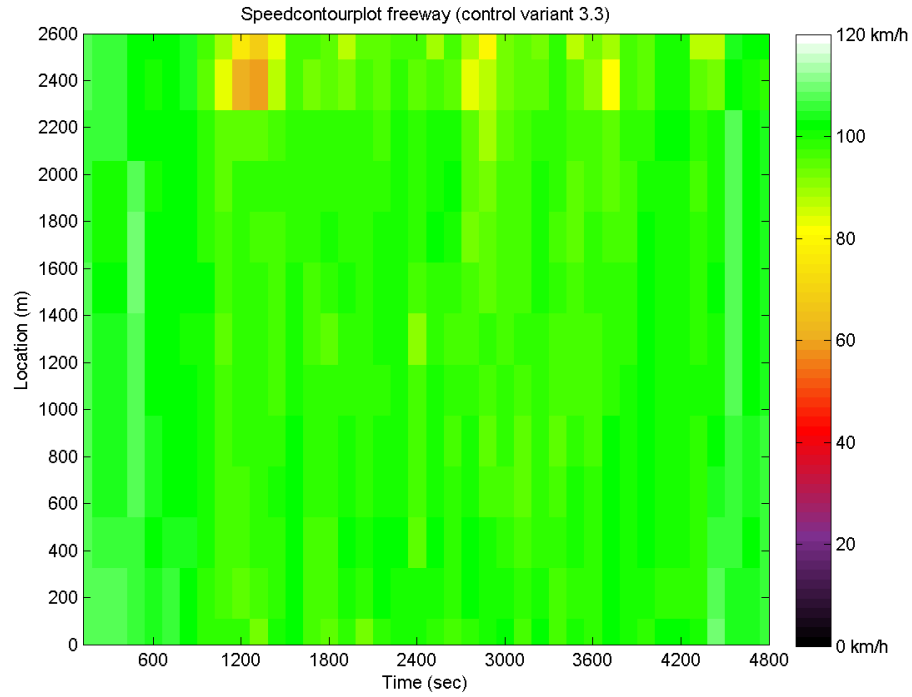


Figure F.6 Speedcontourplot of the freeway with the use of controller 3.3, the on-ramp is located at 2300 m.

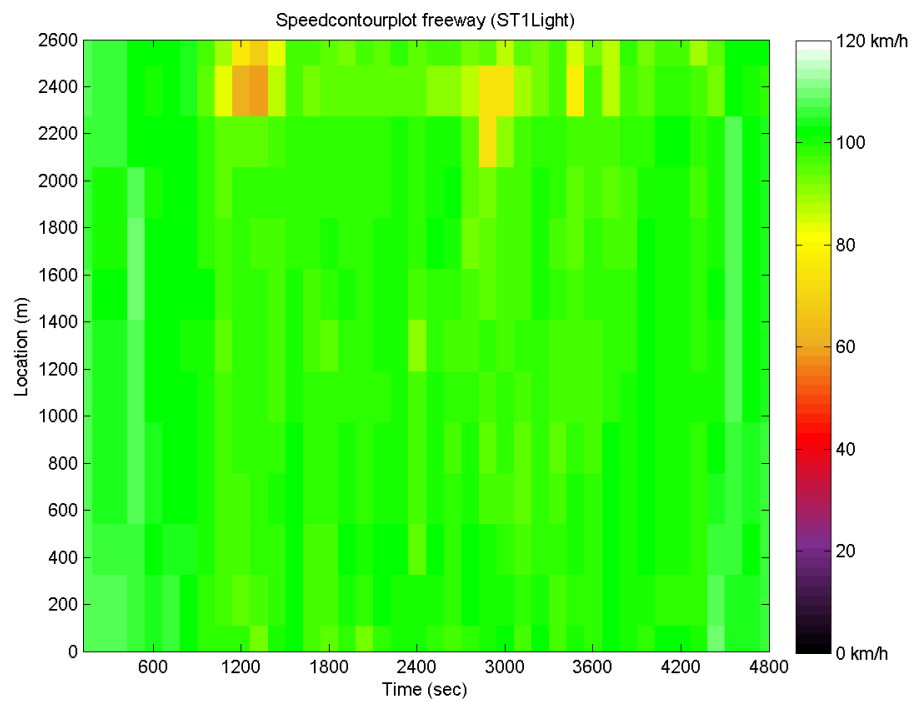


Figure F.7 Speedcontourplot of the freeway with the use of the ST1Light, the on-ramp is located at 2300 m.

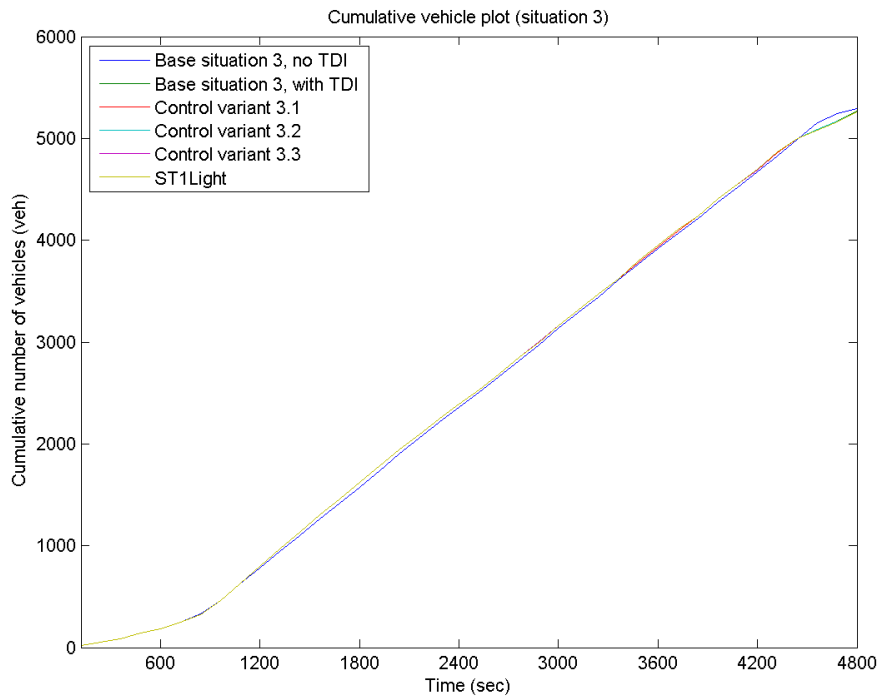


Figure F.8 Cumulative vehicle plot at the freeway for controlled and uncontrolled situations in situation 3.

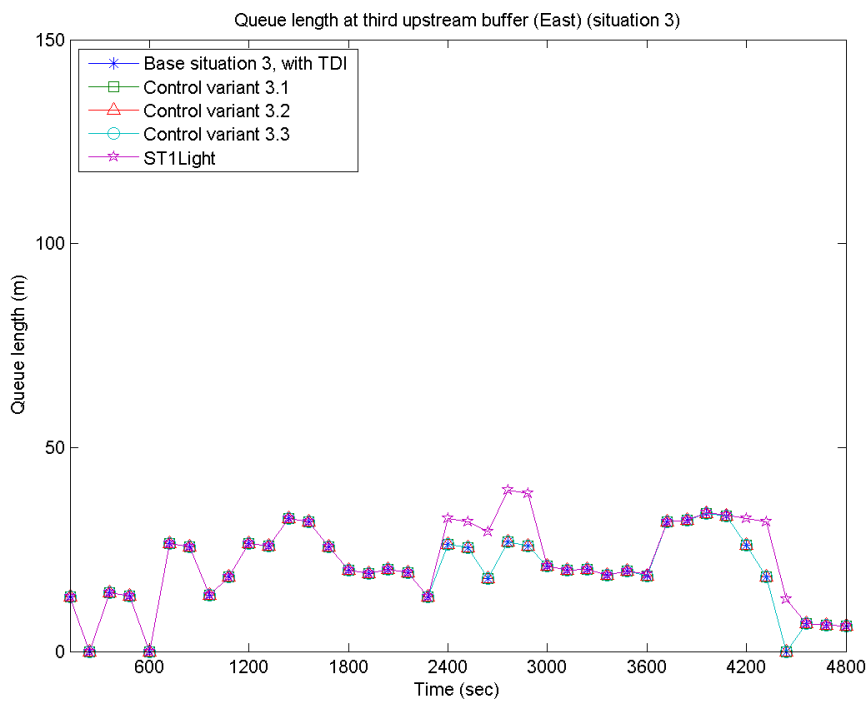


Figure F.9 Queue length at third upstream buffer (East) for the base situation (with ramp meter) and the controllers in situation 3.

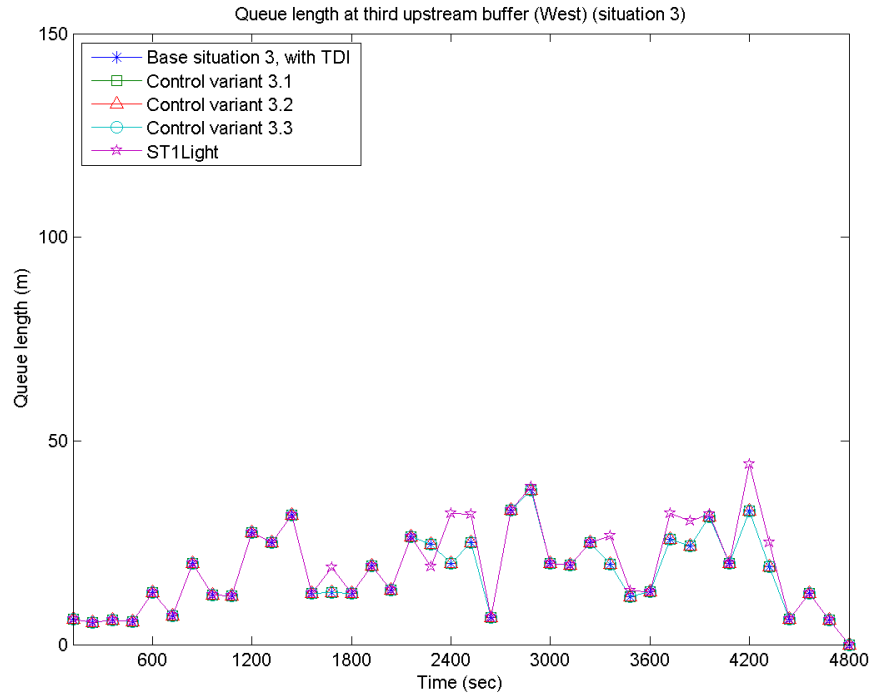


Figure F.10 Queue length at third upstream buffer (West) for the base situation (with ramp meter) and the controllers in situation 3.