Optimising the throughput for an integrated urban-freeway network

Design of an MPC controller using variable speed limits and intersection control

MSc Thesis Report (CIE5060-09)

MSc Civil Engineering track Transport & Planning

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Top figure: Chriszwolle, 2009
Bottom figure: LennartBolks, 2003

In memory of Anneke van der Mark

Preface

This report is my MSc Thesis report. Subject of my MSc Thesis report is the development of a novel integrated urban-freeway network controller. My inspiration for this subject has been present throughout my BSc and MSc studies on the subject of civil engineering. Back in 2008 when I was still exploring my BSc and MSc study opportunities I attended a civil engineering lecture where the advantages of ramp metering were mentioned. This made me think: suppose a ramp meter can prevent congestion due to high freeway usage, wouldn't it create traffic jams that would block urban intersections? Back then, I did not search for an answer, but did things that were more important at that moment; I made my decision to study civil engineering at Delft university of Technology, I obtained my BSc degree, I chose to follow the MSc track Transport & Planning and completed it, save for the MSc Thesis. In choosing the subject for my MSc Thesis, the question resurfaced and the answer was found: an often applied measure to prevent on-ramp jams from blocking urban intersections is setting the ramp metering cycle to its minimum value when the queue length at the on-ramp exceeds a certain threshold value (Muller et al, 2014 [1]). The result of this measure is that as long as the queue length at the on-ramp is too large, the maximum flow that can be metered is admitted onto the freeway, regardless of the flow needed to prevent congestion. An alternative measure is to turn ramp metering off when the queue length becomes too large.

The question and its answer show that urban controllers and freeway controllers influence each other in ways that are not necessarily positive for the traffic processes they attempt to control. As will be explained in the introduction, problems like this gave rise to the development of integrated urban-freeway network controllers. Developing a novel integrated urban-freeway network controller gives the opportunity to find new insights in integrated control methods to improve the efficiency of road use. Therefore, it has been chosen as the subject of my MSc Thesis report.

The path from elementary school to the completion of the MSc Thesis project was a rocky one along which I have many people to thank for helping me get where I am today. No specific order in which one can put these people will do justice to their efforts, therefore I will put them in the order of directness of the influence on the MSc Thesis project they had.

First of all, I would like to thank Goof van de Weg for the quality of his supervision of my MSc Thesis project from the preliminary phase of this project until the final phase. Before the start of my MSc Thesis project, he already provided me with the means to brush up on control theory, particularly the Model Predictive Control strategy. During my MSc Thesis project, he gave me very valuable advice on how to defend the choices I made along the way. Also, he provided me with MATLAB scripts that I only had to edit in order to run the simulations.

I would like to thank Andreas Hegyi for taking over the supervision of my MSc Thesis project when Goof van de Weg was abroad. His advice on improving the MATLAB scripts and testing the results has been very valuable. But also the quality of the reviews of the reports and documents I produced greatly contributed to the final product of the MSc Thesis project.

I would like to thank Serge Hoogendoorn, the chair of my assessment committee, for the great inspiration he provided me with. This has been an important motivation during my MSc Thesis project. Also, his input and the input of other assessment committee members at committee meetings have been an important contribution to the final product of the MSc Thesis project.

Karel Karsen, the study advisor at the Faculty of Civil Engineering and Geosciences of Delft University of Technology, has provided me with very valuable advice from the moment I explored my study opportunities to the moment I was looking for an MSc Thesis project. I would like to express my thanks for his efforts over all these years.

Truusje van der Pauw, the school counselor at my high school, has provided me with very valuable advice in my exploration of study opportunities and arranged for me to meet Karel Karsen. I wish to thank her for her efforts.

Freek Mulder, my mentor at my high school, truly helped me through high school. Thanks to his efforts I managed to grab the chances offered to me and reached my full potential in my high school education. Therefore I express my utmost thanks for his efforts here.

Joke van Beekum was the most important positive force in my education at my elementary school. Thanks to her efforts, I reached my full potential in my elementary school education. Therefore, I express my utmost thanks for her efforts here.

Earlier in my elementary school career, Anneke van der Mark was an important positive force. Unfortunately, she passed away last May, so I chose to write this thesis in memory of her.

My parents Thea and Leo van der Molen-Pols have always been there for me. At home, they helped me with numerous things. Therefore, I wish to thank them for everything in all those years.

Rien van der Molen

Delft, August 2016

Summary

In this MSc Thesis project, an integrated urban-freeway network controller is developed to improve throughput with respect to coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account) in the situation of congestion caused by high demand moving from the urban network to the freeway. This is done with the following design goals in mind:

- Improved throughput with respect to the situation with coordinated controllers
- A computation time that allows for real-time control

After development the controller is evaluated, fulfilling the sub-objectives:

- Develop the integrated urban-freeway network controller
- Evaluate the integrated urban-freeway network controller

The method used for developing the integrated controller is combining urban and freeway control algorithms, integrating them.

In chapter 2 algorithms are selected based on criteria that make them promising. With the promising control algorithms there are 38 possible integrations. This amount of combinations is reduced by subsequently removing algorithms that require significant alteration for integration and removing algorithms that can be expected to take a long time to be integrated. Out of the remaining 3, one is selected based on considerations of requirements and existing integrated algorithms. The selection is to minimise the amounts of requirements with respect to the traffic flow model and the optimisation complexity. Furthermore, the selection is to suggest a different integration than the considered existing integrated algorithms. This results in the selection of the integration of a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC*.

In chapter 3 the controller is developed this way. It chooses urban green time shares, initial positions of head and tail of the speed-limited area and speeds of head and tail of the speed-limited area at each update time. In between update times, the urban green time shares and the speeds of head and tail of the speed-limited area are constant. The chosen values are subject to constraints with respect to green time shares (should have values in between 0 and 1 and sums over conflicts should be at most 1), initial positions of head and tail of speed-limited area (should be in between upstream and downstream bounds and the position of the head should be equal to or more downstream than the position of the tail), speed of head and tail of the speed-limited area (should be at most the effective speed of the speed-limited area when downstream speeds are positive and upstream speeds are negative) and the control and prediction horizons (from the control horizon until the prediction horizon the green time shares and the speeds of head and tail of the speed-limited area are constant). The chosen values are chosen to optimise the total time spent over the prediction horizon based on its traffic model.

In chapter 4 a simulation is set up so the developed controller can be evaluated. For evaluation, the following evaluation criteria have been formulated:

- Total time spent in the network by all vehicles; this is a performance indicator that has to show improvement with respect to the situation with coordinated control.
- Computation time; this is a performance indicator to check whether or not the computation time allows for real-time control.
- Qualitative behaviour; this evaluation is to check if it is likely the controller would function in the field. This is the case when it behaves as predicted.

The developed controller in this MSc Thesis project does not meet all three evaluation criteria. Although it does achieve the expected effects and reduces the total time spent more than the coordinated controllers, it does so with unexpected behaviour and a computation time that surpasses the update time.

In chapter 5 these results are considered in the light of the limitations of the developed controller. Based on this consideration many recommendations are found. The primary recommendations deal with the problems the controller has with the evaluation criteria. The recommended solution to deal with the problem with respect to computation time is to do further research in the effects of the traffic flow model and the controller update time and subsequently to adapt the traffic flow model, to adapt the controller update time, to adapt the optimisation function, to increase the number of cores the controller uses in parallel computing and to improve the efficiency of the MATLAB scripts the controller uses. The recommended solution to deal with the unexpected behaviour the controller achieves the expected effects with is doing further research into this behaviour.

A secondary recommendation is to do research into the controller's sensitivity for the initial control signal. The need for this research exists as test simulations have shown that the controller is quite sensitive to its initial control signal. In order to cope with this sensitivity, the initial control signal was chosen to be close to the theoretical optimum following from the simplified analytical calculation on which the values of the disturbances are based. This tied together the initial control signal, the scenario and the control actions, thus makes the controller unsuitable for application in other scenarios. To solve this problem, research into the sensitivity for the initial control signal is needed.

A tertiary recommendation is to simulate more scenarios in future research to determine how the controller behaves under different scenarios.

If the controller is to be developed further, a wider scope is needed. Such a wider scope brings with it subjects for further research that have not been considered in this MSc Thesis project. Such subjects include data detection, data processing, actuation, controller imperfections apart from modelling imperfections, the effect of imperfections in the predictions of the disturbances and the possibilities to enhance the controller with other control algorithms. For such enhancements, it is recommended to use METALINE or linear optimal ramp metering algorithms when considering enhancing with ramp metering and to use iterative route advice when considering enhancing with route choice algorithms.

Contents

1 Introduction

Improving the efficiency of road use has many benefits to society: reductions of emissions, reductions in travel times and increases in productivity. Therefore, many traffic management measures exist that have road use efficiency as one of their design goals.

However, not all traffic management measures that have road use efficiency as one of their design goals result in efficient road use in practice. For instance, one could consider an urban arterial with traffic signals at each intersection that minimise the delay faced by traffic from all their approaches. If the traffic following the arterial faces a red signal at each individual intersection, the arterial is not efficiently used. Situations like this gave rise to coordinated signal controllers (Papageorgiou et al, 2003). Similarly, controllers have been developed that coordinate many ramp metering installations along a freeway arterial. Thus there are coordinated controllers in both urban and freeway networks. Advantage of coordinated controllers is that they take the effect of multiple controlled elements (e.g. intersections, on-ramps, speed-limited traffic state areas, route choice distributions etc. [1]) into account. However, they do not take effects outside their respective networks into account, while it is a reality that urban networks and freeway networks are often connected.

This limitation of coordinated controllers can cause problems at the connection between urban networks and freeway networks. For instance, a traffic jam might form on the freeway at an on-ramp because the on-ramp received large amounts of traffic from the urban network where throughput was maximised. Similarly, the maximisation of throughput in the urban network might result in not giving enough green time to an off-ramp, causing queues to grow on the off-ramp and eventually to spill back onto the freeway.

Problems like these gave rise to the development of integrated urban-freeway network controllers. Integrated urban-freeway network controllers integrate the coordination of controlled elements in the urban network and the freeway network. While this is a logical step, it is not as straightforward as it may seem.

[1] Traffic signals and ramp metering installations are commonly referred to as actuators: devices a controller uses to control a controlled element. The controlled elements for traffic signals and ramp metering installations are intersections and on-ramps, respectively. Speed-limited traffic state areas are defined as areas in a space-time diagram (such that space is described along the considered road and time from an arbitrary starting point) with a single speed limit (that is lower than the free speed of the road to which it is applied) and a single density. Their actuators are speed limit gantries, whereas the actuators for route choice distributions are variable message signs and navigation systems reporting travel times due to these route choice distributions (these navigation systems may not be directly controlled by a controller controlling route choice distributions, but may be implicitly or explicitly taken into account by the controller).

A complicating factor for integrated urban-freeway network controllers is that such an integration causes a strong increase in the number of controlled elements, which is one of the factors that causes the integrated urban-freeway network controller to become much more complex. This strong increase in controlled elements stems from the fact that coordinated controllers in an urban network have much more controlled elements per kilometre of network length as coordinated controllers in a freeway network have; an example would be the integration of a coordinated controller on the freeway network controlling a 3 kilometre freeway stretch with three ramp meters at on-ramps 1 kilometre apart and three coordinated controllers controlling 3 kilometre long urban arterials with signals at intersections 300 metres apart. Where before integration the highest number of controlled elements was 10, integration made it rise to 33.

The coupling of urban roads and freeway roads forms another factor that causes the integrated urban-freeway network controller to become much more complex. This is a result of the fact that urban roads and freeway roads differ in an extent that they require to be modelled differently; even if the same model is used, the model parameters need to be different. So an integrated urban-freeway network controller always faces challenges in the coupling of the different road types.

This increase of controller complexity further complicates the development of integrated urban-freeway network controllers. Therefore, only a limited amount of integrated urban-freeway network controllers have been developed. Field implementation of integrated urban-freeway network controllers is even rarer, as more complex controllers require more complex communication with sensors and actuators and more computation time. These are all complicating factors for implementation. This allows for developing a novel integrated urban-freeway network controller, which in turn allows for the discovery of new insights that help improving the efficiency of road use in the future. Therefore, the development of a novel integrated urban-freeway network controller has been chosen as the subject of this MSc Thesis project. This choice will be motivated in section 1.1.

1.1 Motivation

The subject of the MSc Thesis project is *the development of a novel integrated urban-freeway network controller*. The choice of this subject is motivated by the opportunity to find new insights in integrated control methods to improve the efficiency of road use. This opportunity exists as only a limited amount of integrated urban-freeway network controllers have been developed and field implementation of integrated urban-freeway network controllers is even rarer. This forms a motivation for the choice of this subject as well, as limited field implementation allows room for improvement with respect to implemented controllers. Further underpinning of the choice of the subject of this MSc Thesis project is given by the problem description, objectives and scope of the MSc Thesis project. These are sections 1.2, 1.3 and 1.4, respectively.

1.2 Problem description

The development of a novel integrated urban-freeway network controller is to be aimed at the solution of a problem. In theory, integrated urban-freeway network controllers could solve many problems, including problems that only involve the freeway network or only involve the urban network. However, integrated urban-freeway network controllers would provide a solution for such isolated problems that is at best as good as the solutions coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account) would provide. On the other hand, one can expect that integrated urban-freeway network controllers would provide a better solution for problems that involve both the freeway network and the urban network. Therefore, such problems will be considered here. Examples of such problems are:

- Congestion due to an incident in the urban network in the vicinity of an off-ramp
- Congestion due to an incident in the freeway network in the vicinity of an on-ramp
- Congestion due to a jam wave (i.e. a jam of which the head and the tail propagate upstream at roughly the same speed) in the freeway network
- Congestion due to high demand of traffic moving from the freeway network to the urban network
- Congestion due to high demand of traffic moving from the urban network to the freeway network

Given the fact that the time allotted to the MSc Thesis project is limited, only one of such problems can be chosen. Therefore, the choice for the latter problem is made. Reason for this choice is that this problem was one of the problems that gave rise to the development of integrated urban-freeway network controllers; coordinated urban network controllers handle this situation by maximising the throughput of the urban network and leaving any resulting congestion on the freeway network as a problem for the freeway network controller. Any integrated urban-freeway network controller should at least under certain circumstances be able to improve the situation for the traffic with respect to the situation with coordinated controllers.

According to the *design methodology for traffic control systems* by Hegyi (2014 [1]) a problem description aimed at the development of a control system needs to be characterised by an undesired situation and a desired situation. The undesired situation is characterised by decreased throughput due to the capacity drop on the freeway due to congestion formation resulting from high demand of traffic moving from the urban network to the freeway network. The desired situation is characterised by improved throughput with respect to the situation with coordinated controllers. This improved throughput is possible as the integrated urban-freeway network controller distributes any negative impacts of its control actions on throughput over both networks. On the other hand, coordinated controllers face the fact that the freeway controller has to prevent the capacity drop on its own, concentrating any negative impacts of control actions to do so in the freeway network.

1.3 Objectives

The development of a novel integrated urban-freeway network controller is to result in a controller that is able to improve the throughput with respect to the situation with coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account). In order to do so, the computation time the controller uses needs to allow for real-time control. Therefore, there are two design goals for the controller:

- Improved throughput with respect to the situation with coordinated controllers
- A computation time that allows for real-time control

As a result, the main objective of this MSc Thesis project can be defined as follows: *To develop an integrated urban-freeway network controller with the design goals in mind.*

In order to check the quality of the controller, evaluation is necessary. This results in two sub-objectives:

- Develop the integrated urban-freeway network controller
- Evaluate the integrated urban-freeway network controller

1.4 Scope

Given the objectives in section 1.3, the scope of the MSc Thesis project needs to be limited. These limitations will be applied such that the subject of the MSc Thesis project as it is motivated in section 1.1 and the problem description will be reflected best by the resulting MSc Thesis project.

The subject of the MSc Thesis project as it is motivated at the beginning of this section allows for the limitation to keep future implementation of the controller in mind when developing it. According to Van de Weg (2013) this limitation can be observed by making sure the controller has the following properties:

- The qualitative behaviour is not too different from that of controllers that have been implemented in the field
- The controller has a similar control approach and computational complexity as controllers that have been implemented in the field
- The controller makes use of technologies that are currently available or will be available in the near future

Considering the work by Van de Weg (2013), the first two properties can be observed by using existing urban and freeway controllers as building blocks for the integrated urban-freeway network controller to be developed in this MSc Thesis project. Existence in this context should be considered in a broad manner, as it should for instance include using variable speed limits to limit inflow into links that would become congested and face a capacity drop without limiting inflow. This broad view requires limiting the scope such that only the control algorithms within the integrated urban-freeway network controller are considered. This limitation removes data detection, data processing and actuation from the scope, as well as any controller imperfections apart from modelling imperfections.

The third property can be observed by limiting the control algorithms to be taken into account to signal control algorithms, ramp metering algorithms, variable speed limit algorithms and route guidance algorithms. This limits the types of control algorithms to be used for integration. However, the controller resulting from this MSc Thesis project may be enhanced with other control algorithms in future research. This possibility needs to be taken into account in the recommendations.

As only the control algorithms within the integrated urban-freeway network controller are to be considered, evaluation has to take place by means of simulation. Similar to the work by Van de Weg (2013) it will be more important to show that the integrated urban-freeway network controller acts as predicted than to assess the integrated urban-freeway network controller to a very realistic scenario. Therefore, both the simulation network and traffic situation that make up the scenario can be kept simple in the controller evaluation.

1.5 Research approach and Thesis outline

Based on the objectives and the scope, the research approach is to consider control algorithms for both the urban and the freeway network as building blocks for the control algorithm within integrated urban-freeway network controller, to use these building blocks to develop the control algorithm within the integrated urban-freeway network controller and to evaluate the integrated urban-freeway network controller. The results of this evaluation need to be discussed before conclusions can be drawn and recommendations can be formulated. Thus the steps for the approach that can be distinguished are:

- Literature review (considering potential building blocks)
- Controller development (using the building blocks)
- Controller evaluation
- Discussion
- Conclusions and recommendations

It is logical to devote a chapter of the report to each of the steps. Therefore, the outline for this MSc Thesis report is as follows:

2 Literature review

Chapter 2 contains the literature review. The goal of the literature review is to identify the most promising control algorithms for both the urban and the freeway network. This will be done by identifying criteria that make a control algorithm promising and subsequently assessing algorithms found in literature on these criteria.

3 Controller development

Chapter 3 contains the controller development. Based on the results of the literature review, the controller will be developed by combining the promising control algorithms. This will be done by elaborating upon all relevant aspects of the controller. As it is dependent on the promising control algorithms which aspects of the controller are relevant, the relevant aspects are identified first.

4 Controller evaluation

Chapter 4 contains the controller evaluation. This evaluation needs to take place by simulation. In order to do so, all information necessary to replicate the simulation needs to be assembled. This is referred to as the simulation set-up. Based on the simulation set-up, evaluation criteria are formulated to make a sensible evaluation. Once that is done, the situation without any control measures, the situation with coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account) and the situation with the developed controller will be assessed on the evaluation criteria.

5 Discussion

Based on the results of the controller evaluation, the results are discussed in chapter 5 in the light of the limitations of the developed controller. Both limitations originating from the scope and limitations resulting from choices made in the development of the controller will be considered.

6 Conclusions and recommendations

Based on the discussion, conclusions are drawn in chapter 6 and recommendations are formulated for future research

The report is concluded with the references and the list of annexes.

2 Literature review

The goal of the literature review is to identify the most promising control algorithms for both the urban and the freeway network. This will be done by identifying criteria that make a control algorithm promising and subsequently assessing algorithms found in literature on these criteria.

Given the scope the only control algorithms that are to be considered are signal control algorithms, ramp metering algorithms, speed limit algorithms and route guidance algorithms. Therefore, it is logical to assess these algorithms in separate sections following the section where the criteria are identified.

Given the fact that the time allotted to the MSc Thesis project is limited, not all of these algorithms can be considered. The algorithms that are considered have been found during the literature research and together form a set of algorithms that is considered diverse enough to consider the literature research as completed.

The first thing to do is identifying the criteria, so that will be done in section 2.1. Then in section 2.2 signal control algorithms will be assessed, in section 2.3 ramp metering algorithms, in section 2.4 speed limit algorithms and in section 2.5 route guidance algorithms. One algorithm has been considered that combines a ramp metering algorithm and a speed limit algorithm. This algorithm will be elaborated upon in section 2.6. In section 2.7, it is noted that some algorithms exist that integrate these algorithms. From this, a conclusion will be drawn in section 2.8.

2.1 Criteria to identify algorithms as promising

Given the goal of the literature review, identifying criteria that make a control algorithm promising can be done by considering how a control algorithm as part of an integrated urban-freeway network controller would contribute to the desired situation defined in the problem description.

The integrated urban-freeway network controller needs to improve throughput with respect to the situation with coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account). It needs to do so by distributing any negative impacts of its control actions on throughput over both networks. Given the undesired situation defined in the problem description, the control actions need to involve the reduction of flow towards links downstream of on-ramps such that the flow in the link(s) where congestion would occur if no control actions were taken remains at capacity. So a main functionality that a potential algorithm needs to have is the ability to reduce flow towards downstream links based on the capacity of those links and the other flows towards those links. Depending on the network, those downstream links may be multiple links downstream from the location where the control actions are applied.

Checking algorithms for such a functionality may not be straightforward, as such a functionality may only be partially present. For instance, a potential algorithm may be able to reduce the flow towards downstream links based on the capacity of those links and the other flows towards those links, but only if the other flows towards those links are unhindered on their way there. Such an algorithm would only work in under-saturated conditions, where the output of one controlled element would affect the input of downstream elements (Van de Weg et al, 2016). The desired situation requires algorithms that can adapt to under-saturated, saturated and over-saturated conditions. Over-saturated conditions are characterised by the fact that the output of one controlled element affects the input of upstream elements, whereas under saturated conditions there is no direct influence.

Therefore, the criteria should be formulated such that together they guarantee the presence of such a functionality. Doing so results in the following criteria:

- The ability to reduce inflow based on the needs of (further) downstream links; this criterion forms a necessary, but not sufficient condition to guarantee the presence of such a functionality. The other criteria cover what is lacking in this criterion.
- The coordination between different controlled elements; in order to reduce the flow towards downstream links based on the capacity of those links and the other flows towards those links, the algorithm needs to be able to determine how these other flows are affected by other controlled elements. Controlled elements in this context are intersections, on-ramps, speed-limited traffic state areas and route choice distributions. Speed-limited traffic state areas are defined as areas in a space-time diagram (such that space is described along the considered road and time from an arbitrary starting point) with a single speed limit (that is lower than the free speed of the road to which it is applied) and a single density.
- The ability to adapt to different traffic conditions (under-saturated, saturated or over-saturated); as pointed out above, the algorithm needs to be able to determine the other flows both when those flows are hindered and when those flows are unhindered.

Based on the objectives, it is important as well to make sure the controller to be developed has a computation time that allows for real-time control. This can be done by adding the criterion that an efficient computation algorithm is to be used. Therefore, the criteria to be used for determining if the algorithms are promising are the following:

- Ability to reduce inflow based on the needs of (further) downstream links
- Coordination between different controlled elements
- Ability to adapt to different traffic conditions (under-saturated, saturated or over-saturated)
- Usage of an efficient computation algorithm

2.2 Signal control algorithms

In this section, an assessment of signal control algorithms will be given. Signal control algorithms aim to distribute green times over conflicting approaches during signal cycles in order to maximise intersection throughput while respecting intersection constraints. Inspired by Papageorgiou et al (2003), one can categorise signal control algorithms as follows:

- Isolated intersection control
- Fixed time coordinated control
- Coordinated traffic-responsive control
- Optimal coordinated control

Each of the signal control algorithms belonging to a category will be elaborated upon in their designated subsections. Subsequently, an overview of the assessment of these algorithms will be given to conclude this section.

2.2.1 Isolated intersection control

Isolated intersection control involves the control of intersections regardless of how other intersections in the network are controlled. Isolated intersection control comes in two main forms:

- Fixed time strategies
- Traffic responsive strategies

Each of these strategies will be discussed in this subsection.

Fixed time strategies

Fixed time strategies control intersections by giving green to a number of approaches in a fixed pattern called a structure, consisting of stages (Salomons, 2014). This structure is independent of the actual traffic demands and is based on minimisation of the delays based on off-line measurements of the traffic demands (Papageorgiou, 2003). The following three methods to do so will be described here:

- SIGSET (Allsop, 1971)
- Uniform cycle time method (Courage & Papapanou, 1977)
- SIGCAP (Allsop, 1976)

Following the descriptions the methods will be assessed on the criteria to determine if they are promising.

SIGSET

According to Papageorgiou et al (2003) and Salomons (2014), the SIGSET method by Allsop (1971) optimises a nonlinear total delay function which was derived by Webster (1958), while respecting linear constraints. The result of this optimisation is the so-called Webster cycle time for structures. By comparing the Webster cycle time for different structures, a structure with a shortest cycle time is found. This structure is subsequently chosen and implemented.

Uniform cycle time method

According to Salomons (2014), the uniform cycle time method by Courage & Papapanou (1977) is based on the assumption that all traffic arrives uniformly distributed at the intersection. The result of this assumption is the so-called uniform cycle time for structures. By comparing the uniform cycle time for different structures (if necessary by considering a critical path through the structure consisting of approaches out of which some can have green at the same time such that the critical path cycle time is larger than the structure cycle time), a structure with the shortest cycle time is found. This structure is subsequently chosen and implemented.

SIGCAP

According to Papageorgiou et al (2003), the SIGCAP method by Allsop (1976) makes use of the constraint that the saturation flow for an approach (which is the average flow crossing the stop line of an approach when traffic from that approach is crossing the stop line during green and yellow coming from a queue and continuing unhindered beyond the stop line) multiplied by the share of the cycle time that approach has effectively green (has green or yellow and traffic is using it to cross the stop line) has to be larger than or equal to the traffic demand. It multiplies the demand side of this constraint with a variable it tries to maximise. Based on this, an appropriate structure is chosen and implemented.

<u>Assessment of fixed time strategies</u>

Table 2.1 gives an overview of the assessment of the fixed time strategies with the criteria to determine if they are promising.

Table 2.1 Overview of the assessment of fixed time strategies

Criterion	SIGSET	Uniform cycle time method	SIGCAP
Ability to reduce inflow based on the needs of (further) downstream links	No	No	No
Coordination between different controlled elements	No	No	No
Ability to adapt to different traffic conditions	No	No	No
Usage of an efficient computation algorithm	Yes, simple calculations for limited amounts of structures	Yes, simple calculations for limited amounts of structures	Yes, linear programming

Traffic responsive strategies

Traffic responsive strategies control intersections by giving green to a number of approaches based on the detection of traffic on the approaches of the intersection. This can be done with a predetermined structure where only the switching is altered based on traffic detection (Papageorgiou et al, 2003) or with a changeable structure (Salomons, 2014). In total, three algorithms are distinguished here:

- Vehicle interval method (Papageorgiou et al, 2003)
- Uniform cycle time method for traffic responsive strategies (Courage & Papapanou, 1977)
- MOVA (Vincent & Young, 1986)

Each of these algorithms will be described before they are assessed on the criteria to determine if they are promising.

<u>Vehicle interval method</u>

The vehicle-interval method starts to operate in a stage at a time T before the minimum green time for the stage has been spent (Papageorgiou et al, 2003). If during the time T no vehicle is detected on the approaches that have green during that stage, the controller moves to the next stage. If during the time T one or more vehicles are detected on these approaches, the controller checks if the number of vehicles on other approaches has surpassed a certain threshold. If so, the controller moves to the next stage, if not, the controller prolongs the green time for that stage by time T.

During prolongations, the controller performs the same checks as during time T. If the controller has reached a maximum number of prolongations, it moves to the next stage.

Uniform cycle time method for traffic responsive strategies

According to Salomons (2014), the uniform cycle time method by Courage & Papapanou (1977) can be used for traffic responsive strategies by using the on-line determined demands in the determination of the shortest uniform cycle time. The structure with the shortest cycle time is implemented until new measurements become available.

MOVA

According to Papageorgiou et al (2003), MOVA (Vincent & Young, 1986) has a similar approach as the vehicle-interval method. The difference is based on a proposition by Miller (1963) to sophisticate the vehicle interval method. Papageorgiou et al (2003) describe this sophistication as such that instead of checking whether vehicles have been detected during time period T, the controller uses the measurements of the demands to determine the time gain by prolonging the green time for the current stage by a multiple of T smaller than the maximum number of prolongations, measured from the current prolongation. When time gains for each possible multiple have been determined, MOVA determines the largest time gain. If this time gain is negative, the controller switches to the next stage at the end of the current prolongation. If not, the controller prolongs the green time for the current stage by time T.

Assessment of traffic responsive strategies

Table 2.2 gives an overview of the assessment of the traffic responsive strategies with the criteria to determine if they are promising.

Table 2.2 Overview of the assessment of traffic responsive strategies

Criterion	Vehicle interval method	Uniform cycle time method	MOVA
Ability to reduce inflow based on the needs of (further) downstream links	No	No	No
Coordination between different controlled elements	No	No	No
Ability to adapt to different traffic conditions	No	No	No
Usage of an efficient computation algorithm	Yes, only a few simple calculations	Yes, simple calculations for limited amounts of structures	Yes, linear programming

2.2.2 Fixed time coordinated control

Fixed time coordinated control involves the control of multiple intersections based on off-line measurements of the traffic demands (Papageorgiou et al, 2003). Various fixed time coordinated controllers have been developed. The following two algorithms will be described in this subsection:

- MAXBAND (Little, 1966)
- TRANSYT (Robertson, 1969)

Both algorithms will be described before they are assessed on the criteria to determine if they are promising.

MAXBAND

According to Papageorgiou et al (2003), MAXBAND (Little, 1966) considers a network consisting of a two-way arterial along which intersections are placed with known cycle times. The aim of MAXBAND is to align the green phases for the considered arterial approaches at the various intersections such that the average bandwidth b of outbound traffic and $\overline{b}$ of inbound traffic is maximised; see figure 2.1. Since average value and area are directly proportional (Stewart, 2008), this maximisation is found when the area between piecewise linear lines o_1 and o_2 and i_1 and i_2 is maximised. Thus MAXBAND (Little, 1966) maximises these areas by shifting the green phases around while holding the slope (which is the speed vehicles need to drive at the edges of the green wave MAXBAND is creating) of piecewise linear lines o_1 and o_2 and i_1 and i_2 within a certain range.

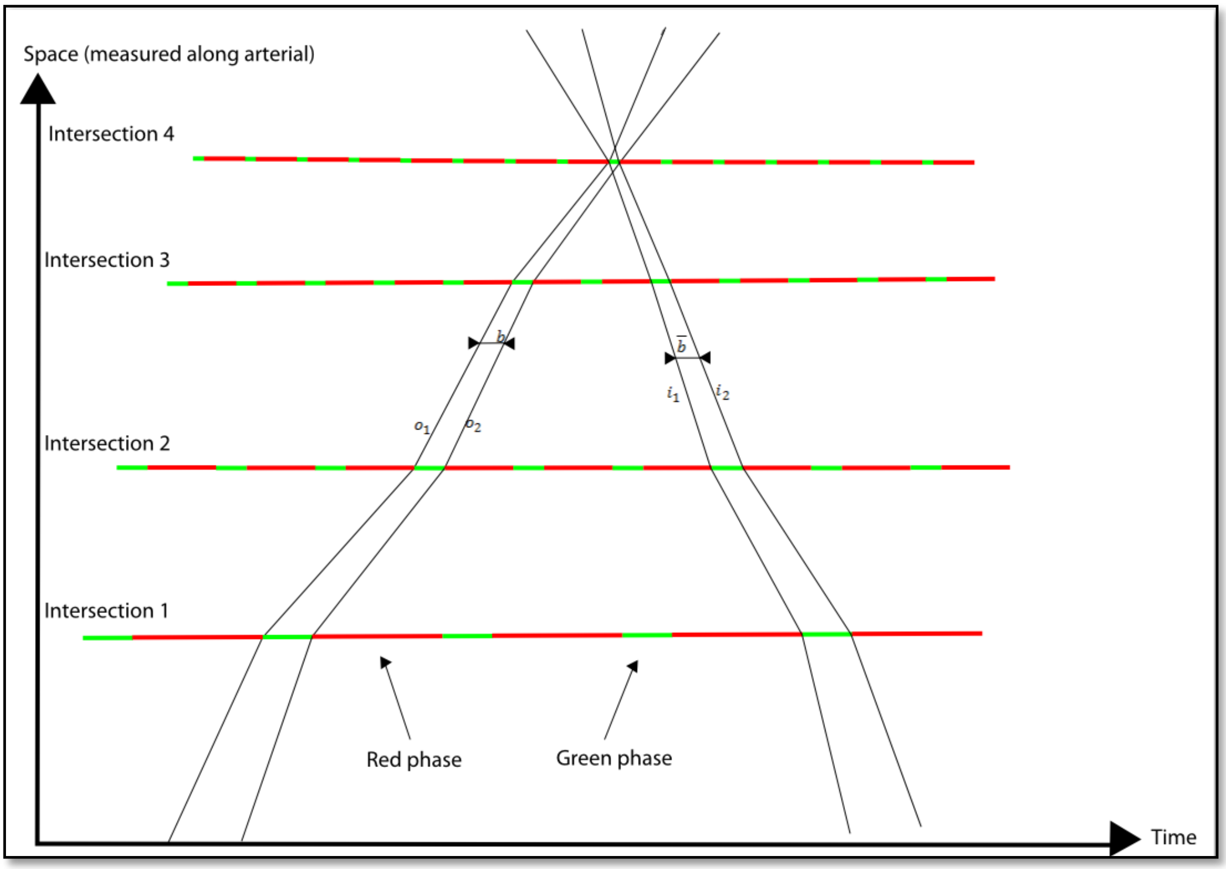

Figure 2.1 MAXBAND aims to align the green phases such that the averages of the depicted bandwidths are maximised (figure inspired by Little, 1969)

TRANSYT

According to Papageorgiou et al (2003), TRANSYT (Robertson, 1969) considers traffic demands at the edge of the considered network. Subsequently, it calculates how the traffic in the network behaves under varying structures for the controlled intersections under the constraint that all cycle times are either a given network cycle time $T_{c;N}$ or half this cycle time. An essential element in the algorithm is how it calculates the traffic demands at intersections which are not located at the edge of the network. It considers unidirectional links connecting the intersections in the network and based on an arrival pattern at the entry of the link, it calculates an output pattern on the link based on platoon dispersion (Muller et al, 2014 [2]). Based on variation of the structures at the intersections, the algorithm can assess a performance indicator based on the traffic behaviour, which it aims to optimise (Papageorgiou et al, 2003).

Assessment of fixed time coordinated control algorithms

Table 2.3 gives an overview of the assessment of the fixed time coordinated control algorithms with the criteria to determine they promising.

Table 2.3 Overview of the assessment of fixed time coordinated control algorithms

Criterion	MAXBAND	TRANSYT
Ability to reduce inflow based on the needs of (further) downstream links	No	No
Coordination between different controlled elements	Yes	Yes
Ability to adapt to different traffic conditions	No, only suitable for under-saturated traffic conditions (Papageorgiou et al, 2003)	No, only suitable for under-saturated traffic conditions (Papageorgiou et al, 2003)
Usage of an efficient computation algorithm	Yes, simple optimisation	Unsure, as calculation of performance indicator can be quite complex

2.2.3 Coordinated traffic-responsive control

Coordinated traffic-responsive control involves the control of multiple intersections based on on-line measurements of the traffic demands (Papageorgiou et al, 2003). Various coordinated traffic-responsive controllers have been developed. The following six algorithms will be described in this subsection:

- SCOOT (Hunt et al, 1982)
- SCATS (RTA, 2015)
- Optimal switching time methods (Papageorgiou et al, 2003)
- Store- and forward based approach (Gazis & Potts, 1963)
- TUC (Diakaki & Papageorgiou, 2002)
- Backpressure (Tassiulas & Ephrimedes, 1992)

Each of these algorithms will be described before they are assessed on the criteria to determine if they are promising.

SCOOT

According to Papageorgiou et al (2003), SCOOT (Hunt et al, 1982) uses measurements of the traffic demands at the edge of the considered network. Subsequently, like TRANSYT, it calculates how the traffic in the network behaves under varying structures for the controlled intersections under the constraint that all cycle times are either a given network cycle time $T_{c;N}$ or half this cycle time. For intersections which are not located at the edge of the network, it considers unidirectional links connecting the intersections in the network, where the output pattern is based on an arrival pattern at the entry of the link and platoon dispersion (Muller et al, 2014 [2]). Based on variation of the structures at the intersections and the cycle time, the algorithm can assess a performance indicator based on the traffic behaviour, which it aims to optimise (Papageorgiou et al, 2003). Once an optimum has been found, the associated structures and cycle times are applied until new measurements become available.

SCATS

SCATS is the product of the Roads & Traffic Authority of New South Wales in Australia (RTA, 2015) which is credited with its development (Tyco Traffic & Transportation, 2015). According to Muller et al (2014 [2]), it uses the measurements of the traffic demands at all intersections to apply the uniform cycle time method for traffic responsive strategies to all intersections. Subsequently, it groups intersections together with a similar cycle time to coordinate them based on the model for traffic flow between the intersections it uses. For this coordination, it specifies a performance indicator which it tries to optimise. Once an optimum has been found, the associated structures and cycle times are applied until new measurements become available.

Optimal switching time methods

The optimal switching time methods form a type of algorithm such that all algorithms of this type can be considered promising under the same conditions. Algorithms of this type are considered by Papageorgiou et al (2003) as a group called *Model-based optimisation methods*. Since this name can cause confusion with other algorithms considered in this chapter, the name *Optimal switching time methods* will be used instead. Optimal switching time methods consider a network with a number of intersections with predefined structures, but the time to switch from the current stage to the next stage at each intersection is to be given a discrete value such that a performance indicator is optimised based on the current measurements of the traffic demands and the traffic behaviour in the network according to the traffic flow model it uses. Once an optimum has been found, the optimal switching time methods switch all intersections from the current stage to the next where the optimal switching time is exactly one time step or where the constraints in the optimisation dictate that switching has to take place now. Then at the next time step new measurements become available and the optimisation is repeated. Due to the presence of discrete variables in the optimisation, various algorithms exist for the optimisation:

- OPAC (Gartner, 1983)
- PRODYN (Farges et al, 1983)
- CRONOS (Boillot et al, 1992)
- RHODES (Sen & Head, 1997)

According to Papageorgiou et al (2003), OPAC uses complete enumeration (calculating all possible choices for the switching times (Verhaeghe, 2007)), whereas PRODYN and RHODES use dynamic programming (splitting up the choice process in stages and optimising per stage when the previous choices were system-optimal (Verhaeghe, 2007)) and CRONOS employs a heuristic global optimisation method (using a set of predefined rules (called heuristics) to find the switching times which might be optimal, but do not necessarily need to be due to the simplifications involved in the heuristics (Verhaeghe, 2007)).

Store- and forward based approach

According to Papageorgiou et al (2003), the store- and forward based approach (Gazis & Potts, 1963) is based on the store- and forward traffic flow model, which is explained in annex 1. The store- and forward traffic flow model allows networks of arbitrary size, topology and characteristics to be described with a linear state-space model. The store- and forward based approach aims to minimise the risk of oversaturation of its links, a risk that can be described by an objective function that allows for quadratic programming. The shares of the cycle time approaches of intersections have effectively green are the variables that are to be given the values associated with the minimum found with quadratic programming. The store- and forward based approach applies these values after each minimisation until new measurements become available.

TUC

According to Papageorgiou et al (2003), TUC (Diakaki & Papageorgiou, 2002) is a feedback algorithm based on the store-and forward based approach. Point of departure is the quadratic programming problem (2.1) explained in annex 1.

$$J = \frac{1}{2} \sum_{k=k_0}^{K} \left(\|\mathbf{x}(k)\|_{\mathbf{P}}^2 + \|\mathbf{u}(k)\|_{\mathbf{Q}}^2 + \|\mathbf{d}(k)\|_{\mathbf{R}}^2 \right) \quad (2.1)$$

By setting $\mathbf{d}(k) = \mathbf{d}^N$ for $k > k_0$, setting $K \to \infty$ and applying the control bounds externally, one can obtain a solution in the form of linear feedback formula (2.2).

$$\mathbf{u}(k) = \mathbf{u}^N - \mathbf{L}\mathbf{x}(k) \quad (2.2)$$

Where $\mathbf{u}^N$ is a nominal value for the control signal $\mathbf{u}(k)$ corresponding to the nominal disturbance $\mathbf{d}^N$. $\mathbf{L}$ is the corresponding feedback gain matrix. TUC uses formula (2.2) to determine its control settings.

TUC has wide applications, as it is suitable for saturated and oversaturated conditions. This follows from the fact that the aim of quadratic programming problem (2.1) is to minimise the risk of oversaturation of the network links. According to Papageorgiou et al (2003), TUC has been implemented in the urban networks of Glasgow (United Kingdom) and Chania (Greece). Furthermore, it has already been applied in an integrated controller: IN-TUC. This integrated controller is discussed in subsection 2.7.1.

Backpressure

According to Le et al (2015), the backpressure algorithm (Tassiulas & Ephrimedes, 1992) controls intersections individually, but considers them in relation to downstream intersections. It does so by estimating for each signal cycle the fraction of traffic that will turn from any of the ingoing links of the considered intersection to any of the downstream intersections. Subsequently, the algorithm considers an ingoing link at the considered intersection. For this ingoing link, the algorithm determines the products of these fractions and the measured queue lengths at these downstream intersections and sums them for all downstream intersections. The result is subtracted from the measured queue length at the considered intersection. This difference is weighted by the saturation flow for the considered ingoing link. The algorithm does this for all ingoing links at the considered intersection that have green during a stage of the signal cycle. The sum of the results is a weight representing the importance of the stage. Based on the weights, the backpressure algorithms gives green to the stage with the highest weight until new measurements become available.

Assessment of coordinated traffic-responsive control

Table 2.4 on the next page gives an overview of the assessment of coordinated traffic responsive control algorithms with the criteria to determine if they are promising.

Table 2.4 Overview of the assessment of traffic responsive control algorithms

Criterion	SCOOT	SCATS	Optimal switching time methods	Store-and forward based approach	TUC	Backpressure
Ability to reduce inflow based on the needs of (further) downstream links	No	No	Yes, assuming a traffic flow model is used that can handle different traffic conditions	Yes	Yes	Yes
Coordination between different controlled elements	Yes	Partially, only between intersections with a similar cycle time	Yes	Yes	Unsure, as coordination may be impaired due to setting disturbances equal to a nominal value	Partially, only under saturated conditions does coordination between subsequent intersections result in coordination between all intersections
Ability to adapt to different traffic conditions	No, only suitable for under-saturated traffic conditions (Papageorgiou et al, 2003)	Unsure, though widely implemented good performance is only reported for under-saturated traffic conditions (Muller et al, 2014 [2])	Yes, assuming a traffic flow model is used that can handle different traffic conditions	No, only suitable for saturated and over-saturated traffic conditions (Papageorgiou et al, 2003)	No, only suitable for saturated and over-saturated traffic conditions (Papageorgiou et al, 2003)	Limited, algorithm does adapt to under-saturated or over-saturated conditions, but is only optimal under saturated conditions
Usage of an efficient computation algorithm	Unsure, as calculation of performance indicator can be quite complex	Yes, simple calculations for limited amounts of structures, followed by limited optimisations	Depends on optimisation algorithm; OPAC, PRODYN and RHODES are not efficient, CRONOS is	Yes, quadratic programming	Yes, linear relations	Yes, simple calculations

2.2.4 Optimal coordinated control

Optimal coordinated control aims to control all traffic signals simultaneously such that an objective criterion is explicitly optimised, similar to the optimal ramp metering strategies presented in subsection 2.3.3 (Papageorgiou et al, 2003). This optimisation is usually based on the outcome of a traffic state prediction model fed with many traffic demand measurements and is subject to constraints. For optimisation, objective criteria may be used such as:

- Total time spent in the network
- Total amount of vehicles served (i.e. number of vehicles that reached the exit points of the network)
- Total vehicle loss hours
- Total amount of speed variation (traffic safety criterion; the lower the speed variation, the safer the traffic operations)
- Total amount of travel time variation (travel time reliability criterion)
- Total amount of emissions (environmental criterion)

Once the objective criterion has been optimised by varying the control signal, multiple strategies exist to implement the thus found optimal control signal:

- Implementing the control signal over the entire prediction horizon. This is known as the *Optimal control strategy*
- Implementing only the first step of the optimal control signal and repeating the optimisation once new measurements become available. This is known as the *Model Predictive Control strategy (MPC strategy)*

The traffic state prediction model used for the optimisation has a major influence on the efficiency of the computation algorithm. Based on this influence, the following two types of algorithms can be distinguished:

- Linear optimal coordinated signal control algorithms
- Nonlinear optimal coordinated signal control algorithms

Each of these types of algorithms will be discussed in this subsection. Subsequently, an overview of the assessment of these algorithms will be given to conclude this subsection.

Linear optimal coordinated signal control algorithms

Similar to how one could formulate linear optimal ramp metering algorithms based on linear traffic state prediction models instead of nonlinear optimal ramp metering algorithms based on nonlinear traffic state prediction models as Papageorgiou et al (2003) discuss, one could also formulate linear optimal coordinated signal control algorithms based on linear traffic state prediction models instead of nonlinear optimal coordinated signal control algorithms based on nonlinear traffic state prediction models. Such a traffic state prediction model cannot take signal plans explicitly into account due to their nonlinear nature. It can however take green time shares for stages into account. Those are defined as the share of the cycle time that a stage has green. This allows for certain objective functions to be optimised using linear or quadratic programming, as was explained in annex 1. An example of a linear optimal coordinated signal control algorithm is the model predictive controller using the link transmission model (Van de Weg et al, 2016).

Nonlinear optimal coordinated signal control algorithms
Similar to how nonlinear optimal ramp metering algorithms are based on nonlinear traffic state prediction models (Papageorgiou et al, 2003), nonlinear optimal coordinated signal control algorithms are based on nonlinear traffic state prediction models. This allows for better predictions, but makes optimisation more complex. An example of a nonlinear optimal coordinated signal control algorithm is the intersection control part of the integrated MPC approach by Van den Berg et al (Van den Berg et al, 2007) discussed in subsection 2.7.2.

Assessment of optimal coordinated control algorithms
Table 2.5 gives an overview of the assessment of optimal coordinated signal control algorithms with the criteria to determine if they are promising.

Table 2.5 Overview of the assessment of optimal coordinated signal control algorithms

Criterion	Linear optimal coordinated signal control algorithms	Nonlinear optimal coordinated signal control algorithms
Ability to reduce inflow based on the needs of (further) downstream links	Yes	Yes
Coordination between different controlled elements	Yes	Yes
Ability to adapt to different traffic conditions	Yes, assuming a traffic flow model is used that can handle different traffic conditions to determine the future states in the linear traffic state prediction model	Yes, assuming a traffic flow model is used that can handle different traffic conditions to determine the future states in the nonlinear traffic state prediction model
Usage of an efficient computation algorithm	Yes, assuming the objective criterion allows for linear or quadratic programming	No, because traffic signal settings are optimised at individual intersections; this means a large number of variables have to be optimised with a nonlinear traffic state prediction model

2.2.5 Assessment of signal control algorithms
In tables 2.1-2.5 signal control algorithms have been assessed on the criteria to determine if they are promising. The assessment has been simplified with colour coding in traffic signal style; green if a criterion is met, yellow if an algorithm is given the benefit of the doubt and red if a criterion is not met. This plays an important role in limiting the number of possible integrations.

Given that the algorithms are to be used for the development of the novel integrated urban-freeway network controller, the possible integrations are combinations of at least one urban algorithm and at least one freeway algorithm. In this chapter the following algorithms are considered:

- Signal control algorithms in this section; these are urban algorithms
- Ramp metering algorithms in section 2.3; these are freeway algorithms
- Speed limit algorithms in section 2.4; these are freeway algorithms
- Route guidance algorithms in section 2.5; these algorithms control both the urban and the freeway network, thus any combination involving them is a possible integration
- Combined algorithms in section 2.6; there is only one combined algorithm considered in this chapter, and it combines a ramp metering algorithm and a speed limit algorithm, thus it is a freeway algorithm

Based on this definition, a formula for the number of possible integrations is derived in annex 2. Based on this formula, there is a need to limit the number of possible integrations. This can be done by limiting the number of promising algorithms.

Limiting the number of promising integrations can be achieved by considering any algorithm with a red marking in tables 2.1-2.5 as not promising. Result of doing so is that only 3 signal control algorithms can be considered as promising:

- Optimal switching time methods
- The backpressure algorithm
- Linear optimal coordinated signal control algorithms

However, the green and yellow markings in tables 2.1-2.5 do place some requirements on these algorithms. An overview:

- Optimal switching time methods:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The optimisation algorithm to be used is CRONOS
- The backpressure algorithm:
  - The limited coordination under under-saturated and over-saturated conditions should not affect the ability of the algorithm to reduce flow towards downstream links based on the capacity of those links and the other flows towards those links
- Linear optimal coordinated signal control algorithms:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The objective criterion needs to allow for linear or quadratic programming

These requirements will be taken into account in section 2.8, when a conclusion is drawn on the algorithms to be used for integration.

2.3 Ramp metering algorithms

In this section, an assessment of ramp metering algorithms will be given. Ramp metering is defined as limiting the flow at an on-ramp by means of a traffic signal. The flow value is determined by the green, yellow and red times of the traffic signal. Aim of limiting this flow is to prevent jam formation directly downstream of the on-ramp. The ramp metering algorithms that have been found in the literature can be categorised as follows (Papageorgiou et al, 2003):

- Fixed time ramp metering strategies
- Reactive ramp metering strategies
- Optimal ramp metering strategies

Each of the ramp metering algorithms belonging to a category will be elaborated upon in their designated subsections. Subsequently, an overview of the assessment of these algorithms will be given to conclude this section.

2.3.1 Fixed time ramp metering strategies

Fixed time ramp metering strategies limit the flow onto the freeway based on the current time of the day and historical data (Papageorgiou et al, 2003); no on-line measurements are used. Given that a ramp meter is a traffic signal at an on-ramp and thus only allows traffic to enter the freeway during the green phase, constraints can be formulated to prevent congestion and have acceptable ramp metering rates while optimising objective criteria. Fixed time ramp metering strategies use objective criteria such as:

- The number of served vehicles is to be maximised
- The total travel distance is to be maximised
- The ramp queues are to be balanced

These objective criterions result in linear or quadratic programming problems. Thus fixed time ramp metering strategies solve linear or quadratic programming problems. Table 2.6 on the next page gives an overview of the assessment of the fixed time ramp metering strategies with the criteria to determine if they are promising.

Table 2.6 Overview of the assessment of fixed time ramp metering strategies

Criterion	Assessment of fixed time ramp metering strategies
Ability to reduce inflow based on the needs of (further) downstream links	Yes
Coordination between different controlled elements	No
Ability to adapt to different traffic conditions	No
Usage of an efficient computation algorithm	Yes, linear or quadratic programming

2.3.2 Reactive ramp metering strategies

Reactive ramp metering strategies involve the control of ramp meters based on on-line measurements of flows and occupancies (Papageorgiou et al, 2003). Occupancies are the measured counterparts of densities[2]. The following three algorithms will be described in this subsection:

- Demand-capacity strategy (Masher et al, 1974)
- ALINEA (Papageorgiou et al, 1991)
- METALINE (Diakaki & Papageorgiou, 1994)

Following the descriptions the algorithms will be assessed on the criteria to determine if they are promising.

Demand-capacity strategy

According to Muller et al (2014 [1]), the demand-capacity strategy (Masher et al, 1974) is one of the best known strategies for reactive ramp metering. According to Muller et al (2014 [1]) it attempts to create a flow at a downstream location of an on-ramp that is a safety margin under its capacity. This safety margin allows for variations in the capacity. The demand-capacity strategy measures the inflow upstream of the on-ramp and the occupancy downstream of the on-ramp, as depicted in figure 2.2.

Based on the measurements, the algorithm determines what the ramp metering rate should be. If the occupancy is such that no congestion has yet formed, the metering rate is equal to the target flow downstream of the on-ramp minus the inflow upstream of the on-ramp. If the occupancy is such that congestion has formed, the ramp metering rate is set to its minimum value.

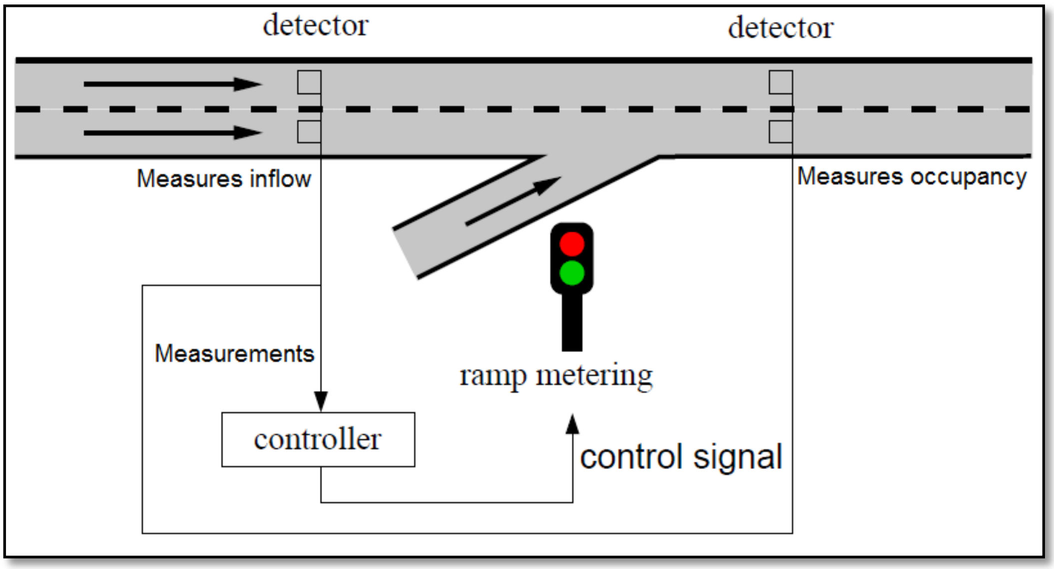

Figure 2.2 Measurements for the demand-capacity strategy (Adapted from Hegyi, 2014 [2])

[2] Occupancy and density are linearly related, as can be derived from Hoogendoorn (2007). Detector loops *cannot* measure densities directly, but can measure occupancies directly. Therefore, when densities need to be determined from actual traffic flow, occupancies are often measured with detector loops and linearly transformed into densities. This transformation step is often not mentioned and occupancy and density are often interchanged; a convention that is used in this report as well.

ALINEA

According to Muller et al (2014 [1]), ALINEA (Papageorgiou et al, 1991) aims to create an occupancy downstream of an on-ramp such that it is a safety margin under the critical occupancy, which corresponds to the critical density. This safety margin allows for variations in the critical occupancy. ALINEA measures the occupancy downstream of an on-ramp as depicted in figure 2.3.

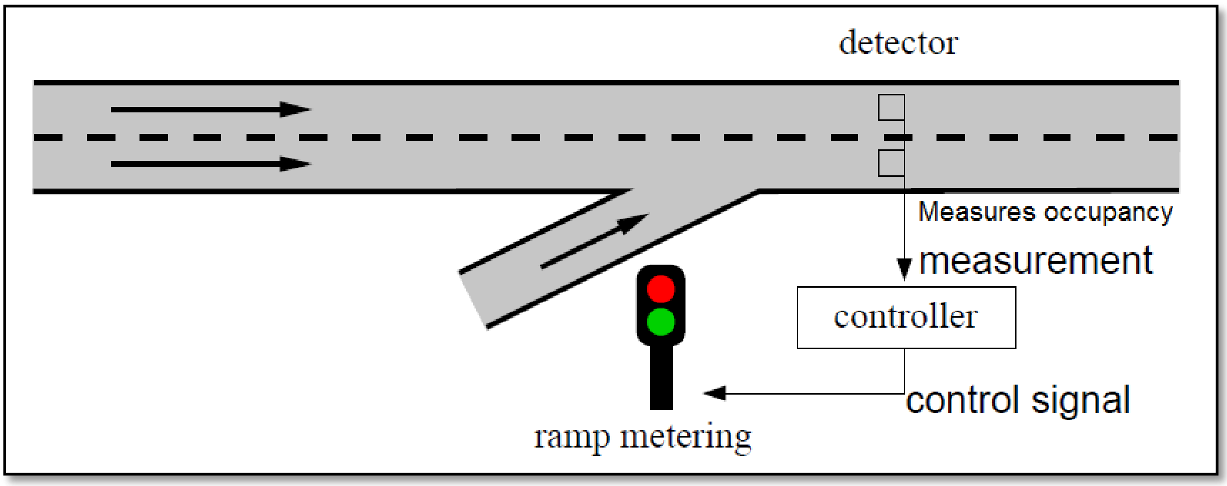

Figure 2.3 Measurements for ALINEA (Adapted from Hegyi, 2014 [2])

Based on the measurements, the algorithm determines what the ramp metering rate should be. It assumes it should be increased by a constant multiple of the difference between the target occupancy and the measured occupancy. The constant it uses is called the feedback gain, and its value is based on heuristic reasoning.

METALINE

According to Papageorgiou et al (2003), METALINE (Diakaki & Papageorgiou, 1994) aims to control multiple on-ramps simultaneously. In order to do so it uses a number of occupancy measurements which it stores in a vector $\mathbf{o}$. A subset of these occupancy measurements, the measurements directly downstream of on-ramps, it stores in a vector $\mathbf{c}$. The target values for these measurements are stored in a vector $\mathbf{c}^*$. Finally, the ramp metering rates are stored in a vector $\mathbf{q}$. METALINE determines the metering rates at time step $k+1$ based on measurements at time step k and $k+1$ with equation (2.3)[3].

$$\mathbf{q}(k+1) = \mathbf{q}(k) + \mathbf{O}\big(\mathbf{o}(k+1) - \mathbf{o}(k)\big) + \mathbf{C}\big(\mathbf{c}^* - \mathbf{c}(k+1)\big) \tag{2.3}$$

Where the measurement gain matrix $\mathbf{O}$ and the control gain matrix $\mathbf{C}$ need to be suitably designed to prevent instability and/or undesirable behaviour (the latter could also be solved by introducing constraints and alternative formulas in case constraints are violated).

[3] Papageorgiou et al (2003) use time steps $k-1$ and k, but in accordance with chapter 3 where time steps k and $k+1$ are used, equation (2.3) is adapted to use these time steps as well.

Assessment of reactive ramp metering strategies

Table 2.7 gives an overview of the assessment of the reactive ramp metering strategies with the criteria to determine if they are promising.

Table 2.7 Overview of the assessment of reactive ramp metering strategies

Criterion	Demand-capacity strategy	ALINEA	METALINE
Ability to reduce inflow based on the needs of (further) downstream links	Yes	Yes	Yes
Coordination between different controlled elements	No	No	Yes
Ability to adapt to different traffic conditions	No, only suitable for under-saturated traffic conditions (Muller et al, 2014 [1])	Yes, suitable for under-saturated, saturated and over-saturated traffic conditions (Muller et al, 2014 [1])	Yes, field tests have shown this coordinated algorithm performs well; comparable to ALINEA (Papageorgiou et al, 2003)
Usage of an efficient computation algorithm	Yes, only a few simple calculations	Yes, only a few simple calculations	Yes, only a few simple calculations

2.3.3 Optimal ramp metering strategies

Optimal ramp metering strategies aim to control all on-ramps simultaneously such that an objective criterion is explicitly optimised (Papageorgiou et al, 2003). This optimisation is usually based on the outcome of a traffic state prediction model fed with many ramp queue measurements and many occupancy measurements and is subject to constraints. The objective criteria that can be used for optimal ramp metering strategies are the same as the objective criteria that can be used for optimal coordinated signal control. Examples of these criteria have been given in subsection 2.2.4. Once the objective criterion used for optimal ramp metering strategies is optimised, the same implementation strategies exist as presented in subsection 2.2.4.

The traffic state prediction model used for the optimisation has a major influence on the efficiency of the computation algorithm. Based on this influence, the following two types of algorithms can be distinguished:

- Linear optimal ramp metering algorithms
- Nonlinear optimal ramp metering algorithms

Each of these algorithms will be discussed in this subsection. Subsequently, an overview of the assessment of these algorithms will be given to conclude this subsection.

Linear optimal ramp metering algorithms

While nonlinear optimal ramp metering algorithms are based on nonlinear traffic state prediction models (Papageorgiou et al, 2003), one could also formulate linear optimal ramp metering algorithms based on linear traffic state prediction models. This allows for certain objective functions to be optimised using linear or quadratic programming, as was explained in annex 1.

Nonlinear optimal ramp metering algorithms

Nonlinear optimal ramp metering algorithms are based on nonlinear traffic state prediction models (Papageorgiou et al, 2003). This allows for better predictions as traffic behaves nonlinear. For instance, freeway traffic exhibits capacity drop phenomena. These phenomena cause the outflow out of congestion to be lower than the free flow capacity and are illustrated in the example fundamental diagrams in annex 1. Downside of the better predictions a nonlinear traffic state model can make is that optimisation becomes much more complex.

Assessment of optimal ramp metering strategies

Table 2.8 gives an overview of the assessment of the optimal metering strategies with the criteria to determine if they are promising.

Table 2.8 Overview of the assessment of optimal ramp metering strategies

Criterion	Linear optimal ramp metering algorithms	Nonlinear optimal ramp metering algorithms
Ability to reduce inflow based on the needs of (further) downstream links	Yes	Yes
Coordination between different controlled elements	Yes	Yes
Ability to adapt to different traffic conditions	Yes, assuming a traffic flow model is used that can handle different traffic conditions to determine the future states in the linear traffic state prediction model	Yes, assuming a traffic flow model is used that can handle different traffic conditions to determine the future states in the nonlinear traffic state prediction model
Usage of an efficient computation algorithm	Yes, assuming the objective criterion allows for linear or quadratic programming	No, because ramp metering rates are optimised at individual on-ramps; this means a large number of variables have to be optimised with a nonlinear traffic state prediction model

2.3.4 Assessment of ramp metering algorithms

In tables 2.6-2.8 ramp metering algorithms have been assessed on the criteria to determine if they are promising. Like in subsection 2.2.5, the assessment has been simplified with colour coding in traffic signal style and any algorithm with a red marking in tables 2.6-2.8 is considered as not promising. Result of doing so is that only 2 ramp metering algorithms can be considered as promising:

- METALINE
- Linear optimal ramp metering algorithms

However, the green markings in tables 2.6-2.8 do place some requirements on these algorithms. An overview:

- METALINE:
  - No requirements
- Linear optimal ramp metering algorithms:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The objective criterion needs to allow for linear or quadratic programming

These requirements will be taken into account in section 2.8, when a conclusion is drawn on the algorithms to be used for integration.

2.4 Speed limit algorithms

In this section, an assessment of speed limit algorithms will be given. Speed limit algorithms as considered here use variable speed limits that are to be shown on speed limit gantries to reduce the inflow in potential jam areas downstream. The speed limit algorithms that will be discussed in this section are:

- SPECIALIST (Hegyi et al, 2008)
- Local feedback based mainstream traffic flow controller (Carlson et al, 2011)
- Variable speed limit MPC for jam wave resolution (Hegyi et al, 2005 [1])
- Parameterised variable speed limit MPC (Van de Weg et al, 2015)

Each of these speed limit algorithms are elaborated upon in their designated subsections. Subsequently, an overview of the assessment of these algorithms will be given to conclude this section.

2.4.1 SPECIALIST

According to Hegyi & Hoogendoorn (2010), the SPECIALIST algorithm is based on a fundamental diagram model. As was explained in annex 1, fundamental diagram models model stretches of roadway with constant density, speed and flow with moving shocks between them which have speeds corresponding to the slope in the flow-density fundamental diagram. The SPECIALIST algorithm uses this model property to attempt to resolve a jam wave (i.e. a jam of which the head and the tail propagate upstream at roughly the same speed) introducing a stretch of roadway with a speed limit. This is sketched in figure 2.4 by placing a space-time diagram, which describes space along the road and time from an arbitrary starting point, next to the flow-density diagram.

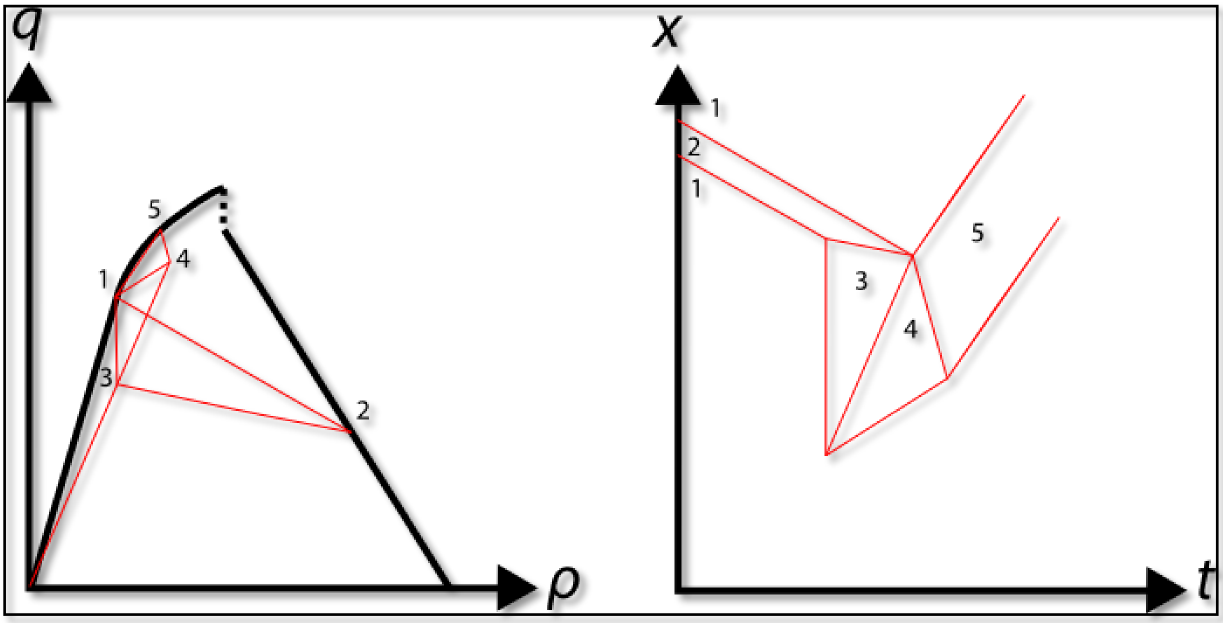

Figure 2.4 Sketch of the workings of the SPECIALIST algorithm based on the fundamental diagram (left) and the space-time diagram (right) (Adapted from Hegyi & Hoogendoorn, 2010)

In figure 2.4, a jam wave (traffic state 2) is moving upstream. Once the SPECIALIST algorithm activates, a speed limit is imposed, which creates traffic state 3 (Hegyi & Hoogendoorn, 2010). This reduces the inflow into the jam wave, which subsequently dissipates. However, in the wake of traffic state 3, somewhat busier traffic state 4 has been created. The SPECIALIST algorithm converts traffic state 4 into traffic state 5 by releasing the speed limit appropriately.

2.4.2 Local feedback based mainstream traffic flow controller

The local feedback based mainstream traffic controller aims to create an occupancy at a bottleneck such that it is a safety margin under the critical occupancy, which corresponds to the critical density (Carlson et al, 2011). This safety margin allows for variations in the critical occupancy. The local feedback controller creates this occupancy by imposing a speed limit upstream of the bottleneck which reduces the inflow into the bottleneck, which may or may not cause congestion at the roadway stretch where the speed limit is imposed. Typically, congestion is caused as the inflow surpasses the capacity of the bottleneck, and the algorithm operates under the conditions sketched in figure 2.5.

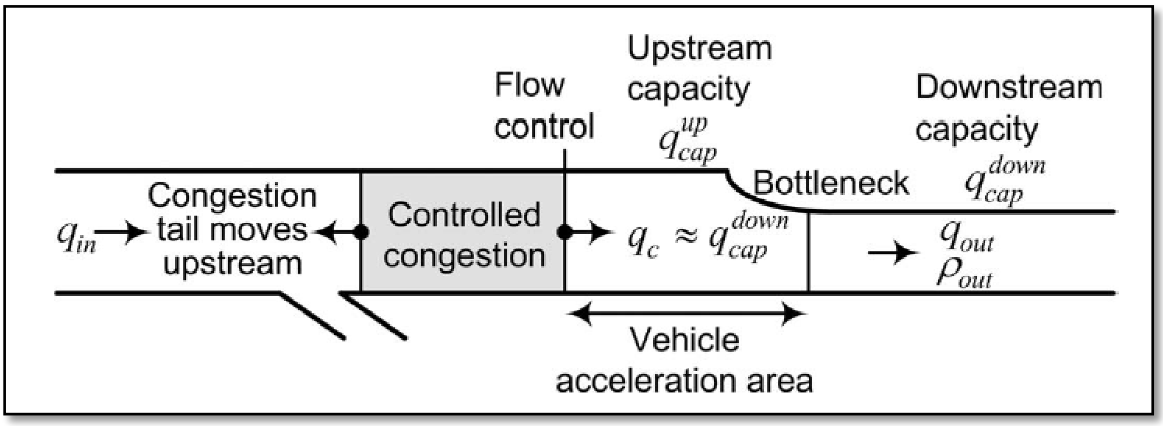

Figure 2.5 Sketch of the typical conditions under which the local feedback based mainstream traffic controller operates (Source: Carlson et al, 2011)

The algorithm sets a new target outflow value for the outflow of the roadway stretch where the speed limit is imposed based on measurements of the current density in the bottleneck (Carlson et al, 2011). Subsequently, the algorithm sets a new value for the speed limit (expressed as a fraction of the free flow speed) based on the difference between the current measured outflow and the new target outflow value for the outflow out of the roadway stretch where the speed limit is imposed. It finds these values based on linear relationships. The parameters in these relationships should be tuned by simulations.

2.4.3 Variable speed limit MPC for jam wave resolution

The variable speed limit MPC (Model Predictive Control) for jam wave resolution (i.e. resolution of jams of which of which the head and the tail propagate upstream at roughly the same speed) is based on the METANET traffic flow model, which is explained in annex 1 (Hegyi et al, 2005 [1]). The variable speed limit MPC for jam wave resolution uses an extended version of the METANET traffic flow model to allow for variable speed limits. The main aim of the algorithm is the resolution of jam waves, but other applications are thinkable as well. The algorithm uses this extended version of the METANET traffic flow model to optimise the speed limits in the individual segments, such that an objective function is minimised while respecting a certain number of constraints. The objective function is a weighted combination of the total time spent by all vehicles on the road and the total control variations measured over the discrete units (segments and time steps). Once the objective function has been minimised, the algorithm applies the optimal speed limits to the segments until new measurements become available.

2.4.4 Parameterised variable speed limit MPC

The parameterised variable speed limit MPC (Model Predictive Control) is based on the METANET traffic flow model, which is explained in annex 1 (Van de Weg et al, 2015). The METANET traffic flow model is extended to allow for several things typical of the situation the controller is to control, including variable speed limits and a speed-limited area. A speed-limited area is a composed area in a space-time diagram; it is composed of traffic state areas that share a single speed limit that is lower than the free speed of the road to which it is applied. The parameterised variable speed limit MPC uses this extended METANET traffic flow model to optimise the starting position and the speeds of the head and the tail of the speed-limited area, such that the total time spent by all the vehicles on the road is minimised while respecting a certain number of constraints. Once minimised, the parameterised variable speed limit MPC applies the optimal starting position and speeds of the head and the tail of the speed-limited area until new measurements become available.

2.4.5 Assessment of speed limit algorithms

Table 2.9 gives an overview of the assessment of speed limit algorithms with the criteria to determine if they are promising.

Table 2.9 Overview of the assessment of speed limit algorithms

Criterion	SPECIALIST	Local feedback based mainstream traffic controller	Variable speed limit MPC for jam wave resolution	Parameterised variable speed limit MPC
Ability to reduce inflow based on the needs of (further) downstream links	Yes	Yes	Yes	Yes
Coordination between different controlled elements	Yes, there are multiple speed-limited traffic state areas	No, there is only one speed-limited traffic state area	Yes, there are multiple speed-limited traffic state areas	Yes, there are multiple speed-limited traffic state areas
Ability to adapt to different traffic conditions	No, algorithm is built for resolving one specific combination of under-saturated and over-saturated conditions	No, only suitable for saturated and over-saturated traffic conditions (Papageorgiou et al, 2003)	Yes, suitable for under-saturated, saturated and over-saturated traffic conditions	Yes, suitable for under-saturated, saturated and over-saturated traffic conditions
Usage of an efficient computation algorithm	Yes, very low computational demand (Hegyi & Hoogendoorn, 2010)	Yes, only a few simple calculations	No, because speed limits are optimised in individual segments; this means a large number of variables have to be optimised with a nonlinear traffic state prediction model	Yes, only the position of head and tail of the speed-limited area have to be optimised; moreover, once this has been done during the first time step, the constraints guarantee it is easier for subsequent time steps

In table 2.9 speed limit algorithms have been assessed on the criteria to determine if they are promising. Like in subsection 2.2.5, the assessment has been simplified with colour coding in traffic signal style and any algorithm with a red marking in tables 2.9 is considered as not promising. Result of doing so is that only the parameterised variable speed limit MPC can be considered as promising. It can be observed that the green markings in table 2.9 do not place any requirements on this algorithm. This will be taken into account in section 2.8, when a conclusion is drawn on the algorithms to be used for integration.

2.5 Route guidance algorithms

In this section, an assessment of route guidance algorithms will be given. The route guidance algorithms that will be discussed in this section are:

- Travel time display (Papageorgiou et al, 2003)
- One shot route advice (Papageorgiou et al, 2003)
- Iterative route advice (Papageorgiou et al, 2003)
- In-vehicle route guidance algorithms

Each of these route guidance algorithms are elaborated upon in their designated subsections. Subsequently, an overview of the assessment of these algorithms will be given to conclude this section.

2.5.1 Travel time display

The travel time display algorithm is an algorithm that places travel times from a bifurcation node in a network to other nodes in the network on a Variable Message Sign (VMS) such that drivers can make an informed decision on their usage of alternative routes to reach their destination (Papageorgiou et al, 2003). An example of such a VMS in operation is shown in figure 2.6.

Figure 2.6 Example of a VMS in operation: it shows the travel time + delays via two alternative routes to the city of Utrecht (Source: Chriszwolle, 2010)

The travel times on a VMS can either be instantaneous or predictive (Papageorgiou et al, 2003). The former is simpler, as only the current traffic conditions on the links connecting the nodes need to be taken into account in the travel time calculation. This however results in a systematic error that is larger the larger the changes in the traffic conditions, which tend to be largest during queue growth or dissipation. Predicted travel times are however difficult to obtain, as they are dependent on both the destination of the drivers and the reaction to the travel times to be displayed.

2.5.2 One shot route advice

The one shot route advice algorithm is an algorithm that places route advice at bifurcation nodes in networks (Papageorgiou et al, 2003). Such route advice may be direct (e.g. "Traffic to destination D follow route R") or indirect (by giving information on certain aspects of the traffic conditions on a route). Like with the travel time display algorithm, this information may be instantaneous or predictive. In the former case, the advice is given such that the resulting use of the different routes is in accordance with the current traffic conditions. In the latter case, a traffic flow model is run once based on the current traffic state and control measures and the future demand over a certain time horizon to predict the future traffic conditions to give the route advice such that the resulting use of the different routes is in accordance with the predicted future traffic conditions.

2.5.3 Iterative route advice

The iterative route advice algorithm is an algorithm that, like one shot route advice, places route advice at bifurcation nodes in networks (Papageorgiou et al, 2003). Difference is that it gives the direct or indirect route advice such that user-optimum or system-optimum objective criteria are explicitly optimised. Examples of system-optimal criteria have been given in subsection 2.2.4. User-optimal criteria are more difficult to formulate; the user-equilibrium conditions formulated first by Wardrop (1952) enable to formulate a user-optimum travel time criterion: the advice should be given such that the resulting use of the different routes minimises the travel time differences between routes from the same bifurcation nodes to the same destination nodes (the latter are the nodes where the alternative routes meet again; they are unrelated to the actual destinations of the drivers). Once the objective criterion used in the algorithm is optimised, the same implementation strategies exist as presented in subsection 2.2.4.

2.5.4 In-vehicle route guidance algorithms

In-vehicle route guidance algorithms are de facto instantaneous one shot route advice algorithms with the difference that they continuously give advice to the driver, and not just at bifurcation nodes in the networks. The advice is based on travel time distributions of links and real-time information on the actual travel time (Fu, 2001). Based on the real-time information on the actual travel time, the expected values of the travel time distributions are approximated, and the results are used in path-searching algorithms. These path-searching algorithms may take only travel time into account, but travel time reliability (Kaparias et al, 2007) or other objectives (Blue et al, 2007) may also be added. As a result, the path-searching algorithms attempt to maximise the perceived quality of the advised route.

2.5.5 Assessment of route guidance algorithms

Table 2.10 gives an overview of the assessment of route guidance algorithms with the criteria to determine if they are promising.

Table 2.10 Overview of the assessment of route guidance algorithms

Criterion	Travel time display	One shot route advice	Iterative route advice	In-vehicle route guidance algorithms
Ability to reduce inflow based on the needs of (further) downstream links	Yes	Yes	Yes	Yes
Coordination between different controlled elements	No	No	Yes	No
Ability to adapt to different traffic conditions	Depends; no if instantaneous, yes if predictive	Depends; no if instantaneous, yes if predictive	Yes, assuming a traffic flow model is used that can handle different traffic conditions to determine the future states used in the optimisation of the objective criterion	No
Usage of an efficient computation algorithm	Depends; yes if instantaneous, unsure if predictive	Depends; yes if instantaneous, unsure if predictive	Yes, assuming a linear traffic state prediction model is combined with an objective criterion that allows for linear or quadratic programming	Yes

In table 2.10 route guidance algorithms have been assessed on the criteria to determine if they are promising. Like in subsection 2.2.5, the assessment has been simplified with colour coding in traffic signal style and any algorithm with a red marking in table 2.10 is considered as not promising. Result of doing so is that only iterative route advice can be considered as promising. It can be observed that the green markings in table 2.10 place some requirements on this algorithm:

- A traffic flow model needs to be used that can handle different traffic conditions
- This traffic flow model needs to result in a linear traffic state prediction model
- The objective criterion needs to allow for linear or quadratic programming

These requirements will be taken into account in section 2.8, when a conclusion is drawn on the algorithms to be used for integration.

2.6 Combined algorithms

One algorithm is considered that combines a ramp metering algorithm and a speed limit algorithm. This is the MPC (Model Predictive Control) for optimal coordination of ramp metering and variable speed limits (Hegyi et al, 2005 [2]). This algorithm is based on the METANET traffic flow model, which is explained in annex 1 (Hegyi et al, 2005 [2]). It uses an extended version of the METANET traffic flow model to allow for variable speed limits and mainstream destinations. The algorithm uses the extended METANET traffic flow model to optimise the speed limits and ramp metering rates, such that the total time spent by all the vehicles on the freeway network is minimised while respecting a certain number of constraints. The algorithm can vary the speed limits per individual segment and vary the ramp metering rates per on-ramp. Once the total time spent by all vehicles on the freeway network is minimised, the algorithm applies the control measures until new measurements become available.

Table 2.11 gives an overview of the assessment of MPC for optimal coordination of ramp metering and variable speed limits.

Table 2.11 Overview of the assessment of MPC for optimal coordination of ramp metering and variable speed limits

Criterion	Assessment of MPC for optimal coordination of ramp metering and variable speed limits
Ability to reduce inflow based on the needs of (further) downstream links	Yes
Coordination between different controlled elements	Yes
Ability to adapt to different traffic conditions	Yes
Usage of an efficient computation algorithm	No, because speed limits are optimised in individual segments; this means a large number of variables have to be optimised with a nonlinear traffic state prediction model

In table 2.11 the MPC for optimal coordination of ramp metering and variable speed limits has been assessed on the criteria to determine if it is promising. Like in subsection 2.2.5, the assessment has been simplified with colour coding in traffic signal style. As a result, the MPC for optimal coordination of ramp metering and variable speed limits cannot be considered as promising because of the red marking in table 2.11. This will be taken into account in section 2.8, when a conclusion is drawn on the algorithms to be used for integration.

2.7 Integrated algorithms

Some algorithms exist that integrate algorithms from the previous sections. These include:

- IN-TUC (Diakaki et al, 2000)
- Integrated MPC approach (Van den Berg et al, 2007)
- PPA hierarchical control approach (Hoogendoorn et al, 2013)
- Coordinated ramp metering and intersection signal control (Su et al, 2014)
- Linear Quadratic MPC for integrated route guidance and ramp metering (Han et al, 2015)

Each of these algorithms will be discussed in their designated subsections. Subsequently, conclusions will be drawn on how knowledge of these algorithms can help integrate the algorithms that are promising for integration.

2.7.1 IN-TUC

According to Papageorgiou et al (2003), IN-TUC (Diakaki et al, 2000) aims to integrate TUC with ALINEA and instantaneous one-shot route advice. In order to do so, it uses common measurement data from the corridor network it aims to control to run the individual algorithms; the integration comes from the fact that the control signals from TUC and ALINEA are used as input for the instantaneous one shot route advice, as is depicted in figure 2.7.

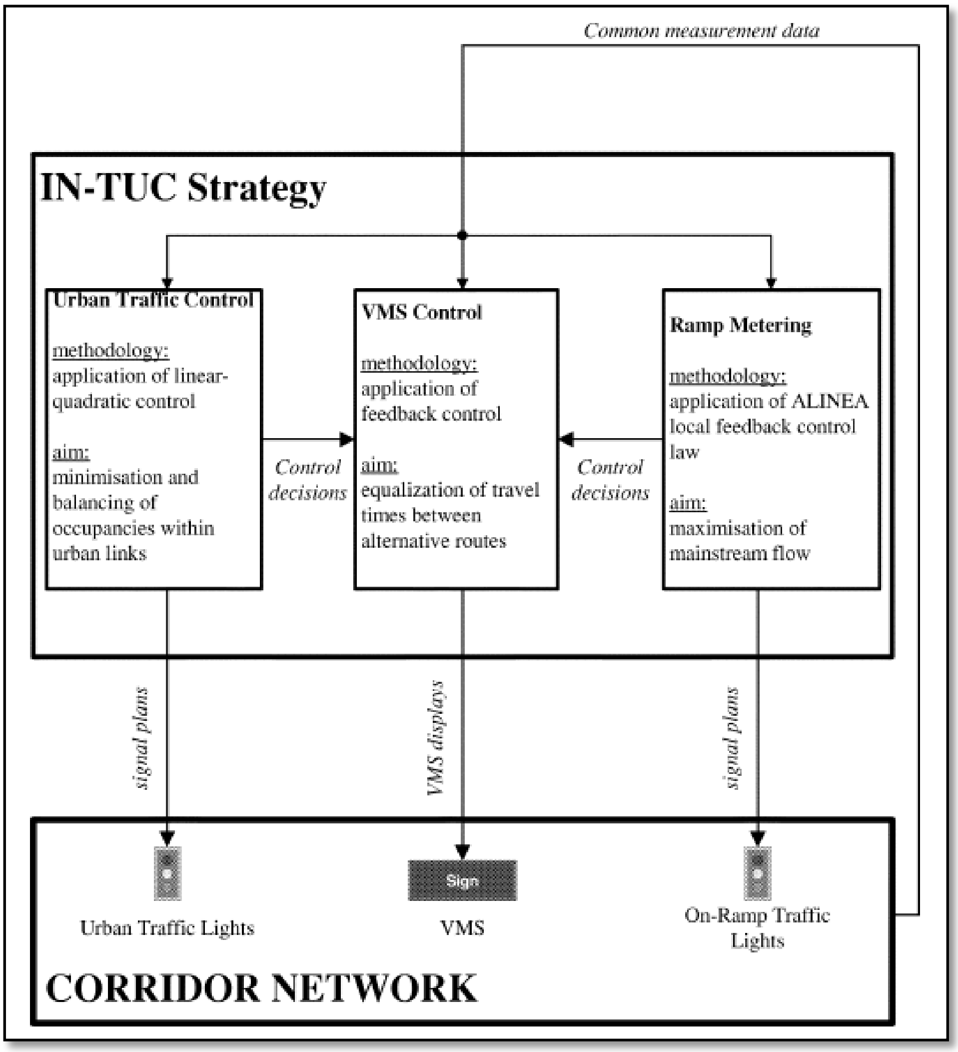

Figure 2.7 Functional architecture of IN-TUC (source: Papageorgiou et al, 2003)

2.7.2 Integrated MPC approach

The integrated MPC (Model Predictive Control) approach uses measurements of all the traffic variables its traffic flow model (which needs to be able to model both freeway and urban traffic; for the freeway traffic it uses the METANET traffic flow model and for the urban traffic it uses the extended Kashani model; both are explained in annex 1) needs to describe the current state (Van den Berg et al, 2007). Subsequently, it uses the current state and the traffic flow model to optimise an objective function by varying the ramp metering rates and intersection cycle times over a certain control horizon, given a number of constraints. Once an optimum has been found, the associated control strategy is implemented until new measurements become available. Like the PPA hierarchical control approach in subsection 2.7.3, the integrated MPC approach employs some hierarchy as well, as it allows the ramp meter controller to determine how it is going to achieve its ramp metering rate and the intersection controller to work out the structure needed to produce the desired cycle times.

2.7.3 PPA hierarchical control approach

The PPA hierarchical control approach aims to integrate urban and freeway controllers via hierarchical control (Hoogendoorn et al, 2013). The hierarchical system used in the PPA hierarchical control approach is depicted in figure 2.8.

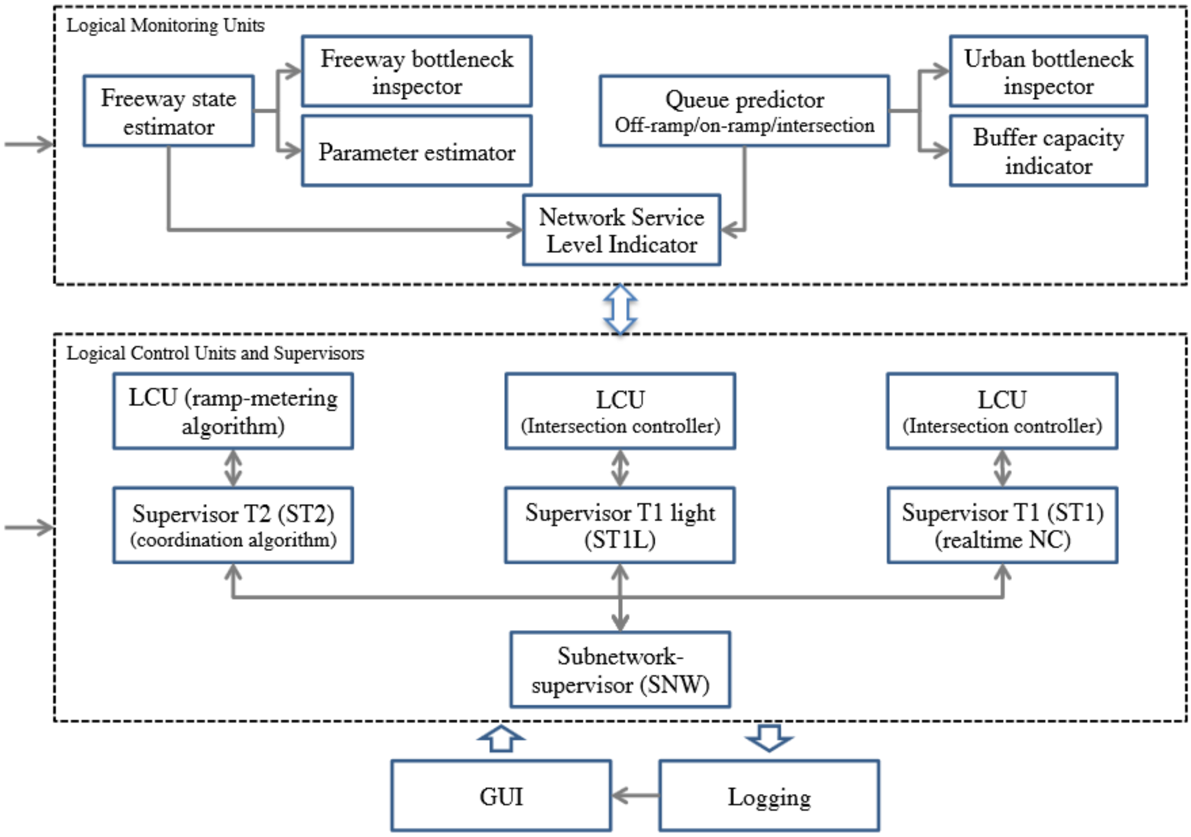

Figure 2.8 Hierarchical system used in the PPA hierarchical control approach (Source: Hoogendoorn et al, 2013)

The Logical Monitoring Units (LMU's) perform and analyse the measurements needed at the highest hierarchical control layer (Hoogendoorn et al, 2013). The Freeway Bottleneck Inspector (FBI) determines the predicted location of freeway bottlenecks based on the determination of so-called *hot zones* (locations with a high probability of traffic jam formation based on measurements of speed, flow and density) and historical data. Independently, the Parameter Estimator (PE) estimates the critical density and the capacity at a collection of potential bottlenecks it was given by the Freeway State Estimator (FSE) based on measurements of speed, flow and density. The FSE receives the results from the FBI and the PE and determines which bottlenecks to report to the Network Service Level Indicator (NSLI) and which collection of bottlenecks to give to the PE for subsequent estimations. The Urban Bottleneck Inspector (UBI) determines the presence of urban bottlenecks, which are queues causing spillback or approaches of intersections which are oversaturated. The Buffer Capacity Indicator (BCI) compares the current queue lengths with the allowed queue lengths and reports the difference. Based on the results from the UBI and the BCI, the Queue Predictor (QP) predicts the evolution of queues along the urban arterial. The NSLI collects the information from the FSE and the QP and combines it with an estimate of the current level of service based on the average density and the standard deviation of the density in the network according to the generalised network fundamental diagram depicted in figure 2.9.

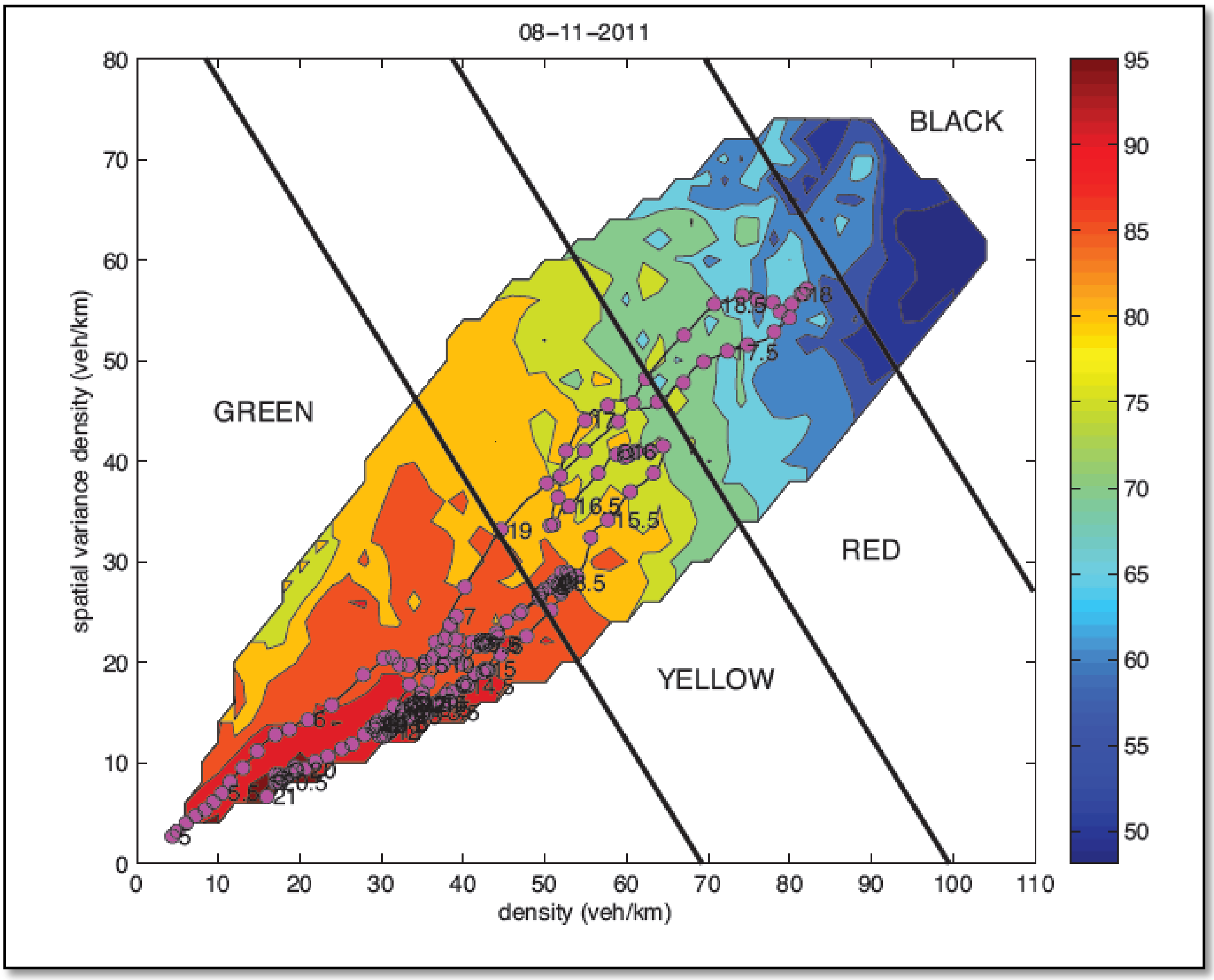

Figure 2.9 the generalised network fundamental diagram depicting the average speed in km/h on the A10. The various levels of service the Network Service Level Indicator (NSLI) could indicate based on the average density in veh/km (horizontal axis) and standard deviation of the density in veh/km (vertical axis) are indicated as well. To give an impression on how the level of service might vary over the day, a trajectory for the measurements of a particular day with the time in hours since midnight is also depicted (Source: Hoogendoorn et al, 2013)

The Logical Control Units (LCU's) and Supervisors (ST1, ST1L, ST2 and SNW, see figure 2.8) use the information from the Network Service Level Indicator (NSLI) to coordinate the control actions (Hoogendoorn et al, 2013). If the information from the NSLI does not give rise to coordination, the LCU's function autonomously; the ramp meters use the ALINEA algorithm (see subsection 2.3.2) and the intersection controllers use isolated intersection control (see subsection 2.2.1). The LCU's provide information of their current operation to their respective Supervisors (ramp meters to ST2 and intersection controllers to ST1 and ST1L). Each of these Supervisors provides this information to the SNW. With this information and the information from the NSLI, the SNW determines the control action to be taken: continue the current control strategy or change the coordination by changing the buffer space configuration or stopping coordination. Based on this control action, Supervisor ST1 determines how to effectuate this buffer space configuration on the main arterial while minimising the vehicle loss hours on the main arterial, Supervisor ST1L determines how to prevent the on-ramp queue from passing a certain threshold and Supervisor ST2 determines how to coordinate the ramp meters. To do so, it appoints a certain ramp meter as Master ramp and upstream ramp meters as Slaves, and orders them to meter such that the Master ramp and the

Slaves run out of buffer space in such a fashion that a "run-out wave" travels downstream from the Slaves to the Master ramp.

2.7.4 Coordinated ramp metering and intersection signal control

Ramp metering and intersection signal control can be coordinated (in the definitions used in this report this coordination is equivalent to integration) in many ways. Examples are the integrated MPC approach from subsection 2.7.2 and the PPA hierarchical control approach from subsection 2.7.3. Su et al (2014) propose simpler coordination by merely coordinating the ramp meter and its adjacent intersection. For the ramp meter they propose the ALINEA algorithm[4] and for the intersection controller they propose an algorithm that aims to optimise and objective function that contains both the sum of ratios of green time and desired green times and the available space for vehicles on the on-ramp for the streams feeding it. The available space for vehicles on the on-ramp for streams feeding it is a function of both algorithms and as such integrates both algorithms.

2.7.5 Linear Quadratic MPC for integrated route guidance and ramp metering

Linear Quadratic MPC for integrated route guidance and ramp metering aims to integrate route guidance controllers and ramp meter controllers (Han et al, 2015). The route guidance controllers involved in this integration are instantaneous one shot route advice algorithms giving route advice at on-ramps on whether to take this on-ramp or the next. The integrated algorithm uses measurements throughout the combined urban-freeway network to predict what the response of the traffic process will be to the ramp metering rates, while taking the reaction to the instantaneous route advice into account. Based on this prediction, it predicts the performance, defined by an objective function which it tries to optimise. As the objective criterion it tries to optimise is the outflow out of the network, the objective function describes the amount of traffic in the network, which needs to be minimised. This is done via quadratic programming.

2.7.6 Conclusions

From the algorithms discussed in this section, it can be concluded that an integration of signal control algorithms, ramp metering algorithms, speed limit algorithms and route guidance algorithms has not yet been attempted. Integration of signal control algorithms and ramp metering algorithms happens for a majority of the considered integrated algorithms; IN-TUC, the integrated MPC approach, the PPA hierarchical control approach and the coordinated ramp metering and signal control all apply it; IN-TUC, the PPA hierarchical control approach and the coordinated ramp metering and signal control with simplifications (the store-and forward based approach, heuristics and limited integration (only one intersection and one on-ramp), respectively) and the integrated MPC approach in detail. IN-TUC even takes route guidance into account as well. Route guidance is taken into account in detail by the Linear Quadratic MPC for integrated route guidance and ramp metering, where it is integrated with ramp metering. Speed limit algorithms have not yet been used in integrated algorithms. They have been used in the MPC for optimal coordination of ramp metering and variable speed limits however, which combines ramp metering and variable speed limits, as was noted in section 2.6.

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[4] Su et al (2014) propose UP ALINEA, but UP ALINEA only differs from ALINEA in the sense that it does not directly measure the occupancy downstream of the on-ramp, but estimates it from the occupancy on the freeway upstream of the on-ramp, the freeway flow upstream of the on-ramp and the ramp metering rate. As estimation of measured values is not part of the algorithm, as it is part of the state estimation, UP ALINEA and ALINEA are equivalent from an algorithm point of view.

It can be noticed that integration is done by using control algorithms that have the same control rules (e.g. feedback control, see annex 1); IN-TUC and the PPA hierarchical control approach integrate feedback algorithms, whereas the integrated MPC approach, the Linear Quadratic MPC for integrated route guidance and ramp metering and the MPC for optimal coordination of ramp metering and variable speed limits integrate algorithms that are more or less of the model predictive control type. Therefore, the knowledge of the algorithms discussed in this section can be used to conclude that it is logical for the algorithms that are to be used for integration to have the same control rules.

2.8 Conclusion

Based on sections 2.2-2.6, the following control algorithms have been identified as promising for integration:

- Signal control algorithms:
  - Optimal switching time methods
  - The backpressure algorithm
  - Linear optimal coordinated signal control algorithms
- Ramp metering algorithms:
  - METALINE
  - Linear optimal ramp metering algorithms
- Speed limit algorithms:
  - Parameterised variable speed limit MPC
- Route guidance algorithms:
  - Iterative route advice
- Combined algorithms:
  - None

These control algorithms are promising, provided the following requirements are met:

- Optimal switching time methods:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The optimisation algorithm to be used is CRONOS
- The backpressure algorithm:
  - The limited coordination under under-saturated and over-saturated conditions should not affect the ability of the algorithm to reduce flow towards downstream links based on the capacity of those links and the other flows towards those links
- Linear optimal coordinated signal control algorithms:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The objective criterion needs to allow for linear or quadratic programming
- METALINE:
  - No requirements
- Linear optimal ramp metering algorithms:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - The objective criterion needs to allow for linear or quadratic programming
- Parameterised variable speed limit MPC:
  - No requirements

- Iterative route advice:
  - A traffic flow model needs to be used that can handle different traffic conditions
  - This traffic flow model needs to result in a linear traffic state prediction model
  - The objective criterion to be used allows for linear or quadratic programming

Assuming these requirements are met, one can calculate the number of possible integrations with the formula derived in annex 2. The result is that there are 38 possible integrations. Considering the novel integrated urban-freeway network controller to be developed can only be based on one of these integrations, there is a serious need to remove possible integrations in order to make the decision on the algorithms to be used for the development of this controller. One way to do so is by taking into account that these algorithms are currently not integrated and thus need to be altered in order to be integrated. Therefore it seems logical to remove the algorithms which require significant alteration for integration. This is expected for:

- Optimal switching time methods, as it is expected that the optimisation of switching times cannot be easily combined with the optimisation of other control actions
- The backpressure algorithm, as it is expected that the use of weights to determine what stages at intersections should have green cannot be easily combined with other control actions
- METALINE, as it is expected that the measurement gain matrix and control gain matrix need to be redesigned to combine the control actions of the ramp metering installations with other control actions

Removing these algorithms from the list of promising integrations reduces the number of possible integrations to 10, based on the formula derived in annex 2.

As was explained in subsection 2.2.5, sometimes algorithms were given the benefit of the doubt during the assessment on the criteria to determine if they are promising. It is of course preferable if this happened as little as possible. For the algorithms involved in the remaining possible integrations, this did not happen at all, so the previous removal of possible integration has been proven beneficial in view of this aspect.

Further reduction of the number of promising integrations can be achieved by removing the algorithms that can be expected to take a long time to be integrated in an integrated urban-freeway network controller, as the time allotted to this MSc Thesis project is limited. From the remaining algorithms, it is expected that iterative route advice will take a long time to be integrated, so that algorithm is removed as well. This reduces the number of possible integrations to 3, based on the formula derived in annex 2.

The remaining possible integrations are:

- A *Linear optimal coordinated signal control algorithm* & a *Linear optimal ramp metering algorithm* & *Parameterised variable speed limit MPC*
- A *Linear optimal coordinated signal control algorithm* & a *Linear optimal ramp metering algorithm*
- A *Linear optimal coordinated signal control algorithm* & *Parameterised variable speed limit MPC*

Between these integrations a choice will need to be made for the integrated urban-freeway network controller to be developed.

It can be noticed that each of these integrations carry requirements on their individual algorithms. The first two integrations carry 4 requirements on their individual algorithms, whereas the third only carries 2 requirements on its individual algorithms. This can be considered as a reason to choose this integration for the controller to be developed.

It is possible to compare these integrations to the integrated algorithms in section 2.7. As was mentioned there, there are quite some algorithms that integrate signal control algorithms and ramp metering algorithms. Thus proposing a new one may not be that beneficial for improving the efficiency of road use. Therefore the second integration can be considered as a less desirable choice.

Based on these reasons, the choice is made to integrate a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC*. Consequence of this choice is that the following requirements need to be met for the *Linear optimal coordinated signal control algorithm* that is used:

- A traffic flow model needs to be used that can handle different traffic conditions (under-saturated, saturated or over-saturated)
- The objective criterion needs to allow for linear or quadratic programming

These requirements will be taken care of in chapter 3. Other disadvantages that come with this choice is that signal plans cannot be explicitly taken into account (models that can handle signal plans result in nonlinear traffic state models) and that only one speed limit is used, instead of multiple speed limits to slow down traffic that is to encounter a speed limit. However, these disadvantages follow from the approximations that are used to keep the computation time limited. Therefore, these disadvantages are accepted.

3 Controller development

In this chapter, a controller will be developed by combining the promising control algorithms from chapter 2. As the control algorithms to be combined are a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC*, the resulting controller will be of the Model Predictive Control (MPC) type. Controllers of this type can be described with the general framework in figure 3.1.

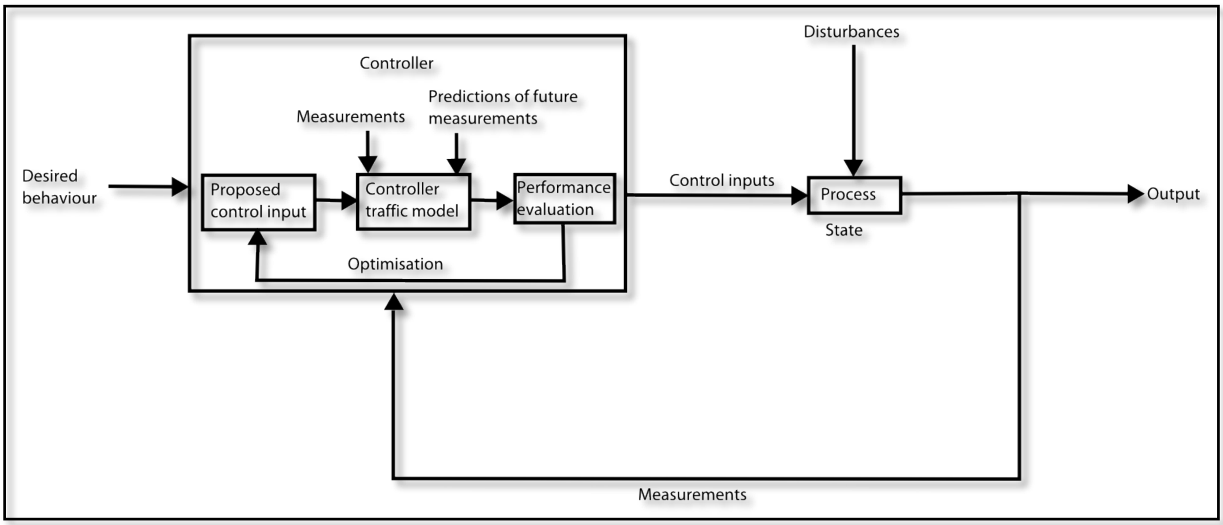

Figure 3.1 General framework of an MPC controller (figure inspired by Hegyi, 2014 [2])

Controller development requires elaboration on all relevant aspects of this framework. This can be simplified by distinguishing the *inside world* (inside the controller box) and the *outside world* (outside of the controller box). While only the *inside world* needs to be developed, the controller needs to be evaluated by simulating the *outside world*. The controller itself simulates the outside world with a controller traffic model. To simplify the evaluation, it seems reasonable to use the same traffic flow model for simulation as for the controller itself (albeit that the controller itself will use some slight alterations in order to run its optimisation depicted by the loop inside the controller box). Therefore, the traffic flow model will be described in section 3.1. Then the optimisation problem the controller is to solve is described in section 3.2. Subsequently section 3.3 provides an overview of the control problem. This overview gives an insight on how the controller works, what its control signal is, what disturbances it needs to deal with and what the state and output of the process are. The chapter is concluded with section 3.4, where the controller is summarised.

3.1 The traffic flow model

This section will describe the traffic flow that will be used for the simulation. The controller is to use the same traffic flow model, albeit with some slight alterations in order to solve its optimisation problem. These alterations will be discussed in section 3.2.

The traffic flow model consists of two parts that are to be connected: an urban part and a freeway part. A choice needs to be made upon the traffic flow model to be used for the urban part, as the traffic flow model for the freeway part had already been chosen: the extended METANET model. This choice will be made in subsection 3.1.1, where the assumptions to which both parts and their connections are subject to will be elaborated upon as well. Then the urban part will be elaborated upon in subsection 3.1.2. The extended METANET traffic flow model, which was introduced in subsection 2.4.4 will be elaborated upon in subsection 3.1.3. Subsequently, subsection 3.1.4 will elaborate upon the connection of the models.

3.1.1 Traffic flow model choice and assumptions

In this subsection, a choice will be made for the traffic flow model to be used for the urban part of the traffic flow model. Following this choice, the assumptions to which the urban part and the freeway part of the traffic flow model are subject, as well as their connections, will be presented.

Choice of the urban traffic flow model

The urban traffic flow model needs to meet a requirement based on the choice for the integration made in section 2.8: it should be able to handle different traffic conditions. According to annex 1, the following models qualify for this requirement[5]:

- Fundamental diagram models combined with the spatial intersection node model
- Fundamental diagram models combined with the capacity proportional node model
- Fundamental diagram models combined with the capacity consumption equivalence node model
- Fundamental diagram models combined with the single server node model
- Fundamental diagram models combined with the equal outlink delay node model
- Link transmission model
- Extended Kashani model

From these options, the link transmission model is chosen, because it results in a linear state prediction model (Van de Weg et al, 2016). For instance, the extended Kashani model does not, as it takes signal plans in account (Van den Berg et al, 2007). The fact that the link transmission model does not take signal plans into account is one of the main disadvantages of this choice. But this is the consequence of the choice made in section 2.8, and the reason this disadvantage is accepted is that it simplifies the calculation.

[5] Of course, these or other models can be adapted to meet this requirement. Doing so could have a positive influence on the controller to be developed. However, given the time allotted to the MSc Thesis project, such adaptations will not be considered.

Assumptions

The assumptions to which the urban part and the freeway part of the traffic flow model are subject, as well as their connections, are the following:

- In urban links, traffic enters and exits a link under first-in-first-out (FIFO) conditions (Yperman, 2007)
- The disturbances are known (Yperman, 2007). In section 3.3 it is derived that the disturbances are:
    - The turn fractions
    - The urban exit capacities
    - The urban entrance demands
    - The mainstream destination densities
    - The mainstream origin demands
- Traffic inside a link is not directly affected by disturbances (Yperman, 2007)
- All parameters used in the model are known (Yperman, 2007). The parameter values are chosen in section 4.1.2
- Traffic is expressed in continuous terms
- The METANET model assumes the traffic arrives at mainstream origins with speeds equal to the mean speed in the first segment downstream of a mainstream origin
- The METANET model assumes the traffic drives from on-ramps with the same speed as the traffic on the freeway parallel to the on-ramp
- The METANET model assumes off-ramps are free
- On-ramps and off-ramps are urban links, as reasoned in subsection 3.1.4
- The connected model assumes the density on the off-ramp can be approximated by dividing the number of vehicles on the off-ramp by the length of the off-ramp
- The time step k refers to the interval $[Tk; T(k+1))$ where T $[\mathrm{h}]$ is the model sampling time (Van de Weg et al, 2016)
- The same model sampling time is used for the urban and the freeway network, as reasoned in subsection 3.1.4.
- At time step k, all time-dependent variables are known, except the following, as reasoned in subsection 3.3.1[6]:
    - Reduction factors used in the node model within the link transmission model (Yperman, 2007)
    - Reduction factors used for urban entrances (Yperman, 2007)
    - The outflow out of the on-ramp
- The model uses the values of the time-dependent variables at time step k to determine their values at time step $k+1$

[6] This assumption is iterative; if one starts with the same assumption without exceptions, one finds these exceptions. When one adds these exceptions, there is no need to adapt the assumptions anymore.

3.1.2 The urban traffic flow model

The link transmission model consists of a link model for updating the link dynamics and a node model to connect the links (Yperman, 2007). As such, two of the most important elements of the link transmission model, links and nodes, have been mentioned. Other important elements, entrances and exits, can be modelled with the link model. These elements, along with the main variables used by the link transmission model, are depicted in figure 3.2.

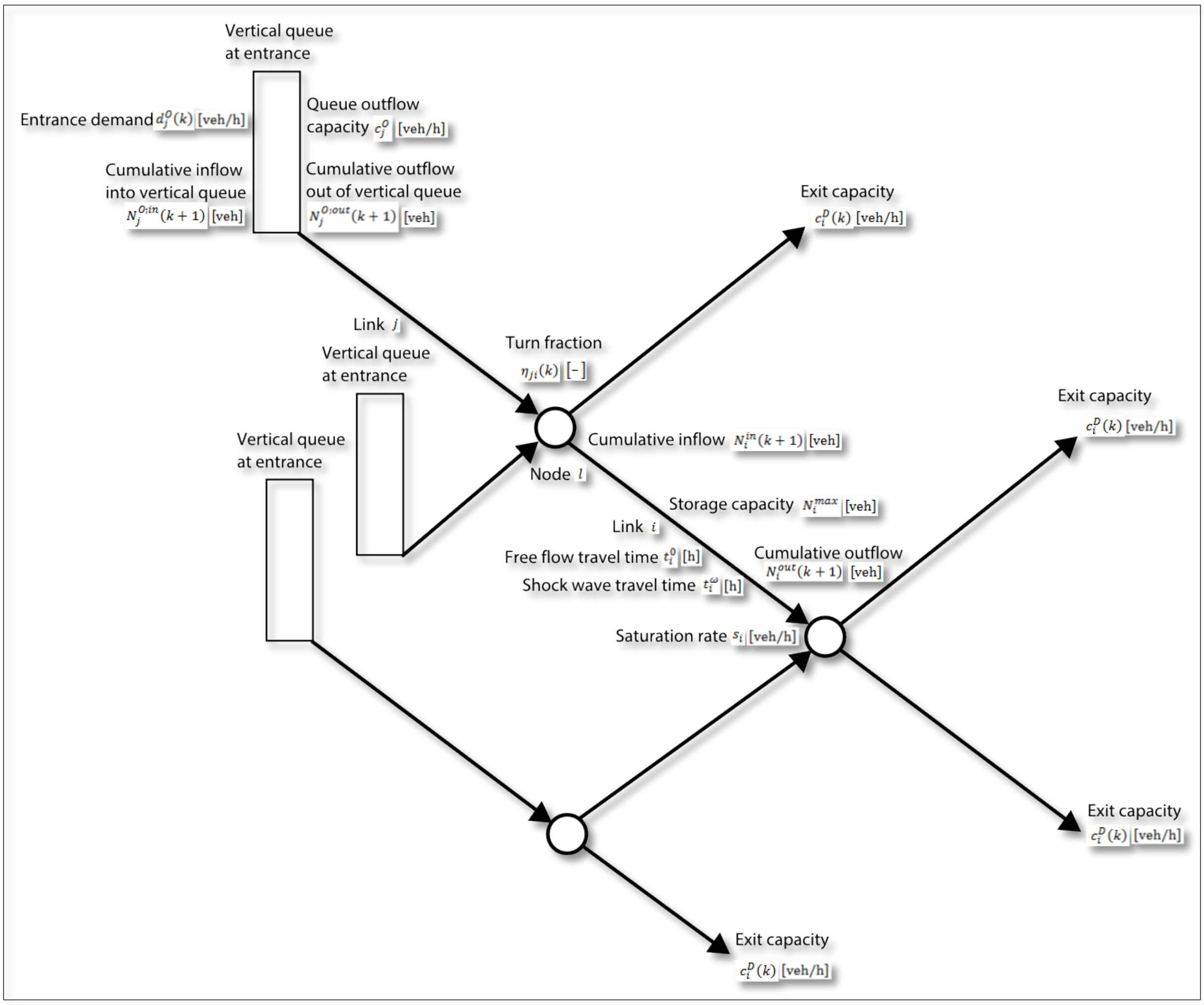

Figure 3.2 Elements of the link transmission model with main variables as used in an example network (figure inspired by Van de Weg et al, 2016)

While the link model is unique, different node models can be used to connect the links. Here, the proposition by Van de Weg et al (2016) to use a demand-proportional node model is followed.

In this subsection, the link model will be elaborated upon first. The link model calculates the cumulative inflow into the vertical queue, the cumulative outflow out of the vertical queue and maximum values for the cumulative inflows and outflows for links. These maximum values form restrictions for the cumulative inflows and outflows of previous and subsequent links. The node model applies these restrictions in order to determine the values for the cumulative inflows and outflows for the links. Elaboration on the node model will conclude this subsection.

The link model

The link model describes the link dynamics of link i by the cumulative inflow $N_i^{in}(k)$ [veh] and the cumulative outflow $N_i^{out}(k)$ [veh] (Yperman, 2007). The model has two maximum values $N_i^{out;max;1}(k+1)$ and $N_i^{out;max;2}(k+1)$ for the cumulative outflow curve, given by equations (3.1) and (3.2):

$$N_i^{out;max;1}(k+1) = N_i^{out}(k) + s_i b_i(k) T \tag{3.1}$$

$$N_i^{out;max;2}(k+1) = \gamma_i^0 N_i^{in}\left(k - k_i^0 + 2\right) + \left(1 - \gamma_i^0\right) N_i^{in}\left(k - k_i^0 + 1\right) \tag{3.2}$$

The first maximum value $N_i^{out;max;1}(k+1)$ gives the outflow if during the whole green time for link i (which is a fraction $b_i(k)$ $[-]$ of the cycle time, a fraction known as the green time share given to traffic from link i) saturation flow s_i [veh/h] is served. The second maximum value $N_i^{out;max;2}(k+1)$ gives the outflow if the inflow a free flow travel time t_i^0 [h] ago is served unhindered. In equation (3.2) the fraction γ_i^0 $[-]$ is given by:

$$\gamma_i^0 = k_i^0 - \frac{t_i^0}{T}$$

Where k_i^0 is the integer number of time steps the free flow travel time takes up. This is found by rounding up the quotient of free flow travel time and model sampling time to the nearest integer, and the model requires it to be at least 2 to guarantee CFL conditions. In formula form:

$$k_i^0 = \left\lceil \frac{t_i^0}{T} \right\rceil$$

$$k_i^0 \geq 2$$

The model states that the maximum value of the cumulative outflow curve is the minimum of those two maximum values. Equation (3.3) puts this in formula form:

$$N_i^{out;max}(k+1) = \min\left(N_i^{out;max;1}(k+1); N_i^{out;max;2}(k+1)\right) \tag{3.3}$$

Based on the current cumulative outflow and the maximum value for the cumulative outflow at the next time step, the desired cumulative inflow for a link at the next time step can be calculated:

$$N_i^{in;des}(k+1) = N_i^{in}(k) + \sum_{j \in I_i^{in}} \eta_{ji}(k)\left(N_j^{out;max}(k+1) - N_j^{out}(k)\right) \tag{3.4}$$

Where the set I_i^{in} contains the indexes of links feeding link i and $\eta_{ji}(k)$ $[-]$ is the turn fraction from link j to link i. The model calculates a value for the maximum cumulative inflow of link i as well, which is given by equation (3.5).

$$N_i^{in;max}(k+1) = \gamma_i^{\omega} N_i^{out}(k - k_i^{\omega} + 2) + (1 - \gamma_i^{\omega}) N_i^{out}(k - k_i^{\omega} + 1) + N_i^{max} \tag{3.5}$$

Where, analogous to equation (3.2):

$$\gamma_i^{\omega} = k_i^{\omega} - \frac{t_i^{\omega}}{T}$$

$$k_i^{\omega} = \left\lceil \frac{t_i^{\omega}}{T} \right\rceil$$

$$k_i^{\omega} \geq 2$$

The function of the node model is to determine the cumulative inflows and outflows $N_i^{in}(k+1)$ and $N_i^{out}(k+1)$ by applying the restrictions previous and subsequent links cause based on their maximum values for the cumulative inflows and outflows. The interaction between these values for a link i under the influence of discrete vehicles entering and exiting the link at times $t_{i;v}^{in}$ and $t_{i;v}^{out}$ is depicted in figure 3.3.

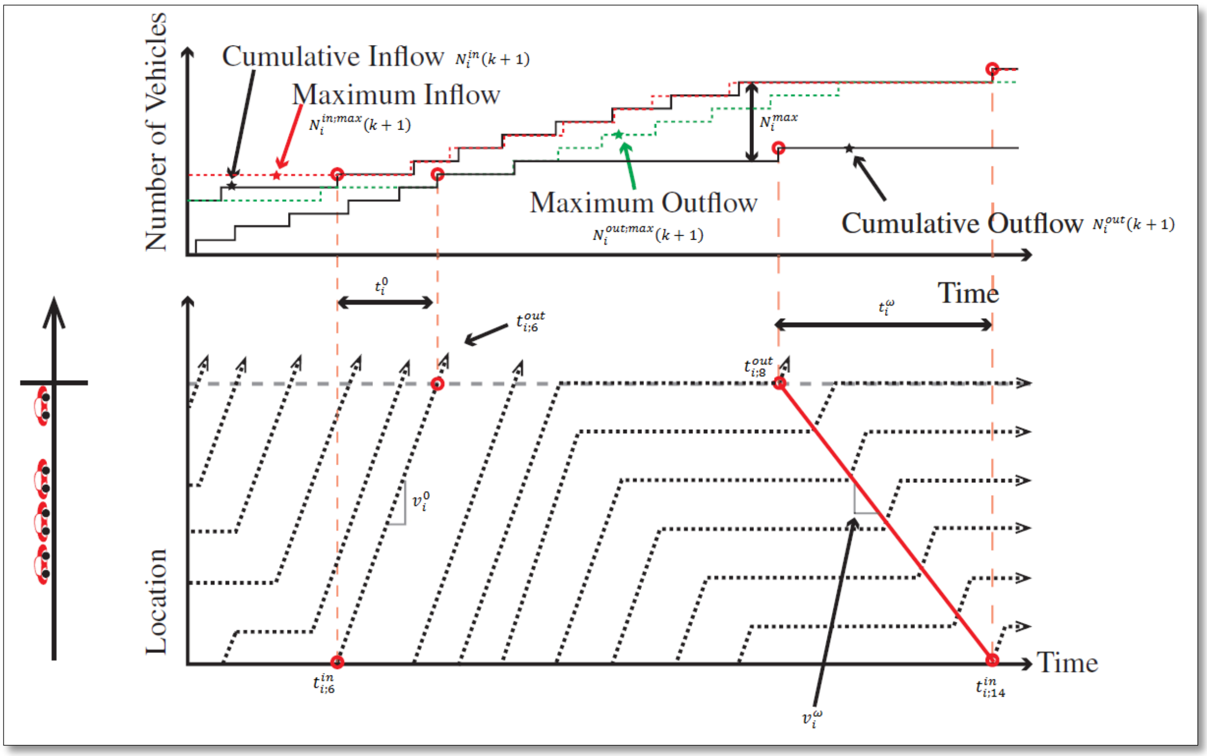

Figure 3.3 Interactions between cumulative inflows and outflows and their maximum values for an urban link under influence of discrete vehicles entering and exiting (Adapted from Van de Weg et al, 2016)

The outputs $N_i^{in}(k+1)$ and $N_i^{out}(k+1)$ combined with the entrance inflows $N_j^{O;in}(k+1)$, entrance outflows $N_j^{O;out}(k+1)$ and exit outflows $N_i^{D;out}(k+1)$ form the set of outputs of the link transmission model. These latter three outputs will be expressed in the next equations.

The exit outflow $N_i^{D;out}(k+1)$ is not only bounded by the maxima in equations (3.1) and (3.2), but also by the exit capacity $c_i^D(k)$ [veh/h] as shown by equations (3.6) and (3.7):

$$N_i^{D;out;max}(k+1) = N_i^{D;out}(k) + c_i^D(k)T \quad (3.6)$$

$$N_i^{D;out}(k+1) = \min\left(N_i^{out;max;1}(k+1); N_i^{out;max;2}(k+1); N_i^{D;out;max}(k+1)\right) \quad (3.7)$$

The model uses vertical queues for entrances. The inflow $N_j^{O;in}(k+1)$ into the vertical queue is given by:

$$N_j^{O;in}(k+1) = N_j^{O;in}(k) + d_j^O(k)T \quad (3.8)$$

Where $d_j^O(k)$ [veh/h] is the demand at this entrance. The maximum outflow $N_j^{O;out;max}(k+1)$ is given by the minimum of the inflow and the queue outflow capacity c_j^O [veh/h]:

$$N_j^{O;out;max}(k+1) = \min\left(N_j^{O;out}(k) + c_j^O T; N_j^{O;in}(k+1)\right) \quad (3.9)$$

Based on this maximum cumulative outflow, a reduction factor $r_j^{in}(k)$ is calculated:

$$r_j^{in}(k) = \min\left(\frac{N_i^{in;max}(k+1) - N_i^{in}(k)}{N_j^{O;out;max}(k+1) - N_j^{O;out}(k)}; 1\right) \quad (3.10)$$

Which is used to reduce the outflow out of the vertical queue if necessary:

$$N_j^{O;out}(k+1) = N_j^{O;out}(k) + r_j^{in}(k)\left(N_j^{O;out;max}(k+1) - N_j^{O;out}(k)\right) \quad (3.11)$$

The node model

The node model used in the link transmission model is the demand-proportional node model proposed by Van de Weg et al (2016). Its task is to use $N_i^{in;des}(k+1)$ and $N_i^{in;max}(k+1)$ as input to produce the outputs $N_i^{in}(k+1)$ and $N_i^{out}(k+1)$. This requires an iterative procedure for each node, as restrictions in downstream links (outgoing links) will restrict the outflow of upstream links (incoming links). The general idea is to find the outgoing link of a node that is most restrictive on the inflow, to limit the outflows of incoming links feeding this link accordingly, to check how this affects the outgoing links and to apply the resulting restrictions as well. The procedure for node l is as follows:

1) Initialize the node model. To this end, set:
$$\tilde{N}_i^{in;max}(k+1) = N_i^{in;max}(k+1)$$
$$\tilde{N}_i^{in;des}(k+1) = N_i^{in;des}(k+1)$$
$$\tilde{\eta}_{ji}(k) = \eta_{ji}(k)$$
2) Compute the reduction factors $r_i^{in}(k)$:
$$r_i^{in}(k) = \min\left(\frac{\tilde{N}_i^{in;max}(k+1) - N_i^{in}(k)}{\tilde{N}_i^{in;des}(k+1) - N_i^{in}(k)}; 1\right) \tag{3.12}$$
3) If all reduction factors are equal to one, go to step 10. Otherwise, find the index $i^{r;min}$ of the link with the lowest reduction factor:
$$i^{r;min} = \arg\left(\min_{i \in I_l^{out}}\left(r_i^{in}(k)\right)\right) \tag{3.13}$$
4) Find the set I_l^{to} of links j for which $\tilde{\eta}_{j i^{r;min}}(k) > 0$
5) Find the reduced maximum cumulative outflow $\tilde{N}_j^{out;max}(k+1)$ for all j in the set I_l^{to} with the formula:
$$\tilde{N}_j^{out;max}(k+1) = N_j^{out}(k) + r_{i^{r;min}}^{in}(k)\left(N_j^{out;max}(k+1) - N_j^{out}(k)\right) \quad \text{for } \forall j \in I_l^{to} \tag{3.14}$$
6) Thus the flows out of the links j in the set I_l^{to} are known. This also means they will not be affected by any reduction factor anymore, so the node can be considered without these links. To do so, reduce the maximum allowed inflow of outgoing links i by subtracting the flows from the links in the set I_l^{to}:
$$\tilde{N}_i^{in;max}(k+1) = \tilde{N}_i^{in;max}(k+1) - \sum_{j \in I_l^{to}} \tilde{\eta}_{ji}(k)\left(\tilde{N}_j^{out;max}(k+1) - N_j^{out}(k)\right) \tag{3.15}$$
7) Similarly, reduce the desired inflows:
$$\tilde{N}_i^{in;des}(k+1) = \tilde{N}_i^{in;des}(k+1) - \sum_{j \in I_l^{to}} \tilde{\eta}_{ji}(k)\left(\tilde{N}_j^{out;max}(k+1) - N_j^{out}(k)\right) \tag{3.16}$$
8) Lastly, set all turn fractions for which j is in the set I_l^{to} to zero to consider the node without them. Thus:
$$\tilde{\eta}_{ji}(k) = 0 \quad \text{for } \forall j \in I_l^{to} \cap \forall i \in I_l^{out} \tag{3.17}$$
9) Go to step 2
10) All reduction factors are equal to one, thus all cumulative outflows have been found:
$$N_j^{out}(k+1) = \tilde{N}_j^{out;max}(k+1) \tag{3.18}$$
And the cumulative inflows can be calculated:
$$N_i^{in}(k+1) = N_i^{in}(k) + \sum_{j \in I_l^{in}} \eta_{ji}(k)\left(N_j^{out}(k+1) - N_j^{out}(k)\right) \tag{3.19}$$

3.1.3 The freeway traffic flow model

The extended METANET traffic flow model, as described by Van de Weg et al (2015), is an extension of the original METANET model as proposed by Kotsialos et al (2002 [1]). This original model will first be elaborated upon, before the extensions will be discussed.

The original METANET model

The original METANET model as proposed by Kotsialos et al (2002 [1]) has been described by many authors (e.g. Van de Weg et al (2015) and Van den Berg et al (2007)), but the description of Hegyi et al (2005 [2]) will be used here for the elaboration.

The METANET model divides the freeway network in links m which are subdivided in segments i $(1; 2; \dots; n_{seg;m})$ as depicted in figure 3.4. Each link m has uniform characteristics and is connected to other links via nodes. This means that major changes in geometry such as on-ramps, off-ramps and lane drops occur at nodes. Each segment i of link m is characterised by the traffic density $\rho_{m;i}(k)$ [veh/km/lane], the mean speed $v_{m;i}(k)$ [km/h] and the outflow $q_{m;i}(k)$ [veh/h].

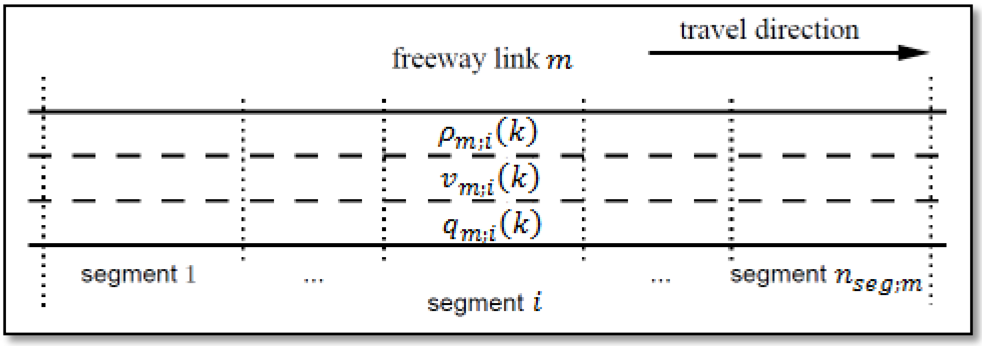

Figure 3.4 Division of freeway links in segments by the METANET model (Adpted from Hegyi, 2014 [2])

The following equations describe the evolution of the characteristic variables for the segments over time. The outflow is determined each time step based on the values of the traffic density and mean speed at that time step. This is done with equation (3.20)[7]:

$$q_{m;i}(k+1) = n_m \rho_{m;i}(k+1) v_{m;i}(k+1) \tag{3.20}$$

Where n_m is the number of lanes in link m. Subsequently, the METANET model determines the traffic density and mean speed at the next time step with equations (3.21) and (3.22):

$$\rho_{m;i}(k+1) = \rho_{m;i}(k) + \frac{T}{\ell_{seg;m} n_m}\Big(q_{m;i-1}(k) - q_{m;i}(k)\Big) \tag{3.21}$$

$$v_{m;i}(k+1) = v_{m;i}(k) + R(f_1) + C(f_2) - A(f_3) - \delta_o O(f_4) - \delta_L L(f_5) \tag{3.22}$$

Where $\ell_{seg;m}$ denotes the length of the segments in link m, $R(f_1)$ is the relaxation term, $C(f_2)$ is the convection term, $A(f_3)$ is the anticipation term, δ_o is a dichotomous variable that has value 1 in the segment downstream of an on-ramp and 0 in all other segments, $O(f_4)$ is the on-ramp term, δ_L is a dichotomous variable that has value 1 in the segment upstream of a lane drop and 0 in all other segments and $L(f_5)$ is the lane drop term. The relaxation term describes that drivers try to achieve a desired speed for the given density. The convection term describes the speed change due to inflow of vehicles with a different speed. The anticipation term describes how drivers change their

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[7] In accordance with the assumption that at time step k the values of all time-dependent variables are known except for the given exceptions, the METANET model as to be used here needs to do its calculations to determine the values at time step $k+1$. This differs from how many authors write down this equation, as they write it down for time step k.

speed due to density changes downstream. The on-ramp term describes the speed reduction caused by merging phenomena. Finally, the lane drop term describes the speed reduction caused by weaving phenomena. The sets f_1, f_2, f_3, f_4 and f_5 are the sets of variables that these terms are dependent on. The sets are given by:

$f_1 = \rho_{m;i}(k); v_{m;i}(k)$

$f_2 = v_{m;i}(k); v_{m;i-1}(k)$

$f_3 = \rho_{m;i+1}(k); \rho_{m;i}(k)$

$f_4 = q_o(k); v_{m;1}(k); \rho_{m;1}(k)$

$f_5 = \rho_{m;n_{seg;m}}(k); v_{m;n_{seg;m}}(k)$

Where $n_{seg;m}$ is the number of segments of link m. Consequently, the variables in the set f_5 characterise the last segment of link m. Furthermore, the terms are given by:

$$R(f_1) = \frac{T}{\tau}\left(V\left(\rho_{m;i}(k)\right) - v_{m;i}(k)\right)$$

$$C(f_2) = \frac{T}{\ell_{seg;m}} v_{m;i}(k)\left(v_{m;i-1}(k) - v_{m;i}(k)\right)$$

$$A(f_3) = \frac{\nu T}{\tau \ell_{seg;m}} \frac{\rho_{m;i+1}(k) - \rho_{m;i}(k)}{\rho_{m;i}(k) + \kappa}$$

$$O(f_4) = \frac{\varphi T q_o(k) v_{m;1}(k)}{\ell_{seg;m} n_m \left(\rho_{m;1}(k) + \kappa\right)}$$

$$L(f_5) = \frac{\phi T (n_m - n_{m+1}) \rho_{m;n_{seg;m}}(k) \left(v_{m;n_{seg;m}}(k)\right)^2}{\ell_{seg;m} n_m \rho_m^{crit}}$$

Where τ, ν, κ, φ and ϕ are model parameters, where the desired speed $V\left(\rho_{m;i}(k)\right)$ and the origin outflow $q_o(k)$ are given by equations (3.23)-(3.25) and where ρ_m^{crit} is the critical density for link m.

$$V\left(\rho_{m;i}(k)\right) = v_m^0 \exp\left(-\frac{1}{a_m}\left(\frac{\rho_{m;i}(k)}{\rho_m^{crit}}\right)^{a_m}\right) \tag{3.23}$$

$$q_o(k) = \min\left(d_o(k) + \frac{w_o(k)}{T}; q_o^{cap} r_o(k); q_o^{cap} \frac{\rho_m^{jam} - \rho_{m;1}(k)}{\rho_m^{jam} - \rho_m^{crit}}\right) \tag{3.24}$$

$$w_o(k+1) = w_o(k) + T\left(d_o(k) - q_o(k)\right) \tag{3.25}$$

In equation (3.23) v_m^0 is the free flow speed of link m and a_m is a model parameter for link m. In equation (3.24) $d_o(k)$ is the demand at origin o, $w_o(k)$ is the amount of vehicles waiting at origin o, q_o^{cap} is the free flow capacity of origin o, $r_o(k) \in [0; 1]$ is the metering rate of origin o (in the original METANET model, origins can occur both at the mainstream and at on-ramps, so this allows for both mainstream and ramp metering) and ρ_m^{jam} is the jam density of link m. Note that the initial amount of vehicles waiting at origin o needs to be known.

It can be noted that if the mean speed in a segment becomes zero, the outflow becomes zero. This in turn causes the density to remain at its maximum value, which in turn causes the mean speed to remain at zero. Therefore, full links will remain full in the original METANET model. To avoid this, the original METANET model has included a minimum speed v_{min} that forms a constraint for $v_{m;i}(k+1)$:

$$v_{m;i}(k+1) \geq v_{min} \quad \text{for } \forall m; i$$

The nodes in the METANET model are modelled as depicted in figure 3.5. Flows that enter a node p are distributed over the leaving links m according to the turn fractions $\beta_{p;m}(k)$ from node p to link m:

$$q_{m;0}(k) = \beta_{p;m}(k) \sum_{\mu \in I_p} q_{\mu;n_{seg;\mu}}(k) \quad \text{for } \forall m \in O_p \tag{3.26}$$

Where $q_{m;0}(k)$ is the outflow of node p into segment 1 of link m, I_p is the set of freeway links entering node p, $q_{\mu;n_{seg;\mu}}(k)$ is the outflow of the last segment of link μ and O_p is the set of freeway links exiting node p.

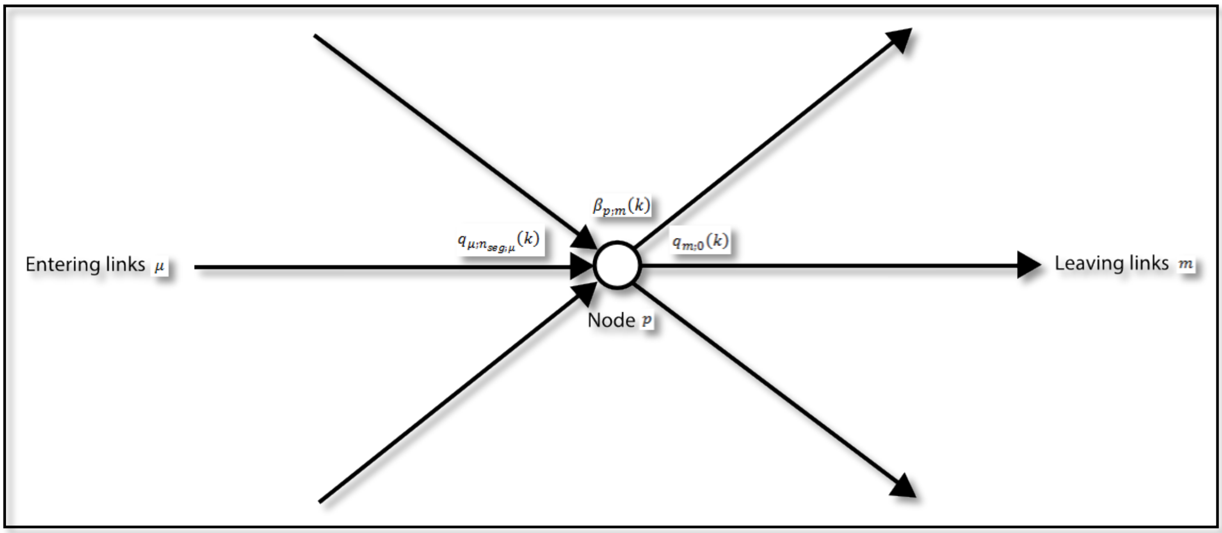

Figure 3.5 Modelling of nodes in the METANET model

The effects of next and previous segments used in speed evolutions are calculated at nodes with the following formulas:

$$\rho_{\mu;n_{seg;\mu}+1}(k) = \frac{\sum_{m \in O_p} \left(\rho_{m;1}(k)\right)^2}{\sum_{m \in O_p} \rho_{m;1}(k)} \tag{3.27}$$

$$v_{m;0}(k) = \frac{\sum_{\mu \in I_p} v_{\mu;n_{seg;\mu}}(k)\, q_{\mu;n_{seg;\mu}}(k)}{\sum_{\mu \in I_p} q_{\mu;n_{seg;\mu}}(k)} \tag{3.28}$$

While on-ramps, off-ramps and mainstream origins are located at nodes as well, they do not form freeway links and are therefore not part of the freeway network in the original METANET model. Therefore the density on the off-ramps and the mean speed on the on-ramps are ignored in the original METANET model. For mainstream origins, the original METANET model assumes the mean speed at mainstream origins is assumed to be equal to the mean speed in the first segment downstream of the mainstream origin. Based on equations (3.27) and (3.28), the treatment of on-ramps and off-ramps by the original METANET model amounts to assuming that the density on off-ramps is equal to zero (the off-ramp is free) and assuming that the mean speed on the on-ramp is the same as the speed on the freeway segment upstream of the on-ramp node. These assumptions make sense, as the original METANET model does not have to take blocked on-ramps into account and traffic on the on-ramp will adapt its speed to the speed to the freeway parallel to it.

Extensions of the METANET model

The extended METANET traffic flow model, as described by Van de Weg et al (2015), has the extensions that will be described here. To begin with, the model needs to be extended to incorporate variable speed limits in equation (3.22). Hegyi et al (2005 [1]) have formulated a modified version of equation (3.22) such that variable speed limits are incorporated. In this version, $V\left(\rho_{m;i}(k)\right)$ in equation (3.22) is replaced by $W\left(\rho_{m;i}(k)\right)$, which is defined by:

$$W\left(\rho_{m;i}(k)\right) = \min\left(V\left(\rho_{m;i}(k)\right); v_{m;i}^{ctrl}(k)\right) \tag{3.29}$$

Where $v_{m;i}^{ctrl}(k)$ is the variable speed limit in segment i.

A second extension, which also originates from Hegyi et al (2005 [1]), is introduced to model the different nature of mainstream origins and is that a different formula for the origin outflow $q_o(k)$ is used in case the origin is a mainstream origin; equation (3.24) is replaced with equation (3.30):

$$q_o(k) = \begin{cases} \min\left(d_o(k) + \frac{w_o(k)}{T}; q_o^{cap} r_o(k); q_o^{cap} \frac{\rho_m^{jam} - \rho_{m;1}(k)}{\rho_m^{jam} - \rho_m^{crit}}\right) & \text{if } c_1 = 1 \\ \min\left(d_o(k) + \frac{w_o(k)}{T}; q^{lim;\iota;1}(k)\right) & \text{if } c_1 \neq 1 \end{cases} \tag{3.30}$$

Where the variable c_1 has value 1 when o is an on-ramp and 0 otherwise. The variable $q^{lim;\iota;1}(k)$ is defined as:

$$q^{lim;\iota;1}(k) = \begin{cases} n_\iota v^{lim;\iota;1}(k)\rho_\iota^{crit}\left(-a_\iota \ln\left(\frac{v^{lim;\iota;1}(k)}{v_\iota^0}\right)\right)^{-\frac{1}{a_\iota}} & \text{if } v^{lim;\iota;1}(k) < W\left(\rho_\iota^{crit}\right) \\ n_\iota W\left(\rho_\iota^{crit}\right)\rho_\iota^{crit} & \text{if } v^{lim;\iota;1}(k) \geq W\left(\rho_\iota^{crit}\right) \end{cases} \tag{3.31}$$

Where link ι is the link directly downstream of mainstream origin o and where $v^{lim;\iota;1}(k)$ is defined by:

$$v^{lim;\iota;1}(k) = \min\left(v_{\iota;1}^{ctrl}(k); v_{\iota;1}(k)\right) \tag{3.32}$$

A third extension, which originates from from Hegyi et al (2005 [1]) as well, is introduced to model the different reactions of drivers to downstream densities. To this end, the model parameter ν in equation (3.22) is replaced by the variable $\nu_{m;i}(k)$, defined as:

$$\nu_{m;i}(k) = \begin{cases} \nu_{high} & \text{if } \rho_{m;i+1}(k) \geq \rho_{m;i}(k) \\ \nu_{low} & \text{if } \rho_{m;i+1}(k) < \rho_{m;i}(k) \end{cases} \tag{3.33}$$

A fourth extension, which is inspired by Hegyi et al (2005 [2]), is the introduction of mainstream destinations; if the last segment of a link ends at a node with no leaving link, the downstream density $\rho_{m;n_{seg;m}+1}(k)$ is given by:

$$\rho_{m;n_{seg;m}+1}(k) = \max\left(\rho^{DS}(k); \min\left(\rho_{m;n_{seg;m}}(k); \rho_m^{crit}\right)\right) \tag{3.34}$$

Where $\rho^{DS}(k)$ is the destination density which can be used as a boundary condition to the model.

A fifth and final extension was formulated by Van de Weg et al (2015). This extension allows $v_{m;i}^{ctrl}(k)$ to be determined by the position of the head $x^{H;sl}(k)$ and tail $x^{T;sl}(k)$ of the speed-limited area. This is done with the following formula:

$$v_{m;i}^{ctrl}(k) = \begin{cases} v^{eff} & \text{if } x^{H;sl}(k) > x_{m;i} \wedge x^{T;sl}(k) < x_{m;i} + \ell_{seg;m} \wedge x^{H;sl}(k) > x^{T;sl}(k) \\ v_m^0 & \text{Otherwise} \end{cases} \tag{3.35}$$

Where $x_{m;i}$ is the starting position of segment i.

3.1.4 The connection of the models

The urban traffic flow model and the freeway traffic flow model are capable of modelling internal traffic movements, inflow from entrances and outflow into exits for their respective networks. That means they need to be connected when modelling the connection between their respective networks. Those connections are known as on-ramps and off-ramps. In this subsection, formulas will be formulated based on the models to be connected to model these network elements.

These formulas will be based on how these connections are to be modelled; among other ways to model them, they can be modelled as an urban link, a freeway link or they can be split into an urban link and a freeway link. The best way to make a choice in this case is to consider what aspects of these connections are relevant in their modelling and to seek a modelling that can handle these aspects.

Relevant aspects for the modelling of these connections are the three traffic conditions that the urban and freeway traffic flow models also needed to handle: under-saturated, saturated and over-saturated conditions. Therefore, the modelling needs to take into account both free flow travel time and shockwave travel time. The link transmission model does this adequate, therefore it seems reasonable to model the connections as urban links.

Another choice that needs to be made at this point is whether or not to use different sampling times for the urban and freeway networks, like Van den Berg et al (2007) did. They proposed to use a freeway sampling time that is a whole multiple of the urban sampling time. However, Van de Weg et al (2015) and Van de Weg et al (2016) used models with a controller sampling time of 10 seconds. As it is possible to use a model sampling time that is equal to the controller sampling time (Van de Weg et al, 2015), it seems reasonable to use the same sampling time for the urban and freeway networks.

Based on these choices, the formulas will be formulated for the on-ramps and the off-ramps.

On-ramps
On-ramps were already a part of the extended METANET traffic flow model via equations (3.30) (when $c_1 = 1$) and (3.25). Therefore, these two equations provide an easy starting point for modelling on-ramps and will be repeated here:

$$q_o(k) = \begin{cases} \min\left(d_o(k) + \frac{w_o(k)}{T}; q_o^{cap} r_o(k); q_o^{cap} \frac{\rho_m^{jam} - \rho_{m;1}(k)}{\rho_m^{jam} - \rho_m^{crit}}\right) & \text{if } c_1 = 1 \\ \min\left(d_o(k) + \frac{w_o(k)}{T}; q^{lim;\iota;1}(k)\right) & \text{if } c_1 \neq 1 \end{cases} \quad (3.30)$$

$$w_o(k+1) = w_o(k) + T\big(d_o(k) - q_o(k)\big) \quad (3.25)$$

However, now that the choice has been made to model the on-ramps as urban links, the variable $q_o(k)$ for on-ramps needs to be determined by the urban traffic flow model. This can be done by using equation (3.7) for the cumulative outflow out of the on-ramp:

$$N_i^{D;out}(k+1) = \min\left(N_i^{out;max;1}(k+1); N_i^{out;max;2}(k+1); N_i^{D;out;max}(k+1)\right) \quad (3.7)$$

In which the variables $N_i^{out;max;1}(k+1)$, $N_i^{out;max;2}(k+1)$ and $N_i^{D;out;max}(k+1)$ are determined by equations (3.1), (3.2) and (3.6), which will be repeated here as well:

$$N_i^{out;max;1}(k+1) = N_i^{out}(k) + s_i b_i(k) T \quad (3.1)$$

$$N_i^{out;max;2}(k+1) = \gamma_i^0 N_i^{in}\big(k - k_i^0 + 2\big) + \big(1 - \gamma_i^0\big) N_i^{in}\big(k - k_i^0 + 1\big) \quad (3.2)$$

$$N_i^{D;out;max}(k+1) = N_i^{D;out}(k) + c_i^D(k) T \quad (3.6)$$

Now, in order to make the cumulative outflow out of the on-ramp consistent with the traffic situation on the freeway, one must associate each of these variables with the terms within the minimum function for on-ramps in equation (3.30). Close observation reveals that the first term corresponds to free flow, the second term to saturation flow (due to ramp metering) and the third term to downstream capacity. Since $N_i^{out;max;1}(k+1)$ corresponds to saturation flow, $N_i^{out;max;2}(k+1)$ corresponds to free flow and $N_i^{D;out;max}(k+1)$ corresponds to downstream capacity, one can make the cumulative outflow out of the on-ramp consistent with the traffic situation on the freeway by making $d_o(k)$ and $w_o(k)$ obsolete for on-ramps, setting $s_i = q_o^{cap}$ and defining:

$$b_i(k) = r_o(k) \quad \text{if } c_2 = 1 \quad (3.36)$$

$$c_i^D(k) = q_o^{cap} \frac{\rho_m^{jam} - \rho_{m;1}(k)}{\rho_m^{jam} - \rho_m^{crit}} \quad \text{if } c_2 = 1 \quad (3.37)$$

Where the variable c_2 has value 1 when o is an on-ramp corresponding to link i and 0 otherwise. Using this to calculate the cumulative outflow out of the on-ramp, one can determine $q_o(k)$ with:

$$q_o(k) = \min\left(\frac{N_i^{out;max;2}(k+1) - N_i^{D;out}(k)}{T}; s_i b_i(k); q_o^{cap} \frac{\rho_m^{jam} - \rho_{m;1}(k)}{\rho_m^{jam} - \rho_m^{crit}}\right) \quad \text{if } c_2 = 1 \quad (3.38)$$

Note that the assumption that traffic on the on-ramp will adapt its speed to the on-ramp parallel to it can still be used; downstream capacity forces traffic to reduce its speed while in the link, whereas traffic on an empty on-ramp will basically continue with free flow speed until adapting its speed when exiting the link.

Off-ramps

Off-ramps were not part of the extended METANET model, so the extended METANET model does not provide an easy starting point for modelling off-ramps, as it did with on-ramps. Therefore, the situation faced and the relevant variables are sketched in figure 3.6.

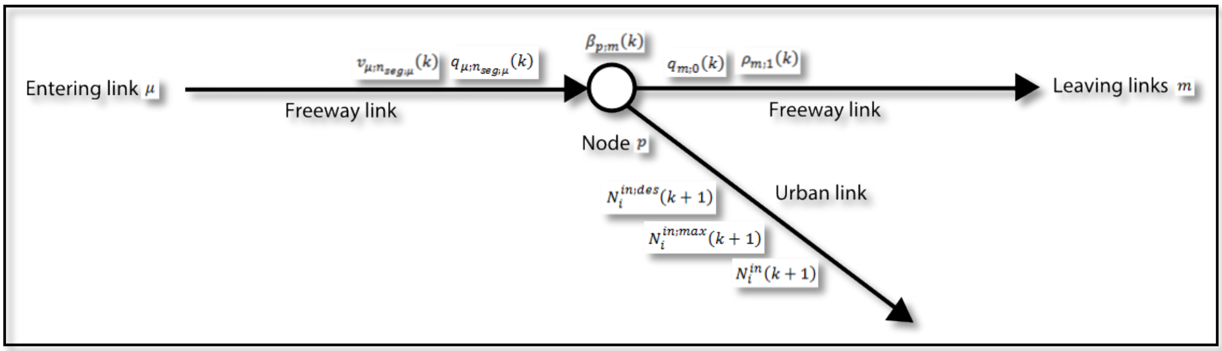

Figure 3.6 Sketch of the situation and the relevant variables

Van den Berg et al (2007) considered off-ramps as well. They proposed to have the realised outflow out of the last segment before the off-ramp to be the minimum of two flow regimes (unrestricted outflow $q_{\mu;n_{seg;\mu}}^{normal}(k)$ and restricted outflow $q_{\mu;n_{seg;\mu}}^{max}(k)$)

$$q_{\mu;n_{seg;\mu}}(k) = \min\left(q_{\mu;n_{seg;\mu}}^{normal}(k); q_{\mu;n_{seg;\mu}}^{max}(k)\right) \quad \text{if } c_3 = 1 \tag{3.39}$$

Where the variable c_3 has value 1 when μ is the link upstream of the off-ramp corresponding to link i and 0 otherwise.

Furthermore, Van den Berg et al (2007) proposed to have the speed associated with this flow adapted as follows:

$$v_{\mu;n_{seg;\mu}}(k) = \begin{cases} v_{\mu;n_{seg;\mu}}^{normal}(k) & \text{if } q_{\mu;n_{seg;\mu}}^{normal}(k) < q_{\mu;n_{seg;\mu}}^{max}(k) \\ v_{\mu;n_{seg;\mu}}^{normal}(k)\dfrac{q_{\mu;n_{seg;\mu}}^{max}(k)}{q_{\mu;n_{seg;\mu}}^{normal}(k)} & \text{if } q_{\mu;n_{seg;\mu}}^{normal}(k) \geq q_{\mu;n_{seg;\mu}}^{max}(k) \end{cases} \quad \text{if } c_3 = 1 \tag{3.40}$$

Within this proposal, the variables $q_{\mu;n_{seg;\mu}}^{normal}(k)$, $v_{\mu;n_{seg;\mu}}^{normal}(k)$ and $\rho_{\mu;n_{seg;\mu}}^{normal}(k)$ are calculated with the extended METANET model, equations (3.20)-(3.22). In order to do so, the downstream density $\rho_{\mu;n_{seg;\mu}+1}(k)$ needs to be calculated with equation (3.27). This requires approximating the off-ramp density, as blocked off-ramps now play a role. As approximation, equation (3.41) is proposed:

$$\rho_{m;1}(k) = \frac{N_i^{in}(k) - N_i^{out}(k)}{\ell_{seg;m} n_m} \quad \text{if } c_4 = 1 \tag{3.41}$$

Where the variable c_4 has value 1 when m is the off-ramp corresponding to link i and 0 otherwise.

As figure 3.6 suggests, it makes sense to determine $q_{\mu;n_{seg;\mu}}^{max}(k)$ with $N_i^{in;max}(k+1)$. As the latter gives the maximum cumulative inflow into the off-ramp, one finds with equation (3.26) that the product of $\beta_{p;m}(k)$ and $q_{\mu;n_{seg;\mu}}^{max}(k)$ must be equal to the difference between $N_i^{in;max}(k+1)$ and $N_i^{in}(k)$ divided by the sampling time T. That way, $q_{\mu;n_{seg;\mu}}^{max}(k)$ is found based on $N_i^{in;max}(k+1)$ with equation (3.42):

$$q_{\mu;n_{seg;\mu}}^{max}(k) = \frac{N_i^{in;max}(k+1) - N_i^{in}(k)}{\beta_{p;m}(k)T} \quad \text{if } c_3 = 1 \wedge c_4 = 1 \tag{3.42}$$

Once $q^{max}_{\mu;n_{seg;\mu}}(k)$ has been determined, it can be used in equation (3.39) to determine $q_{\mu;n_{seg;\mu}}(k)$ and in equation (3.40) to determine $v_{\mu;n_{seg;\mu}}(k)$. The density $\rho_{\mu;n_{seg;\mu}}(k)$ is then determined with:

$$\rho_{\mu;n_{seg;\mu}}(k) = \frac{q_{\mu;n_{seg;\mu}}(k)}{n_\mu v_{\mu;n_{seg;\mu}}(k)} \quad \text{if } c_3 = 1 \tag{3.43}$$

In order to run the extended METANET model, the variables $\rho_{m;i}(k)$ and $v_{m;i}(k)$ need to be known for all links m and all segments i before the calculations start at time step k. Therefore, the calculations for off-ramps need to be run according to equations (3.44)-(3.52)[8]:

$$\rho^{normal}_{\mu;n_{seg;\mu}}(k+1) = \rho_{\mu;n_{seg;\mu}}(k) + \frac{T}{\ell_{seg;\mu} n_\mu}\left(q_{\mu;n_{seg;\mu}-1}(k) - q_{\mu;n_{seg;\mu}}(k)\right) \quad \text{if } c_3 = 1 \tag{3.44}$$

$$v^{normal}_{\mu;n_{seg;\mu}}(k+1) = v_{\mu;n_{seg;\mu}}(k) + R(f_1) + C(f_2) - A(f_3) \quad \text{if } c_3 = 1 \tag{3.45}$$

$$q^{normal}_{\mu;n_{seg;\mu}}(k+1) = n_\mu \rho^{normal}_{\mu;n_{seg;\mu}}(k+1) v^{normal}_{\mu;n_{seg;\mu}}(k+1) \quad \text{if } c_3 = 1 \tag{3.46}$$

$$N^{in;max}_i(k+2) = N^{in;max}_i(\hat{k}+1) \quad \text{if } c_4 = 1 \tag{3.47}$$

$$N^{in}_i(k+1) = N^{in}_i(k) + \beta_{p;m}(k) q_{\mu;n_{seg;\mu}}(k) T \quad \text{if } c_5 = 1 \tag{3.48}$$

$$q^{max}_{\mu;n_{seg;\mu}}(k+1) = \frac{N^{in;max}_i(k+2) - N^{in}_i(k+1)}{\beta_{p;m}(k+1)T} \quad \text{if } c_5 = 1 \tag{3.49}$$

$$q_{\mu;n_{seg;\mu}}(k+1) = \min\left(q^{normal}_{\mu;n_{seg;\mu}}(k+1); q^{max}_{\mu;n_{seg;\mu}}(k+1)\right) \quad \text{if } c_3 = 1 \tag{3.50}$$

$$v_{\mu;n_{seg;\mu}}(k+1) = \begin{cases} v^{normal}_{\mu;n_{seg;\mu}}(k+1) & \text{if } c_6 = 1 \\ v^{normal}_{\mu;n_{seg;\mu}}(k+1) \dfrac{q^{max}_{\mu;n_{seg;\mu}}(k+1)}{q^{normal}_{\mu;n_{seg;\mu}}(k+1)} & \text{if } c_6 \neq 1 \end{cases} \quad \text{if } c_3 = 1 \tag{3.51}$$

$$\rho_{\mu;n_{seg;\mu}}(k+1) = \frac{q_{\mu;n_{seg;\mu}}(k+1)}{n_\mu v_{\mu;n_{seg;\mu}}(k+1)} \quad \text{if } c_3 = 1 \tag{3.52}$$

Where the variable c_3 has value 1 when μ is the link upstream of the off-ramp corresponding to link i and 0 otherwise, the variable $\hat{k}$ is equal to $k+1$, the variable c_4 has value 1 when m is the off-ramp corresponding to link i and 0 otherwise, the variable c_5 has value 1 when variables c_3 and c_4 both have value 1 and 0 otherwise and the variable c_6 has value 1 when $q^{normal}_{\mu;n_{seg;\mu}}(k+1) < q^{max}_{\mu;n_{seg;\mu}}(k+1)$ and 0 otherwise. Based on equation (3.5), one finds:

$$N^{in;max}_i(\hat{k}+1) = \gamma^\omega_i N^{out}_i(\hat{k} - k^\omega_i + 2) + (1-\gamma^\omega_i) N^{out}_i(\hat{k} - k^\omega_i + 1) + N^{max}_i$$

Substituting $\hat{k} = k+1$, this means:

$$N^{in;max}_i(k+2) = \gamma^\omega_i N^{out}_i(k - k^\omega_i + 3) + (1-\gamma^\omega_i) N^{out}_i(k - k^\omega_i + 2) + N^{max}_i$$

Which means that for off-ramps k^ω_i needs to be at least 3 to guarantee CFL conditions. Thus:

$$k^\omega_i \geq 3 \quad \text{if } c_7 = 1$$

Where the variable c_7 has value 1 when link i is an off-ramp and 0 otherwise.

[8] For simplicity of equation (3.45), it is assumed that no lane drops happen at the off-ramp node and that for link μ it holds that $n_{seg;\mu} \geq 2$, which means segment $n_{seg;\mu}$ cannot be the segment downstream of an on-ramp

3.2 The optimisation problem

The optimisation problem is to use control inputs to optimise an objective function while respecting constraints. Therefore, the optimisation problem will be described by describing the control inputs to the traffic flow model in subsection 3.2.1, along with the slight alterations to solve the optimisation problem. Then the objective function will be described in subsection 3.2.2. This section will be concluded with a description of the constraints in subsection 3.2.3.

The optimisation problem is to be solved by the controller. In order for the controller to do so, it needs a controller sampling time describing the length of the time step the controller uses to run its traffic flow model. Even though it is possible to use a model sampling time that is equal to the controller sampling time (Van de Weg et al, 2015), it is advisable to distinguish between the two to allow a difference, as was used by Van de Weg et al (2016). Therefore, the controller time steps will be denoted with k^c which refer to intervals $t \in [T^c k^c; T^c(k^c+1))$, where T^c is the controller sampling time. As was reasoned in subsection 3.1.4, the same controller sampling time is used for both networks.

3.2.1 Control inputs and alterations of the traffic flow model

Control inputs to the traffic flow model are the green time shares given to the traffic in the links and the positions of head and tail of the speed-limited area. The controller needs to choose values for these control inputs for each time step k^c. However, in general, controllers can choose their control inputs selectively over a certain control horizon from $k^c = k_0$ until $k^c = k_0 + N_c$ at selective time steps $k^c = k_0 + n_u k_u$ (Van de Weg, 2015), (Van de Weg, 2016). In this context, k_u is the number of controller time steps between each time the controller chooses its controller inputs and n_u is an integer such that $1 \le n_u \le \frac{N_c}{k_u}$. It is required that k_u is a divisor of N_c, i.e. that $\frac{N_c}{k_u}$ is an integer. When $k_u > 1$, this selective choosing saves computation time by using a controller update time T^u defined as $T^u = k_u T^c$ that is larger than the controller sampling time.

Like with the sampling times, it is possible to used different update times for the urban network and the freeway network. Slight alterations of the traffic flow model are needed to allow for a controller update time capable of saving computation time, and these alterations can be simplified by using the same controller update time in both networks. Therefore it has been chosen to use the same controller update time in both networks.

The first alteration needed to allow for a controller update time capable of saving computation time is that the green time shares are constant over the controller update time:

$$b_i\left(k_0 + \overset{\frown}{k} + 1\right) = b_i\left(k_0 + \overset{\frown}{k}\right) \tag{3.53}$$

Where $n_u k_u \le \overset{\frown}{k} < (n_u+1)k_u - 1$. The second alteration is that the controller determines the position of head and tail of the speed-limited area at time step $k^c = k_0 + k_u$ and the speeds of head and tail at the selective time steps. This means the controller has to choose $x^{H;sl}(k_0 + k_u)$, $x^{T;sl}(k_0 + k_u)$, $v^{H;sl}(k_0 + \breve{k})$ and $v^{T;sl}(k_0 + \breve{k})$ as its control inputs. In this context $\breve{k}$ is defined as $\breve{k} = k_u; 2k_u; \cdots; N_c$. Selective choosing can then be guaranteed by keeping the speeds of head and tail constant over the controller update time:

$$v^{H;sl}\left(k_0 + \overset{\frown}{k} + 1\right) = v^{H;sl}\left(k_0 + \overset{\frown}{k}\right) \tag{3.54}$$

$$v^{T;sl}\left(k_0 + \overbrace{k} + 1\right) = v^{T;sl}\left(k_0 + \overbrace{k}\right) \tag{3.55}$$

This enables to keep track of the position of head and tail of the speed-limited area over the entire control horizon:

$$x^{H;sl}\left(k_0 + \breve{k}\right) = x^{H;sl}(k_0 + k_u) + \sum_{j=k_0+k_u}^{k_0+\breve{k}-1} v^{H;sl}(j)T^c \tag{3.56}$$

$$x^{T;sl}\left(k_0 + \breve{k}\right) = x^{T;sl}(k_0 + k_u) + \sum_{j=k_0+k_u}^{k_0+\breve{k}-1} v^{T;sl}(j)T^c \tag{3.57}$$

It can be noted that the controller cannot choose the control inputs for the first k_u controller time steps. In other words, the controller cannot choose the control inputs for $k^c = k_0 + n_s$, where n_s is an integer such that $0 \leq n_s < k_u$. The control inputs for these time steps were determined by previous control actions. This means that if the previous control actions included application of a speed-limited area, the controller cannot choose $x^{H;sl}(k_0 + k_u)$ and $x^{T;sl}(k_0 + k_u)$ anymore, as these are fixated by the previous control actions via equations (3.56) and (3.57). This has a direct influence on the constraints, therefore further elaboration will follow in subsection 3.2.3.

Equation (3.35) implies that the gradient of the objective function with respect to the positions and speeds of head and tail of the speed-limited area is discontinuous. As it is favourable to use gradient-based optimisation techniques, which require continuous gradients, Van de Weg et al (2015) propose to make the gradient continuous by introducing a parameter $\gamma_{m;i}(k^c)$. This parameter is to denote the fraction of segment i that is covered by speed limits. It is calculated as follows:

$$\gamma_{m;i}(k^c) = \max\left(\frac{\ell_{seg;m} - S\left(x^{T;sl}(k^c)\right) - E\left(x^{H;sl}(k^c)\right)}{\ell_{seg;m}}; 0\right) \tag{3.58}$$

Where $S\left(x^{T;sl}(k^c)\right)$ is the start term defining the distance from the start of the segment to the tail of the speed-limited area and $E\left(x^{H;sl}(k^c)\right)$ is the end term defining the distance from the head of the speed-limited area to the end of the segment. The terms are defined by:

$$S\left(x^{T;sl}(k^c)\right) = \max\left(x^{T;sl}(k^c) - x_{m;i}; 0\right)$$

$$E\left(x^{H;sl}(k^c)\right) = \max\left(x_{m;i} + \ell_{seg;m} - x^{H;sl}(k^c); 0\right)$$

And the parameter is used to determine $v_{m;i}^{ctrl}(k^c)$ such that a continuous gradient is obtained:

$$v_{m;i}^{ctrl}(k^c) = \gamma_{m;i}(k^c)v^{eff} + \left(1 - \gamma_{m;i}(k^c)\right)V\left(\rho_{m;i}(k^c)\right) \tag{3.59}$$

This concludes the slight alterations of the traffic flow model needed to solve the optimisation problem. The controller uses the following equations with a controller time step k^c in its traffic flow model:

- (3.1)-(3.21)
- (3.22) with:
  - Equation (3.23) to define $V\left(\rho_{m;i}(k^c)\right)$
  - Equation (3.25) to determine $w_o(k^c + 1)$
  - The adaptations from equations (3.29)-(3.34)
  - The on-ramp model (3.36)-(3.38)
  - The off-ramp model (3.44)-(3.52) with equation (3.41) to determine the off-ramp density
  - Equations (3.58) and (3.59) to determine $v_{m;i}^{ctrl}(k^c)$
- (3.26)-(3.28)

3.2.2 Objective function

The objective function is determined by the objective criteria. Examples of objective criteria have been given in subsection 2.2.4. Given the desired situation defined in the problem description, one can choose objective criteria that correspond to that situation. While the first three correspond to that situation, they are quite similar; if, under given inflow, one would want to reduce the total time spent, one would increase the number of vehicles served and decrease the vehicle loss hours. Given that Van de weg et al (2015) and Van de Weg et al (2016) use the total time spent as their objective criterion, it seems reasonable to follow that choice. Given that the total time spent by all vehicles in the network can be calculated by calculating the number of vehicles in each link and each entrance during each time step, multiplying it by the sampling time and adding the results together over a certain prediction horizon from $k^c = k_0$ until $k^c = k_0 + N_p$ where $N_p \geq N_c$, one can write the objective function J as the sum of total time spent in the urban network J_U and the total time spent in the freeway network J_F. This results in:

$$J = J_U + J_F \tag{3.60}$$

According to Van de Weg et al (2016), the total time spent in the urban network can be formulated as:

$$J_U = T^c \sum_{k^c=k_0}^{k_0+N_p} \left(\sum_{i \in I^L} \left(N_i^{in}(k^c) - N_i^{out}(k^c) \right) + \sum_{j \in I^O} \left(N_j^{O;in}(k^c) - N_j^{O;out}(k^c) \right) \right) \tag{3.61}$$

Where I^L is the set of all links and I^O is the set of all entrances. Similarly, according to Van de Weg et al (2015), the total time spent in the freeway network can be formulated as:

$$J_F = T^c \sum_{k^c=k_0}^{k_0+N_p} \left(\sum_{m;i \in I_{FL}} \rho_{m;i}(k^c) \ell_{seg;m} n_m + \sum_{o \in I_{FO}} w_o(k^c) \right) \tag{3.62}$$

Where I_{FL} is the set of indexes of all pairs of segments and links and I_{FO} is the set of all origin indexes corresponding to mainstream origins.

There was a requirement present on the objective criterion to be used for the *Linear optimal coordinated signal control algorithm* part of the controller; it needed to allow for linear or quadratic programming. If this requirement is not met, the amounts of traffic lights cause the controller to have a long computation time. Therefore, it needs to be checked if the used objective criteria allow for linear or quadratic programming in the context of an urban network. According to Van de Weg et al (2016), the optimisation problem (3.61) in the context of an urban network is linear with linear inequality constraints. Thus the total time spent is a criterion that meets this requirement.

However, it should be noted that optimisation problem (3.62) is a nonlinear optimisation problem, as the METANET model is a nonlinear traffic model. Since the METANET model introduces nonlinearity via the on-ramps and off-ramps, the optimisation problem (3.61) is nonlinear in the context of the integrated urban-freeway network. This makes the optimisation problem (3.60) a nonlinear optimisation problem. However, it is expected that the computation time for this nonlinear optimisation problem is shorter than it would be if the optimisation problem (3.61) had been a nonlinear optimisation problem in the context of an urban network.

3.2.3 Constraints

The controller that optimises the objective function given by equation (3.60) faces constraints due to various limitations. These may be physical limitations (e.g. traffic cannot drive faster than the free flow speed) or controller limitations (e.g. the green time shares of all approaches of an intersection need to be in between 0 and 1). Both the urban traffic flow model and the freeway traffic flow model bring in their own constraints. Providing these constraints are met, no constraints for the connections are needed (Van de Weg, 2015),(Van de Weg, 2016). Therefore, the urban and freeway constraints will now be elaborated upon.

Urban constraints

The urban constraints stem from the fact that the green time shares for all conflicting approaches have to add up to 1 and cannot be negative (Van de Weg, 2016). This can be surmised in the following two constraints:

$$0 \leq b_i(k^c) \leq 1 \tag{3.63}$$

$$\sum_{i \in I_j^{conflict}} b_i(k^c) \leq 1 \tag{3.64}$$

Where the set $I_j^{conflict}$ is the set of links j which are in conflict with each other.

Beyond the control horizon, the control inputs should remain constant. This results in an additional constraint:

$$b_i\left(k_0 + \tilde{k} + 1\right) = b_i\left(k_0 + \tilde{k}\right) \quad \text{if } N_c \leq \tilde{k} < N_p \tag{3.65}$$

Where $\tilde{k} = 1; 2; \ldots; N_p$.

Freeway constraints

The freeway constraints constrain the initial position and speeds of head and tail of the speed-limited area. Thus there are constraints that constrain $x^{H;sl}(k_0 + k_u)$ and $x^{T;sl}(k_0 + k_u)$ and there are constraints that constrain $v^{H;sl}(k_0 + \tilde{k})$ and $v^{T;sl}(k_0 + \tilde{k})$. First the former will be considered, then the latter.

The initial position of the head and tail have to lie within the upstream bounds $x^{H;0}(k_0)$ and $x^{T;0}(k_0)$ and downstream bounds $x^{H;end}(k_0)$ and $x^{T;end}(k_0)$ (Van de Weg, 2015):

$$x^{H;0}(k_0) \leq x^{H;sl}(k_0 + k_u) \leq x^{H;end}(k_0) \tag{3.66}$$

$$x^{T;0}(k_0) \leq x^{T;sl}(k_0 + k_u) \leq x^{T;end}(k_0) \tag{3.67}$$

In the situation that the previous control actions did not include application of a speed-limited area, these upstream and downstream bounds are easily determined; they correspond to upstream and downstream bounds of the freeway network, which can be denoted with x_0 and x_{end}, respectively. However, in the situation that the previous control actions did include application of a speed-limited area, the initial positions of the head and tail are fixated as follows:

$$x^{H;sl}(k_0 + k_u) = x^{H;sl}(k_0) + v^{H;sl}(k_0)T^u \tag{3.68}$$

$$x^{T;sl}(k_0 + k_u) = x^{T;sl}(k_0) + v^{T;sl}(k_0)T^u \tag{3.69}$$

The situations for previous control can be incorporated in constraints (3.66) and (3.67) by defining:

$$x^{H;0}(k_0) = \begin{cases} x_0 & \text{if } c_8 \neq 1 \\ x^{H;sl}(k_0) + v^{H;sl}(k_0)T^u & \text{if } c_8 = 1 \end{cases} \tag{3.70}$$

$$x^{H;end}(k_0) = \begin{cases} x_{end} & \text{if } c_8 \neq 1 \\ x^{H;sl}(k_0) + v^{H;sl}(k_0)T^u & \text{if } c_8 = 1 \end{cases} \tag{3.71}$$

$$x^{T;0}(k_0) = \begin{cases} x_0 & \text{if } c_8 \neq 1 \\ x^{T;sl}(k_0) + v^{T;sl}(k_0)T^u & \text{if } c_8 = 1 \end{cases} \tag{3.72}$$

$$x^{T;end}(k_0) = \begin{cases} x_{end} & \text{if } c_8 \neq 1 \\ x^{T;sl}(k_0) + v^{T;sl}(k_0)T^u & \text{if } c_8 = 1 \end{cases} \tag{3.73}$$

Where the variable c_8 has value 1 when the the previous control actions included application of a speed-limited area and 0 otherwise.

The initial position of the head should be equal to, or more downstream than the initial position of the tail:

$$x^{H;sl}(k_0 + k_u) \geq x^{T;sl}(k_0 + k_u) \tag{3.74}$$

In order to ensure that drivers only enter and exit the speed-limited area once, the head and tail are allowed to propagate downstream with at most v^{eff}. Upstream, they are allowed to propagate with any speed. This results in the following constraints:

$$v^{H;sl}(k_0 + \tilde{k}) \leq v^{eff} \tag{3.75}$$

$$v^{T;sl}(k_0 + \tilde{k}) \leq v^{eff} \tag{3.76}$$

Finally, beyond the control horizon the speeds of head and tail should remain constant. This results in the following constraints:

$$v^{H;sl}(k_0 + \tilde{k} + 1) = v^{H;sl}(k_0 + \tilde{k}) \quad \text{if } N_c \leq \tilde{k} < N_p \tag{3.77}$$

$$v^{T;sl}(k_0 + \tilde{k} + 1) = v^{T;sl}(k_0 + \tilde{k}) \quad \text{if } N_c \leq \tilde{k} < N_p \tag{3.78}$$

The set of freeway constraints is thus formed by equations (3.66)-(3.67) and (3.74)-(3.78).

3.3 Overview of the control problem

In this section, an overview is given of the control problem. In order to do so, it is necessary to distinguish the state of the process, the control inputs, the disturbances and the output of the process. These distinctions will be based on the descriptions of the model calculations and the controller calculations. The model calculations will be described in subsection 3.3.1, whereas the controller calculations will be described in subsection 3.3.2. The state, control inputs, disturbances and outputs of the control problem are the subject of subsection 3.3.3 and the section will be concluded with the overview in section 3.3.4.

3.3.1 Description of the model calculations

The model calculations can be best described by assuming that all time-dependent variables at time step k are known, except for the ones that are dependent on time-dependent variables at time step $k+1$ and including the historical information needed to run the model. Close inspection of the model reveals that the exceptions are formed by $r_i^{in}(k)$[9], $r_j^{in}(k)$ and $q_o(k)$. The needed historical information is given by:

- $N_i^{in}(k-1); N_i^{in}(k-2); \cdots; N_i^{in}\left(k-k_i^0+1\right)$
- $N_i^{out}(k-1); N_i^{out}(k-2); \cdots; N_i^{out}(k-k_i^{\omega}+1)$

Thus, to know the values of all time-dependent variables at time step k, some values of time-dependent variables at time step $k+1$ are to be known. When these are known, the model has a full set of values for the time dependent variables at time step k and can move on to time step $k+1$. Figure 3.7 shows how this is done.

3.3.2 Description of the controller calculations

The controller calculations are to determine the control variables $b_i\left(k_0+\breve{k}\right)$, $x^{H;sl}(k_0+k_u)$, $x^{T;sl}(k_0+k_u)$, $v^{H;sl}\left(k_0+\breve{k}\right)$ and $v^{T;sl}\left(k_0+\breve{k}\right)$ such that the constraints (3.63)-(3.65), (3.66)-(3.67) and (3.74)-(3.78) are met. Once these are determined, the controller performs the calculations depicted in figure 3.8 to move from an incomplete set of values for time-dependent variables at time step k^c (the same values are missing as were missing in the model calculations) to a complete set and subsequently to the same incomplete set at time step k^c+1. Once all values from time step $k^c=k_0$ until time step $k^c=k_0+N_p$ are known, they can be used to evaluate the objective function J defined by equations (3.60)-(3.62). The controller strives to optimise the result.

[9] Because $r_i^{in}(k)$ is calculated during each iteration of the node model, it varies over subsequent iterations. At the end of each time step, all values for $r_i^{in}(k)$ are equal to one.

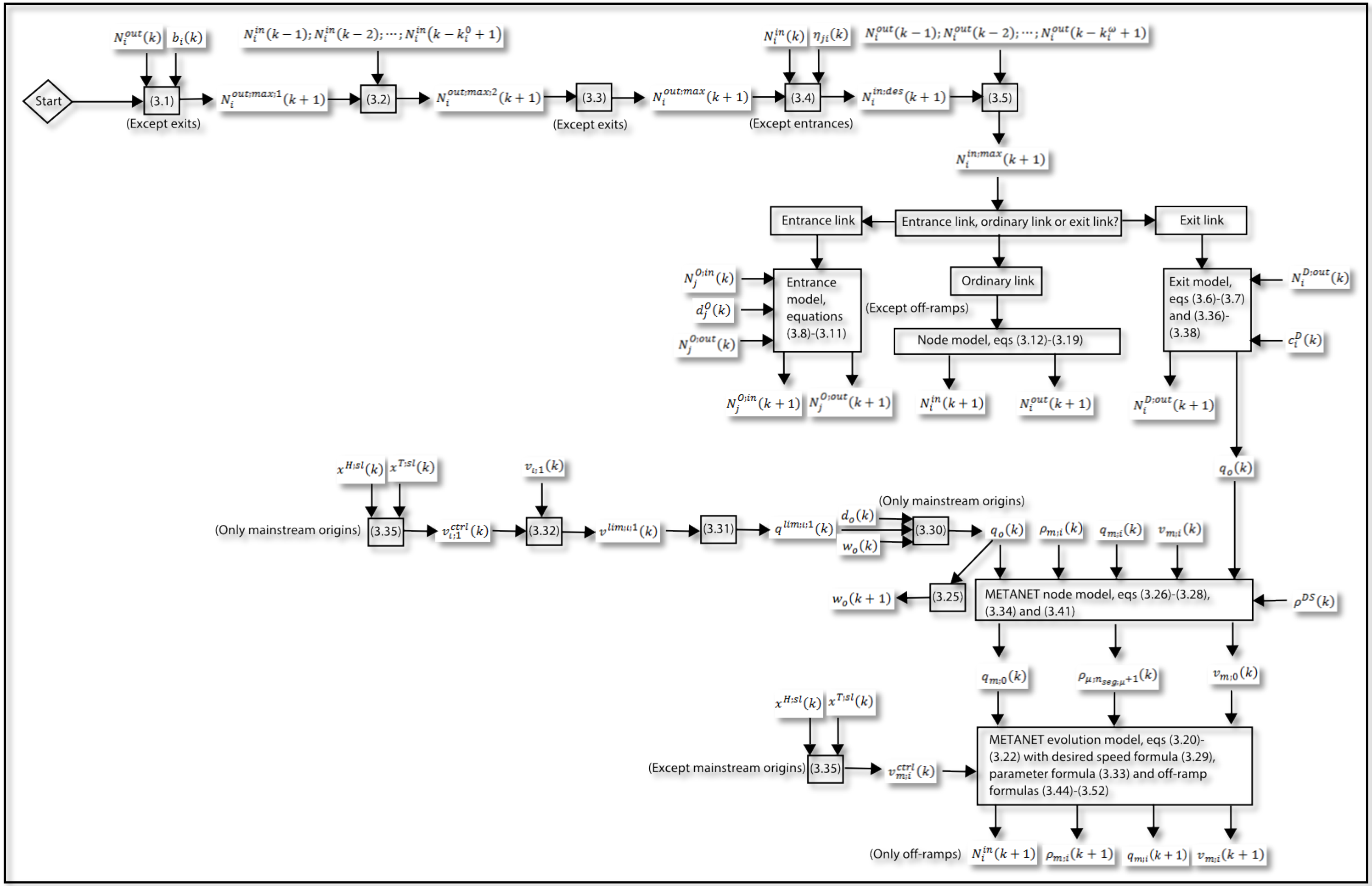

Figure 3.7 Scheme of the model calculations used to move from time step k to time step $k+1$

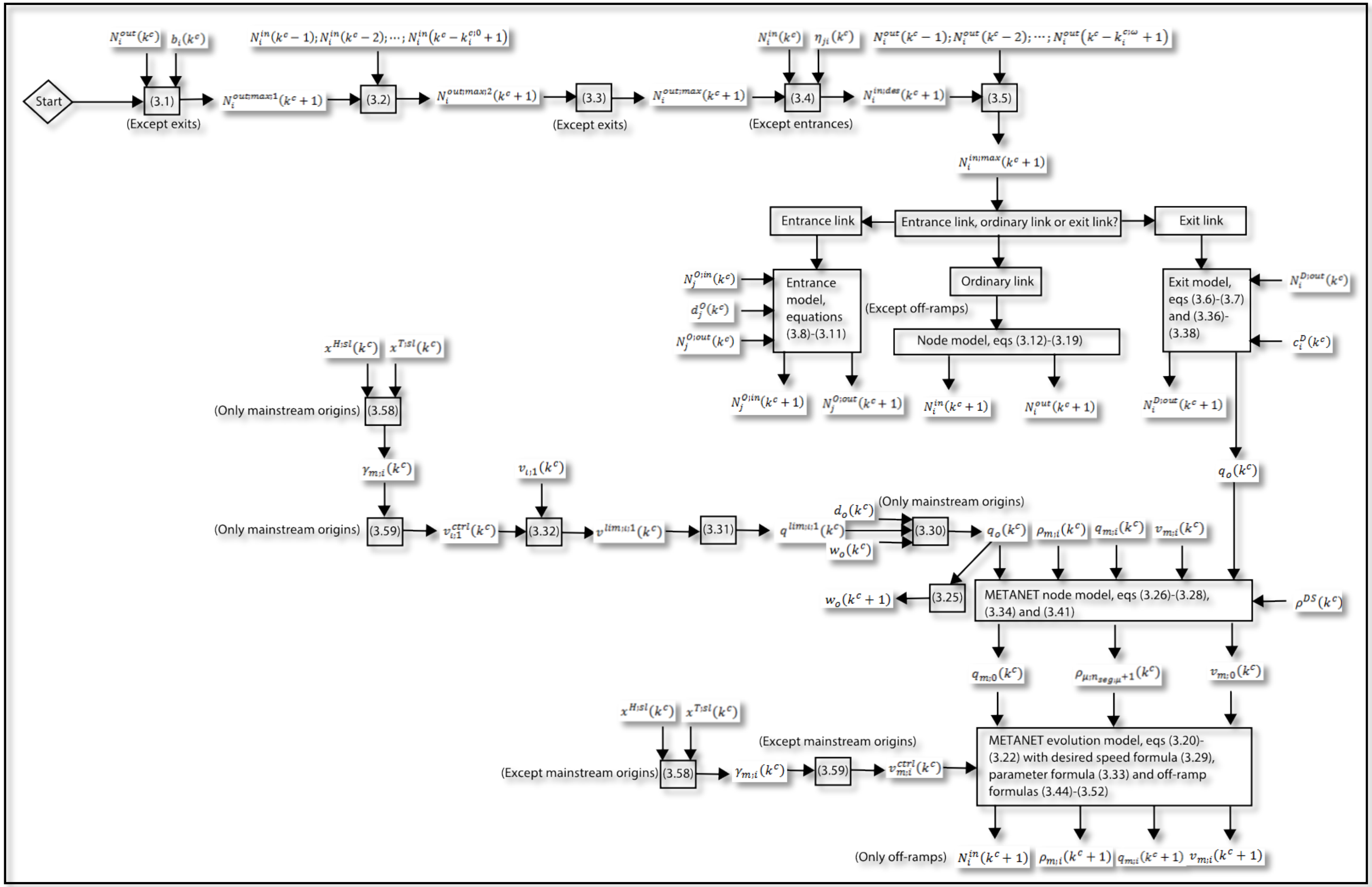

Figure 3.8 Scheme of the model calculations used to move from time step k^c to time step $k^c + 1$

3.3.3 State, control inputs, disturbances and outputs

The state of the process, the control inputs, the disturbances and the output of the process can best be identified by considering individual network elements. For the urban network these elements are urban links and entrances to the urban network, for the freeway network these elements are freeway segments and mainstream origins. Therefore, the state, the control inputs, the disturbances and the output of the process are identified for these networks, respectively. With these results the state of the process, the control inputs, the disturbances and the output of the process can be described.

Urban network

The urban network consists of links and entrances to the urban network. These network elements will now be considered

The state of a link contains all the information to determine the future states given all the inputs affecting the link (Hegyi, 2014 [2]). Given the controller calculations described in figure 3.8 and the constraints that are to be met, the state $\mathbf{x}_i^L(k^c)$ consists of the historical information discussed in section 3.3.1, the current values $N_i^{out}(k^c)$ and $N_i^{in}(k^c)$, the freeway density in the first segment downstream of the on-ramp $\rho_{m;1}(k^c)$ and the outflow out of the freeway node into the off-ramp link $q_{m;0}(k^c)$. Therefore:

$$\mathbf{x}_i^L(k^c) = \begin{bmatrix} N_i^{out}(k^c) \\ \vdots \\ N_i^{out}\left(k^c - k_i^{c;\omega}\right) \\ N_i^{in}(k^c) \\ \vdots \\ N_i^{in}\left(k^c - k_i^{c;0}\right) \\ \rho_{m;1}(k^c) \\ q_{m;0}(k^c) \end{bmatrix} \tag{3.79}$$

The control inputs $\mathbf{u}_i^L(k^c)$ for a link consist of the effective green time shares $b_i(k^c)$ used by the link. Therefore:

$$\mathbf{u}_i^L(k^c) = b_i(k^c) \tag{3.80}$$

Disturbances $\mathbf{d}_i^L(k^c)$ for a link consist of the turn fractions $\eta_{ji}(k^c)$ and the exit capacity $c_i^D(k^c)$. Therefore:

$$\mathbf{d}_i^L(k^c) = \begin{bmatrix} \eta_{ji}(k^c) \\ c_i^D(k^c) \end{bmatrix} \tag{3.81}$$

The output of a link $\mathbf{y}_i^L(k^c)$ can be considered as the contribution of the link to the objective function J. Based on equation (3.61), this means:

$$\mathbf{y}_i^L(k^c) = \left(N_i^{in}(k^c) - N_i^{out}(k^c)\right) T^c \tag{3.82}$$

Similarly, the state of an entrance to the urban network $\mathbf{x}_j^O(k^c)$, the control inputs $\mathbf{u}_j^O(k^c)$, the disturbances $\mathbf{d}_j^O(k^c)$ and the output $\mathbf{y}_j^O(k^c)$ are given by:

$$\mathbf{x}_j^O(k^c) = \begin{bmatrix} N_j^{O;out}(k^c) \\ N_j^{O;in}(k^c) \end{bmatrix} \tag{3.83}$$

$$\mathbf{u}_j^O(k^c) = [\emptyset] \tag{3.84}$$

$$\mathbf{d}_j^O(k^c) = d_j^O(k^c) \tag{3.85}$$

$$\mathbf{y}_j^O(k^c) = \left(N_j^{O;in}(k^c) - N_j^{O;out}(k^c)\right) T^c \tag{3.86}$$

Where $[\emptyset]$ represents an empty vector, as the controller cannot influence the inflows and outflows of the vertical queues directly. Only indirect influence is possible via filling link i downstream of origin j.

Freeway network

The freeway network consists of freeway segments and mainstream origins. These network elements will now be considered.

The state of a freeway segment contains all the information to determine the future states given all the inputs affecting the segment (Hegyi, 2014 [2]). Given the controller calculations described in figure 3.8, the state $\mathbf{x}_{m;i}^S(k^c)$ consists of the freeway density in the segment $\rho_{m;i}(k^c)$ and the downstream segment $\rho_{m;i+1}(k^c)$, the mean speed in the segment $v_{m;i}(k^c)$ and the upstream segment $v_{m;i-1}(k^c)$ and the outflow $q_o(k^c)$ from both mainstream origins and on-ramps. Therefore:

$$\mathbf{x}_{m;i}^S(k^c) = \begin{bmatrix} \rho_{m;i}(k^c) \\ \rho_{m;i+1}(k^c) \\ v_{m;i}(k^c) \\ v_{m;i-1}(k^c) \\ q_o(k^c) \end{bmatrix} \tag{3.87}$$

The control inputs $\mathbf{u}_{m;i}^S(k^c)$ for a segment consist of the location and speed of head and tail of the speed-limited area. Therefore:

$$\mathbf{u}_{m;i}^S(k^c) = \begin{bmatrix} x^{H;sl}(k^c) \\ v^{H;sl}(k^c) \\ x^{T;sl}(k^c) \\ v^{T;sl}(k^c) \end{bmatrix} \tag{3.88}$$

Disturbances $\mathbf{d}_{m;i}^S(k^c)$ for a segment consist of the turn fractions $\beta_{p;m}(k^c)$ and the destination density $\rho^{DS}(k^c)$. Therefore:

$$\mathbf{d}_{m;i}^S(k^c) = \begin{bmatrix} \beta_{p;m}(k^c) \\ \rho^{DS}(k^c) \end{bmatrix} \tag{3.89}$$

The output of a link $\mathbf{y}_{m;i}^S(k^c)$ can be considered as the contribution of the link to the objective function J. Based on equation (3.62), this means:

$$\mathbf{y}_{m;i}^S(k^c) = \rho_{m;i}(k^c)\ell_{seg;m} n_m T^c \tag{3.90}$$

Similarly, the state of a mainstream origin $\mathbf{x}_o^{MO}(k^c)$, the control inputs $\mathbf{u}_o^{MO}(k^c)$, the disturbances $\mathbf{d}_o^{MO}(k^c)$ and the output $\mathbf{y}_o^{MO}(k^c)$ are given by:

$$\mathbf{x}_o^{MO}(k^c) = \begin{bmatrix} v_{\iota;1}(k^c) \\ w_o(k^c) \end{bmatrix} \tag{3.91}$$

$$\mathbf{u}_o^{MO}(k^c) = \begin{bmatrix} x^{H;sl}(k^c) \\ v^{H;sl}(k^c) \\ x^{T;sl}(k^c) \\ v^{T;sl}(k^c) \end{bmatrix} \tag{3.92}$$

$$\mathbf{d}_o^{MO}(k^c) = d_o(k_c) \tag{3.93}$$

$$\mathbf{y}_o^{MO}(k^c) = w_o(k^c)T^c \tag{3.94}$$

The state of the process, the control input, the disturbances and the output of the process

The state of the process, the control inputs, the disturbances and the output of the process can be identified by stacking the state, control inputs, disturbances and output of the individual network elements and eliminating duplicate information. Duplicate information can be eliminated by replacing $\mathbf{x}_i^L(k^c)$ by $\mathbf{x}_i^{L;S}(k^c)$, $\mathbf{x}_{m;i}^S(k^c)$ by $\mathbf{x}_{m;i}^{S;S}(k^c)$, $\mathbf{x}_o^{MO}(k^c)$ by $\mathbf{x}_o^{MO;S}(k^c)$, $\mathbf{u}_{m;i}^S(k^c)$ and $\mathbf{u}_o^{MO}(k^c)$ by $\mathbf{u}_F(k^c)$, defined as follows:

$$\mathbf{x}_i^{L;S}(k^c) = \begin{bmatrix} N_i^{out}(k^c) \\ \vdots \\ N_i^{out}(k - k_i^{\omega}) \\ N_i^{in}(k^c) \\ \vdots \\ N_i^{in}(k - k_i^0) \end{bmatrix} \tag{3.95}$$

$$\mathbf{x}_{m;i}^{S;S}(k^c) = \begin{bmatrix} \rho_{m;i}(k^c) \\ v_{m;i}(k^c) \\ q_o(k^c) \end{bmatrix} \tag{3.96}$$

$$\mathbf{x}_o^{MO;S}(k^c) = w_o(k^c) \tag{3.97}$$

$$\mathbf{u}_F(k^c) = \begin{bmatrix} x^{H;sl}(k^c) \\ v^{H;sl}(k^c) \\ x^{T;sl}(k^c) \\ v^{T;sl}(k^c) \end{bmatrix} \tag{3.98}$$

Then the state of the process, the control inputs, the disturbances and the output of the process are given by:

$$\mathbf{x}(k^c) = \begin{bmatrix} \mathbf{x}_1^{L;S}(k^c) \\ \vdots \\ \mathbf{x}_{n_L}^{L;S}(k^c) \\ \mathbf{x}_1^{O}(k^c) \\ \vdots \\ \mathbf{x}_{n_O}^{O}(k^c) \\ \mathbf{x}_{1;1}^{S;S}(k^c) \\ \vdots \\ \mathbf{x}_{n_{FL};n_{seg;n_{FL}}}^{S;S}(k^c) \\ \mathbf{x}_1^{MO;S}(k^c) \\ \vdots \\ \mathbf{x}_{n_{FO}}^{MO;S}(k^c) \end{bmatrix} \tag{3.99}$$

$$\mathbf{u}(k^c) = \begin{bmatrix} \mathbf{u}_1^L(k^c) \\ \vdots \\ \mathbf{u}_{n_L}^L(k^c) \\ \mathbf{u}_1^O(k^c) \\ \vdots \\ \mathbf{u}_{n_O}^O(k^c) \\ \mathbf{u}_F(k^c) \end{bmatrix} \tag{3.100}$$

$$\mathbf{d}(k^c) = \begin{bmatrix} \mathbf{d}_1^L(k^c) \\ \vdots \\ \mathbf{d}_{n_L}^L(k^c) \\ \mathbf{d}_1^O(k^c) \\ \vdots \\ \mathbf{d}_{n_O}^O(k^c) \\ \mathbf{d}_{1;1}^S(k^c) \\ \vdots \\ \mathbf{d}_{n_{FL};n_{seg;n_{FL}}}^S(k^c) \\ \mathbf{d}_1^{MO}(k^c) \\ \vdots \\ \mathbf{d}_{n_{FO}}^{MO}(k^c) \end{bmatrix} \tag{3.101}$$

$$\mathbf{y}(k^c) = \begin{bmatrix} \mathbf{y}_1^L(k^c) \\ \vdots \\ \mathbf{y}_{n_L}^L(k^c) \\ \mathbf{y}_1^O(k^c) \\ \vdots \\ \mathbf{y}_{n_O}^O(k^c) \\ \mathbf{y}_{1;1}^S(k^c) \\ \vdots \\ \mathbf{y}_{n_{FL};n_{seg;n_{FL}}}^S(k^c) \\ \mathbf{y}_1^{MO}(k^c) \\ \vdots \\ \mathbf{y}_{n_{FO}}^{MO}(k^c) \end{bmatrix} \tag{3.102}$$

Where:

n_L:	The number of urban links
n_O:	The number of entrances to the urban network
n_{FL}:	The number of freeway links
$n_{seg;n_{FL}}$:	The number of segments in freeway link n_{FL}
n_{FO}:	The number of mainstream origins

3.3.4 Overview

Based on the preceding subsections, figure 3.9 gives an overview of the control problem. Once all values from time step $k^c = k_0$ until time step $k^c = k_0 + N_p$ are known, they can be used to evaluate the objective function J defined by equations (3.60)-(3.62). The controller strives to optimise the result.

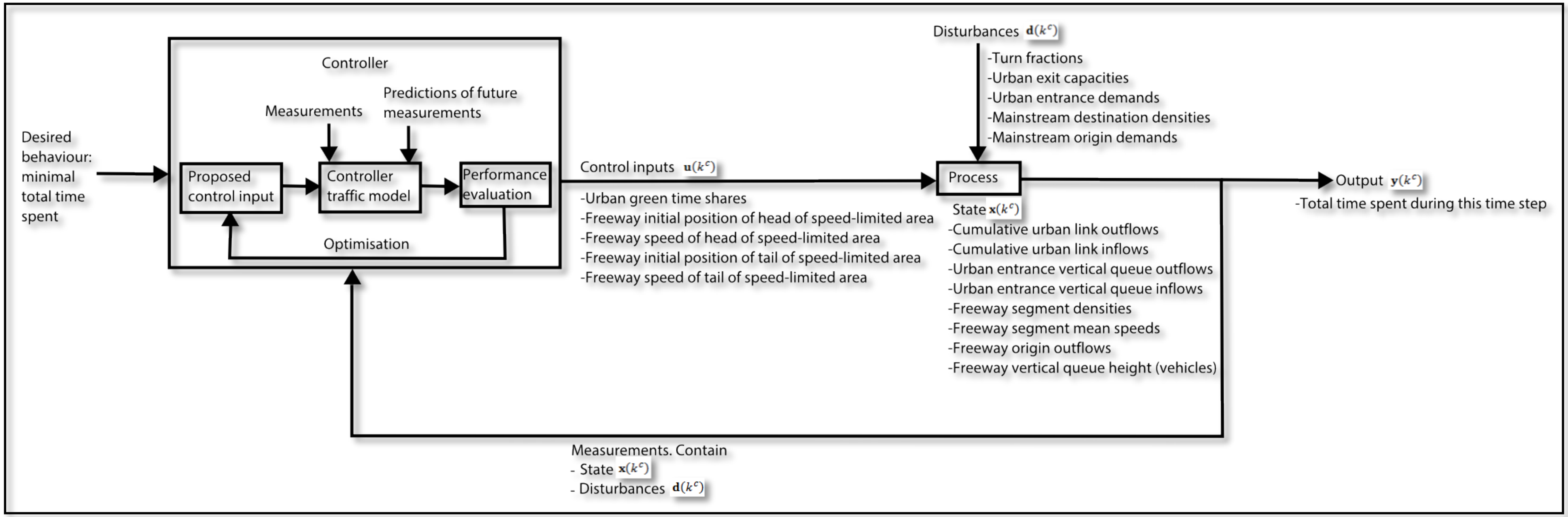

Figure 3.9 Overview of the control problem (figure inspired by Hegyi, 2014 [2])

3.4 Summary of the controller

This section will summarise the controller that has been developed in this chapter. This controller chooses urban green time shares, initial positions of head and tail of the speed-limited area and speeds of head and tail of the speed-limited area at each update time. In between update times, the urban green time shares and the speeds of head and tail of the speed-limited area are constant. The chosen values are subject to the constraints (3.63)-(3.65), (3.66)-(3.67) and (3.74)-(3.78) and are chosen to optimise the total time spent defined by equations (3.60)-(3.62). The controller verifies this with its traffic model defined by the following equations with a controller time step k^c:

- (3.1)-(3.21)
- (3.22) with:
    - Equation (3.23) to define $V\left(\rho_{m;i}(k^c)\right)$
    - Equation (3.25) to determine $w_o(k^c + 1)$
    - The adaptations from equations (3.29)-(3.34)
    - The on-ramp model (3.36)-(3.38)
    - The off-ramp model (3.44)-(3.52) with equation (3.41) to determine the off-ramp density
    - Equations (3.58) and (3.59) to determine $v_{m;i}^{ctrl}(k^c)$
- (3.26)-(3.28)

This traffic model is subject to the assumptions in subsection 3.1.1.

It can be noted that the controller as developed in this chapter is very general, as none of its parameters has been given values. In chapter 4, this controller will be evaluated. In order to do so, all of its parameters will be given values in subsection 4.1.2.

4 Controller evaluation

In order to check the quality of the controller developed in chapter 3, evaluation by means of simulation is necessary. In order to do so, all information necessary to replicate the simulation needs to be assembled. This is referred to as the simulation set-up, which is the subject of section 4.1. Based on the simulation set-up, evaluation criteria are formulated to make a sensible evaluation. This will be done in section 4.2. Once that is done, the situation without any control measures, the situation with coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account) and the situation with the developed controller will be assessed on the evaluation criteria. This assessment forms the results of the controller evaluation, and is the subject of section 4.3. The chapter is concluded with section 4.4, which gives an interpretation of the results.

4.1 Simulation set-up

The simulation set-up contains all information necessary to replicate the simulation. This information can be split up into the following categories:

- Network layout information
- Parameter value information
- Traffic situation information
- Controller information
- Simulation software/hardware information

To each of these information categories a subsection will be devoted.

4.1.1 The simulation network

The simulation network in combination with the traffic situation make up the scenario used in the simulation. Similar to the work by Van de Weg (2013) it will be more important to show that the integrated urban-freeway network controller acts as predicted than to assess the integrated urban-freeway network controller to a very realistic scenario. Therefore, the scenario can be kept simple. Considering the problem description, the simulation network needs to contain an on-ramp to the freeway and an urban network in the direction of that on-ramp. Inspired by Van de Weg et al (2015) and Van de Weg et al (2016) the simulation network in figure 4.1 is proposed.

As the on-ramp and off-ramp are urban links connected to the freeway, they are given special numbers to easily distinguish them from the urban links that have no connection with the freeway.

Although the lengths of the links are parameters to the traffic model of the integrated urban-freeway network controller, they are included in figure 4.1, as the chosen values for these parameters have vastly different proportions than those suggested by figure 4.1.

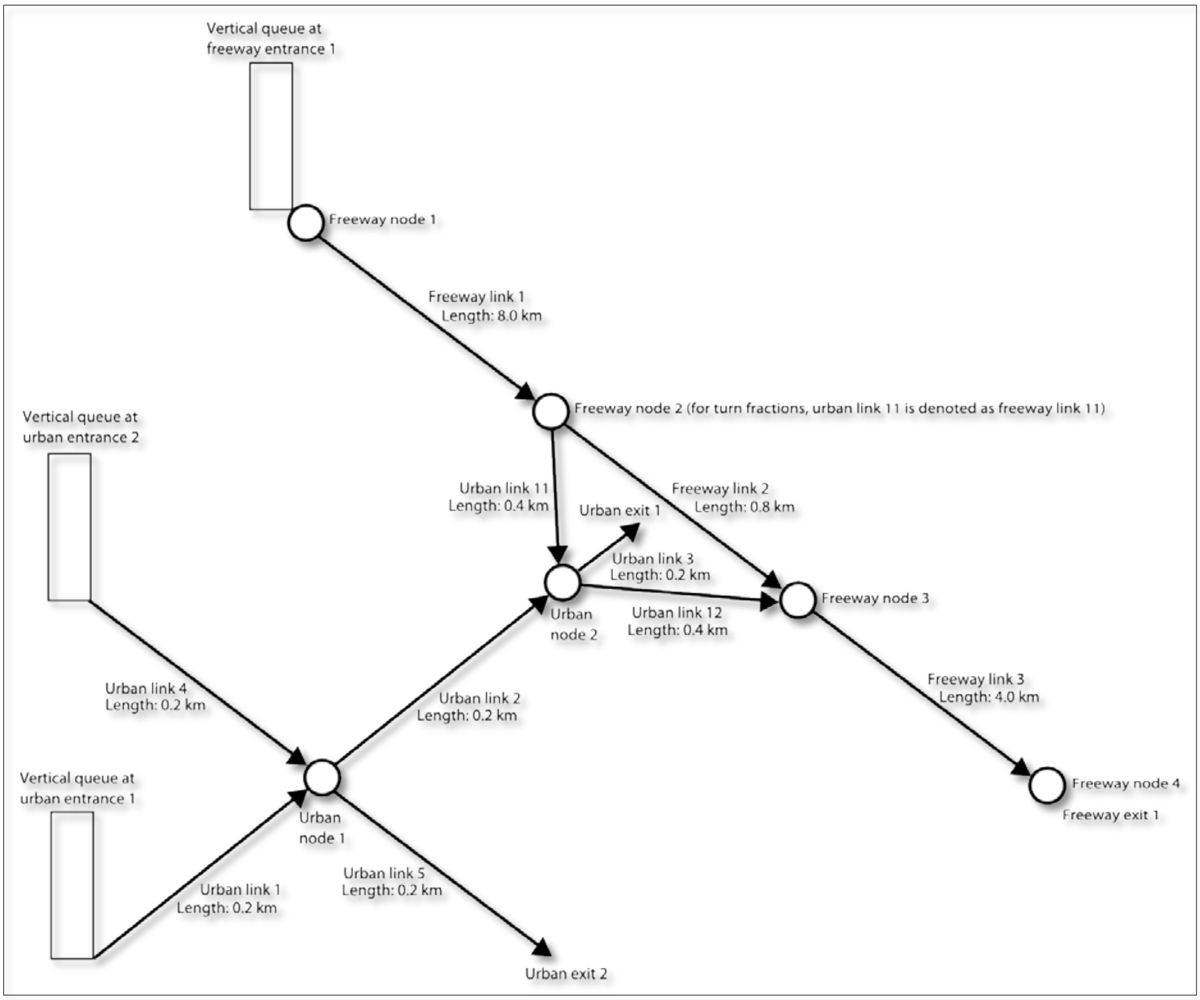

Figure 4.1 The simulation network (figure inspired by Van de Weg et al (2015) and Van de Weg et al (2016))

4.1.2 The parameter values

The parameter values will be given in this subsection. Table 4.1 contains a full list of all parameters in the traffic flow model used by the integrated controller, their values and remarks as to how these values have been obtained.

Table 4.1 Choice for the parameters for the various network elements

Parameter	Value	Remarks
T	10 s	Value adopted from Van de Weg et al (2015) and Van de Weg et al (2016)
T^c	10 s	Value adopted from Van de Weg et al (2015) and Van de Weg et al (2016)
T^u	60 s	Value adopted from Van de Weg et al (2015) and Van de Weg et al (2016)
t_i^0 for $i \in [1;5]$	20 s	Value adopted from Van de Weg et al (2016)
t_i^0 for $i \in [11;12]$	20 s	Assuming a ramp length of 400 m and a free flow speed of 20 m/s (72 km/h)
s_i for $\forall i$	2000 veh/h	Estimate, corresponding to the freeway capacity estimate of 2000 veh/h/lane by Van de Weg et al (2015)
c_j^O for $\forall j$	2000 veh/h	Estimate corresponding to the estimate for s_i
t_i^ω for $i \in [1;5]$	40 s	Value adopted from Van de Weg et al (2016)
t_i^ω for $i \in [11;12]$	80 s	Assuming a ramp length of 400 m and a shock wave speed of 5 m/s (the latter value was used by Van de Weg et al (2016))
N_i^{max} for $i \in [1;5]$	80 veh	Value adopted from Van de Weg et al (2016)
N_i^{max} for $i \in [11;12]$	160 veh	Assuming a ramp length of 400 m and a vehicle length of 2.5 m (the latter value was used by Van de Weg et al (2016))
$\ell_{seg;m}$ for $\forall m$	400 m	Value chosen in order to fit two segments in freeway link 2, while giving freeway link 2 a realistic length compared to the ramps and respecting CFL conditions (the state in each physical element should only be influenced by the adjacent physical elements over the course of a time step (Courant et al, 1928))
$n_{seg;1}$	20	Giving the controller 8 kilometres of upstream road to apply variable speed limits to
$n_{seg;2}$	2	See the choice for $\ell_{seg;m}$
$n_{seg;3}$	10	Giving the simulation 4 kilometres of downstream road in case it is needed
n_m for $\forall m$	2 lanes	Value adopted from Van de Weg et al (2015)
v_{min}	7 km/h	Value used in scripts by G.S. Van de Weg (see subsection 4.1.5)
v^{eff}	50 km/h	Value adopted from Van de Weg et al (2015)
τ	18 s	Value adopted from Kotsialos et al (2002 [1])
v_m^0 for $\forall m$	102 km/h	Value adopted from Kotsialos et al (2002 [1])
a_m for $\forall m$	1.867	Value adopted from Kotsialos et al (2002 [1])
ρ_m^{crit} for $\forall m$	33.5 veh/km/lane	Value adopted from Kotsialos et al (2002 [1])
ν_{high}	65 km^2/h	Value adopted from Hegyi et al (2005 [1])
ν_{low}	30 km^2/h	Value adopted from Hegyi et al (2005 [1])
κ	40 veh/km/lane	Value adopted from Kotsialos et al (2002 [1])
φ	0.0122	Value adopted from Kotsialos et al (1999)
ϕ	2.98	Value adopted from Kostialos et al (2002 [2])
q_o^{cap} for $c_1 = 1$	2000 veh/h	Estimate, corresponding to the freeway capacity estimate of 2000 veh/h/lane by Van de Weg et al (2015)
$r_o(k)$ for $\forall k \wedge c_1 = 1$	1	The controller does not include ramp metering
ρ_m^{jam} for $\forall m$	180 veh/km/lane	Value adopted from Kotsialos et al (1999)
N_p	360	Value obtained from test simulations
N_c	90	Value obtained from test simulations

4.1.3 The traffic situation

The traffic situation is characterised by the disturbances identified in subsection 3.3.4. Therefore, all values of the disturbances during the simulation (up until a prediction horizon after the simulation horizon) need to be given a value. Doing so must result in a situation where congestion occurs due to high demand of traffic moving from the urban to the freeway network, if no control actions are undertaken.

This is not a trivial task, therefore the determination of the traffic situation is started with a rough description: during a peak period, the demands from the freeway network and the urban network for freeway link 3 are such that together they surpass the capacity of 4000 veh/h. Outside of the peak period, these demands are significantly lower than this capacity. The turn fractions, exit capacities and downstream densities are to remain constant.

This simplifies the task to determining the demands, turn fractions, exit capacities and downstream densities during the peak period. However, overseeing the effects of choosing these values is not easy. Therefore, a simplified analytical calculation has been formulated to optimise the effects of the values to be determined in annex 3.

In this simplified calculation, it is assumed that the coordinated freeway controller places a speed-limited area on the freeway to limit the outflow out of freeway link 2 such that the inflow into freeway link 3 from freeway link 2 and urban link 12 add up to the capacity of freeway link 3, thus preventing congestion formation and the associated capacity drop in freeway link 3. As has been pointed out in the problem description, the coordinated urban controller is assumed to take no control actions, as the problems in this traffic situation happen in the freeway network.

The integrated urban freeway network controller is assumed to place a speed-limited area on the freeway to limit the outflow out of freeway link 2 while simultaneously adapting the green time shares given to links 1 and 2 in order to distribute the negative effects of the control actions on throughput over both networks.

This assumed behaviour in the simplified calculation is the expected behaviour of the controllers; the behaviour that needs to be shown. As such, this expected behaviour plays an important role in the evaluation criteria elaborated upon in section 4.2.

A simulation duration of 2 hours is adopted from Van de Weg et al (2016) such that the traffic situation can be described by table 4.2.

Table 4.2 The traffic situation

Variable \ Interval (s)	0-2700	2700-5400	5400-7200	7200-10800
$\eta_{1;2}(k)$	0.9	0.9	0.9	0.9
$\eta_{1;5}(k)$	0.1	0.1	0.1	0.1
$\eta_{4;2}(k)$	0.7	0.7	0.7	0.7
$\eta_{4;5}(k)$	0.3	0.3	0.3	0.3
$\eta_{2;3}(k)$	0.05	0.05	0.05	0.05
$\eta_{2;12}(k)$	0.95	0.95	0.95	0.95
$\eta_{11;3}(k)$	1.0	1.0	1.0	1.0
$\beta_{2;2}(k)$	0.85	0.85	0.85	0.85
$\beta_{2;11}(k)$	0.15	0.15	0.15	0.15
$c_3^D(k)$	2000 veh/h	2000 veh/h	2000 veh/h	2000 veh/h
$c_5^D(k)$	2000 veh/h	2000 veh/h	2000 veh/h	2000 veh/h
$d_1^O(k)$	530 veh/h	530 veh/h	380 veh/h	380 veh/h
$d_2^O(k)$	530 veh/h	530 veh/h	380 veh/h	380 veh/h
$\rho^{DS}(k)$	25 veh/km/lane	25 veh/km/lane	25 veh/km/lane	25 veh/km/lane
$d_1(k)$	3920 veh/h	3920 veh/h	2800 veh/h	2800 veh/h

4.1.4 Controller information

Controller information for the integrated urban-freeway controller has been given in section 3.4 when it was summarised. Now information needs to be given on the coordinated urban and freeway controllers it is to be compared with. The comparison can be simplified by using the urban and freeway controllers the integrated controller consist of, as they are coordinated as that was a criterion for selection in chapter 2. When one does so, the controller information is as presented in this subsection.

The urban controller chooses values for the green time shares in order to optimise the total time spent defined by equation (3.61) using a traffic flow model with a controller time step k^c consisting of equations (3.1)-(3.19) in which the end of the on-ramp is considered as an urban exit with an exit capacity of 2000 veh/h and where the beginning of the off-ramp is considered as an urban entrance where the demands are 15% of the freeway entrance at the same time step. Special attention needs to be given to the value of the cumulative inflow of the off-ramp the controller uses at $k^c = k_0$, as it needs to have the same value as the simulation model calculated.

The freeway controller chooses values for the initial positions of head and tail of the speed-limited area and speeds of head and tail of the speed-limited area at each update time in order to optimise the objective function (3.62) using a traffic flow model with a controller time step k^c consisting of the following equations:

- (3.20)-(3.21)
- (3.22) with:
  - Equation (3.23) to define $V\left(\rho_{m;i}(k^c)\right)$
  - Equation (3.25) to determine $w_o(k^c + 1)$
  - The adaptations from equations (3.29)-(3.34)
  - Equations (3.58) and (3.59) to determine $v_{m;i}^{ctrl}(k^c)$
- (3.26)-(3.28)

In this traffic flow model, the freeway controller assumes the off-ramp is free and that the demand from the on-ramp is equal to the demand from the urban entrances a free flow travel time ago.

4.1.5 The simulation software and hardware

The simulations are carried out using MATLAB R2014b on a computer with a 3.5 GHz processor and 8 Gb RAM. This is done with MATLAB scripts based on MATLAB scripts by G.S. van de Weg. Important aspects such as the network loading, the optimisation function used, the optimisation options used and the initial control signal used will be presented here. For more information the reader is requested to contact the author or the assessment committee.

Network loading

Starting with an empty network is not a realistic situation, but is numerically the simplest solution to start the simulation. Therefore, in the beginning of the simulation, the network is simulated for an hour with the demands from the non-peak period. Then the time steps are reset while the traffic is kept in the network, and the simulation can start with traffic in each location of the network.

Optimisation function

As pointed out in annex 1, there exist so many non-linear solvers for non-linear optimisation problems, that choosing a non-linear solver is difficult in and of itself. Therefore the optimisation function fmincon that was used in the MATLAB scripts made by G.S. van de Weg will be used.

Optimisation options

The optimisation options are the contents of the structure ‘options’ fmincon uses as input. For the algorithm the ‘sqp’ algorithm is used, as test simulations have shown that this algorithm adapts the green time shares faster when they affect the total time spent negatively, while still producing reasonable results for the freeway. The maximum number of iterations ‘MaxIter’ is set to 1000 in accordance with the MATLAB scripts made by G.S. van de Weg. To speed up calculations, parallel computing with 4 cores is used. To help interpreting the results while running the simulation without filling the screen with too much information, ‘final-detailed’ display is chosen. The tolerance for optimality is set to 10^{-1} as knowing the total time spent to one decimal place is considered accurate. The tolerance for constraint violation is set to 10^{-6} as constraint violations are undesirable, but such small constraint violations are considered unlikely to cause problems. The MATLAB scripts have been written such that the green time shares fmincon tries to optimise are in whole percents, such that setting 'TolX' and 'FinDiffRelStep' to 10^{-1} results in knowing the positions of head and tail of the speed-limited area accurate to 0.1 km, knowing their speeds accurate to and 0.1 km/h and knowing the green time shares accurate to 0.1%. To further speed up the calcualtions, diagnostics have been turned off.

Initial control signal

As pointed out in annex 1, different starting points in non-linear solvers may lead to different final solutions. This affects the controller, as it turns out to be quite sensitive to its initial control signal according to test simulations. Therefore, the initial control signal has been chosen to be close to the theoretical optimum following from the simplified analytical calculation on which the values of the disturbances are based. In annex 3, the determination of the initial control signal is explained in detail. The results are that the controller needs to start to optimise at 2110 seconds. As was pointed out in annex 3, before that moment there should be no speed limits active on the freeway and the green time shares should be 50%[10] to avoid unnecessary delays for the traffic (i.e. the situation where no controllers are active). After that, values depend on whether coordinated controllers or the integrated controller are active. Negative speeds indicate upstream propagation. Distances are measured from freeway entrance 1.

<u>Coordinated controllers active</u>
Initial position of the head: 8.4 km
Initial speed of the head: -5 km/h
Initial position of the tail: 8.4 km
Initial speed of the tail: -25 km/h
Initial green time shares: such that traffic is not hindered

<u>Integrated controller active</u>
Initial position of the head: 4 km
Initial speed of the head: -15 km/h
Initial position of the tail: 4 km
Initial speed of the tail: -25 km/h
Initial green time shares: Such that traffic is not hindered except for traffic leaving links 1 and 2; 10% hindrance for that traffic between the time the controller starts to optimise and 5400 seconds

[10] With green time shares of 50%, which make sense given the network as all conflicts are the results of two conflicted approahes, traffic flows are unhindered given the traffic demands. Given that the controllers are no ramp meter controllers, the green time shares for link 12 should be 100% at all times.

4.2 The evaluation criteria

Based on the simulation set-up, an idea exists of the behaviour of the controllers to be compared. Based on this idea evaluation criteria are formulated to make a sensible evaluation.

Since the controllers all optimise the total time spent in the network, the total time spent is a suitable performance criterion. Subsection 4.2.1 elaborates further on how this evaluation criterion can be evaluated during the simulation.

Based on the objectives, it is important as well that the integrated urban-freeway controller has a computation time that allows for real-time control. Therefore, the computation time forms another important evaluation criterion. Subsection 4.2.2 elaborates further on how this evaluation criterion can be evaluated during the simulation.

In subsections 4.1.1 and 4.1.3 it has been pointed out that it is important to show that the controller behaves as predicted. Therefore, the qualitative behaviour forms an evaluation criterion that can show if it is likely the controllers would function in the field. Subsection 4.2.3 elaborates further on how this evaluation criterion can be evaluated during the simulation.

4.2.1 Total time spent

The controllers calculate the total time spent with equations (3.60)-(3.62). It makes sense to make the same calculation using the model sampling time and the simulation duration $T^{sim} = N_{sim}T$ to calculate the total time spent J^{TTS}:

$$J^{TTS} = J_U^{TTS} + J_F^{TTS} \tag{4.1}$$

$$J_U^{TTS} = T \sum_{k=1}^{N_{sim}} \left(\sum_{i \in I^L} \left(N_i^{in}(k) - N_i^{out}(k) \right) + \sum_{j \in I^O} \left(N_j^{O;in}(k) - N_j^{O;out}(k) \right) \right) \tag{4.2}$$

$$J_U^{TTS} = T \sum_{k=1}^{N_{sim}} \left(\sum_{m;i \in I_{FL}} \rho_{m;i}(k) \ell_{seg;m} n_m + \sum_{o \in I_{FO}} w_o(k) \right) \tag{4.3}$$

Now, given that the network is loaded, the results of these calculations are quite arbitrary. One could for instance substantially increase the results by substantially increasing the length of the links in the network. Therefore, one can concretise this evaluation criterion by comparing the total time spent for control actions to the total time spent for the no control action. Expressing the difference between the no control action and the control actions a percentage of the total time spent for the no control situation gives insight in the performance quality of the controller.

This percentage is less arbitrary than the total time spent itself, though some influences of other variables than the control actions themselves are still present. For instance, this percentage is influenced by the length of the peak period, as outside of the peak period no congestion forms in the no control situation, thus there is no need for any control actions to be taken.

4.2.2 Computation time

To check if the computation time allows for real-time control, one needs to know the elapsed time between the beginning and end of an optimisation. This elapsed time can be calculated by MATLAB via the tic and toc commands by placing these commands before and after the fmincon function. Test simulations have shown that the computation time varies from optimisation to optimisation. In order to check if the computation time allows for real-time control, the computation times for all optimisations are to be placed in a histogram.

4.2.3 Qualitative behaviour

Qualitative behaviour can be characterised in various ways. Inspired by the MATLAB scripts by G.S. van de Weg and the graphs presented by Van de Weg et al (2015) and Van de Weg et al (2016) it has been chosen to characterise the qualitative behaviour with:

- Number of vehicles in the urban links over time
- Inflows and outflows for the urban links over time
- Green time shares for the urban links over time
- Mean speeds in the freeway segments over time and space
- Flows out of the freeway segments over time and space
- Densities in the freeway segments over time and space
- Variable speed limits in the freeway segments over time and space
- Vertical queues at origins over time
- Network outflows over time

Doing so makes it possible to characterise the situation with graphs of these aspects. Of course, many occasions are thinkable where these graphs do not change significantly with the control actions. In such cases, graphs can be omitted.

4.3 Simulation results

In this section, the results of the simulation will be presented. Three control actions are considered:

- No control: no control actions are undertaken. There are no variable speed limits on the freeway and the green time shares for all urban links are set to 50% (except urban link 12, which has a green time share of 100%, as no ramp metering is active). This value for the green time shares was inspired by the fact that all conflicts in the network are the results of two conflicted approaches at an intersection.
- Coordinated controllers active: there are two controllers active: an urban controller and a freeway controller. These controllers have been described in subsection 4.1.4.
- Integrated controller active: the controller developed in chapter 3 is active.

For each of these control actions, the situation will be characterised with the graphs used for the analysis of the qualitative behaviour. Once this analysis has been done, the total time spent will be reported. When controllers are active, the reduction percentage will be reported as well as the histogram of the computation time. For each control action a designated subsection is devoted.

4.3.1 No control

When no control actions are undertaken, the situation can be characterised by figures 4.2-4.9.

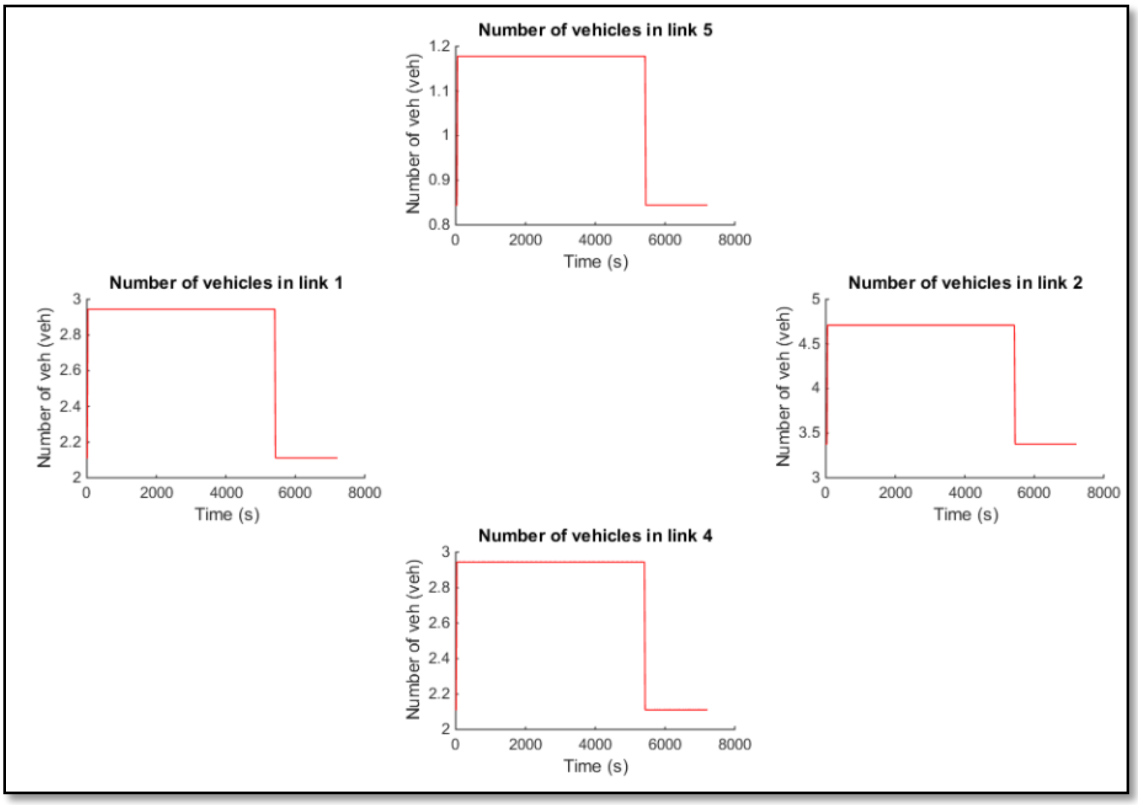

Figure 4.2 The number of vehicles in urban links 1, 2, 4 and 5

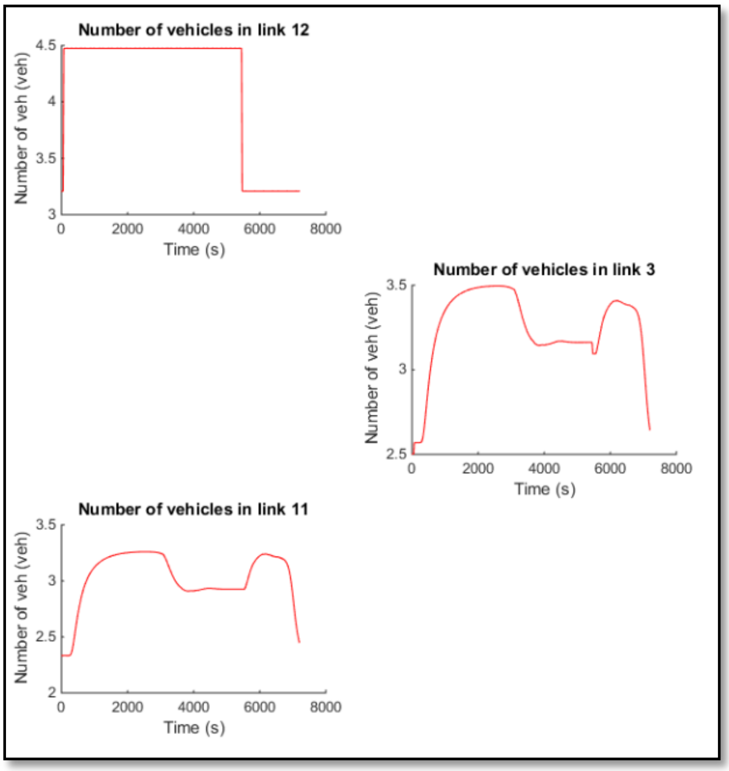

Figure 4.3 The number of vehicles in urban links 3, 11 and 12

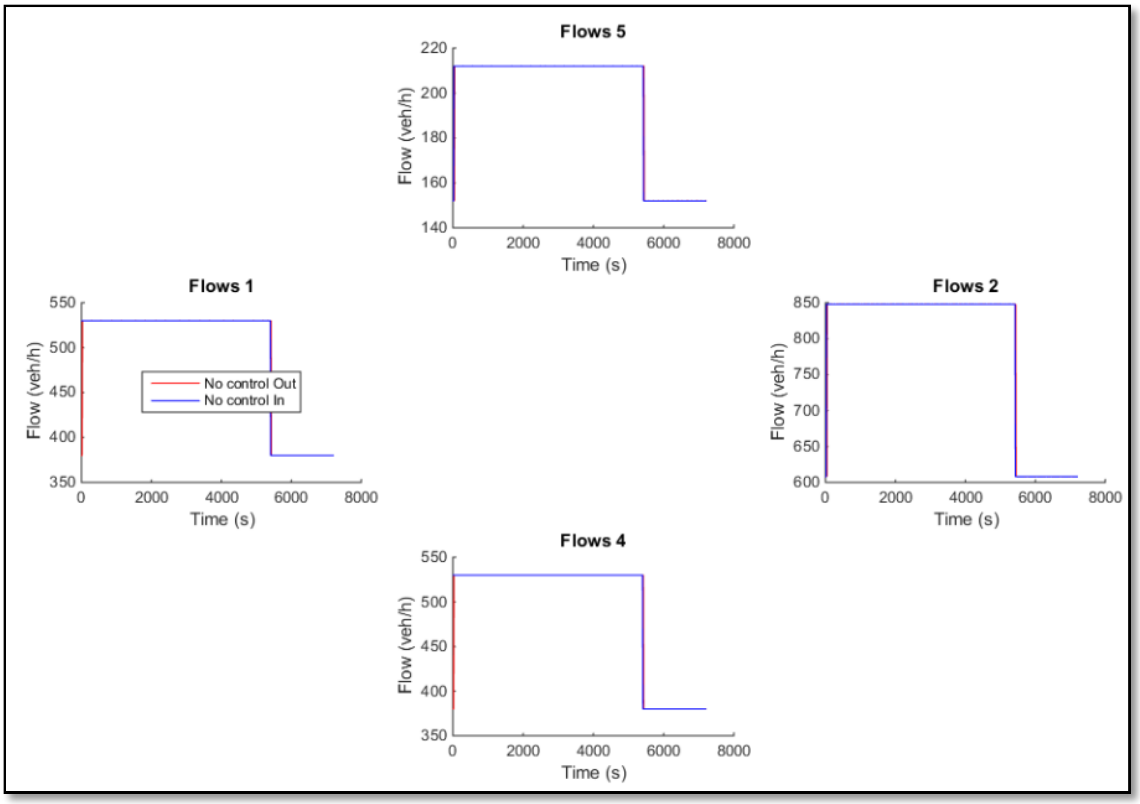

Figure 4.4 The inflows and outflows for urban links 1, 2, 4 and 5

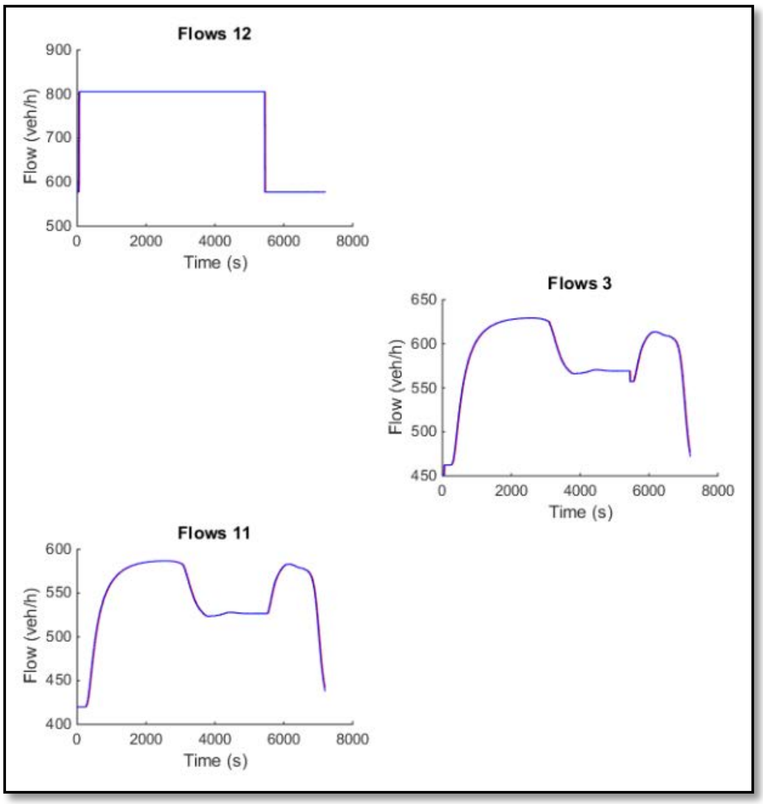

Figure 4.5 The inflows and outflows for urban links 3, 11 and 12

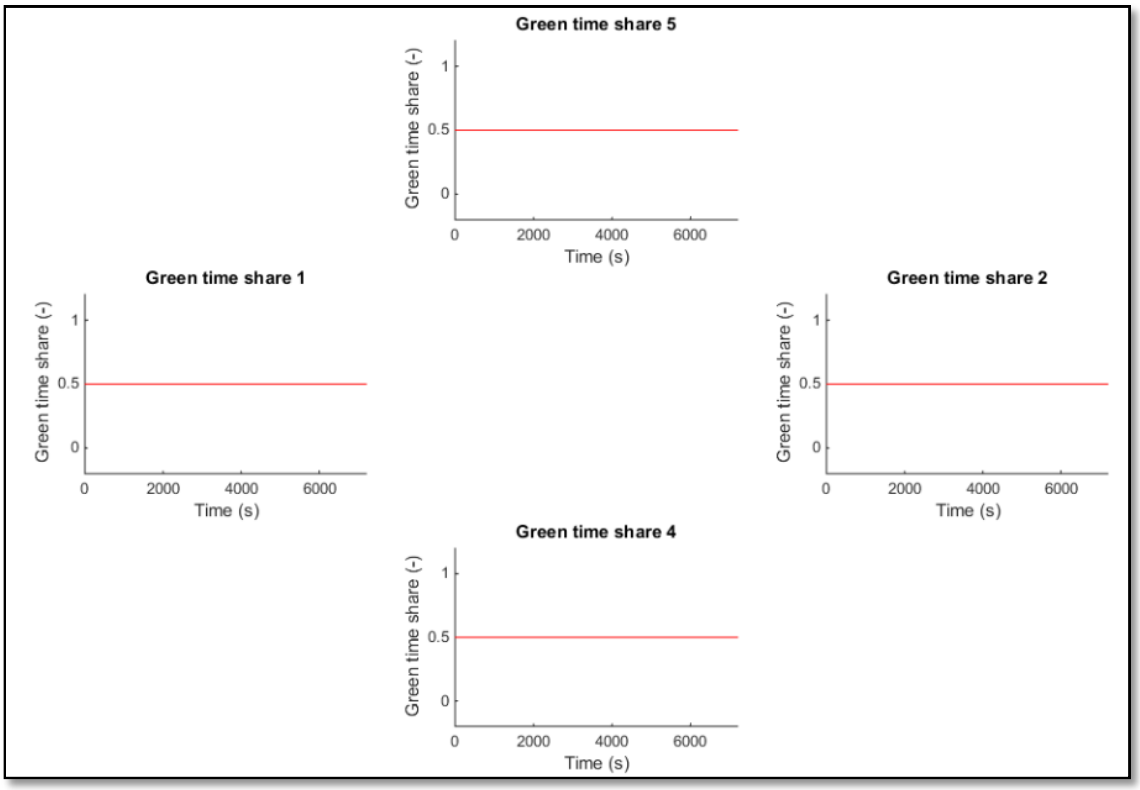

Figure 4.6 The green time shares for urban links 1, 2, 4 and 5

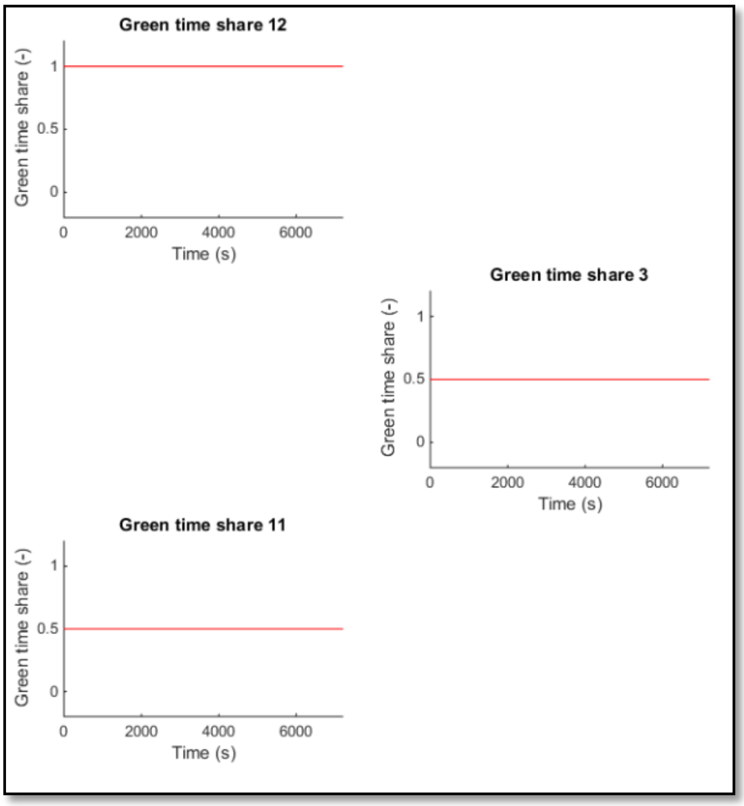

Figure 4.7 The green time shares for urban links 3, 11 and 12

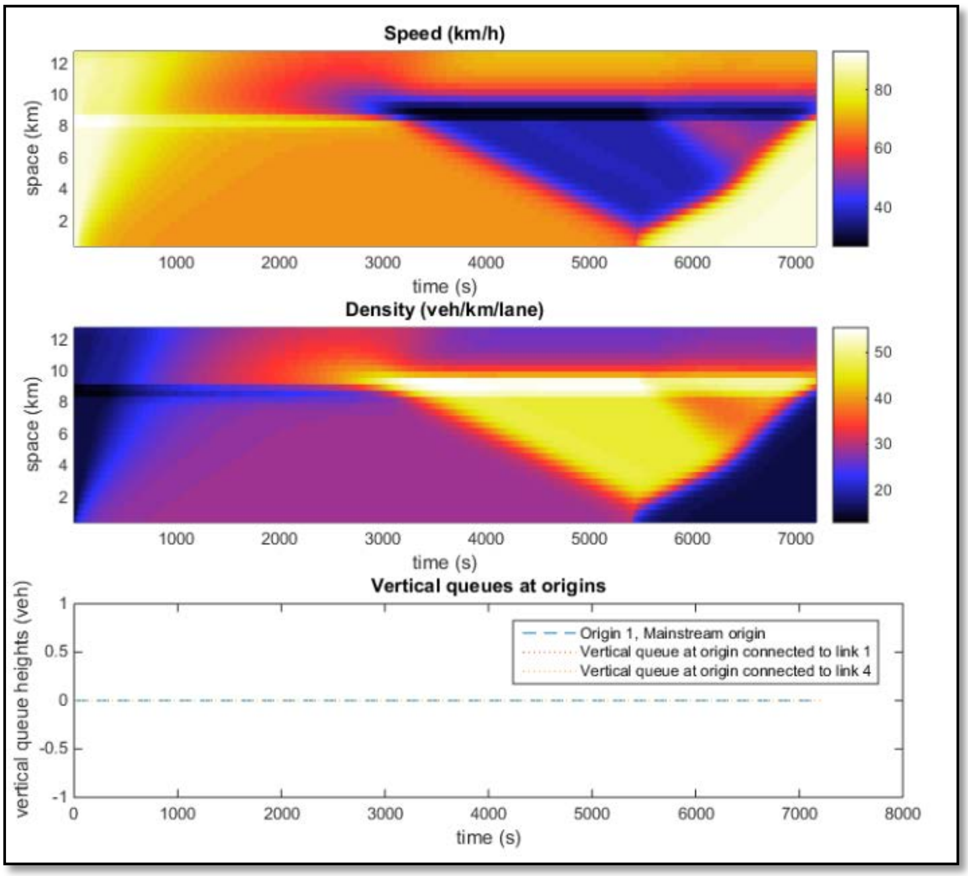

Figure 4.8 Speeds and densities in the freeway segment and vertical queues at origins

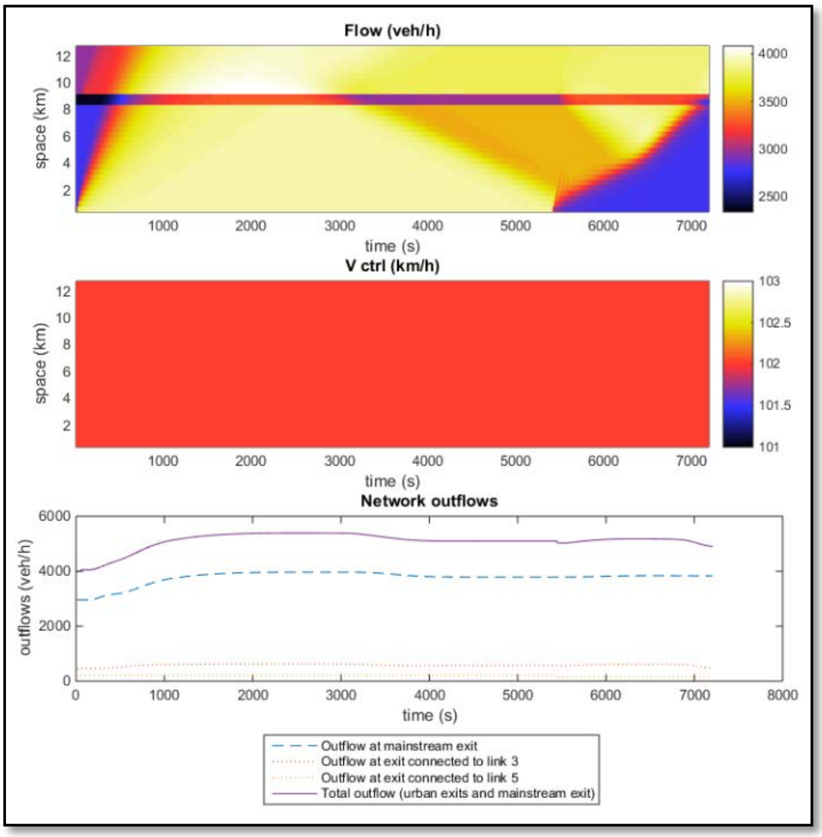

Figure 4.9 Flows and variable speed limits in the freeway segments and network outflows

As can be seen from the figures, congestion builds up in freeway link 3 and then spills back onto the freeway. It does not affect the on-ramp as the flow on the on-ramp is not high enough for spillback to occur. The congestion does affect the off-ramp as it decreases the flow to the off-ramp. This in turn affects the flow in urban link 3, as that link is mainly fed by the off-ramp. When the peak period is passed, the congestion starts to resolve. The total time spent by all vehicles in the network amounts to 1623 veh-h.

4.3.2 Coordinated controllers

When coordinated controllers are activated, the result of the optimisation by the urban controller is that green time shares do not need to be adapted. As a result, the number of vehicles present, the inflows and the outflows do not change for urban links 1, 2, 4, 5 and 12. The number of vehicles present, the inflows and the outflows do change somewhat for urban links 3 and 11 due to the control actions the freeway controller undertakes. See figures 4.10 and 4.11.

The freeway controller applies a speed-limited area as depicted in the second graph of figure 4.13; its effects are visible in figures 4.12 and 4.13. The outflow out of this speed-limited area is such that the congestion onset is prevented, allowing higher network outflows.

This behaviour of the controllers corresponds to the expected behaviour. Therefore, it is likely the controllers would function in the field.

The prevention of congestion onset reduced the total time spent by all vehicles in the network to 1521 veh-h. This amounts to a reduction of 6.3%.

The computation time differs for the two controllers. While the urban controller has computation times that vary from 8-12 seconds, the freeway controller has computation times that are spread out a bit more from 3-18 seconds. Therefore, different bin sizes are used for both controllers. The result in figures 4.14 and 4.15 shows that real-time control is possible as the computation time always stays below the update time of 60 seconds and the spread in computation time is such that it is unlikely the update time will ever be surpassed.

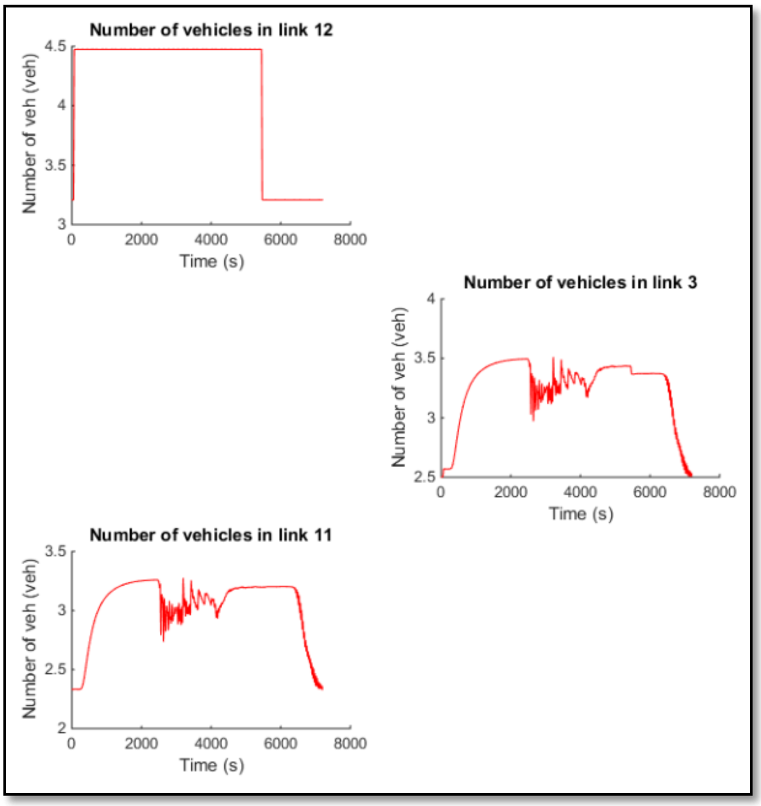

Figure 4.10 The number of vehicles in urban links 3, 11 and 12 when coordinated controllers are active

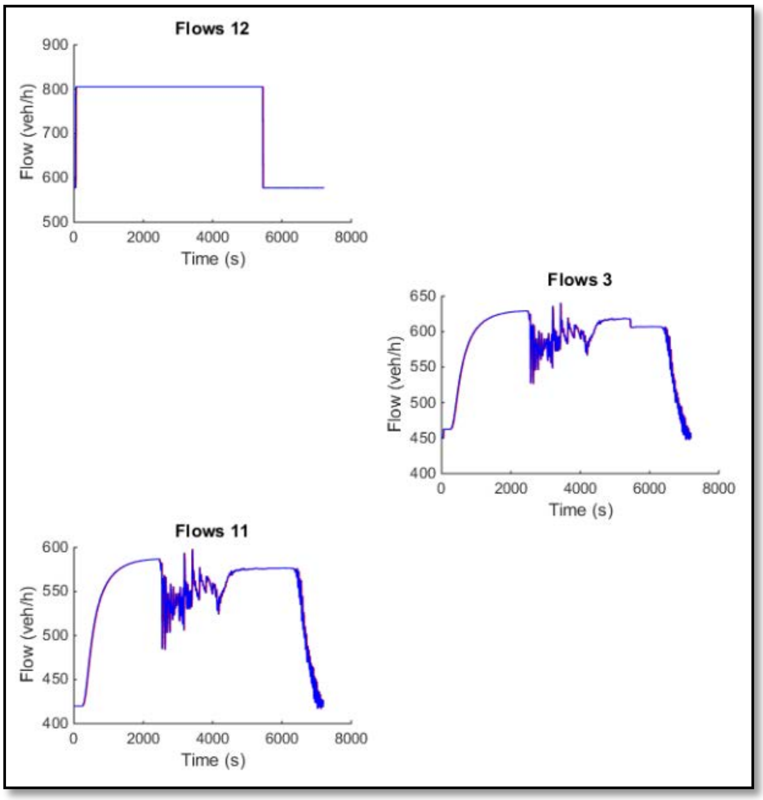

Figure 4.11 The inflows and outflows for urban links 3, 11 and 12 when coordinated controllers are active

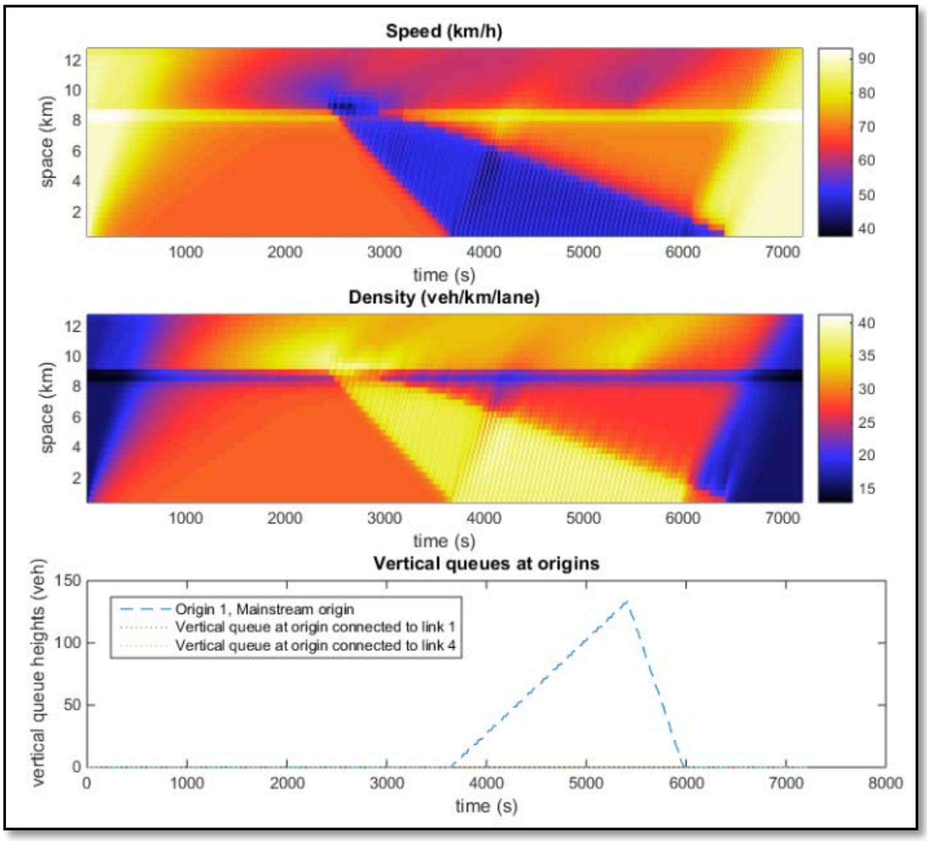

Figure 4.12 Speeds and densities in the freeway segment and vertical queues at origins when coordinated controllers are active

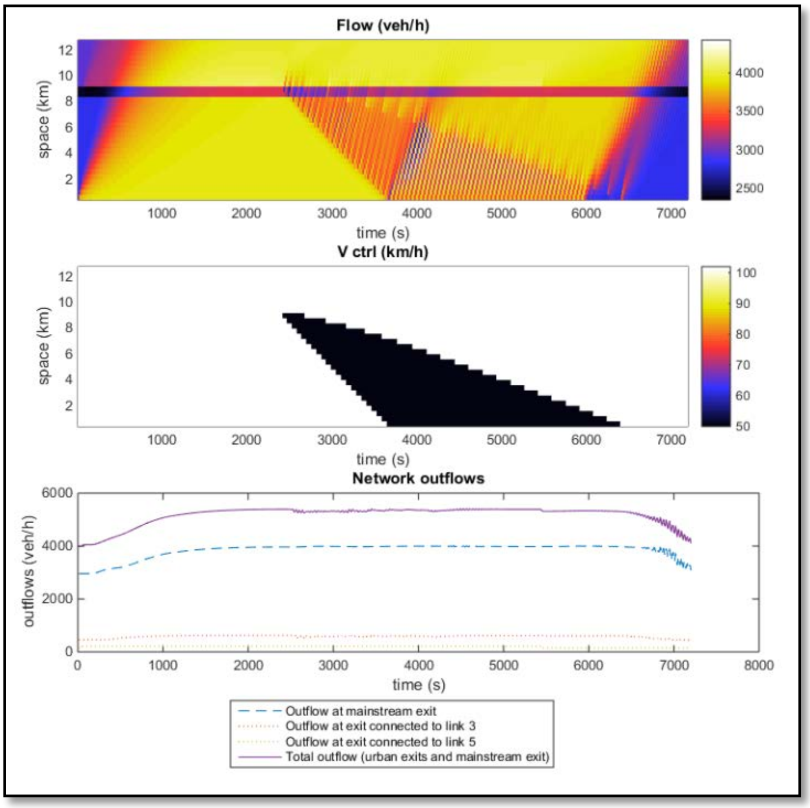

Figure 4.13 Flows and variable speed limits in the freeway segments and network outflows when coordinated controllers are active

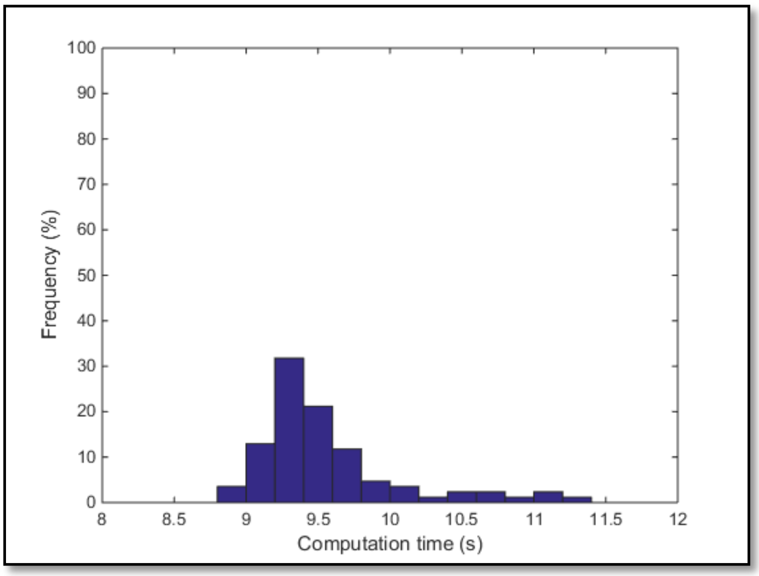

Figure 4.14 Histogram of the computation time for the urban controller when coordinated controllers are active. The computation time should be lower than 60 seconds

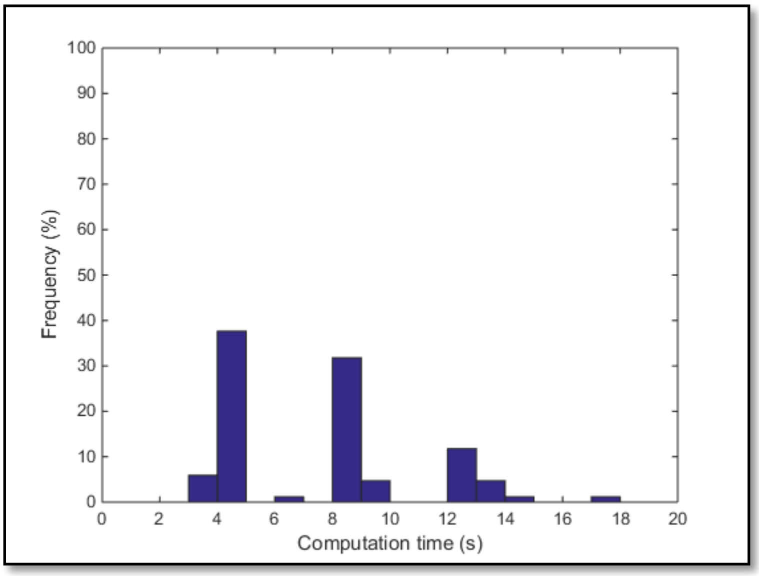

Figure 4.15 Histogram of the computation time for the freeway controller when coordinated controllers are active. The computation time should be lower than 60 seconds

4.3.3 Integrated controller

When the integrated controller is active, the result of the optimisation by the integrated controller is that the green time shares for links 1 and 2 should be adapted, effectively storing traffic in links 1 and 2. At the same time, smaller speed-limited areas are applied on the freeway during the peak period, reducing the flow into freeway link 3, but less than the freeway controller did when coordinated controllers were active. The effect of the storage of traffic in links 1 and 2 can be seen in figures 4.16 and 4.18, the effects of the reduction of flow via the speed-limited areas can be seen in figures 4.17, 4.19, 4.21 and 4.22 and the reduced green time shares are shown in figure 4.20.

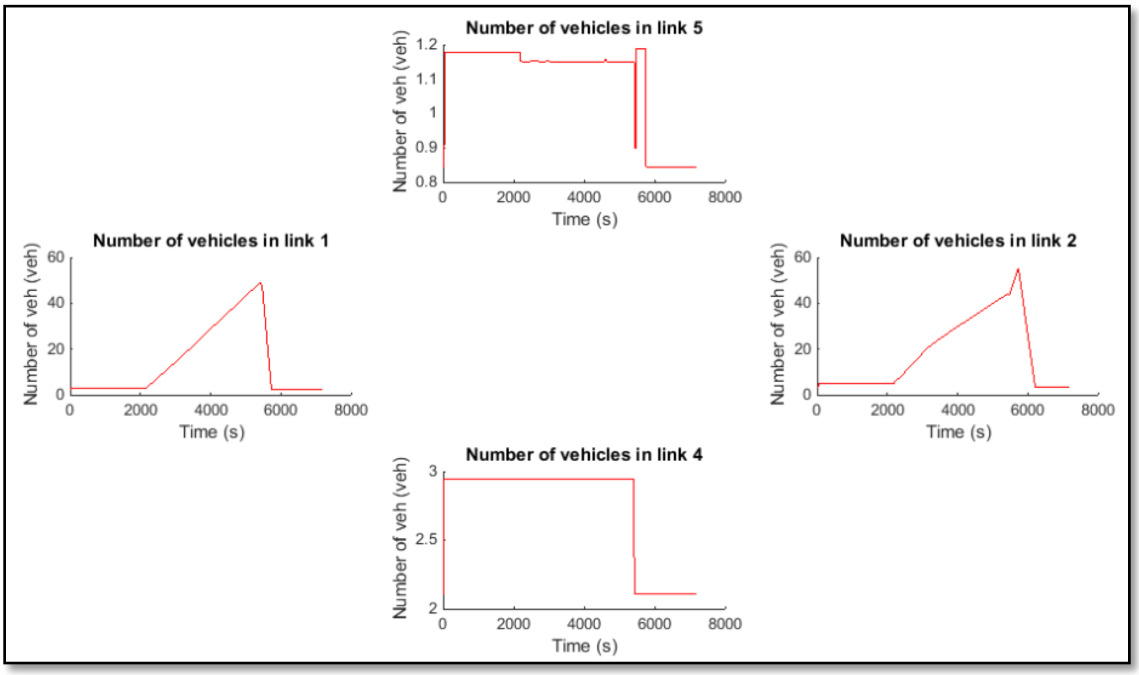

Figure 4.16 The number of vehicles in urban links 1, 2, 4 and 5 when the integrated controller is active

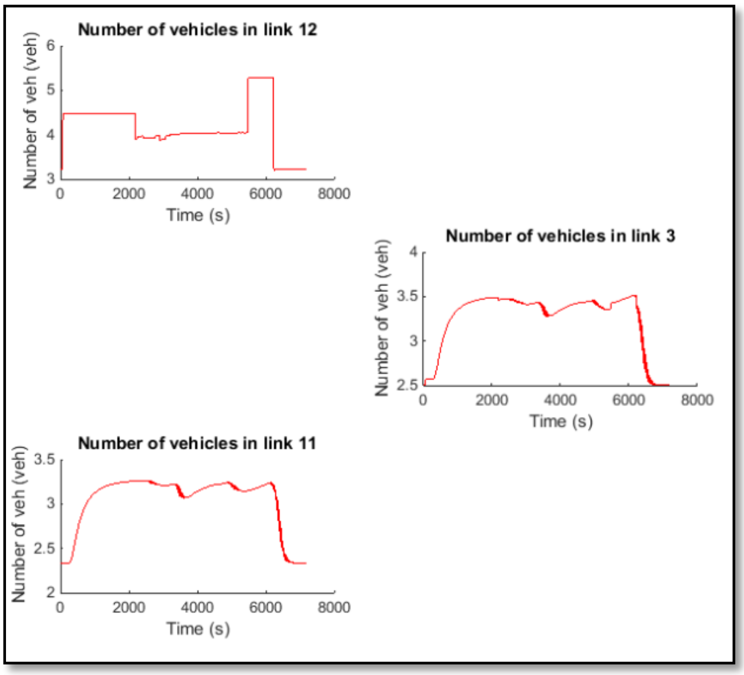

Figure 4.17 The number of vehicles in urban links 3, 11 and 12 when the integrated controller is active

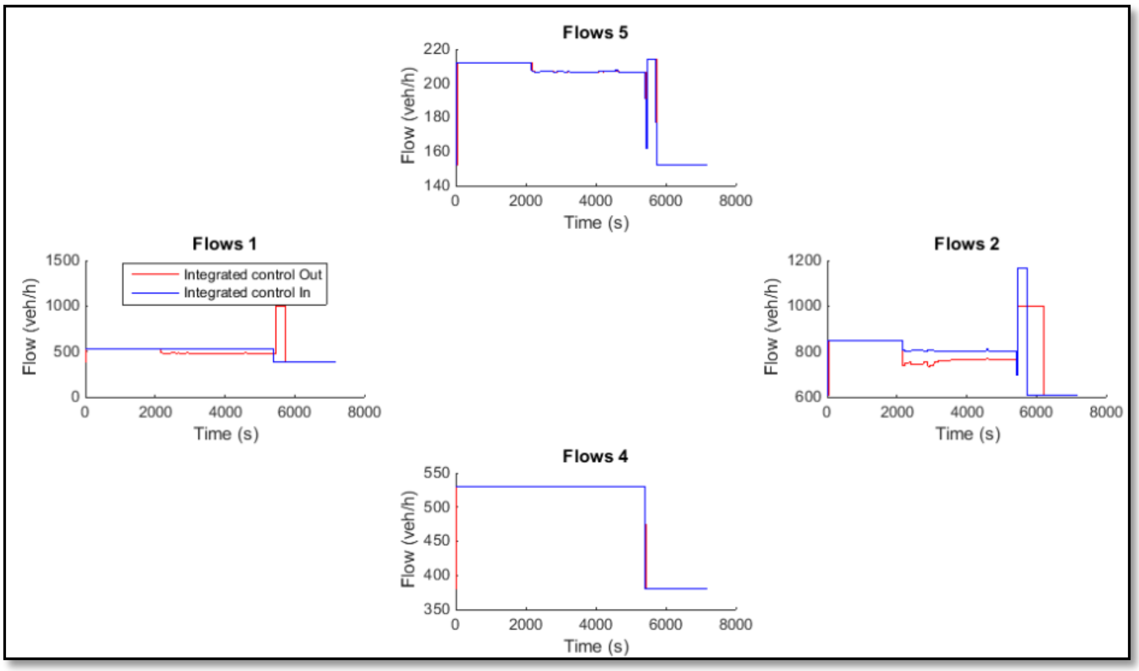

Figure 4.18 The inflows and outflows for urban links 1, 2, 4 and 5 when the integrated controller is active

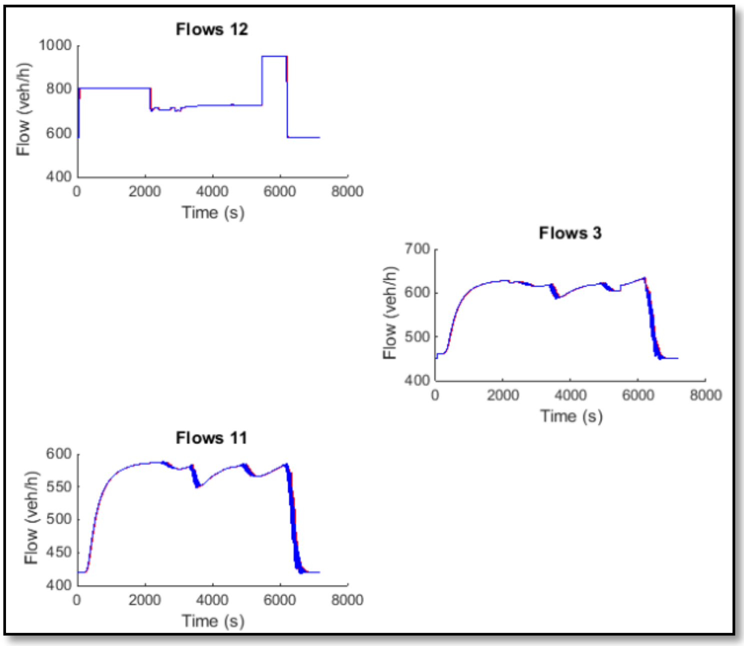

Figure 4.19 The inflows and outflows for urban links 3, 11 and 12 when the integrated controller is active

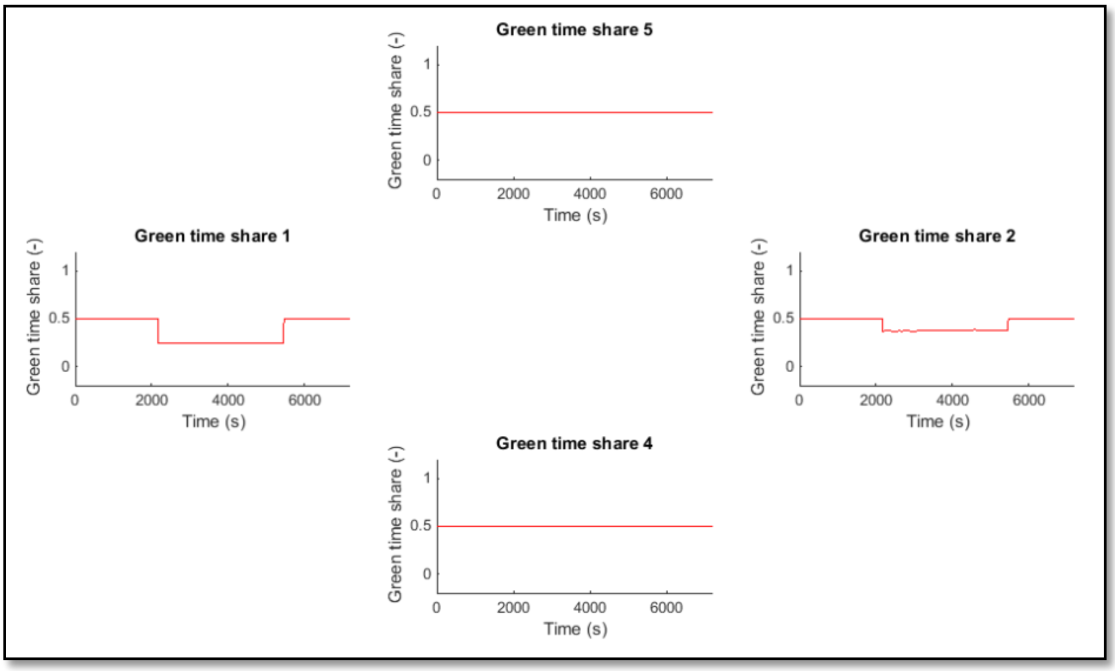

Figure 4.20 The green time shares for urban links 1, 2, 4 and 5 when the integrated controller is active

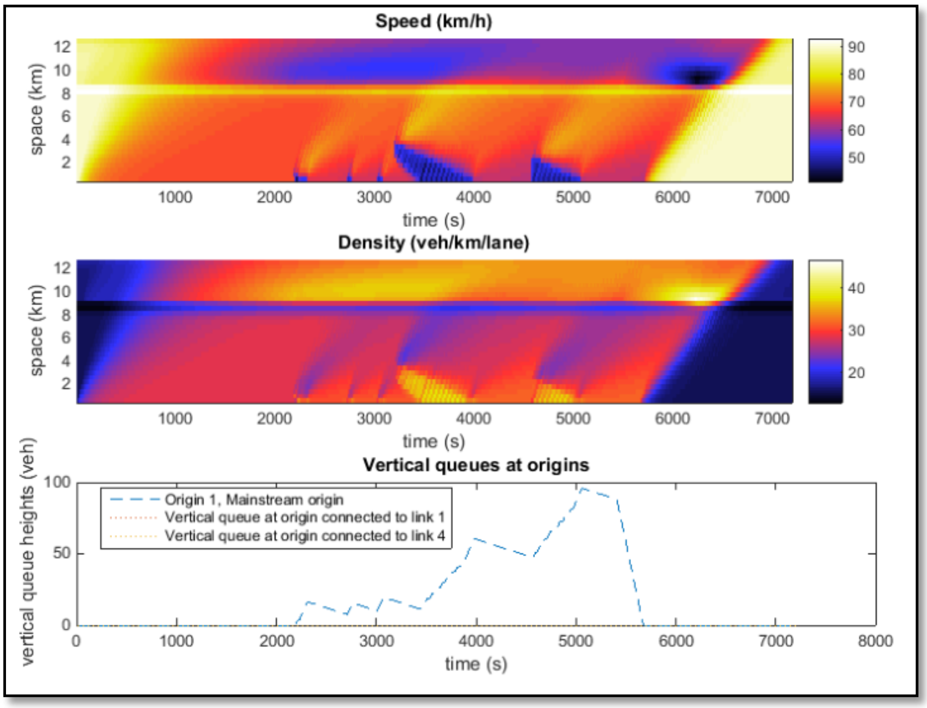

Figure 4.21 Speeds and densities in the freeway segment and vertical queues at origins when the integrated controller is active

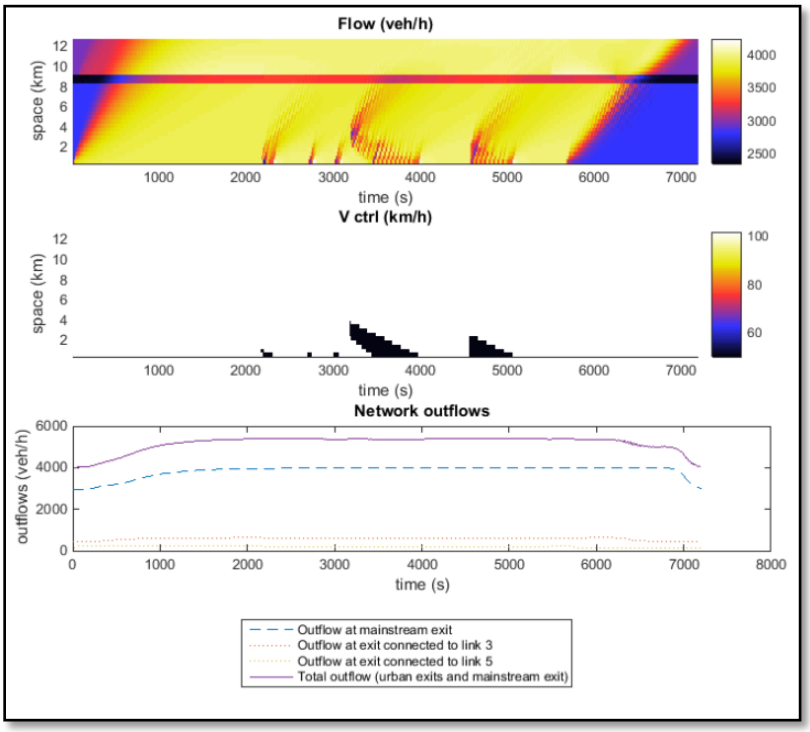

Figure 4.22 Flows and variable speed limits in the freeway segments and network outflows when the integrated controller is active

Although the integrated controller applies several speed-limited areas instead of one as was expected, the effects of these speed-limited areas correspond to expectations: the outflow reduction is less, as the integrated controller distributes the negative effects of the control actions on throughput (i.e. flow reductions) over both networks. So when it comes to effects, the results are as expected. However, the behaviour the controller shows to cause these effects were not expected; as single speed-limited area of a form as depicted in figure 4.13 (with a more upstream starting point resulting from the initial control signal) would have been more expected than the several small speed-limited areas in between 2000 and 3000 seconds. Therefore, it is hard to say if the integrated controller would function in the field.

Since the speed-limited areas that the integrated controller applies reduce the flow less than the speed-limited area that the coordinated freeway controller applies, the flow on the off-ramp increases, causing a higher outflow at the urban exit connected to urban link 3. This in turn reduces the total time spent for all vehicles in the network to 1512 veh-h. This amounts to a reduction of 6.9%.

Placing the computation times in the histogram in figure 4.23 it is immediately obvious that computation times for the integrated controller are far more spread out than for the coordinated controllers. As a result, many computation times surpass the update time of 60 seconds. As a result, real-time control is not possible for the integrated controller.

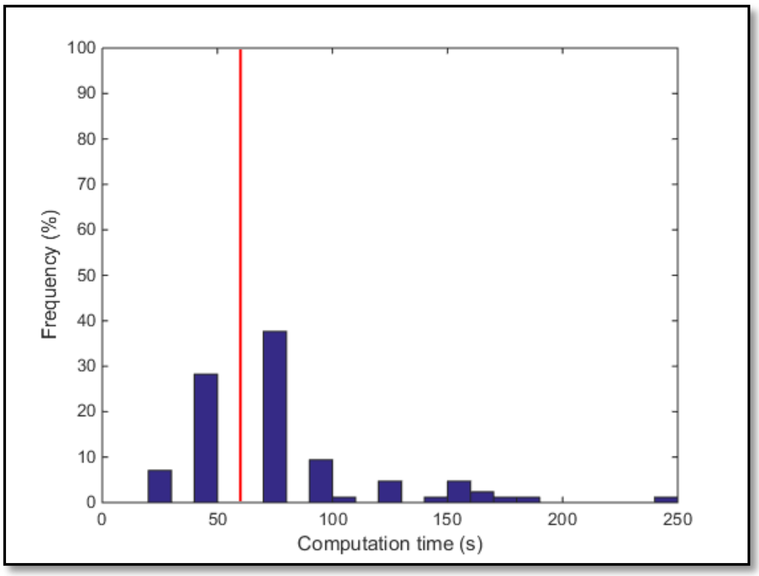

Figure 4.23 Histogram of the computation time for the integrated controller. The red line depicts the update time; for real-time application the controller should have a lower computation time

Since the controller update time is a parameter that can be relatively easily changed, one could be inclined to use a longer controller update time, for example 5 minutes (300 seconds), to enable real-time control. However, choosing a longer controller update time simplifies the optimization problem, therefore a shorter controller update time could also have the desired effect. In order to check the effects of longer controller update times, the simulations have been repeated with controller update times of 3 and 5 minutes.

Special point of attention should be given to the moment the controller should start to optimise. As pointed out in annex 3, control actions should start not later than 2170 seconds. With a controller update time of 3 minutes (180 seconds) the controller should start to optimise at 1990 seconds. With a controller update time of 5 minutes (300 seconds) the controller should start to optimise at 1810 seconds. These values are a consequence of how controller update times have been implemented in the MATLAB scripts.

Results of the repeated simulations are that the controllers have similar effects, but obtain different values for the total time spent. These values are depicted in figure 4.24. While a controller update time of 3 minutes negatively influences the total time spent for the coordinated controllers, the overall trend is that longer controller update times reduce the total time spent. This is counterintuitive, as longer update times imply longer periods of constant control measures, which would make it harder to obtain a more optimal result. A possible explanation is that, since less variables need to be optimised, it is easier for the controller to find optimal values for them.

The computation times tend to shorten with longer controller update times, as shown in figures 4.25-4.30. This suggests choosing a longer controller update time.

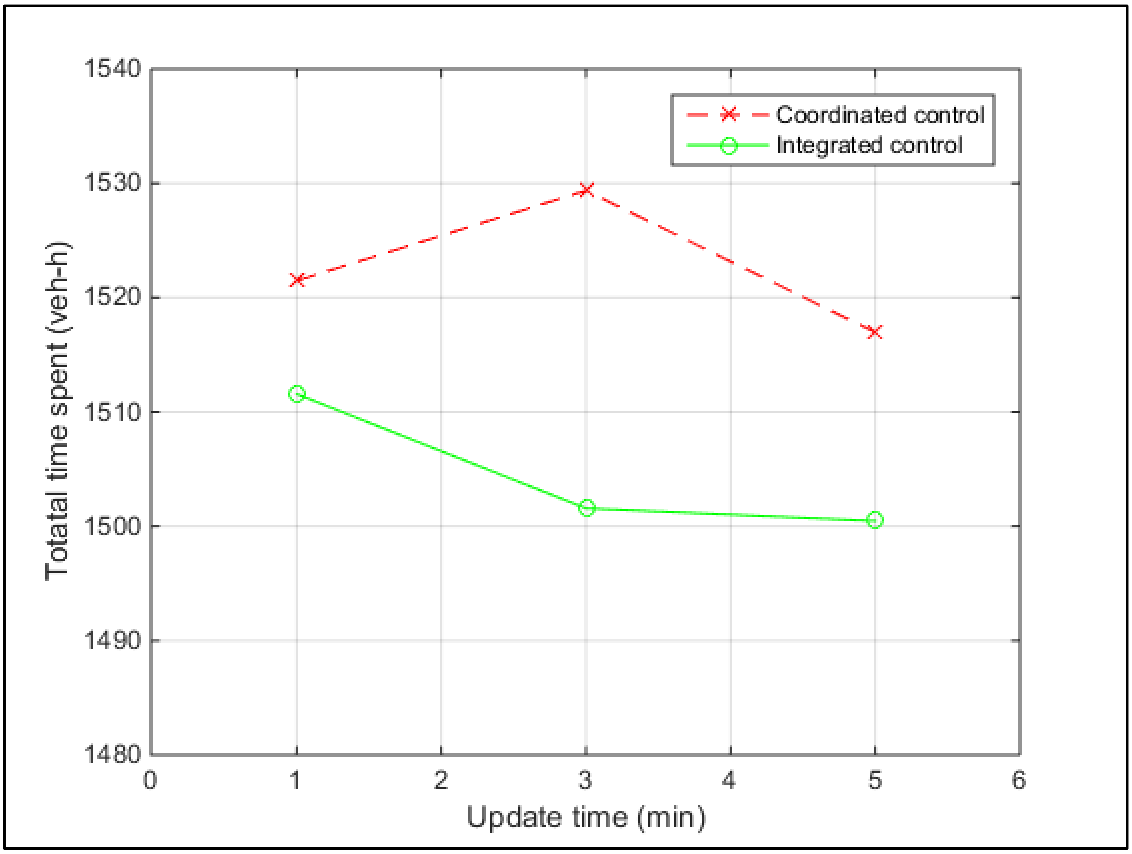

Figure 4.24 Effect of the update time on the total time spent

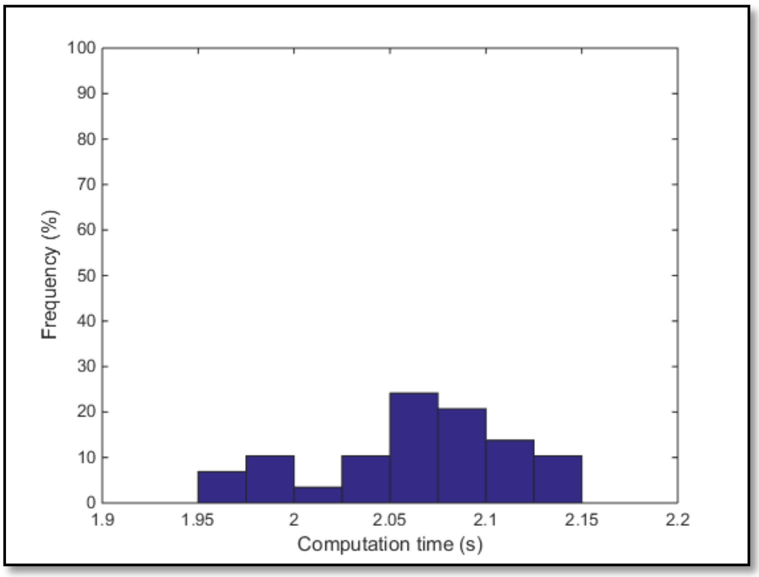

Figure 4.25 Histogram of the computation time for the urban controller when coordinated controllers are active under an update time of 3 minutes (180 seconds)

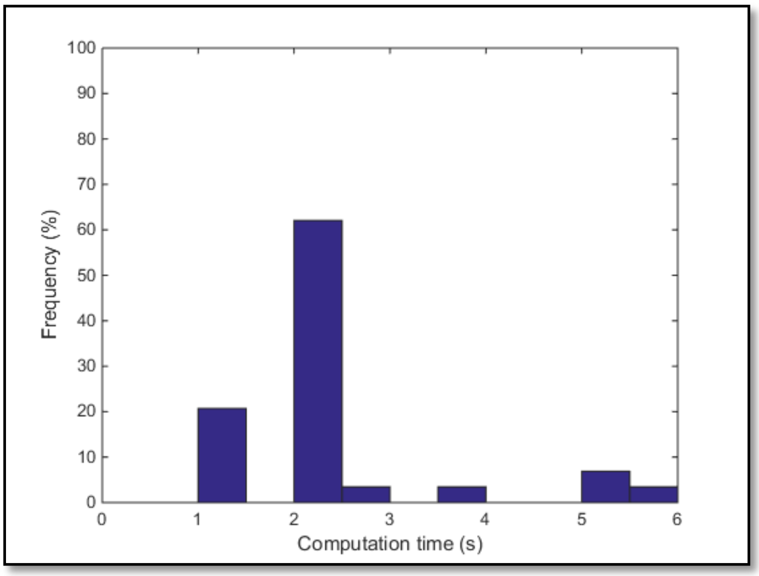

Figure 4.26 Histogram of the computation time for the freeway controller when coordinated controllers are active under an update time of 3 minutes (180 seconds)

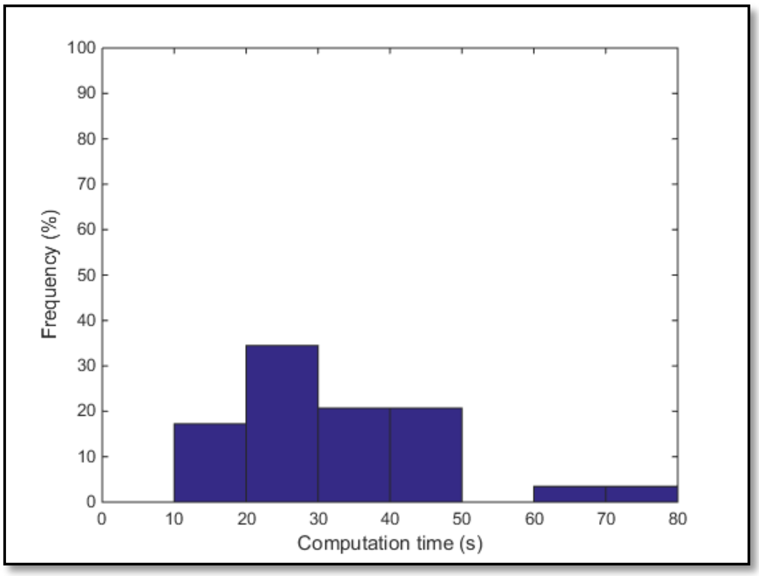

Figure 4.27 Histogram of the computation time for the integrated controller under an update time of 3 minutes (180 seconds)

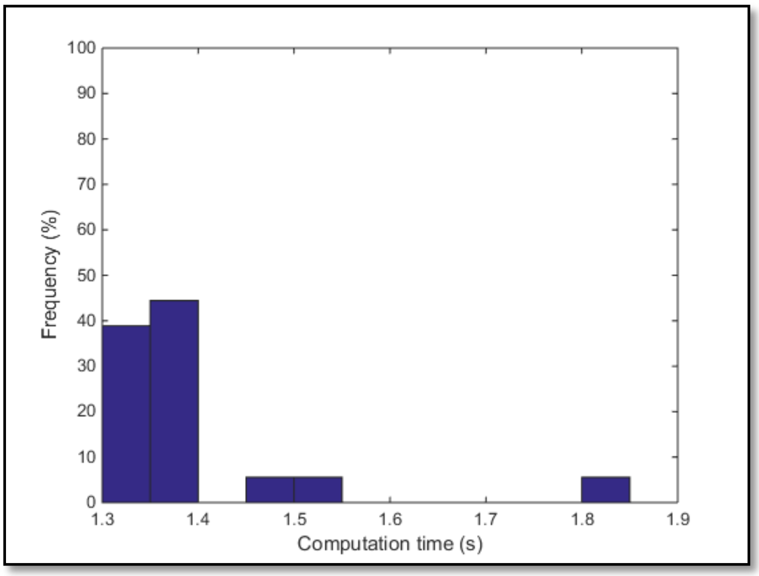

Figure 4.28 Histogram of the computation time for the urban controller when coordinated controllers are active under an update time of 5 minutes (300 seconds)

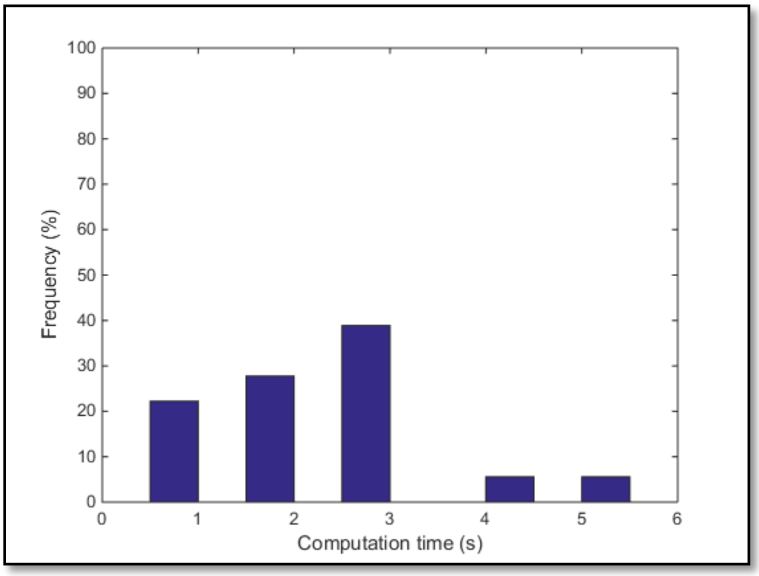

Figure 4.29 Histogram of the computation time for the freeway controller when coordinated controllers are active under an update time of 5 minutes (300 seconds)

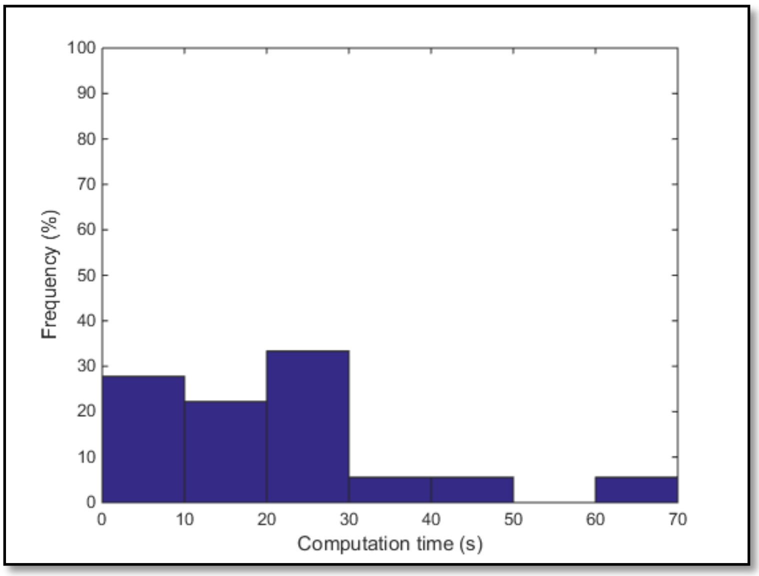

Figure 4.30 Histogram of the computation time for the integrated controller under an update time of 5 minutes (300 seconds)

4.4 Interpretation of the results

In section 4.3 the simulation results have been presented for the no control situation, the situation where coordinated controllers were active and the situation where the integrated controller was active. In this sections, these results will be interpreted.

The results for the no control situation showed what problems occurred in the given traffic situation when no control actions were undertaken; congestion formed on the freeway at the on-ramp and spilled back on the freeway, limiting the outflow via the off-ramp in the process.

When coordinated controllers were active, only the freeway controller took control actions to improve the throughput. The freeway controller did so by applying a speed-limited area to the freeway upstream of the on-ramp, thus limiting the flow towards the on-ramp and preventing the onset of congestion with the associated capacity drop. This behaviour corresponded to the expected behaviour, therefore it is likely the coordinated controllers would function in the field. The coordinated controllers reduce the total time spent by all vehicles in the network by 6.3% in a computation time far below the controller update time, allowing for real-time control. Therefore, one could say the coordinated controllers meet the evaluation criteria.

The integrated controller does not meet all evaluation criteria. It does achieve the expected effects, reducing the flow towards the on-ramp less than in the situation with coordinated controllers while reducing the outflow out of links 1 and 2. Furthermore it does reduce the total time spent by all vehicles in the network by 6.9%. However, it does so with unexpected behaviour and a computation time that surpasses the update time of 60 seconds, making real-time control impossible for the integrated controller. While the problems with computation time could be handled by using a longer update time, the unexpected behaviour needs further research.

5 Discussion

Based on the results of the controller evaluation, the results are discussed in chapter 5 in the light of the limitations of the developed controller. Both limitations originating from the scope and limitations resulting from choices made in the development of the controller will be considered. In section 5.1, the results will be discussed in the light of limitations originating from the scope. In section 5.2, the results will be discussed in the light of limitations resulting from the choices made in the development of the controller. From this, a conclusion will be drawn in section 5.3.

5.1 Limitations originating from the scope

The results are strongly influenced by the limitation that only control algorithms are considered, and not data detection, data processing and actuation nor any controller imperfections apart from modelling imperfections. Such aspects form a major topic of research if the controller is to be developed further.

5.2 Limitations originating from the controller development choices

The results are influenced by the following choices made in the development of the controller:

- The choice to integrate a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC*
- The choice to use the extended METANET model for the freeway part of the traffic flow model and the link transmission model for the urban part of the traffic flow model
- The choice of the assumptions used in the traffic model the controller uses
- The choice of the simulation network
- The choice of the parameters the controller uses
- The choice of the traffic situation
- The choice of the coordinated controllers the controller is to be compared with (the coordinated controllers take the effect of multiple controlled elements within their network into account)
- The choice of the simulation software/hardware

To each of these choices, a subsection will be devoted.

5.2.1 The integration choice

The choice to integrate a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC* has a strong influence on the results. If the controller is to be developed further, one needs to consider the possibilities to enhance the controller with other control algorithms in future research. For such enhancements, one could consider control algorithms that are promising based on the criteria in section 2.1 as such algorithms share the same functionality needed to improve throughput when faced with the problem in the problem description, while distributing any negative impacts of the control actions over the urban and freeway network. So if one wants to enhance the controller with ramp metering, it is recommended to use METALINE or linear optimal ramp metering algorithms. On the other hand, if one wants to enhance the controller with route guidance, it is recommended to use iterative route advice.

5.2.2 The traffic flow model choice

The choice to use the extended METANET model for the freeway part of the traffic flow model and the link transmission model for the urban part of the traffic flow model has a strong influence on the results. One could investigate alternative traffic flow models by letting the algorithms optimise the total time spent by letting them control the variable speed limits and green time shares while entering the alternative traffic flow models into this framework. This could, depending on the traffic flow model, positively or negatively affect the evaluation criteria. This investigation allows for more insights into various aspects of the traffic flow model choice, for instance the choice not to take signal plans into account. As pointed out in section 2.8, this choice is effectively a simplification that saves computation time while approximating the actual traffic process. As such, it is a trade-off. Given the fact that the effect of these trade-offs that came with the traffic flow model choice have not been taken into account in this MSc Thesis project, it is recommended to do further research into these effects.

5.2.3 The choice of traffic flow model assumptions

The traffic flow model assumptions have been presented in subsection 3.1.1. While many assumptions are logical, used by other authors or reasonably have a weak influence on the results, the assumption that all disturbances are known has a strong influence on the results, as it basically means the controller works with a perfect prediction of the disturbances over the control horizon. In the field, predictions are never perfect and therefore, the effect of imperfections in the predictions of the disturbances forms a major topic of research if the controller is to be developed further.

5.2.4 The simulation network choice

The choice of the simulation network has a strong influence on the results, as together with the traffic situation the simulation network forms the scenario that is simulated. The developed controller could have a positive influence on other scenarios than the scenario considered in this MSc Thesis project. For instance, the developed controller could resolve a jam wave on the freeway by applying variable speed limits to the freeway while adapting green time shares for the traffic headed for the on-ramp. Another example would be a scenario where there is a lot of traffic that wants to leave the freeway via the off-ramp. The developed controller could improve the situation by applying variable speed limits to the freeway while adapting green time shares for the traffic headed to the intersection where it comes in conflict with the traffic from the off-ramp. Therefore, it is recommended to simulate more scenarios in future research. In order to do so, research into the sensitivity for the initial control signal is needed, as will be explained in subsection 5.2.6.

5.2.5 The parameter value choice

The parameter values have been presented in subsection 4.1.2. While many values are logical, used by other authors or reasonably have a weak influence on the results, the controller update time has a strong influence on the results with respect to computation time. It is a crucial parameter for determining whether or not real-time control is possible. In subsection 4.3.3 the effects of choosing a longer controller update time have been briefly evaluated. The results suggested choosing a longer controller update time. However, longer update times make it harder to correct mistakes made by imperfections of the predictions of the disturbances. Other methods to make real-time control possible for the controller exist and are presented in subsection 5.2.8.

5.2.6 The traffic situation choice

The traffic situation has a strong influence on the results, as together with the simulation network the traffic situation forms the scenario that is simulated. As was pointed out in subsection 5.2.4 simulation of more scenarios is recommended for future research, but first research into the sensitivity for the initial control signal is needed. As was pointed out in subsection 4.1.5, test simulations have shown that the controller is quite sensitive to its initial control signal. In order to cope with this sensitivity, the initial control signal was chosen to be close to the theoretical optimum following from the simplified analytical calculation on which the values of the disturbances are based. This tied together the initial control signal, the scenario and the control actions, thus makes the controller unsuitable for application in other scenarios. To solve this problem, research into the sensitivity for the initial control signal is needed.

5.2.7 The choice of coordinated controllers for comparison

The coordinated urban and freeway controllers the integrated controller is compared with are basically the urban and freeway controllers the integrated controller consists of. Therefore, this comparison is the fairest to show the advantage of integration.

5.2.8 The choice of the simulation software/hardware

The simulation software/hardware aspects that play a role in the simulation have been presented in subsection 4.1.5. While many of the presented aspects are logical, used by other authors or reasonably have a weak influence on the results, the efficiency of the MATLAB scripts, the optimisation function used and the number of cores used for parallel computing have a strong influence on the results with respect to computation time.

One could reduce the computation time by choosing a different optimisation function. This could be achieved by looking for nonlinear optimisation functions in MATLAB and checking which ones result in a lower computation time for this particular optimisation problem.

Assuming the workload of the optimisation is evenly distributed over all cores used for parallel computing, the computation time varies linearly with the number of cores used. Given that the simulation was run with 4 cores, one could make real-time control possible for the controller by increasing the number of cores used to 17.

Alternatively, one could check the efficiency of the MATLAB scripts with help of the 'profiling' functionality of MATLAB. This functionality shows for each function how long it took to run. This way, inefficient parts of the MATLAB scripts can be identified and rewritten as to reduce their computation time.

These methods to make real-time control possible for the controller have no foreseeable disadvantages for the performance of the controller. However, changing the traffic flow model, as was suggested in subsection 5.2.2, or changing the controller update time, as was suggested in subsection 5.2.5, has multiple effects, both positive and negative. Therefore it is recommended to do further research in the effects of the traffic flow model and the controller update time and subsequently to make real-time control possible by making all five methods to do so work together in order to minimise the computation time for the controller with minimal negative side effects.

5.3 Conclusion

The developed controller in this MSc Thesis project does not meet all evaluation criteria formulated in section 4.2. Although it does achieve the expected effects and reduces the total time spent more than the coordinated controllers, it does so with unexpected behaviour and a computation time that surpasses the update time. Considering these results in the light of the limitations of the developed controller, many recommendations are found. These recommendations will be presented in section 6.2.

One of these recommendations deals with the problem the controller has with the computation time. The recommended solution is to do further research in the effects of the traffic flow model and the controller update time and subsequently to adapt the traffic flow model, to adapt the controller update time, to adapt the optimisation function, to increase the number of cores the controller uses in parallel computing and to improve the efficiency of the MATLAB scripts the controller uses.

Another recommendation that deals with the problems the controller faces in meeting the evaluation criteria has not been addressed in the discussion, as it is not clear what limitation of the controller is responsible for the problem addressed by this recommendation; the unexpected behaviour the controller achieves the expected effects with. This problem can only be dealt with by doing further research, therefore further research into the unexpected behaviour of the controller is recommended.

6 Conclusions and recommendations

Based on the discussion in chapter 5, conclusions will be drawn and recommendations will be given in this chapter. The conclusions will be drawn in section 6.1 and the recommendations will be given in section 6.2.

6.1 Conclusions

In this MSc Thesis project, an integrated urban-freeway network controller is developed to improve throughput with respect to coordinated controllers (i.e. controllers that take the effect of multiple controlled elements within their network into account) in the situation of congestion caused by high demand moving from the urban network to the freeway. This is done with the following design goals in mind:

- Improved throughput with respect to the situation with coordinated controllers
- A computation time that allows for real-time control

After development the controller is evaluated, fulfilling the sub-objectives:

- Develop the integrated urban-freeway network controller
- Evaluate the integrated urban-freeway network controller

The method used for developing the integrated controller is combining urban and freeway control algorithms, integrating them.

To select these control algorithms, they are first assessed on criteria that make them promising. With the promising control algorithms there are 38 possible integrations. This amount of combinations is reduced by subsequently removing algorithms that require significant alteration for integration and removing algorithms that can be expected to take a long time to be integrated. Out of the remaining 3, one is selected based on considerations of requirements and existing integrated algorithms. The selection is to minimise the amounts of requirements with respect to the traffic flow model and the optimisation complexity. Furthermore, the selection is to suggest a different integration than the considered existing integrated algorithms. This results in the selection of the integration of a *Linear optimal coordinated signal control algorithm* and the *Parameterised variable speed limit MPC*.

The controller developed this way chooses urban green time shares, initial positions of head and tail of the speed-limited area and speeds of head and tail of the speed-limited area at each update time. In between update times, the urban green time shares and the speeds of head and tail of the speed-limited area are constant. The chosen values are subject to constraints with respect to green time shares (should have values in between 0 and 1 and sums over conflicts should be at most 1), initial positions of head and tail of speed-limited area (should be in between upstream and downstream bounds and the position of the head should be equal to or more downstream than the position of the tail), speed of head and tail of the speed-limited area (should be at most the effective speed of the speed-limited area when downstream speeds are positive and upstream speeds are negative) and the control and prediction horizons (from the control horizon until the prediction horizon the green time shares and the speeds of head and tail of the speed-limited area are constant). The chosen values are chosen to optimise the total time spent over the prediction horizon based on its traffic model.

To evaluate the controller, a simulation is executed for which three evaluation criteria were formulated:

- Total time spent in the network by all vehicles; this is a performance indicator that has to show improvement with respect to the situation with coordinated control.
- Computation time; this is a performance indicator to check whether or not the computation time allows for real-time control.
- Qualitative behaviour; this evaluation is to check if it is likely the controller would function in the field. This is the case when it behaves as predicted.

The developed controller in this MSc Thesis project does not meet all three evaluation criteria. Although it does achieve the expected effects and reduces the total time spent more than the coordinated controllers, it does so with unexpected behaviour and a computation time that surpasses the update time. Considering these results in the light of the limitations of the developed controller, many recommendations are found. These recommendations will be presented in section 6.2.

One of these recommendations deals with the problem the controller has with the computation time. The recommended solution is to do further research in the effects of the traffic flow model and the controller update time and subsequently to adapt the traffic flow model, to adapt the controller update time, to adapt the optimisation function, to increase the number of cores the controller uses in parallel computing and to improve the efficiency of the MATLAB scripts the controller uses.

Another recommendation that deals with the problems the controller faces in meeting the evaluation criteria has not been addressed in the discussion, as it is not clear what limitation of the controller is responsible for the problem addressed by this recommendation; the unexpected behaviour the controller achieves the expected effects with. This problem can only be dealt with by doing further research, therefore further research into the unexpected behaviour of the controller is recommended.

6.2 Recommendations

The two primary recommendations deal with the problems the developed controller has with meeting the evaluation criteria. The recommended solution to deal with the problem with respect to computation time is to do further research in the effects of the traffic flow model and the controller update time and subsequently to adapt the traffic flow model, to adapt the controller update time, to adapt the optimisation function, to increase the number of cores the controller uses in parallel computing and to improve the efficiency of the MATLAB scripts the controller uses. The recommended solution to deal with the unexpected behaviour the controller achieves the expected effects with is doing further research into this behaviour.

A secondary recommendation is to do research into the controller's sensitivity for the initial control signal. As was pointed out in subsection 4.1.5, test simulations have shown that the controller is quite sensitive to its initial control signal. In order to cope with this sensitivity, the initial control signal was chosen to be close to the theoretical optimum following from the simplified analytical calculation on which the values of the disturbances are based. This tied together the initial control signal, the scenario and the control actions, thus makes the controller unsuitable for application in other scenarios. To solve this problem, research into the sensitivity for the initial control signal is needed.

A tertiary recommendation is to simulate more scenarios in future research to determine how the controller behaves under different scenarios.

If the controller is to be developed further, a wider scope is needed. Such a wider scope brings with it subjects for further research that have not been considered in this MSc Thesis project. Such subjects include data detection, data processing, actuation, controller imperfections apart from modelling imperfections, the effect of imperfections in the predictions of the disturbances and the possibilities to enhance the controller with other control algorithms. For such enhancements, it is recommended to use METALINE or linear optimal ramp metering algorithms when considering enhancing with ramp metering and to use iterative route advice when considering enhancing with route choice algorithms.

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