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Evaluating Multi-Class Model Predictive Control

A comparison of traffic management scenarios and model predictive control during road works on the A15

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Summary

Traffic Control is a part of Dynamic Traffic Management where traffic management measures are controlled to optimize the capacity of networks. Since September 2011 Traffic Management Scenarios are applied to the A15 highway in the Port of Rotterdam Area. Traffic Management Scenarios are the most advanced Traffic Control methods that are applied in practice. The current state of art in Traffic Control is Model Predictive Control, an adaptive method that calculates the optimal control signal and adjusts it to changing traffic states. In this study this method is compared with the current implemented Traffic Management Scenarios for the A15 highway eastbound. Since this highway has a high share of freight traffic from the port, traffic is divided into two user-classes and a multi-class variant of Model Predictive Control will also be compared.

The goal of this study is:
To make a quantitative comparison based on economic costs among Traffic management Scenarios, Single-class Model Predictive Control and Multi-class Predictive Control.

To be able to make this comparison a literature review is done on traffic control, including the two control methodologies that will be compared in this thesis, and multi-class traffic management measures. A categorization of control methodologies will be made to illustrate how Traffic Management Scenarios and model Predictive Control relate. Here will be shown that Traffic Management Scenarios are adaptable methods but that Model Predictive Control is even more adaptable. The traffic management measures that can be controlled by both control methods, ramp metering and route guidance, will also be described. Only route guidance is applied by the current Traffic Management Scenario
Since the used Traffic Management Scenario was created based on experience and Model Predictive Control does not exist in practice yet there is described how both methods should be compared. First some requirements have to be set. These requirements are that the both methods should use the same network, control the same signals and that these control signals will be determined based on the same input data. To analyze the results of both methods, they should produce the same sort of output data. The easiest way to do this is performing a simulation experiment where both Traffic Management Scenario and Model Predictive Control use the same traffic model with a control module in it. The control module then can be replaced by either the Traffic Management Scenario, the Model Predictive Control or remain empty. BOS-HbR is a framework that fulfills these requirements and is therefore used for this study. It uses the A15 highway as its network. BOS-HbR consists of a estimation and prediction component. In the estimation component the input data retrieved from loop detectors is converted to a traffic state which serves as input for the prediction component. The prediction component uses multi-class model Fastlane to predict the traffic state and predict the results of the control method which will be inserted here. The Traffic Management Scenario used for the current study is the 'A15 Haven Uit' scenario developed by Regiodesk. For the current study a Traffic Management Scenario is created within BOS-HbR with

the same (de)activation triggers as 'A15 Haven Uit'. The Model Predictive Controller used in BOS-HbR will use the Matlab function fmincon as its optimization algorithm.

The simulation experiment will be executed for three cases: a heavy peak hour, a regular peak hour and a severe accident. For each case a validation will be done to check if the model predictions for Fastlane matched reality. Also for each of these cases the experiments will be done with 5 demand levels - 90%, 95%, 100%, 105% and 110% of the original expected demand - to measure the robustness of the control methods. For the Traffic Management Scenario the conditions for the rerouting signal at Spijkenisse to be turned on will be described and there will be explained that road users will only comply with this signal if the off-ramp to the alternative route is congestion-free. The variables to be adjusted for the Model Predictive Controller are control interval, control horizon and prediction horizon.
The results of these experiments are discussed basis of the following performance indicators: Total cost, average travel time per user class and robustness.
In the cases of the heavy peak hour applying single-class Model Predictive Control shows double the improvement Traffic Scenarios achieved. In the regular peak hour this improvement was less and in the accident case the relative differences were minimal. In all cases single-class Model Predictive Control performs better than Traffic Management Scenarios, which shows a good improvement over the situation where no traffic control is applied. Multi-class Model Predictive Control has small improvements over single-class Model Predictive Control especially when looked at user-class specific travel times. The multi-class controller reroutes exclusively passenger car traffic and keeps the trucks on the main road. All control cases show an equal sensitivity to demand fluctuations. Overall it can be concluded that Model Predictive Control shows approximately the same improvement over Traffic Management Scenarios as the latter does over a situation where no traffic control is applied.
Since Traffic Management Scenarios performed well in this study it is recommended to apply Traffic Management Scenarios with route guidance to more locations in the Netherlands where this is possible. It can also clear the road for a future implantation of Model Predictive Control. The Traffic Management Scenarios currently used are designed based on experience, it is interesting to see how Traffic Management Scenarios that are designed and optimized with a traffic model will perform. Rerouting the traffic multi-class showed good results for the Model Predictive Controller, therefore researching rerouting multi-class with a Traffic Management Scenario could also be interesting for the Port Area.
Some interesting topics for further research following from this study are applying other traffic management measures except rerouting in the Port area and a behavioral research on how traffic responds to the DRIP signals that guide it, because in this research assumptions on compliance to these signals were made.

Samenvatting

Het regelen van verkeer is een onderdeel van Dynamisch Verkeersmanagement waarbij verkeersmanagement maatregelen worden ingezet om de capaciteit van wegnetwerken te optimaliseren. Sinds september 2011 worden regelscenario's ingezet op de A15 ten zuiden van de Rotterdamse haven. Regelscenario's zijn de meest geavanceerde verkeersmanagementmethoden die op dit moment in de praktijk gebruikt worden. De verkeersmanagementmethode die op dit moment veel wordt gebruikt in wetenschappelijk onderzoek is Model Predictive Control. Dit is een flexibele regelmethode die het optimale regelsignaal berekent en het aanpast aan de hand van de huidige veranderende verkeerstoestand. In dit onderzoek wordt deze methode vergeleken met de regelscenario's op de A15 in oostelijke richting, die op dit moment in gebruik zijn. Deze snelweg heeft een hoog aandeel vrachtverkeer die goederen van de haven naar het achterland vervoert. Daarom wordt het verkeer verdeeld in twee gebruikersklassen en wordt ook een multi-class variant van Model Predictive Control vergeleken.

Het doel van dit onderzoek is daarom:
Een kwantitatieve vergelijking maken op basis van economische kosten tussen regelscenario's, single-class Model Predictive Control en multi-class Predictive Control.

Om deze vergelijking te kunnen maken is een literatuuronderzoek gedaan naar verkeersmanagement, multi-class verkeersmanagement maatregelen inclusief de twee verschillende methodes die vergeleken worden in dit onderzoek. Om te laten zien hoe regelscenario's en Model Predictive Control zich tot elkaar verhouden is een categorisatie gemaakt van regelmethodes. Hieruit blijkt dat een regelscenario een redelijk adaptieve regelaanpak is, maar dat het nog flexibeler kan met Model Predictive Control. Regelscenario's en Model Predictive Control kunnen in het geval van de A15 twee verschillende maatregelen aansturen: toeritdosering en routegeleiding. Op dit moment wordt in de praktijk alleen routegeleiding gebruikt door het regelscenario.
Het huidig gebruikte regelscenario is ontworpen op basis van ervaring en Model Predictive Control wordt nog niet in de praktijk gebruikt. Het is daarom belangrijk dat er eisen gesteld worden, waaraan een vergelijking tussen deze twee methodes moeten voldoen. Beide methoden moeten hetzelfde netwerk gebruiken, dezelfde regelsignalen aansturen en de signalen moeten bepaald worden op basis van dezelfde inputdata. Om de resultaten van het toepassen van beide methodes goed te kunnen vergelijken, moeten ze ook hetzelfde type outputdata gebruiken. De makkelijkste manier om dit te doen is een simulatie-experiment uit te voeren, waarin zowel regelscenario als Model Predictive Controller hetzelfde verkeersmodel gebruiken met een regelmodule. Deze regelmodule kan dan worden ingevuld door het regelscenario, de Model Predictive Controller of het kan leeg worden gelaten. BOS-HbR is een raamwerk dat voldoet aan deze eisen en wordt daarom voor dit onderzoek gebruikt. De A15 wordt gebruikt als zijn netwerk. BOS-HbR bestaat uit twee componenten: een schatter en een voorspeller. De schatter haalt inputdata uit lusdetectors in het wegdek en zet deze om in een verkeerstoestand die als input dient voor de voorspeller. De

voorspeller gebruikt het multi-class verkeersmodel Fastlane om de toekomstige verkeerstoestand te voorspellen en gebruikt de resultaten van de regelmethode, die hier in de regelmodule wordt gevoegd. Het regelscenario dat voor dit onderzoek gebruikt wordt is het 'A15 Haven Uit' scenario, ontwikkeld door Regiodesk. Voor dit onderzoek wordt in BOS-HbR een scenario geprogrammeerd die dezelfde (de-)activatievoorwaarden heeft als 'A15 Haven Uit'. De Model Predictive Controller die in de regelmodule gezet kan worden maakt gebruikt van de Matlabfunctie fmincon als zijn optimalisatiemethode.

Het simulatie-experiment is uitgevoerd voor drie cases: een zware spits, een reguliere spits en een situatie waarin een zwaar ongeval is gebeurd. Voor elk geval is een validatie gedaan om te controleren of de voorspellingen van Fastlane overeenkomen met de werkelijkheid. Ook zijn de experimenten voor elk van deze drie cases worden gedaan met vijf niveaus van verkeersvraag, 90%, 95%, 100%, 105% en 110% van de origineel verwachtte verkeersvraag. Dit om de robuustheid van de regelmethodes te meten. Voor het regelscenario zijn de voorwaardes voor het aanzetten van het signaal bij Spijkenisse beschreven en er is uitgelegd dat weggebruikers alleen het signaal zullen volgen als er geen congestie op de afrit staat en de A15 zelf congestievrij is. De variabelen die voor de Model Predictive Controller aangepast moeten worden zijn het regelinterval, de regelhorizon en de voorspelhorizon.

De resultaten van deze experimenten worden geanalyseerd op basis van de volgende prestatie-indicatoren: totale kosten, gemiddelde reistijd per gebruikersklasse en robuustheid.

In het geval van de zware spits laat de single-class Model Predictive Controller twee keer de verbetering zien die het regelscenario laat zien. In de reguliere spits is deze relatieve verbetering minder groot en het geval van het zware ongeluk is de relatieve verbetering van de regelmethodes onderling minimaal. In alle gevallen laat single-class Model Predictive Control betere resultaten zien dan regelscenario's, die op hun beurt weer een goede verbetering laten zien ten opzichte van het geval waar geen verkeersmanagement wordt toegepast. Multi-class Model Predictive Control heeft een klein verbetering ten opzichte van single-class Model Predictive Control, vooral als er gekeken wordt naar reistijden per gebruikersklasse. De Multi-class routebegeleider leidt alleen personenauto's om en hield het vrachtverkeer op de hoofdroute. Op het gebied van robuustheid scoorden alle regelmethodes gelijk. In zijn geheel kan geconcludeerd worden dat Model Predictive Control ongeveer dezelfde verbetering laat zien ten opzichte van regelscenario's als regelscenario's hebben over een situatie waarin geen verkeersmanagement wordt toegepast.

Omdat regelscenario's in dit onderzoek goede resultaten lieten zien, wordt aanbevolen om regelscenario's met routegeleiding vaker toe te passen op vergelijkbare situaties in Nederland als de A15 in dit onderzoek. Het kan ook de weg vrij maken voor het toepassen van Model Predictive Control in de toekomst. Regelscenario's zijn op dit moment ontworpen op basis van ervaring en het is daarom interessant om te onderzoeken hoe regelscenario's zullen presteren als ze ontworpen en geoptimaliseerd zijn met behulp van een verkeersmodel. Het Multi-class omleiden van verkeer heeft goede resultaten laten zien voor de Model Predictive Controller en het is daarom interessant voor het havengebied om te onderzoeken of dit ook goede resultaten oplevert voor regelscenario's.

Interessante onderwerpen voor verder onderzoek zijn het toepassen van andere verkeersmanagementmaatregelen in het gebied rondom de Rotterdamse haven en gedragsonderzoek naar de reactie van weggebruikers op DRIP's.

Preface

This thesis marks the end of my Master Civil Engineering at the Delft University of Technology where I followed the track Transport & Planning. This research was commissioned by Rijkswaterstaat and done at the ITS Edublab, a cooperation by Rijkswaterstaat and the Delft University of Technology.

First I would to thank daily supervisors for their guidance throughout the thesis: Thomas Schreiter for helping me with the simulation model and inspiring me with his positive feedback and Hans van Lint for providing me with the necessary guidance on writing a structured report. I would also like to thank the other members of the graduation committee: my professor and chair of the committee Serge Hoogendoorn, graduation coordinator Paul Wiggenraad, coordinator of the ITS Edulab Henk Taale, external supervisor Victor Knoop and my supervisor from Rijkswaterstaat Lieke Berghout.

I would also like to thank Aroen Soekroella of the Regiodesk for showing me the traffic control centre and helping me with the information I needed for this thesis.

Furthermore I would like to thank my fellow students from the ITS Edulab for the fun but also useful and interesting discussions, practical jokes, and foosball games. I can look back fondly of this graduation period partly due to the fun times we had.

Last but not least I want to thank my family and Mariëlle for their support during the hard times working on my thesis.

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1 Introduction

The Netherlands have one of the most dense and congested highway networks in the world. According to the Dutch Construction and Infrastructure Federation (DCIF 2012) the expected vehicle loss hours in congestion in 2012 are in between 65 and 70 million hours. Reducing congestion is one of the highest priorities of Rijkswaterstaat, the Dutch executive agency of the ministry of Infrastructure and Environment. The reason why congestion needs to be tackled can be best illustrated by an example: a delivery van takes one hour to deliver a certain package if being delayed by congestion. Not being hindered by congestion, the van would take half an hour. Without congestion the travel time of the van is twice as short and thus he can deliver twice as much, doubling his earnings. Also the van driver would not be happy with the uncertainty of his arrival time. This also holds for person car – commuter – traffic and in higher extent for freight traffic. Therefore we can conclude that time is worth money. In the field of transport and traffic we call this value of time (VoT). Different types of traffic have different values of time. The value of time of freight traffic is about three times as high as person car traffic (Schreiter et al. 2012a). With this value of time the vehicle loss hours can be quantified to economic costs. If a traffic management measure would lower the total travel time spent, we can calculate the economic benefits with this value of time. This research compares two traffic management approaches bases on economic costs.

Rijkswaterstaat separates traffic policy in three categories: building, paying and using. Building stands for constructing new roads and adding lanes to existing roads. In other words: increasing the capacity of the road network. Paying is introducing a different payment system for the use of infrastructure, such as toll roads. Using stands for better utilization of the current infrastructure with traffic management. This last category has received a lot of attention of both the scientific and business field and the current study therefore focuses on this last category. Improving the usage of the current road network can be done by Dynamic Traffic Management (DTM), a set of traffic management measures which improve traffic flow. Some physical examples are Dynamic Route Information Panels (DRIP's) and traffic lights at onramps, also called ramp meters. These DTM measures can also be used for different user classes, such as passenger cars and trucks. These different classes have different characteristics – such as weight, engine power – and behave therefore different. Mixing these user-classes leads to speed differences which in turn lead to overtaking and weaving maneuvers. These weaving maneuvers can cause congestion. Applying user-class specific DTM measures can create certain traffic compositions downstream and slow this process down.

A part of Dynamic Traffic Management is traffic control. With traffic control road traffic can be managed to gain better traffic flows. On the Dutch highways the traffic control is done by Traffic Management Scenarios (TMS). These are sets of predesigned control measures to optimize the actual traffic state based on historical data and experience. Another way to manage highway flows currently widely researched in the field of transportation is Model Predictive Control (MPC). Instead of using historical data, MPC uses the current traffic state and calculates the optimal control signals based on the results of a prediction with a traffic model. In this study these two control approaches will be compared for the first time in combination with the use of the before mentioned multi user-class DTM measures. These traffic control methodologies with multi-user class DTM will be applied to the A15 highway near Rotterdam. The next paragraph will describe this highway.

1.1 Port of Rotterdam and the A15 Highway

The Port of Rotterdam is one of the largest harbors in the world and the number one in Europe. It is therefore of great importance to the economy of the Netherlands to keep this port accessible. There are three modes of transport that connect the port with the hinterland: barge, train and truck. For the latter the highway A15 is the main route, positioned south of the harbor as can be seen in Figure 1.1. Since the harbor is an industrial area there is a lot of commuter traffic as well.

Figure 1.1: Port of Rotterdam and the A15 (Source: Google Maps)

Due to being an access road of the port the A15 has a higher share of truck traffic than other highways in the Netherlands. In Figure 1.2 the truck shares during the day of the A15 are shown. The thick black line is the median of data on workdays and the thin grey lines are quartiles. As can be seen from the figure the truck share in peak hours is between 10 and 15 percent and between 20 and 30 percent off-peak. On the A15 there are a high number of accidents each year and truck accidents are usually more severe than accidents with person cars. Apart from the direct cost of congestion accidents cause, there is also a large economic cost. These factors cause the A15 to be the number 5 in the congestion top 50 in 2011 and the A15 was the number 3 in 2012. The number of vehicle loss hours in 2012 was 2500 (VerkeersInformatieDienst 2013). This highway is therefore an interesting case to apply multi-user-class traffic control.

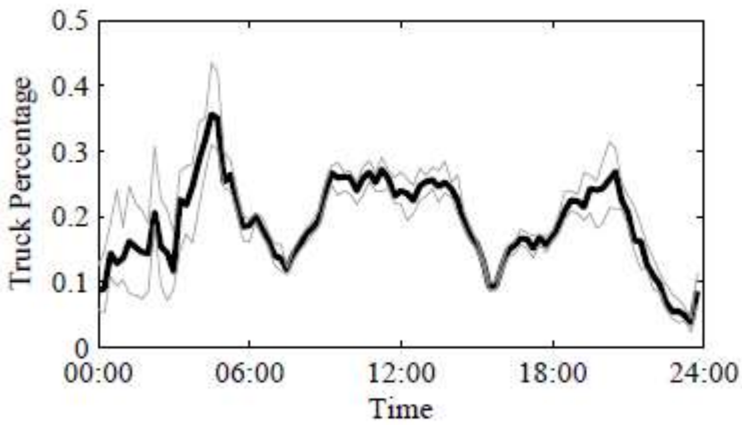

Figure 1.2: Truck share of the A15 (Source: Schreiter)

In the 1960s the Maasvlakte was created by reclamation and the creation of dykes to improve the competitiveness of the Port of Rotterdam. This created a new area to expand to. To meet the current demand and to keep its competitiveness the Port of Rotterdam started the construction of Maasvlakte 2 in 2008. Maasvlakte 2 is expected to be ready in 2013. Freight traffic will increase when this second Maasvlakte will be taken into use and can increase the aforementioned problems.
To respond to the growth of traffic and to solve the current congestion problem on the A15, Rijkswaterstaat started a project to upgrade the A15. This project is the so called MaVa project, where MaVa stands for Maasvlakte – Vaanplein, which are the boundaries of the project. The MaVa project will be executed by the consortium A-lanes. The construction works are underway since 2011 and should be finished in 2015.

1.1.1 MaVa project

In this paragraph the MaVa-project will be shortly introduced. The MaVa-project consists of a series of measures to increase the capacity of the A15 from the Maasvlakte to junction Vaanplein. The MaVa project has been divided its trace into five parts. These five parts can also be seen in Figure 1.3.

- Maasvlakte – Rozenburg: This piece of the trace is called the N15 and does not need any work besides adding a rush hour lane. It was recently extended to 2x2 lanes. The name will only be upgraded from N15 to A15.
- Rozenburg – Spijkenisse: There will be an extra lane added to the road from Rozenburg to Spijkenisse (or the Botlek Bridge). The exit at the Hartelkruis will be adjusted to support better throughput.
- Botlek bridge: There will be a new Botlek bridge built to replace the old one. It will have to open for passing ships less since it will be twice as high and twice as wide.
- Spijkenisse – Vaanplein: At this part of the road stretch a parallel road will be built. The road will then consist of a three-lane main road and a two-lane parallel road.
- Junction Vaanplein: To connect the A15 better with the A29, new viaducts will be build and an extra lane towards the south will be added (A-Lanes 2012).

These changes are made to accommodate the increasing traffic demand expected when the second Maasvlakte will be ready.

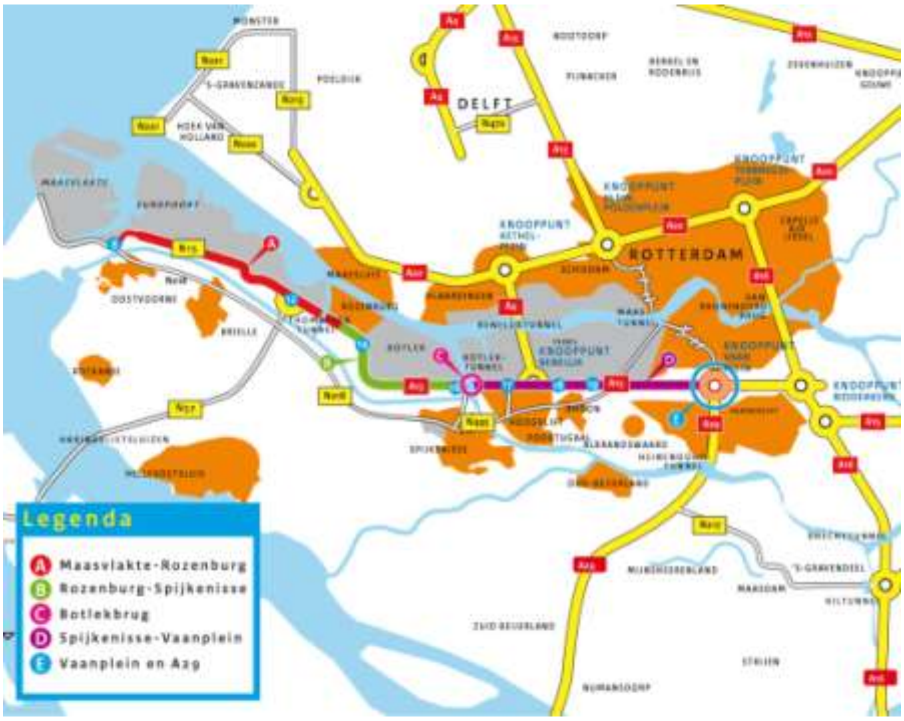

Figure 1.3: MaVa Project

During this construction the capacity of the A15 will be lower than in the normal conditions. A part of the construction contract with A-Lanes is that the availability of the A15 has to be maintained during the construction. This means that the current situation has to be secured during the period of the contract. The current situation means number of lanes and maximum speed on these lanes. The physical capacity of the road remains therefore the same. However the actual capacity can be assumed to be less, since the physical road layout will be changed. The capacity of a road is the maximum number of vehicles that can flow without causing congestion. Lanes will be narrower during construction and the road can be curved to redirect traffic around construction works. In this research the capacity reduction was derived from loop detector data from detectors in the bottlenecks during the construction. This capacity reduction has most influence on the points with the lowest capacity, called bottlenecks. Congestion starts upstream of bottlenecks and is therefore interesting points in the network to apply traffic control on.

1.1.2 Current bottlenecks

The A15 highway eastbound connects the Maasvlakte to the hinterland. The research area for this current study is the road until junction Vaanplein. At this junction the A15 will become a 4 lane road until junction Ridderkerk, where the traffic can split to the south, east and northeast. Currently this part of the A15 suffers from a daily congestion caused at two bottlenecks: one at Charlois and one at Spijkenisse. These bottlenecks can be seen in Figure 1.4.

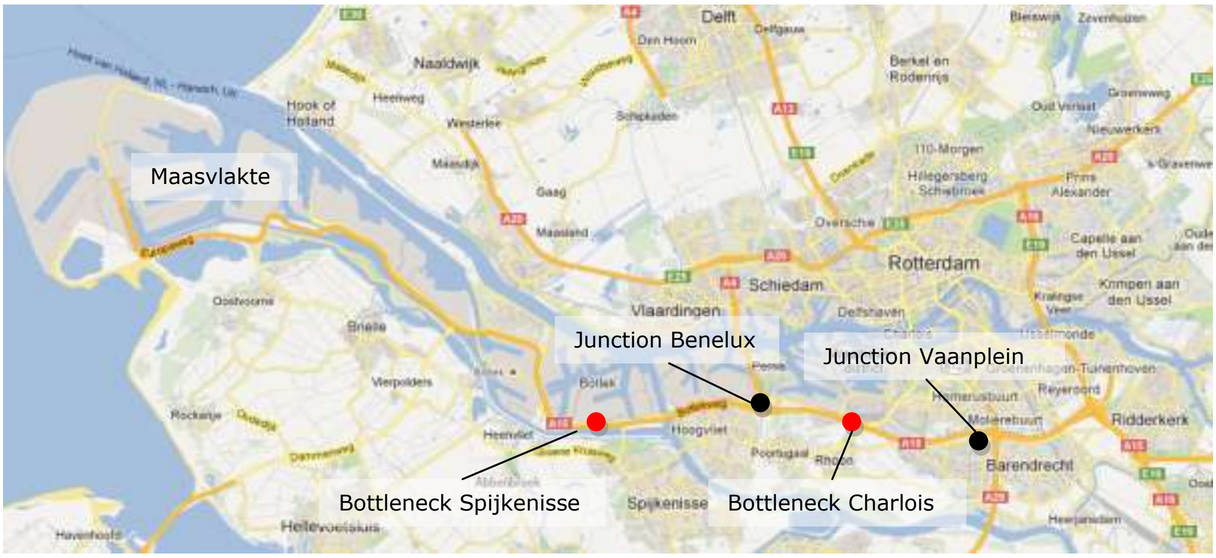

Figure 1.4: Indication of bottlenecks

To illustrate the bottleneck in this trace a speed contour graph of a heavy peak-hour in December 2011 is shown in Figure 1.5. A speed contour graph displays the speed of the traffic at a certain interval in space and time. 'Space' is set out on the vertical axis and 'time' on the horizontal axis. The colors in the graph represent the speed of the traffic at that point in time and space. The color scale is located at the right of the picture. For example a red area represents slow moving vehicles, where a green area represents vehicles with high speed. In the bottom left of the figure an arrow is drawn to represent the direction the traffic is flowing in the graph. We can also draw two lines (in black) where the congestion starts. These are the boundaries where the traffic is in free flow (green) downstream and is slowing down upstream (red). These bottlenecks are at km 56 (Charlois, top black line)) and km 44 (Spijkenisse, bottom black line). The red and black areas show how the congestion propagates upstream in time (downwards from left to right).

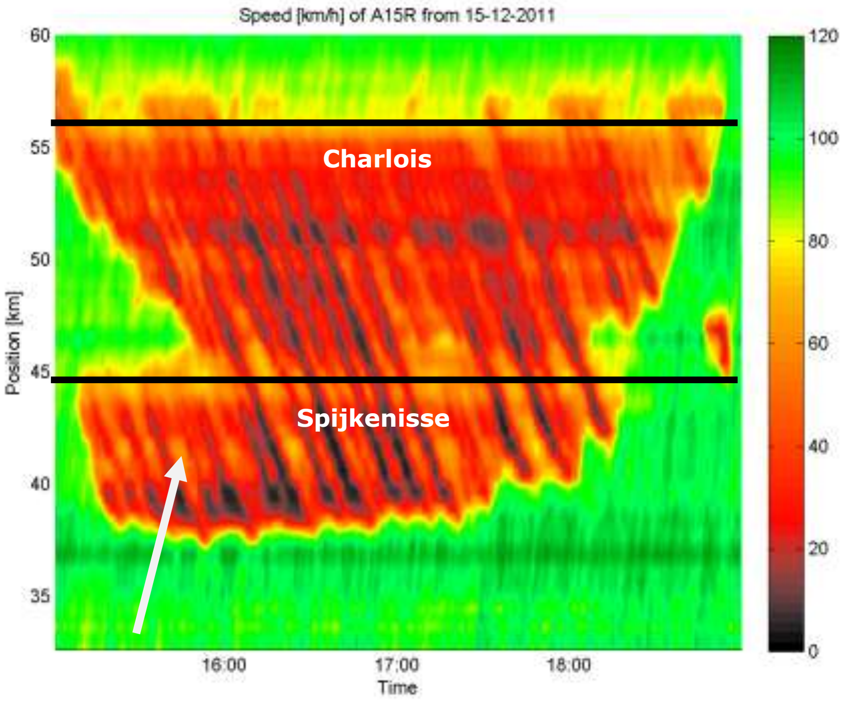

Figure 1.5: Speed contour graph of the bottlenecks, white line indicating the travel direction

To alleviate these bottlenecks we can apply traffic control to the A15 and thus reduce the economic costs. Different kinds of Dynamic Traffic Management measures can be controlled to optimize the traffic state.

1.2 Research Questions

In the previous paragraphs the economical benefits of reducing travel times on the A15 highway near Rotterdam was explained. The goal of this study is:

To make a quantitative comparison based on economic costs among Traffic management Scenarios, Single-class Model Predictive Control and Multi-class Predictive Control.

To answer this research question, a set of sub-questions will be answered:

- How can control methodologies be categorized?
- Which relevant Dynamic Traffic Management (DTM) measures that can be applied to the A15 can be found in literature?
- How can Traffic Management Scenarios and Model Predictive Control be compared?
- What Traffic Management Scenarios are currently in use?
- What are good performance indicators for judging Traffic Control?
- What is the gain of applying Model Predictive Control in comparison to applying Traffic Management Scenarios in terms of total cost and travel time per user-class?
- How do Model Predictive Control and Traffic Management Scenarios respond to changes in the predicted demand?
- What influence has the division of traffic into two user-classes on the performance of the Model Predictive Controller?

1.3 Reader

This study will make a comparison between Traffic Management Scenarios, the current state of the practice and Model Predictive Control. MPC is a widely researched control method, but not implemented in practice yet. The current study aims to examine the gain of implementing this MPC. A model study is performed to compare the methods quantitatively. The research area is the A15 highway from the Maasvlakte to junction Vaanplein in eastern direction. To get an idea how Traffic Management Scenarios and Model Predictive Control relate to other existing methods first in chapter 2 a literature study will be done where different control methods will be categorized. In this literature study there will also be looked at traffic management measures that can be used within these control methods as the actuator. The chosen control methods for the model study 'A15 Haven Uit' (the Traffic Management Scenario) and MPC within BOS-HbR, the used framework for the current study, will be described in chapter 3. 'A15 Haven Uit' is the Traffic Management Scenario developed for the harbor region of the A15 eastbound. The MPC in BOS-HbR is developed for the highway A15 and an alternative parallel route of the A15, the Vondelingenweg. This chapter will describe how the TMS and the MPC will be implemented in the same model to compare them fairly. After this description a choice of the traffic management measures to be implemented will be made. How these control methods will be compared in the model study will be described in the experimental set-up in chapter 4. The model study will be done for three cases: a heavy peak hour, a regular peak hour and for a day where an accident occurred. These three cases were chosen to measure how both control methods perform during daily traffic conditions (the peak hours) and how they perform when an unexpected event happens, this event being an accident. The experimental set-up will also introduce the performance indicators on which the TMS and MPC will be evaluated. Then the performance of both control methods in the model study will be discussed in chapter 5. Finally an answer to the research question will be given in the conclusion of this research and recommendations for the future will be given. In Figure 1.6 the schematic overview of this report and how the different chapters relate to each other can be found. The different chapters are numbered and important related subsections are connected with arrows.

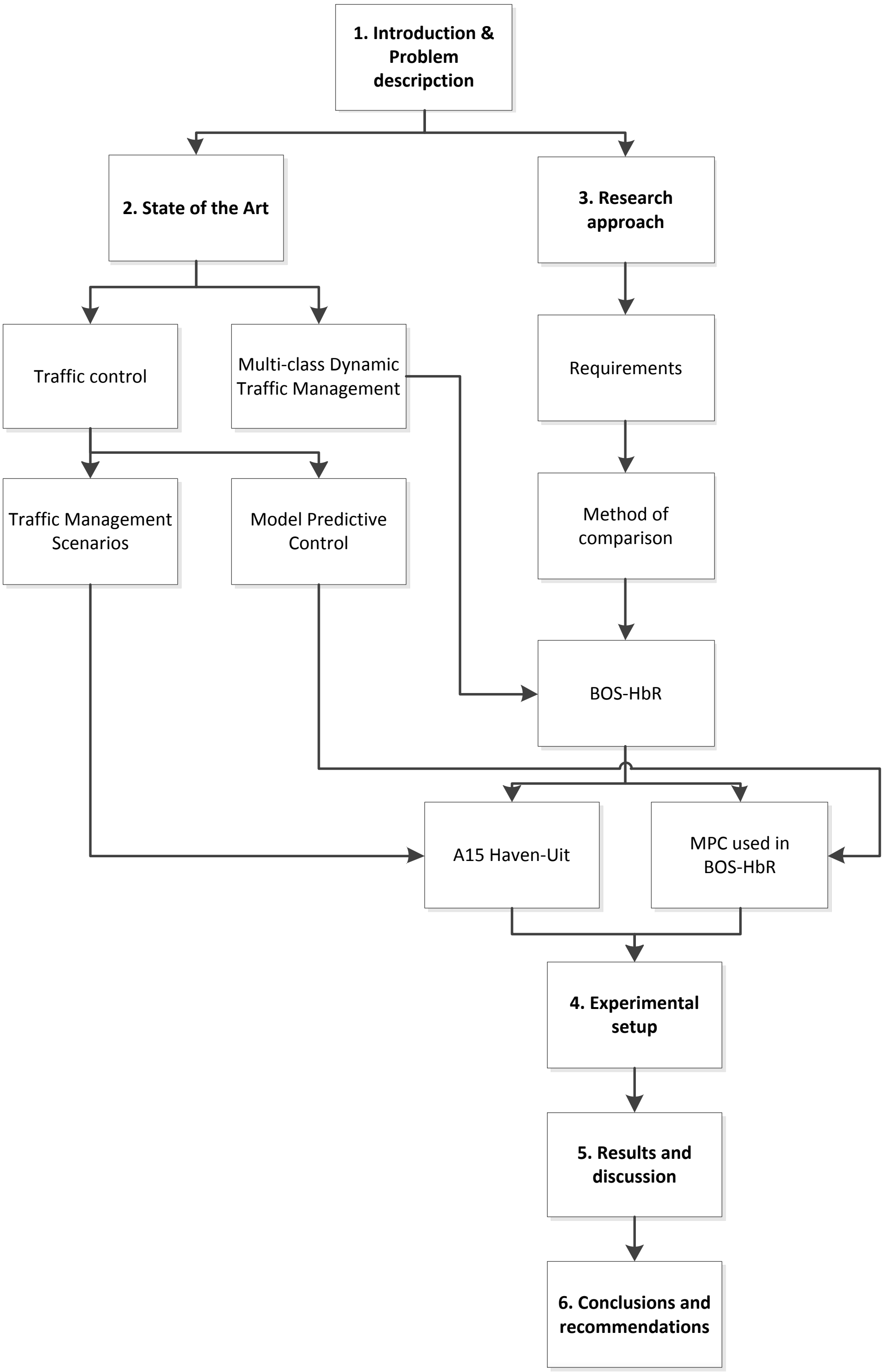

Figure 1.6: Schematic overview of the report

2 State of the Art

In this chapter the state of the art will be discussed. This will be a summary of what can be found in literature about traffic control and in particular Traffic Management Scenarios and Model Predictive Control, and Multi-class Dynamic Traffic Management. Traffic Management Scenarios and Model Predictive Control will be categorized and compared with other traffic control measures based on their properties to sketch a qualitative picture on how these two control measures relate. Firstly traffic control will be introduced. Traffic Management Scenarios and Model Predictive Control will be discussed in paragraph 2.2 and 2.3 respectively. Finally multi-class Dynamic Traffic Management is described in paragraph 2.4.

2.1 Introduction to traffic control

2.1.1 Basic traffic control scheme

Traffic control is a method to guide traffic through a road network and thus increase the capacity of a network to create shorter and more robust travel times for the road user. Every traffic control method can be deduced to a basic scheme shown in Figure 2.1. The traffic state in the systems is measured by traffic sensors, usually loop detectors in the road surface. The state will then be estimated by an algorithm. The estimated state is the input for the controller which will give control signals to traffic actuators as output. These actuators can be traffic lights or information panels.

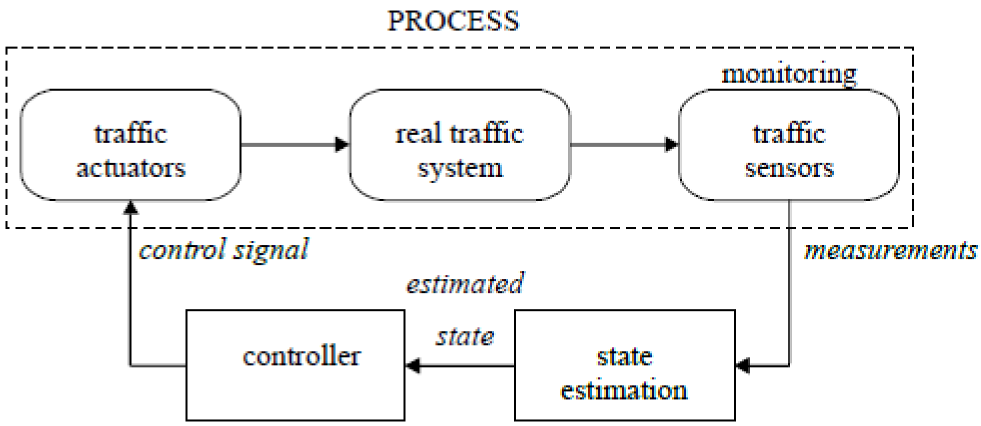

Figure 2.1: General traffic control scheme (Lint et al. 2010)

The process in the figure is displayed as a loop, but this is not necessarily the case. Examples of both open as closed loops can be found in paragraph 2.1.3.
In the rest of this section several control approaches will be introduced and categorized based on their adaptability and prediction horizon. These last two properties will be introduced first.

2.1.2 Control approach properties

In recent years new traffic control technologies arose. To categorize these new technologies as well as the known technologies we can categorize them with two different properties. These properties are adaptability and prediction horizon. A brief explanation follows.

Adaptability

Adaptability is the ability to change the control schemes based on the current situation. Non-adaptive control approaches will have a preprogrammed control scheme which will not change if the circumstances change. To illustrate this we can divide adaptability into three parts:

The first part is the use of live data: A control method can retrieve the current state and use that as input for the control signal or use past data as input. If live data is used the method can also have one or both of the following two properties:

- Feedback: If a control scheme uses live data, it can have an open loop or a closed loop. In an open loop scheme the control signal is applied once, in a closed loop scheme the control scheme gets feedback after the control signal has been implemented and it can change the control signal accordingly.
- Optimization: If a control scheme uses live data, it can run an optimization algorithm to find an optimal control signal or have a preprogrammed control signal. If the control scheme does not use live data, it can still use optimization. This optimization is then based on historical data.

Note that the use of live data does not imply feedback, but using feedback does imply the use of live data. The adaptability of a control scheme is higher when it can be categorized further to the right in Figure 2.2.

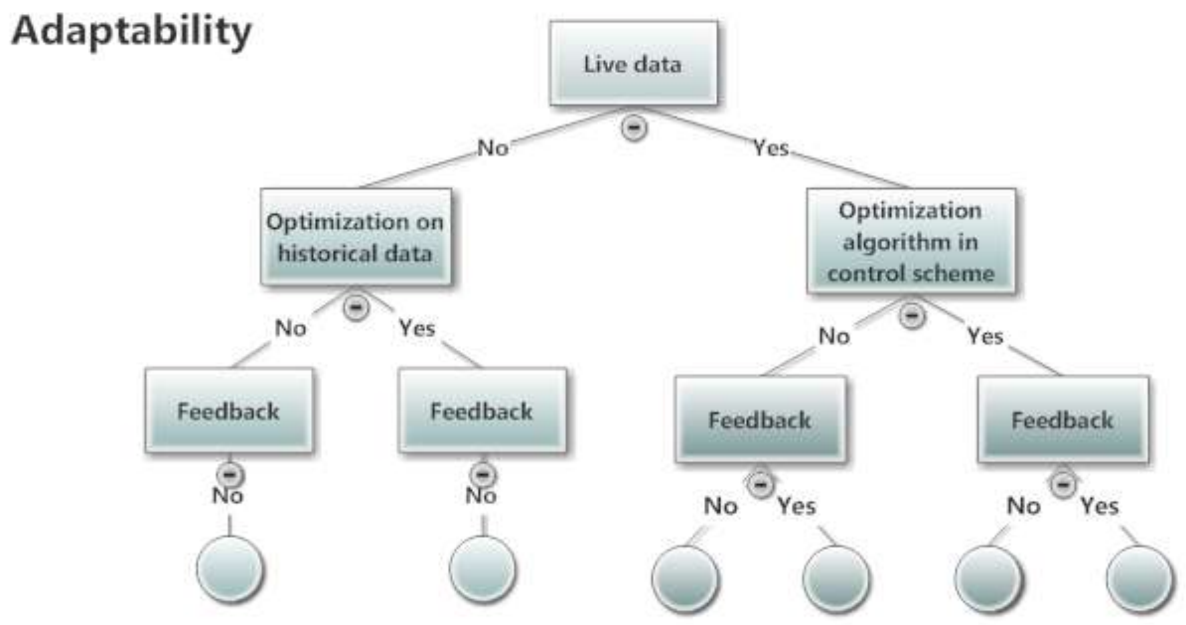

Figure 2.2: Adaptability tree

Prediction horizon and planning

A control approach tries to get a downstream traffic state as good as possible for a certain time forward. The prediction horizon, or planning in cases where the control approach applies a predesigned scheme, is the distance in time forward a control approach looks. A fixed intersection control scheme is an example of a control approach with a prediction horizon of zero. Control scheme will not predict what happens downstream, it only considers the current situation of the intersection. In paragraph 2.2.2 control approaches will be introduced that do predict.

2.1.3 Categorization of traffic control

To categorize the different control approaches, we can use a graph where we can visualize this. The graph used can be seen in Figure 2.3. This graph will be filled in at the end of this paragraph.

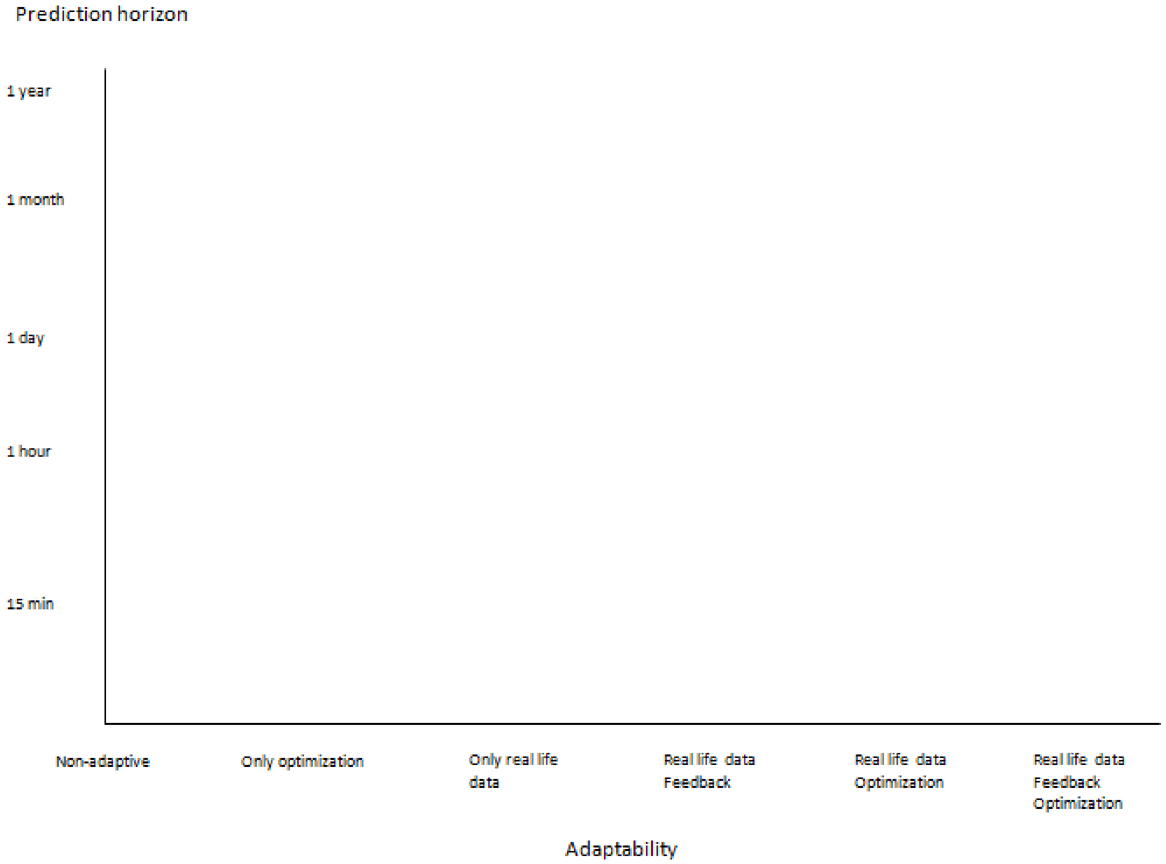

Figure 2.3: Traffic control categorization graph

The higher the adaptability and longer the prediction horizon the higher the computational complexity. We can fill this graph with a few examples of traffic control, to illustrate the position of the different control approaches in comparison with each other. These examples are: controlled intersections with Fixed Time Control, controlled intersections with Vehicle Actuated Control, Optimal Control, Traffic Management Scenarios and Model Predictive Control.

Vehicle Actuated Control and Fixed Time Control

The most common traffic control measures people encounter are controlled intersections. We can distinguish controlled intersections in two phases: design and operation. In the design phase the structure, which is the order and time in which the different traffic lights turn green, is calculated. In the operation phase the designed structure is executed.

Two methods to control an intersection are described, Vehicle Actuated Control and Fixed Time Control. For both holds the following: when a traffic light structure is calculated, the demand is known from historical data. The optimal structure is based on the peak demand of the day. In this phase the structure of the controlled intersection is optimized, and the current traffic state is ignored. The prediction horizon is very long; the structure is calculated based on peak demands during a year. The most commonly used type of control in operation in the Netherlands is Vehicle Actuated Control. Here the cycle time and green times of the controlled intersection are dependent on the presence of vehicles which is measured by detectors in the road surface (Muller et al. 2010). The controller will not get any information downstream of the intersection, so it has no feedback loop there. The controller uses real time data from loop detectors in the asphalt though. Since the cycle times can change based on the demand, there is certain adaptability. The prediction horizon of the operation is equal to the cycle time, which is not more than a few minutes. When there are no detectors used, the controller only executes the pre-calculated structure. This method is called Fixed Time Control.

Traffic Management Scenarios

Traffic management on the highways of the Netherlands is largely done with traffic management scenarios. Traffic management scenarios are a set of control actions which are taken if a traffic jam is detected. As with methods to control intersections, traffic management scenarios can be divided into two phases, the design and the operation. The design of the scenarios is an optimization done with data from loop detectors over a couple of years, as is with Vehicle Actuated Control and Fixed Time Control discussed before. The prediction horizon here is therefore very long. The adaptability is the same as for these two intersection control methods. In operation the traffic management scenarios are adaptive to a limited extent, since the control scenarios are simply put 'on' or 'off' based on the current traffic situation. This turning 'on' and 'off' of the scenarios is managed by a human controller. The length of the period the scenarios are put on can change, but other parameters such as green time of ramp meters are fixed. These values are not optimized, so we can speak of feedback with a human in the loop, and no optimization. Traffic management scenarios are executed at traffic control centers and are activated by people. These traffic controllers can predict what will happen to the traffic state in the near future based on experience although this is not a calculated prediction. The prediction based on the current traffic state and experience of a traffic controller is short compared to a prediction done by a traffic model. So traffic management scenarios have a low prediction horizon.

Optimal Control

Optimal control approaches are open loop control approaches. They retrieve a traffic state, calculate the optimal control signal and then apply that signal. If we look again at adaptability, optimal control can thus be defined as open loop control that uses real time data and optimization. The prediction horizon varies with the method, but it can be from a few minutes to a few hours.

Model Predictive Control

In Model Predictive Control the traffic state is retrieved with loop detectors and estimated with an estimation method. The controller predicts the future traffic state, then optimizes a control signal (of e.g. a ramp meter) and applies it. The prediction horizon for this method varies from 5 minutes to 2 hours. Each cycle the traffic state is calculated so the controller gets feedback on how it performed, therefore MPC is very adaptive. Model Predictive control will be further explained in paragraph 2.4.

Conclusion

To conclude we can fill in Figure 2.3 with the control approaches mentioned before.

The abbreviations used in the figure are as follows:

CI: Controlled intersection;

TMS: Traffic management scenarios;

MPC: Model Predictive Control

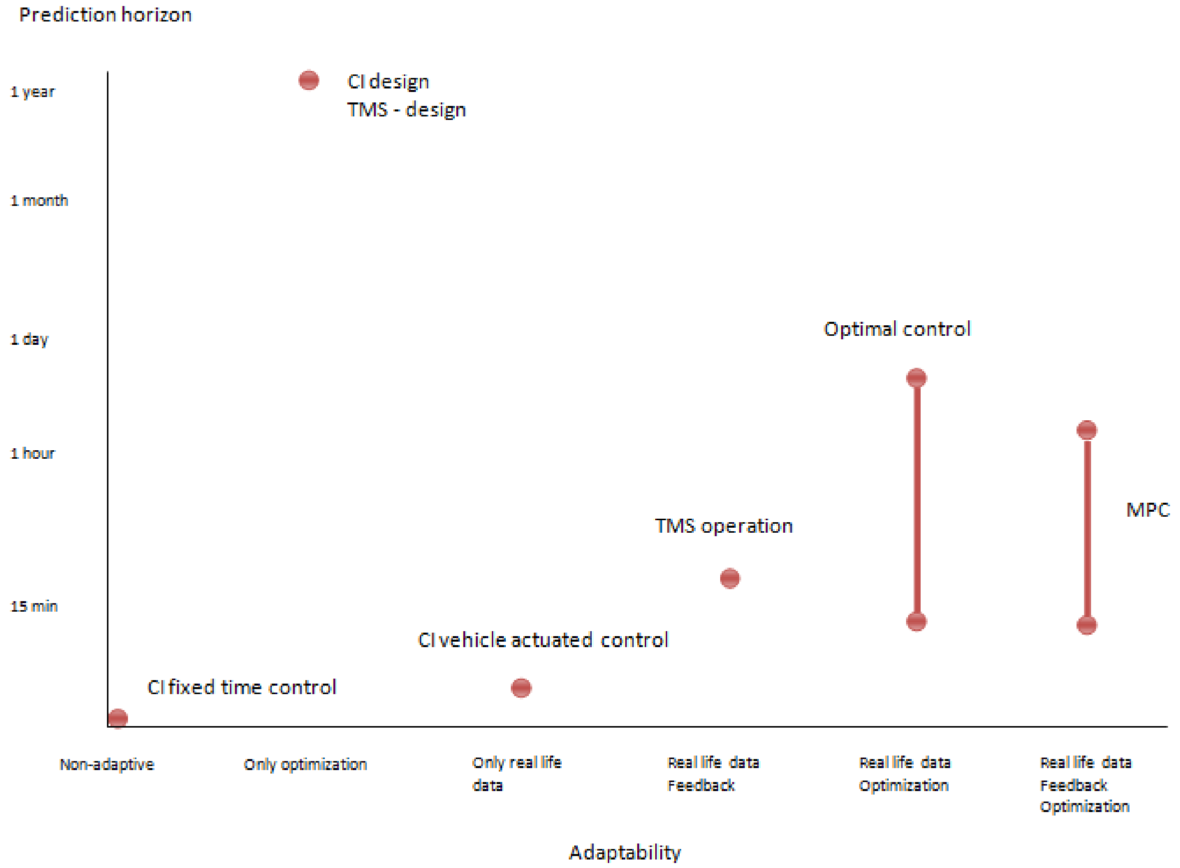

Figure 2.4: Traffic control graph

The figure shows that the recent developments are place more to the upper right in the figure. Higher adaptability and a longer prediction horizon require more computational power. A control measure that would be more to the upper right is something that could be considered better. The reason such a measure possibly does not exist yet is that the computation time of such a measure would be too long to be effective.

In this research the comparison will be made between the state of the practice, which is the use of Traffic Management Scenarios and currently used on the A15, and the state of the art, which is Model Predictive Control. These will be explained in the next two paragraphs.

2.2 Traffic Management Scenarios

As was mentioned in the last paragraph, Traffic Management Scenarios will be explained here. Traffic Management Scenarios are the current state of the practice. This means that they are currently applied to control the highway network of the Netherlands.

2.2.1 GGB

Traffic Management Scenarios (TMS) are the result of 'Gebiedsgericht Benutten' (GGB) which means Regional Cooperative Traffic Management, a process approach to create regional traffic management. This approach unites different stakeholders within a region to come to solutions for regional traffic problems. This method analyzes roads and describes their function. These functions can be: freeways, urban belt-ways, urban axis and regional connecting roads. After this a priority map can be made by drawing different preferred and alternative routes from the areas of interest around the network. Roads that are used heavily in this assignment have a high priority. Roads that are unused or lightly used can be considered support roads. Support roads can be used to redirect traffic. Then a level of service for each of these roads can be determined which will be called the frame of reference. If the desired level of service of a certain road is higher than the actual situation, GGB calls this a bottleneck. Note that this definition is different to the one used in traffic management. To alleviate these roads, traffic management can be applied (Adams et al. 2011). This can lead to the design of Traffic Management Scenarios. Traffic Management Scenarios are optimized based on historical loop detector data. This way TMS are likely to solve congestion that resembles a typical peak-hour in the past.

2.2.2 Basic principle

In this research traffic management scenarios that reroute traffic are considered. Traffic Management Scenarios can also apply other Dynamic Traffic Management measures, such as dynamic speed limits, but these are not considered in this research. A TMS is proposed to be activated by a human controller in a traffic centre when the traffic matches activation criteria – or trigger - e.g. the traffic flows traveling below a certain average speed. The controller checks if the measures to be applied are available. For rerouting these measures are alternative routes, so in this case the controller checks if these routes are available. This availability can be a flow or speed limit. If the scenario is triggered and the measures to be used are available, the controller activates the TMS. The TMS will be deactivated if the measures become unavailable, e.g. the alternative route will become congested, or the traffic matches deactivation criteria – or deactivation triggers. This process can be summarized in a flow chart which can be seen in Figure 2.5.

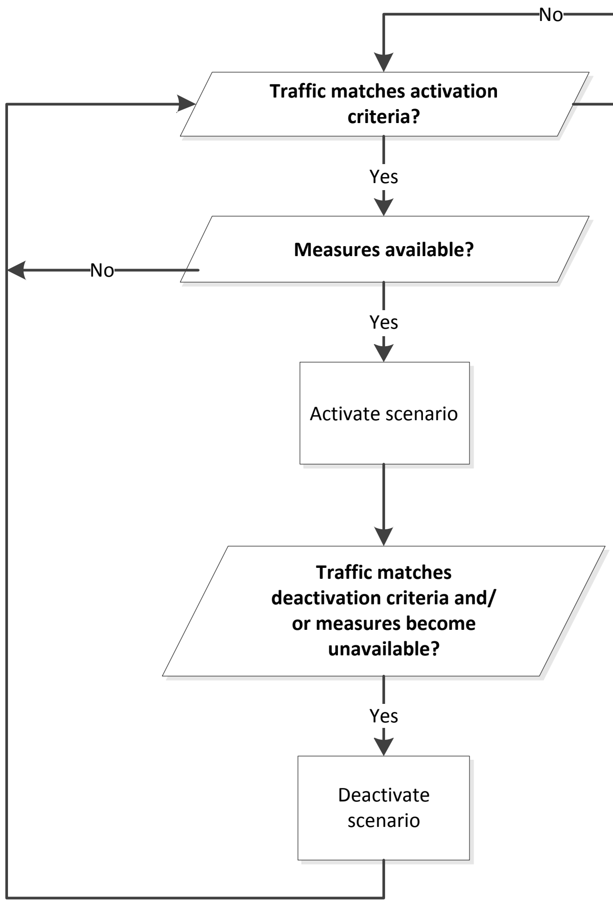

Figure 2.5: Traffic Management Scenario flowchart

2.2.3 Advantages and disadvantages

Here the advantages and disadvantages of TMS will be described shortly.

Advantages

- Feedback: Traffic Management Scenarios retrieve the current traffic state by detectors in the road surface. The traffic can also be monitored with cameras next to the road. An operator involved in the process can see the results of the control actions of the scenario and adjust accordingly.
- Complexity during operation: During operation TMS have almost no calculation time at all. A controller sets the scenario in motion after being warned by a trigger, the same holds for turning off the scenario.

Disadvantages

- Design based on experience: Traffic engineers can create well performing Traffic Management Scenarios (Bereik 2011), but design based on traffic models can compute exact control signals for which the traffic system will perform best.
- Adaptability: During operation the scenario can be turned on or off, but cannot be changed in operation.
- Human operator in the loop: The traffic system is a complex system with too many degrees of freedom to handle without support.

2.3 Model Predictive Control

In this paragraph Model Predictive Control will be explained. Also the advantages and disadvantages will be mentioned.

2.3.1 Basic principle

Model Predictive Control consists of four elements: prediction, performance evaluation, optimization and a control action. In this paragraph we will introduce the scheme and describe the different elements shortly.

Prediction: The future behavior of a traffic system is predicted for a so called time horizon. This will be done with a traffic model. The prediction has three inputs of which two are shown in Figure 2.6. These are:

- The current state of the traffic system;
- The planned control signal;
- Expected disturbances (demand).

The traffic state has three variables of which two can be measured by loop detectors. These are speed and flow. The density can be derived with these variables from the fundamental diagram (Hoogendoorn et al. 2005). The disturbances are external influences on traffic which cannot be controlled, such as the weather and distractions.

Performance evaluation: The performance is measured by an objective function. This can be the development of the traffic state during the prediction period, but also takes the planned control signal into consideration, since some signals are less desirable than others.

Optimization: The MPC controller finds the optimal control signal by using a optimization algorithm.

Control action: The optimization has a control action as output. The control action can activate for example: ramp metering (Heygi et al. 2005), enabling a peak hour lane, route guidance or dynamic speed limits. The new traffic state will be predicted using this control action. This control action is the new input for the traffic system.

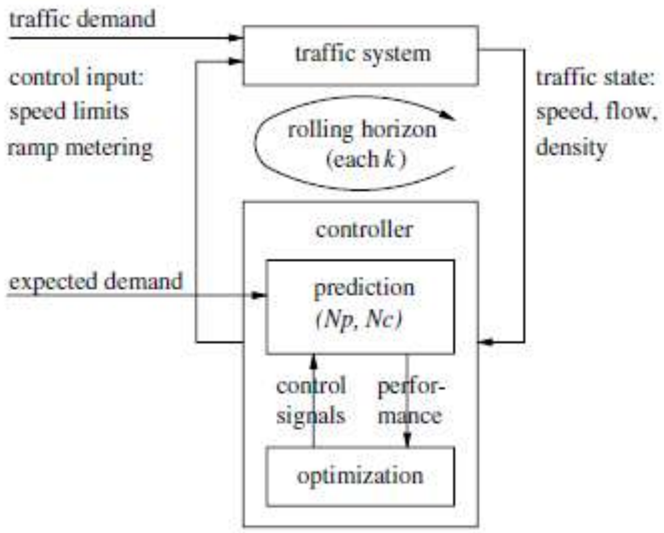

Figure 2.6: Model Predictive Control loop (Source: (Heygi 2004))

2.3.2 Formal description (Heygi 2004)

MPC's use two different time steps, one for the simulation (T) and one for the controller (T_c), where T is a fraction of T_c, with $T_c = MT$, where M is an integer. The time can then be noted as kT and k_cT_c. Note that this leads to $k = Mk_c$.

Prediction

It is assumed that the future state is a function of the current state $x(k)$, the vector of control inputs $u(k_c)$ and disturbance vector $d(k)$. This results in:

$$x(k+1) = f(x(k), u(k_c), d(k)) \tag{2.1}$$

With:

$$Mk_c \leq k < (k_c + 1)M$$

The prediction is repeatedly applying (2.1) during the simulation. The inputs for the prediction are the expected disturbances

$$\mathrm{d}(k) = [d(k)d(k+1)...(d(k+MN_p - 1)] \tag{2.2}$$

And control signals

$$\mathrm{u}(k_c) = [u(k_c \mid k_c)u(k_c + 1 \mid k_c)...u(k + N_p - 1 \mid k_c) \tag{2.3}$$

This is a matrix of all computed control signals at time steps $k_c...k + N_p - 1$ based on the information known at time step k_c. The future traffic states can now be predicted based on (2.1), (2.2) and (2.3):

$$\mathrm{x}(k) = [x\wedge(k+1 \mid k)...x\wedge(k\_MN_p - 1)]$$

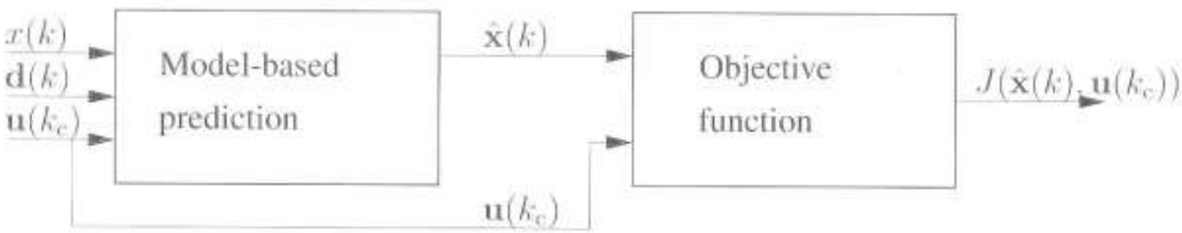

Figure 2.7: MPC objective function

Performance evaluation

The performance of the traffic system is calculated based on the prediction $\mathrm{x}(k)$ and control inputs $\mathrm{u}(k_c)$. This performance evaluator (expressed as $J(\mathrm{x}(k), \mathrm{u}(k_c))$) can be for example 'total travel time spent' in the network or 'total cost'.

Optimization

The controller finds control signal $\mathrm{u}(k_c)$ that minimizes $J(\mathrm{x}(k), \mathrm{u}(k_c))$ for any given state $x(k)$. The control inputs are only optimized for the control horizon N_c. The optimization block in Figure

2.8 has an algorithm that minimizes $J(\mathrm{x}(k), \mathrm{u}(k_c))$, suitable for the traffic model and objective function. The optimal control signal is noted by $\mathrm{u}^*(k_c)$.

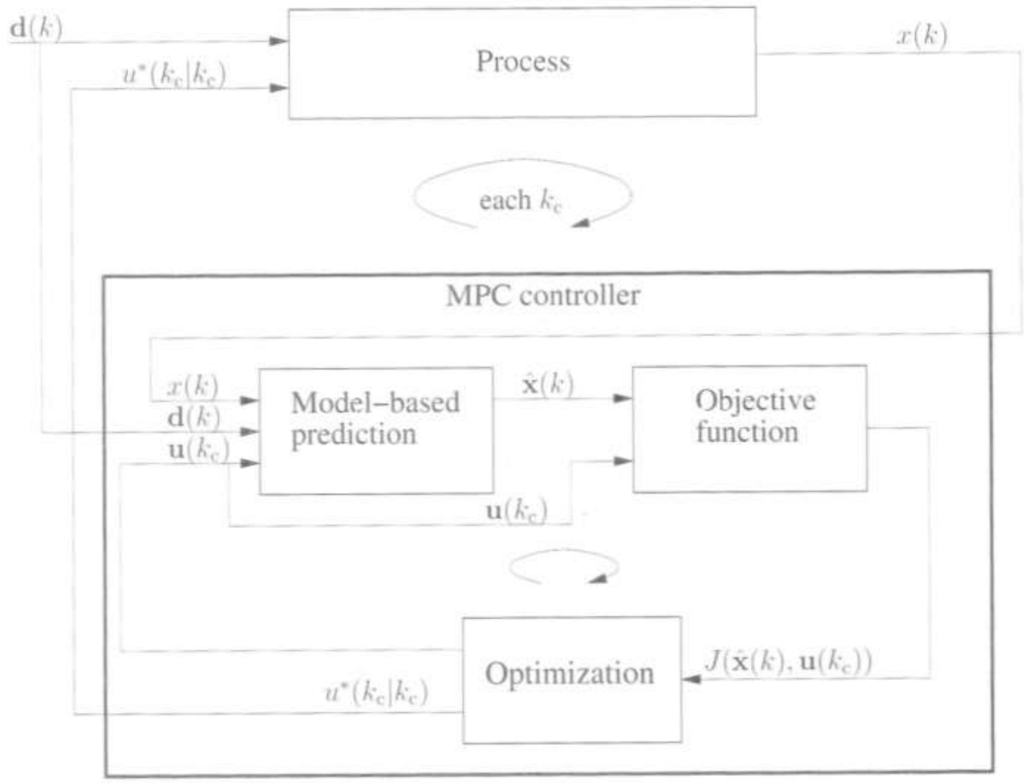

Figure 2.8: MPC control scheme (Heygi 2004)

Control action

Only the first column from matrix $\mathrm{u}^*(k_c)$ is used in the process. In the rolling horizon the procedure from prediction to control is repeated at controller time step $k_c + 1$ with the prediction horizon shifted one time step forward.

2.3.3 Advantages and disadvantages

Here the advantages and disadvantages of MPC will be described shortly.

Advantages

- Feedback: MPC works with a rolling horizon k_c. For each k_c the actual (traffic) state is taken as input for the model. This means that the real effects of the control actions are used for the model. The continuously updating of the model prevents model mismatches and unknown disturbance $d(k)$ to create suboptimal control actions.
- Few variables to tune: Only prediction horizon N_p, control horizon N_c and the parameters of the objective function need to be tuned. The determination of the two horizon variables is relatively easy while the parameters of the objective function require some iterations of adjustment.

- Constraint formulation: In control problems control values, signal rate of change and state of the process are often bound by minimum and maximum values. In MPC these constraints are easily incorporated in the optimization part of the loop (see Figure 2.8).
- Modularity: The MPC controller consists of different modules: the prediction model, objective function, constraints and optimization algorithm. These modules can be independently replaced, without affecting one of the other modules.
- Adaptability: This modular structure also implies that the model can update each iteration so changing process behavior can be implemented in the controller. This was also explained in paragraph 2.1.

Disadvantages

- Complexity: In general, optimal control technologies can become too complex computationally and mathematically speaking if the control horizon is long or the number of degrees of freedom is large.
- Availability of correct data: An MPC can only function if the traffic system can be measured.
- Calculation time: For complex systems the control horizon is bound by the computation time the traffic model needs to find the optimal signal.
- Valid traffic model: For each application of MPC a traffic model is needed that is valid for the situation where it is applied.
- Optimization: In a complex solution space multiple optima exist. Optimization methods can get caught in local optima where the global optimum has to be found.

2.4 Multiclass Dynamic Traffic Management

The control methods discussed before use traffic management measures. Because the A15 highway has a high share of truck percentage this research will investigate multi-class Dynamic Traffic Management measures. Two of these measures will be described in this paragraph, for these measures are considered for this research: ramp metering and route guidance. Peak hour lanes are not possible during construction and dynamic speed limits are impossible due to the building contract. The speed limit has to be constant on a 100 km/h.

2.4.1 Ramp metering

To prevent traffic from breaking down into congestion the inflow can be reduced. On highways this can be done with ramp metering. A ramp meter is a traffic light on an onramp dosing the inflow on the main carriageway. Ramp meters are usually single class and do not make distinctions between vehicle classes. When one of the goals is to optimize the economic costs (Schreiter et al. 2012a) or create an optimal traffic composition on the main carriageway one can introduce a multi-class ramp meter (MCRM). The onramp can be divided into two lanes, one for each class, assuming the use of two vehicle classes (Schreiter et al. 2011a). An illustration of a MCRM can be found in Figure 2.9

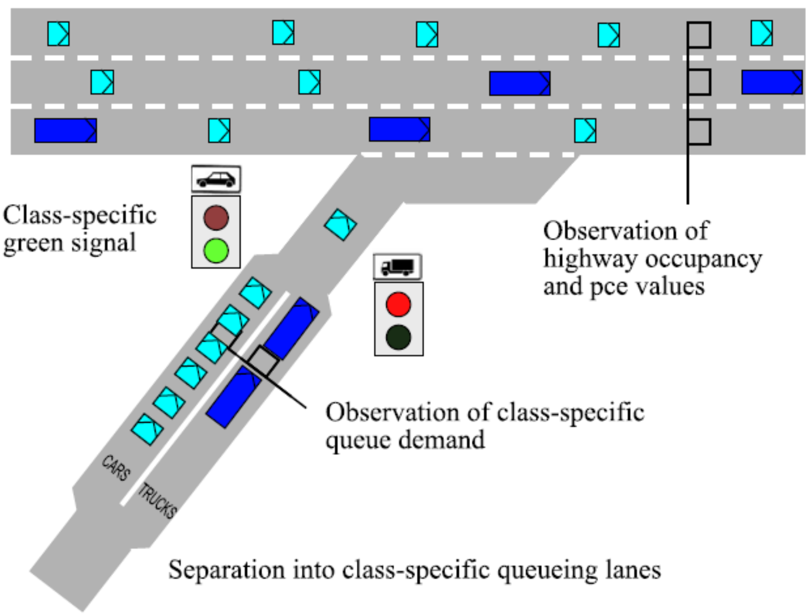

Figure 2.9: Multi-class Ramp Meter (Schreiter et al. 2011a)

2.4.2 Route guidance

To make optimal use of the existing capacity a traffic controller can reroute traffic. This way a main route can maintain a free flow state due to traffic rerouted to an alternative route. This is done by activating Dynamic Route Information Panels (DRIP's) located alongside the road. (Landman et al. 2012). To gain homogeneity on roads and to minimize economic costs car and freight traffic can be rerouted separately. This has had positive results (Schreiter et al. 2012b).

2.4.3 Multi-class Dynamic Traffic Management and Model Predictive Control

The combination of multi-class DTM and MPC has received attention in recent years. An MPC controller with multi-class dynamic speed limits and multi-class ramp metering showed a improvement of 7% on the total travel time in the network (Deo et al. 2009). A research on MPC and route guidance shows an improvement of 10% during incident conditions (Schreiter et al. 2012b).

2.5 Synthesis

In this chapter a literature review was done on traffic control, including the two control methodologies that will be compared in this thesis, and multi-class traffic management measures. First a categorization of control methodologies was made to illustrate how TMS and MPC relate. As Figure 2.4 shows clearly is that both methods can be called adaptable to the traffic situation, where MPC uses feedback and an optimization algorithm in its control loop where TMS only uses feedback with a human controller in the loop. It can be concluded that MPC is more adaptable based on these criteria than TMS. This categorization was followed by a detailed description of how TMS and MPC work. Finally ramp metering and route guidance were described. These control measures are applicable in the current infrastructure where peak-hour lanes and dynamic speed limits are not. In the next chapter will be explained that ramp metering is also not an option for this research.

3 Research approach

In chapter 2 several traffic control approaches were described and it was explained that Traffic Management Scenarios and Model Predictive Control will be compared. In addition the comparison between single-class and multi-class Model Predictive Control will be made. The requirements for a fair comparison of the two approaches will be discussed in 3.1 and it will be explained how the two approaches should be compared fairly in 3.2. Furthermore the BOS-HbR framework, which stands for Decision support system for the Port of Rotterdam Authority (In Dutch Beslissing Ondersteunend Systeem voor het Havenbedrijf Rotterdam), will be described in 3.3. This is a framework that fulfills the criteria from 3.1 and 3.2 and is used in this research to compare TMS and MPC. Finally 3.4 and 3.5 will discuss the TMS and MPC used and implemented in BOS-HbR for this research and respectively.

3.1 Requirements

To create a fair comparison between TMS and MPC the method of comparison must fulfill a set of requirements. These requirements should enable valid conclusions and recommendations at the end of this thesis.

3.1.1 Network

Technically two methods can be tested on different networks and used to calculate what the (relative) gain of applying a control measure is. However, this does not create a fair comparison unless different networks have the same properties e.g. length, capacity, number and locations of bottlenecks. Therefore using the same network in preferably the same traffic model is advised.

3.1.2 Signals

Both methods should be able to change the same control signals. Signals that can be controlled by one method while the other cannot can influence the output of the comparison. For example, if MPC can control a virtual ramp meter while the TMS cannot, the MPC can perform better for this is the result of applying a ramp meter instead of applying MPC. To be certain that an improvement is the result of applying a control method and not a control measure, the same control measures and signals should be used.

3.1.3 Input data

It is moreover important that both methods react to the same type of input data. This means that the starting point of each method should be the same. Both methods can use loop detector data as input and derive speeds, flows and densities. For example, operators in the traffic control center can also use video camera images, but these are not available for an MPC and cannot be used for one.

3.1.4 Output data

A more obvious requirement for a comparison is that the output must deliver the same kind of data so that the performance of both methods can be evaluated. Also the comparison method should deliver data that is needed calculate values of performance indicators. An example of good output data is loop detector data in the case that both control methods can be applied in practice. Then TMS and MPC can be compared well. However, since MPC is not applied in the current practice, this is not a feasible situation. Another way to compare these two methods is by predicting the results of both methods with the same traffic model.

3.2 Method of comparison

To compare a control method applied in practice and one that is currently only applied in science has some restrictions. MPC cannot be applied in practice yet since the systems are not available yet. Therefore this research uses a simulation experiment. A general scheme for this comparison can be seen in Figure 3.1.

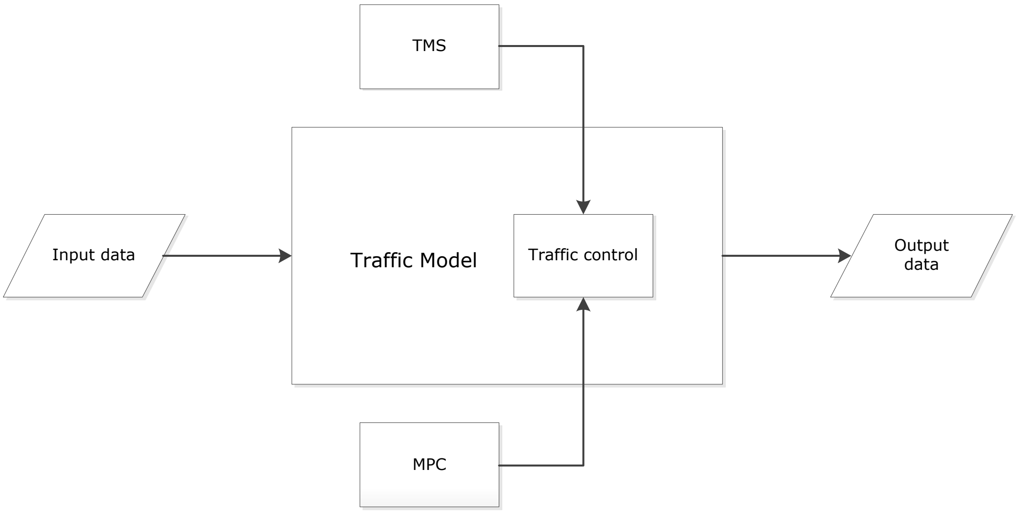

Figure 3.1: Scheme for comparing control methods

As can be seen in the figure the simulation experiment uses the same input data for both the TMS as the MPC. By using the same traffic model both methods will also have the same type of output data. The analysis on how the control methods perform can be done with the same performance indicators judging the same kind of data. The control component in the traffic model should be a changeable module and should have the possibility to be left out to model a base case.
In this research there is chosen for a framework called BOS-HbR that uses this scheme. BOS-HbR will be discussed in the next paragraph.

3.3 BOS-HbR

BOS-HbR (Schreiter et al. 2011b) is an existing MPC framework developed specifically for the A15 highway in the eastern direction commissioned by the Port Authority of Rotterdam. The daily congestion on this highway and the frequent accidents on this road in combination with relatively high average value of time of the traffic make this road stretch a delicate link in the hinterland connection of the port. The network of the model will be introduced in paragraph 3.3.1. The estimator used in this network is the Adaptive Smoothing Method (Treiber et al. 2002) and it uses the first order multi-class traffic model Fastlane (Lint et al. 2008) as its predictor. These methods will be illustrated in paragraph 3.3.2. As was mentioned in the introduction, this highway has a high share of truck traffic and therefore multiple user classes will be defined in paragraph 3.3.3.

3.3.1 Network

The network that BOS-HbR uses can be found in Figure 3.2. It shows the A15 highway in the eastern direction. The red stars are the bottlenecks during the evening peak hour. BOS-HbR uses route guidance as actuators, which redirect traffic to an alternative route marked in blue in the figure.

Figure 3.2: BOS-HbR network

3.3.2 Control scheme

In **Fout! Verwijzingsbron niet gevonden.** the control scheme of BOS-HbR is shown. This is an pplied example of Figure 2.6. It consists of three parts which will be described in this paragraph. The control part in this research will be done either by a TMS or an MPC. The TMS and MPC uses will be described in 3.4 and 3.5 respectively.

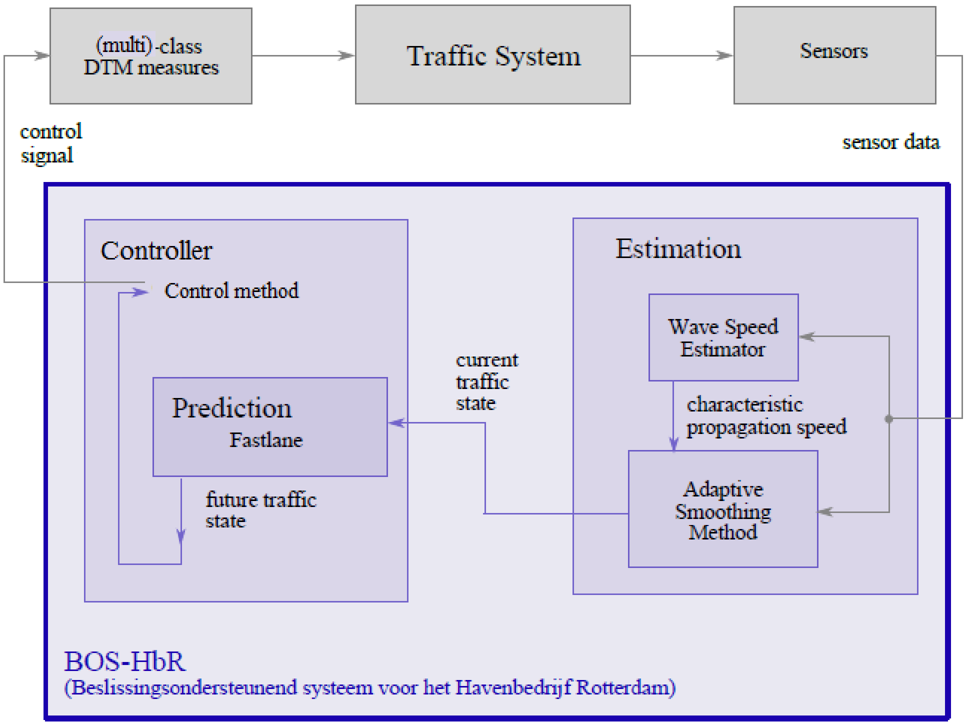

Figure 3.3: Control scheme of BOS-HbR (Schreiter 2012)

Estimation

Firstly the current traffic state, which will serve as the input data for the experiment, is estimated by collecting loop-detector data from the Regiolab and Roportis databases, in these databases data from the A15 and the Vondelingenweg are stored. This data is filtered by the Adaptive Smoothing Method (Treiber et al. 2002). This method interpolates missing values along space and time according to the way the traffic state propagates. In free flow conditions, the traffic state propagates downstream with the current speed; in this case 85 km/h is used to save calculation time. In congested conditions the traffic state propagates with a negative speed which is estimated by the Wave Speed Estimator (Schreiter 2012) and propagates therefore downstream. The weight on which the data point will be interpolated by is based on the values of the surrounding data. Low speeds indicate congestion and high speeds indicate free flow. Secondly the traffic composition is estimated by historical data.

Prediction

The predictor predicts the future traffic state. It predicts where and when congestion will occur. Also it predicts the effect of different Dynamic Traffic Management measures. As was mentioned before, the traffic model is the multi-class model Fastlane (Lint et al. 2008). The use of Fastlane is appropriate due to the high percentage of truck traffic on this highway. Fastlane is a cell based traffic model that models the different vehicle classes. These vehicle classes are modeled by a passenger-car equivalent value (pce-value), which is, contrary to most traffic models, dependent on the traffic state. An example of this can be seen in Figure 3.4. If traffic is in free flow, the space a truck occupies is around 50 meters where the space a passenger-car occupies is 40 meters. In congested situations this is 20 meters and 7 meters respectively. The input traffic demand is estimated based on historical traffic data. For each day of the week the median two years of 15 minute aggregated data is used (Schreiter et al. 2011b).

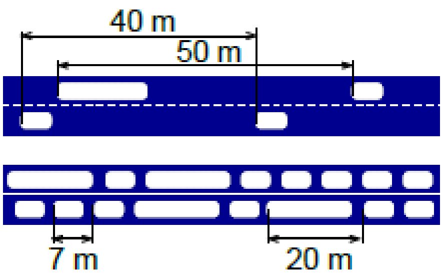

Figure 3.4: Dynamic pce-values (Schreiter et al. 2011b)

Control measures

The control outputs of BOS-HbR are the activation of two different points where route guidance is given and a multi-class ramp meter. For this research only rerouting is used since rerouting is available within the current infrastructure and is therefore used in the TMS. In Figure 3.5 the locations are shown where the traffic is rerouted in the model. At the bottleneck Spijkenisse, traffic can enter the alternative route and can return to the A15 at bottleneck Charlois. There is also an option to reroute the traffic back to the A15 directly after the Botlek Bridge with a control signal.

Figure 3.5: Detailed network of BOS-HbR (Schreiter et al. 2012b)

Not all traffic can be rerouted in this network. Traffic that does not enter at the beginning of the network or does not exit at the end of the network cannot be rerouted. This traffic is considered 'background'-traffic which will be simulated to create realistic traffic situations, but on which the traffic control has no effect.

3.3.3 User classes

In Table 3.1 the different user classes of BOS-HbR are introduced. There are two main classes: passenger cars and trucks. Both of these classes are divided into a re-routable and non re-routable class. For the Value of Time (VOT) is assumed that cars have a VOT of 15 €/hour and trucks a three times as high VOT (45 €/hour).

Table 3.1: User classes of BOS-HbR

Nr.	User-class	Destination	Max speed (km/h)	VOT(€/h)	Reroutable
1	car	Charlois	110	15	Yes
2	truck	Charlois	85	45	Yes
3	car	Before end of the network	110	15	No
4	truck	Before end of the network	85	45	no

Unlike the MPC the A15 Haven Uit scenario makes no distinction between user classes in its control strategy. However since the same traffic model (i.e. Fastlane) as in the MPC in BOS-HbR is used, the traffic was modeled multi-class. Thus the prediction of the traffic state takes multiple user-classes into account, but the control signal does not.

3.4 Traffic Management Scenario A15 Haven Uit

A15 Haven Uit is a Traffic Management Scenario for traffic in the Port that travels in eastern direction. It was designed to be executed from the Regiodesk, a cooperation between Rijkswaterstaat, the Provincie Zuid-Holland, the municipalities of Rotterdam and The Hague, and the city regions of Rotterdam and The Hague created from a successful GGB approach. The Regiodesk is located at the traffic management centre in Rhoon (Bereik 2011). The TMS is created based on Traffic Management expertise and not created based on a traffic model. Therefore before implementing the scenarios, a short test phase was run to see if the scenario responded well. The scenarios focus on rerouting traffic that travels from origins in the port area to destinations within the port area from the A15 to alternative routes. This means that the scenarios look at traffic that travels within the region and uses the A15 and are not focused on traffic traveling to the hinterland. Since BOS-HbR reroutes traffic that is already on the A15, assumptions have to be made to compare the control philosophy of the two control measures. These assumptions will be described in subparagraph 3.4.1. The control scheme will be discussed in subparagraph 3.4.2.

3.4.1 Implementation into the model

The A15 Haven Uit scenario is a scenario that reroutes traffic from zones in the Port area before it enters the A15. There are currently no circuits that reroute traffic from the A15 (Houtriet 2011). Therefore, to compare the TMS with MPC, a scenario was created that reroutes traffic from the A15, based on the rules the A15 Haven Uit scenario uses. These rules will be illustrated in the next subparagraph.

Also, since both the TMS and the MPC have access to the same historical loop detector data, they both use the same predicted traffic demand. To evaluate the performance of the TMS the resulting traffic state will be predicted with the traffic model Fastlane, as is done for the MPC.

3.4.2 Control scheme

In Figure 3.6 the control scheme of the Traffic Management Scenario is shown. It consists of two parts, the activation part and the deactivation part. In the activation part the scheme checks if activation conditions are met and then activates the route guidance. The activation part checks if the speed at the bottleneck at Charlois drops below 50 km/h and then checks for the availability of the alternative route by looking at the Botlek bridge openings, verifying a flowing traffic state by a speed minimum of 30 km/h and checking cameras on the route for accidents. The deactivation part checks if the traffic state on the main route has improved by checking the speed in the bottleneck. If it is over 55 km/h the rerouting is turned off. It also turns off when the alternative route becomes unavailable. This is checked by aforementioned cameras, Botlek bridge openings and if the speed on the alternative route drops below 20 km/h.

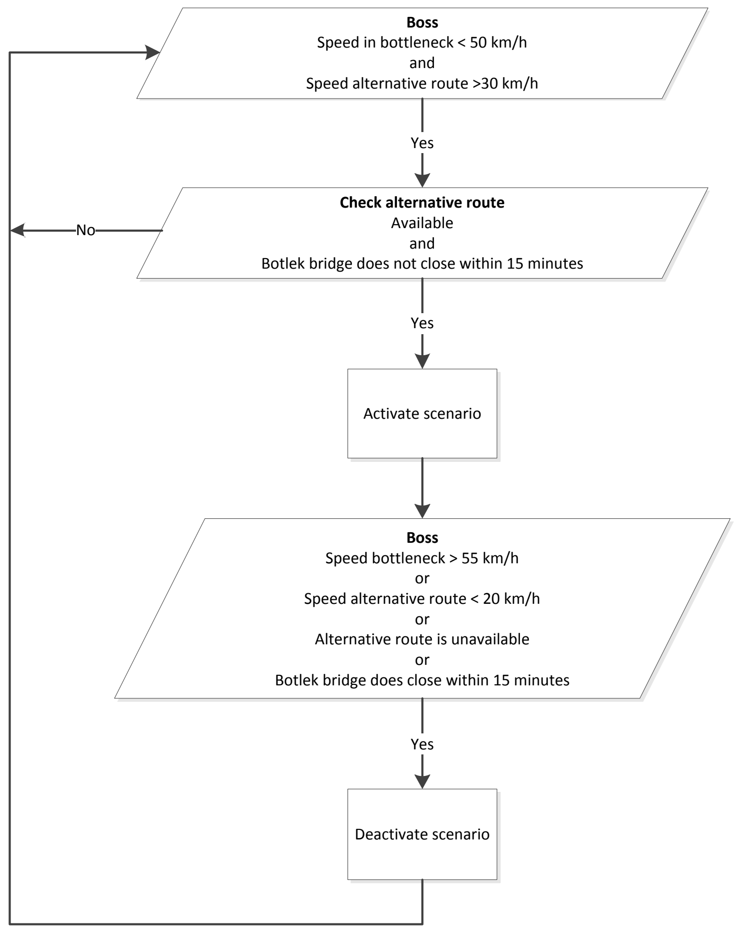

Figure 3.6: Control scheme Traffic Management Scenario

3.5 Model Predictive control

The MPC used for this research is the one developed by Thomas Schreiter in a PhD thesis commissioned by Delft University of Technology and the Verkeersonderneming, a cooperation between the Port Authority of Rotterdam, the municipality of Rotterdam and Rijkswaterstaat.

3.5.1 Implementation into the model

In 3.3 the estimation and prediction components of the framework BOS-HbR were described. The MPC uses these components. In the control component an optimal control with an intern feedback loop is used. The scheme for this control component can be seen in Figure 3.7where it is integrated in the control scheme of BOS-HbR shown in Figure 3.3. The performance function here calculates the total cost based on the density matrices. It sums every minute spent in the network for each vehicle and multiplies that with its Value of Time. Any terminal costs here are ignored. Terminal costs are costs that are a result of the traffic state at the boundaries of the optimization. These boundaries are the start of the network – if congestion spills back to the start of the network this will create extra costs that the objective function does not take into account. The optimization algorithm used to find the optimal control signals is the fmincon function of Matlab. This is a gradient bases method, which means that it finds the optimal solution by following the steepest gradient in the solution space until the gradient is close to zero. If the gradient is close to zero a local optimum is found, since in an optimum, the gradient is zero (Schreiter 2012).

3.5.2 Control scheme

In order to get a good picture of the control scheme of the MPC, the complete control scheme of BOS-HbR with the Model Predictive Controller is shown in Figure 3.7.

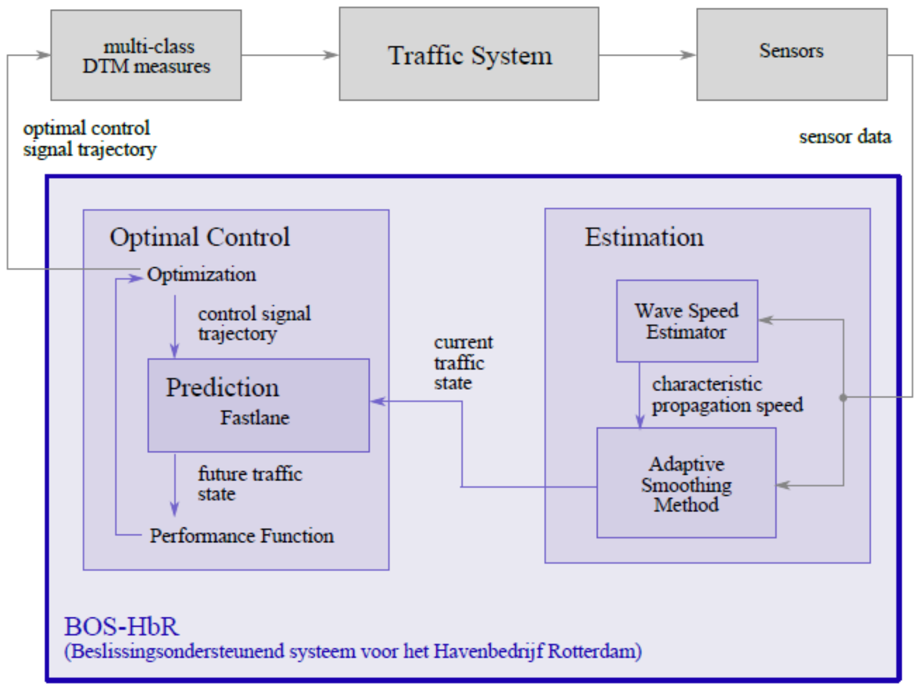

Figure 3.7: Scheme of BOS-HbR with MPC implemented

3.6 Synthesis

This chapter described how a practically applied control method and a method not applied yet in practice should be compared in a fair way. First some requirements were set. These requirements were that the both methods should use the same network, control the same signals and that these control signals were determined based on the same input data. To analyze the results of both methods both methods should produce the same sort of output data. The easiest way to do this is performing a simulation experiment where both TMS and MPC use the same traffic model with a control module in it. The control module then can be replaced by either the TMS, the MPC or remain empty. BOS-HbR is a framework that fulfills these requirements. It uses the A15 highway discussed in chapter 1 as its network. BOS-HbR consists of a estimation and prediction component. In the estimation component the input data retrieved from loop detectors is converted to a traffic state which serves as input for the prediction component. The prediction component uses multi-class model Fastlane to predict the traffic state and predict the results of the control method which will be inserted here. The TMS used for the current study is the 'A15 Haven Uit' scenario developed by Regiodesk. For the current study a TMS was created within BOS-HbR with the same (de)activation triggers as 'A15 Haven Uit'. The MPC used in BOS-HbR will use the Matlab function fmincon as its optimization algorithm. In the next chapter the setup of this simulation experiment will be described.

4 Experimental setup

In chapter 3 the outline for the simulation experiment was set. This chapter will explain the choices made for this experiment. The experiment will compare TMS with single-class MPC and single-class MPC with multi-class MPC. Table 4.1 illustrates how the three are related.

Table 4.1: The compared control methods

Single-class TMS	
Single-class MPC	**Multiclass MPC**

In this chapter the simulation environment and circumstances will be described and the results of these experiments will be evaluated in chapter 5. First in paragraph 4.1 the used Dynamic Traffic Management measure will be introduced. Second, in paragraph 4.2 it will be explained how the TMS A15 Haven Uit was implemented in the BOS-HbR framework. Then in 4.3 the values for the different parameters of the MPC will be motivated. The experiment will be done for three cases: a day with heavy peak hour, a day with a regular peak hour, and a day on which an accident occurred. These different cases will be further described in paragraph 4.4. In 4.5 it will be discussed how the road construction affected the capacity of the bottleneck near Charlois, followed by a validation to check if the model used for this simulation experiment is fit. To test travel time robustness, the experiment has to be done with different levels of demand, discussed in 4.6. Paragraph 4.7 will explain what data is needed to assess the results with the different performance indicators.

4.1 DTM Measures

For this experiment multi-class route guidance will be considered for the Model Predictive Controller. In the experiment for the TMS the route guidance will be single-class, since this is the current situation. In exploratory experiments was shown that the route guidance signal after Charlois, described in 3.3.2, is not used in an optimal solution calculated by the MPC controller (Schreiter 2012). Therefore in the experiment this signal will not be used. Note that optimizing one control signal is not as complicated as optimizing multiple. Theoretically the gain of using MPC over TMS will increase with complexity and thus using more control signals to optimize.

4.2 Simulation of the scenario A15 Haven Uit

As was mentioned in the previous chapter, to compare MPC with the 'A15 Haven Uit' scenario, the network of BOS-HbR will be used. Therefore the scenario has to be modified to be fit for the model. This will be done manually by the author based on the visual traffic state, which is plotted in Figure 1.5. The rules for the TMS will remain the same; the scheme shown in Figure 3.6 will be followed. Note that the human controller in the current study thus is replaced by the author of this thesis, following the rules set by the 'A15 Haven Uit' Scenario. In reality the human controller has knowledge of the current traffic state and can predict the future from experience and can adjust the control signal 'on the fly'. In this research a traffic state predicted by Fastlane was used. This

can lead to different results on how the control signal is applied in reality and how it is applied in the current study.
In this case, the route guidance will be turned on if the speed right before the bottleneck will drop below 50 km/h and the alternative route has an average speed over 30 km/h. The route guidance will be turned off if the speed of the alternative route drops below 20 km/h or the speed right before the bottleneck will rise above 55 km/h. In practice this means that the Traffic Management Scenario will not reroute all of the re-routable traffic in the model. The experiments with the TMS were done with a rerouting percentage such that the off-ramp to the alternative route remained congestion-free. For each level of demand – discussed in 4.5 – the highest rerouting percentage (in steps of 10%) for which congestion from bridge openings on the alternative route did not spill back to the off-ramp were found. These percentages can be found in Appendix A. The assumption here is that the compliance of the re-routable traffic is 100% until the alternative route is congested. This way the 'best' realistic TMS will be compared to the MPC which should give an optimal solution

4.3 MPC parameters

An MPC has a few different parameters that can be tweaked as was mentioned in paragraph 2.3.3. These different parameters are: control interval, prediction horizon, control horizon, and control objective. The control interval used for the MPC is 15 minutes. This means that the control signal can only change each 15 minutes. This is short enough to bring the traffic state to optimal conditions fast enough. If the control interval is long, the MPC cannot react fast enough on changes in demand or changes in the traffic state owing to the application of its control signal. The control interval should be longer than the computation time of the MPC to compute this control signal and has therefore a lower boundary for this value. Also, if the control interval is too traffic intensities on the main and alternative route can start oscillating, which leads to undesired traffic conditions (Heygi 2004). The control horizon on 30 minutes. Since the control signal can change every 15 minutes there is no need to optimize the signal for longer than 30 minutes, since it will probably change after 15 minutes due to the recalculation of the traffic state after the control interval, in this case 15 minutes. The prediction horizon is set to 1 hour so the MPC has to take the traffic state after its control horizon ends into account. This can prevent the MPC leaving undesired traffic states at the end of its control horizon. The control objective of MPC is minimizing the total cost. As was mentioned before, the Port area is of high economic value to the Netherlands and therefore this total cost is the main performance indicator.

4.4 Cases

The scenarios and the MPC will be tested for three different cases. These different cases will be a heavy evening peak hour on a winter day, in this case December 15th 2011, a regular peak hour, December 13th 2011 and a day where an accident happened, in this case November 17th 2011 at 15:00. The experiments during the peak hour are held at 17:00, in the middle of the peak hour (considered evening peak hours last from 15:00 until 19:00). This time slot was chosen in order to have a starting traffic state within the peak hour and the guarantee that this peak hour does not wane yet. The accident is modeled as an event in BOS-HbR that limits the capacity for time the accident lasts.

4.5 Road construction

The model simulation will take place during road construction on the A15. To simulate the environment during the construction as good as possible an estimation of the traffic state during the construction was done to retrieve data from the bottlenecks with which the current capacity of the bottlenecks could be determined. It showed that the capacity of the bottleneck at Charlois was reduced from 4800 vehicles per hour to 4200 vehicles per hour. This was therefore applied in the model. The bottleneck at Spijkenisse showed no change in capacity and was therefore not changed.

4.5.1 Validation

BOS-HbR is validated for multiple peak days and days with an accident (Schreiter 2012). Since the capacity of the bottleneck was changed due to the construction, the model was validated for this new situation. The validation also shows if the assumptions regarding the predicted demand are sound. Figure 4.1 shows the estimation of the traffic state for 15:00 to 19:00 on 15 December 2011 on the left. This date will be used to model the heavy peak hour. On the right a prediction is done by Fastlane for 17:00 to 18:00 given the traffic state at 17:00 when no control is applied. It shows that existing stop-and-go-waves (the two black lines going downward) continue and the little improvement in traffic state after these stop-and-go-waves have dissolved. It shows that Fastlane has a realistic prediction of the traffic state for this peak hour.

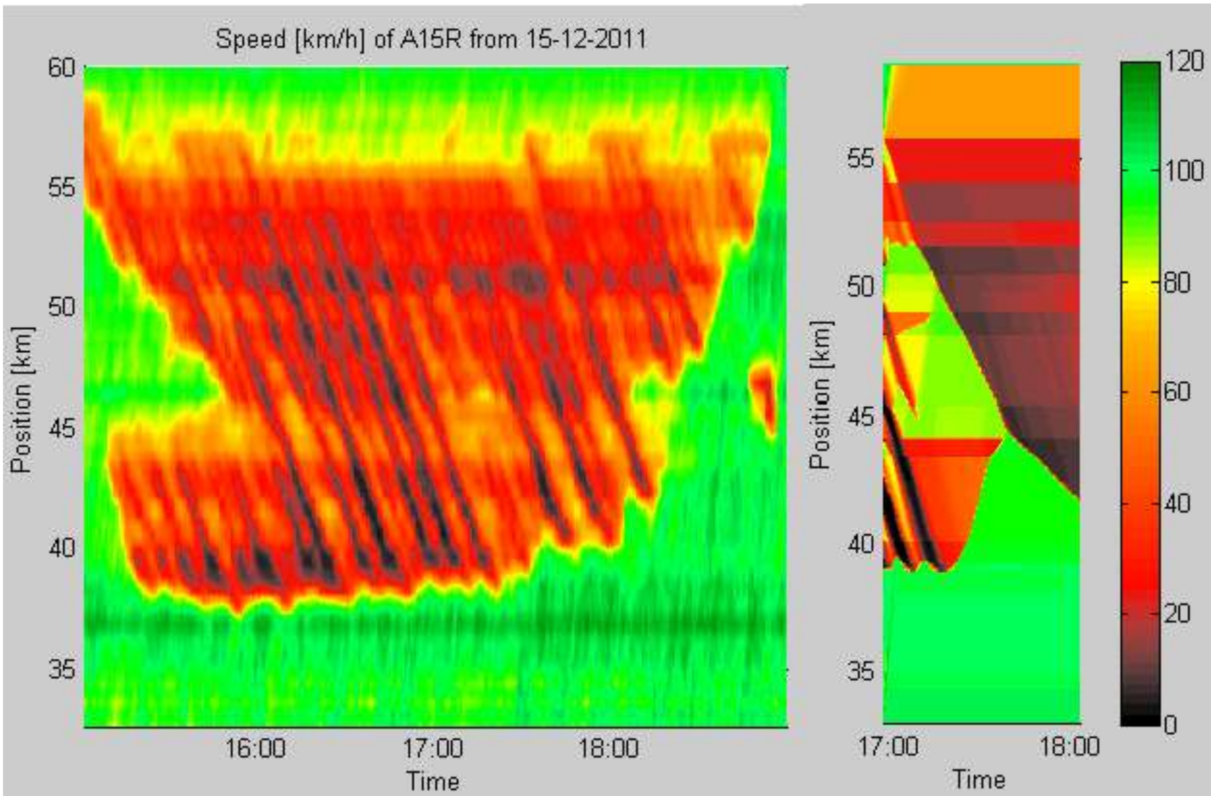

Figure 4.1: Estimation versus Prediction on 15-12-2011

In Figure 4.2 on the left the estimation for December 13th 2011 is shown. It is clear that this is a less heavy peak period than on December 15th. The congestion starts a little later and the congestion from bottleneck Charlois only spills back to the bottleneck at Spijkenisse between 16:00

and 17:00. After 17:00 there is little to no congestion at bottleneck Spijkenisse. The prediction of Fastlane from 17:00 until 18:00 in the figure on the right shows this as well. The prediction there shows no congestion at bottleneck Spijkenisse as does the estimation and the congestion at Charlois is of comparable length. Therefore we can conclude that the model is also valid for this day.

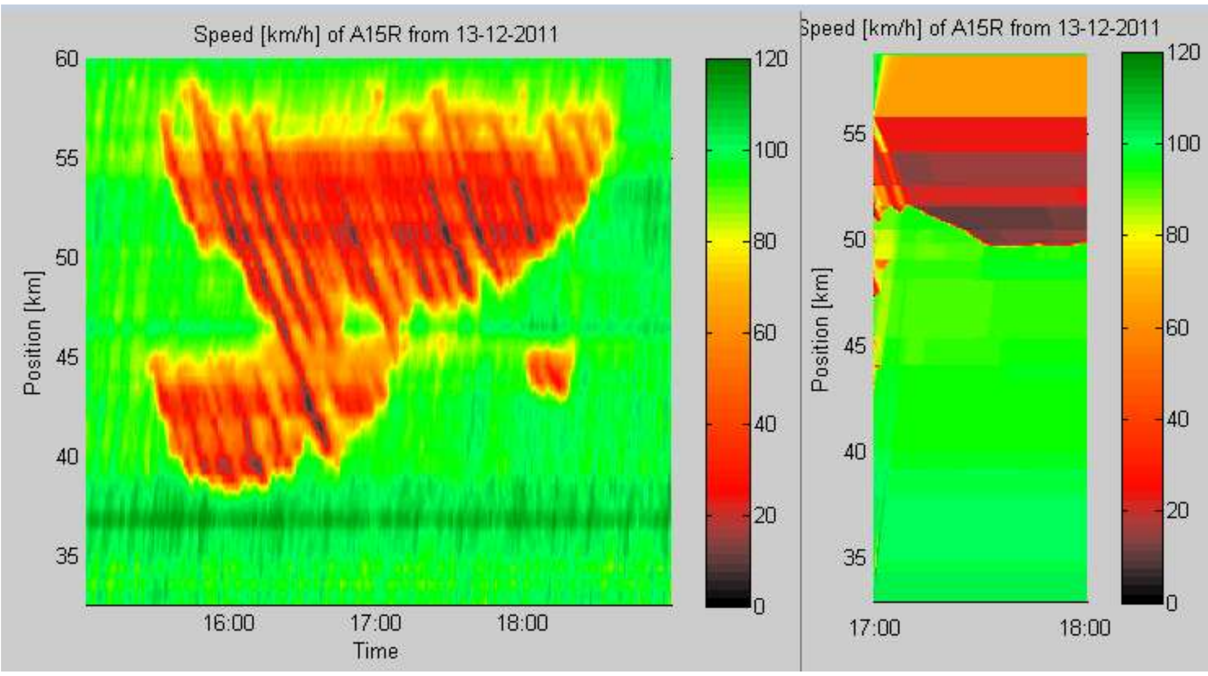

Figure 4.2: Estimation versus Prediction on 13-12-2011

In the case of the accident an event was added to the model, simulating the accident. In Figure 4.3 the speed contour graph of the estimation on 17 November 2011 from 15:00 to 19:00 is shown. The accident on that day occurred on 14:50 and the road got cleared one hour later. The capacity of the road at kilometer 51 drops to 2500 vehicles per hour. The accident causes a heavy traffic jam for 1 hour as can be seen as the black area in the picture. After the accident is cleared the daily congestion at bottleneck Charlois is immediately visible.

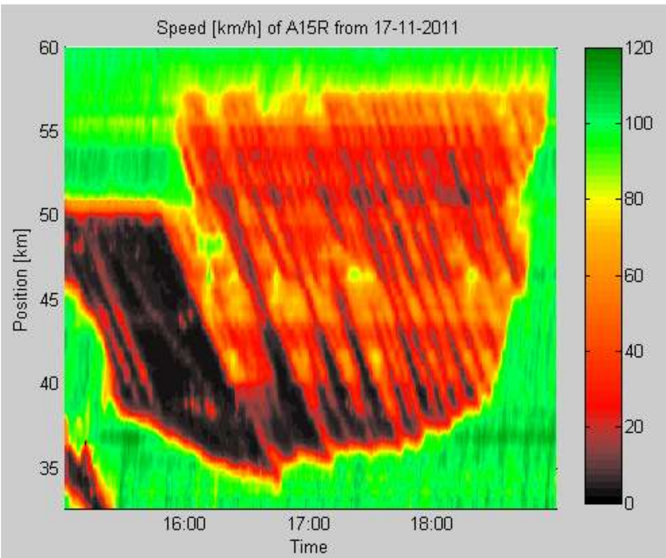

Figure 4.3: Estimation on 17-11-2011 15:00

In Figure 4.4 the speed contour graphs of predictions ran at 15:00, 15:15, 15:30 and 15:45 can be seen. What can be seen from the figures is that the response of the traffic system is the same as seen in the estimation: there is a large black area picturing the heavy traffic jam the accident causes. However, after the accident ends, the daily congestion seen in Figure 4.4 is not as heavily predicted as in Figure 4.3. Still the model resembles the real situation well enough to consider it valid.

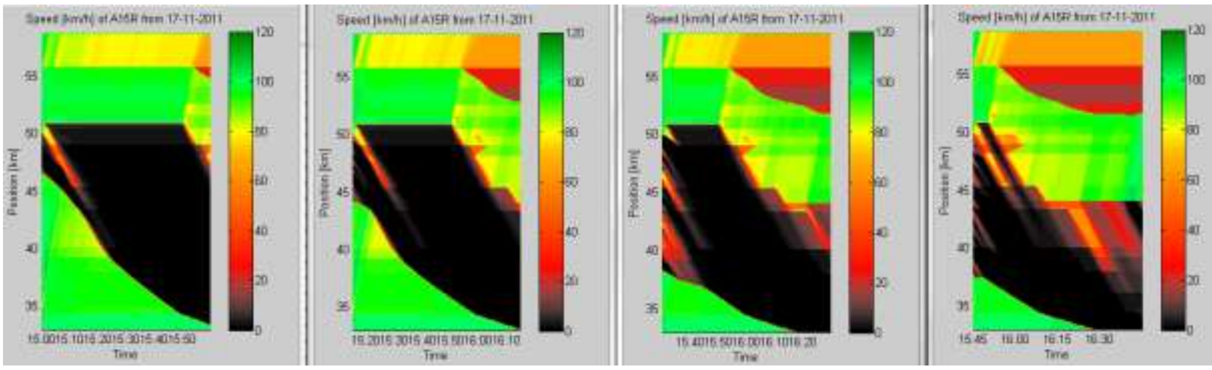

Figure 4.4: Prediction of 1 hour on 17-11-2011 for 15:00, 15:15, 15:30 and 15:45 respectively

4.6 Levels of demand

To show how sensitive different methods are in their results to variations in demand, each experiment is done with five different levels of demand. These five different levels are 90%, 95%, 100%, 105% and 110% of the original calibrated demand pattern of BOS-HbR. The demand patterns are based on historical loop detector data.

4.7 Performance indicators

Performance indicators are introduced to evaluate the performance of the Traffic Management Scenario and Model Predictive Control. The following data has to be retrieved from the experiments to assess the different cases on the performance indicators: total cost, average travel time spent per vehicle class and visual traffic state.

4.7.1 Total Cost

The port area is of high economic value to the Netherlands with a high share of truck traffic. It is therefore appropriate to use total cost as a performance indicator, so the travel time of truck and person car traffic can be weighed accordingly. Therefore, in this research, the most important performance indicator will be considered the total cost. Total cost is measured by multiplying the total time all vehicles of each class spend in the network by its value of time (VOT).

$$TC = TTS_{passenger\_cars} * VOT_{passenger\_cars} + TTS_{trucks} * VOT_{trucks} \quad (4.1)$$

Where $TTS_u = \sum_x \sum_t k_{x,t}^u$

The value of time of trucks is assumed to be €45 per hour, for passenger cars this is assumed to be €15 (Schreiter et al. 2012a).

4.7.2 Average travel time spent per vehicle class

Different control solutions can be compared on travels times per class. One can analyze how each control method affects the travel times of each vehicle class. This is especially useful when analyzing travel time robustness, the next performance indicator. Since for the whole network speeds, densities and flows are stored for time and location for each vehicle class, we can let virtual vehicles travel through the network according to the speeds and record their travel time. This can give an indication on how the different control methods perform for each user class. In Figure 4.5 is shown how this works. A white line is an example of a virtual vehicle travelling on the A15. A travel time through the network can be calculated by subtracting the entry time from the time the vehicle exits the network.

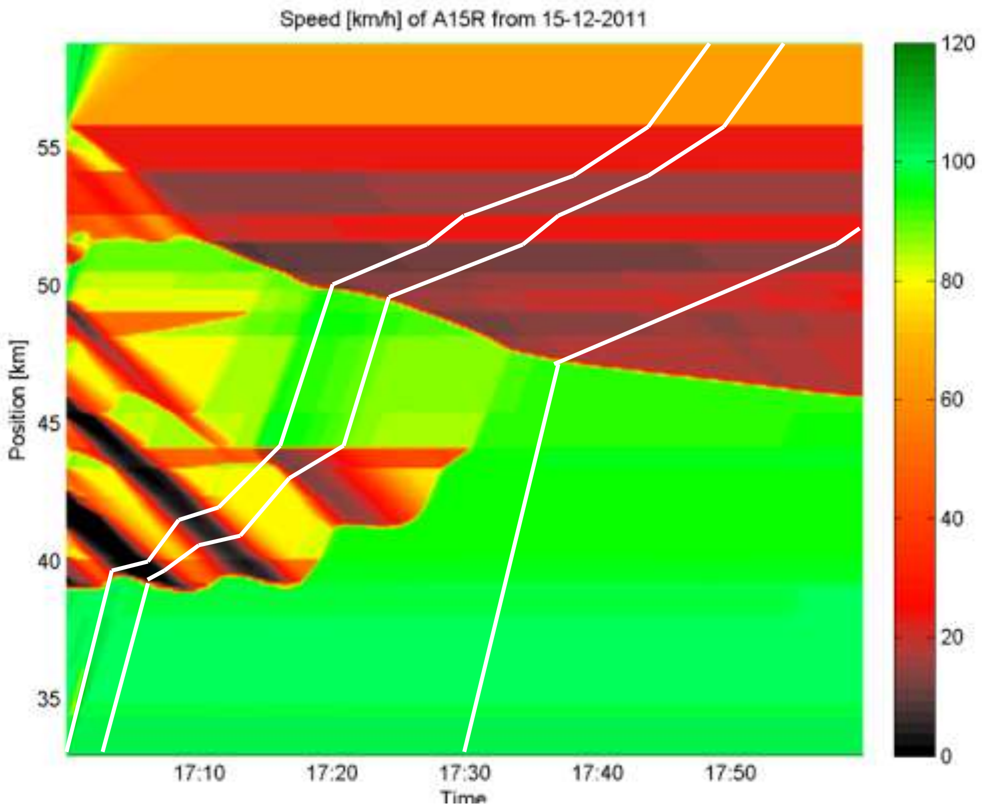

Figure 4.5: virtual vehicles travelling through a speed contour map

Note that the most right white line does not reach the end of the network. Therefore it will not be included in the calculation. This criterion weighs the travel times of the vehicles early after the implementation of the control signal heaviest.

4.7.3 Travel time robustness

Truck traffic benefits from robust travel times. For trip planning a transport company needs to know how long a certain trip approximately lasts. Therefore a control solution has to be analyzed on how well it performs with demand fluctuations. If a demand fluctuation has little effect on predicted travel times the control method performs well. Therefore the experiments are done with different demand levels, as mentioned in paragraph 4.6 in order to measure how robust travel times are for each different user class. If the demand changes the travel time should change accordingly.

4.8 Synthesis

This chapter described the setup of the simulation experiment. The simulation experiment will be done for the previous described single-class TMS, single-class MPC and multi-class MPC. In chapter 4 was mentioned that there were two control signals to be optimized for the MPC, one at Spijkenisse and one directly after the Botlek bridge. The one after the Botlek bridge was never used in exploratory experiments and therefore left out this experiment. The experiment will be executed for three cases: a heavy peak hour, a regular peak hour and a severe accident. For each case a validation was done to check if the model predictions for Fastlane matched reality, which was positively concluded. Also for each of these cases the experiments will be done with 5 demand levels: 90%, 95%, 100%, 105% and 110% of the original expected demand to measure the robustness of the control methods. In Table 4.2 the different combinations of the experiment are summarized. For the TMS the conditions for the rerouting signal at Spijkenisse to be turned on were described and it was explained that road users will only comply with this signal if the off-ramp to the alternative route is congestion-free. Therefore, for each case compliance levels in steps of 10% were determined before executing the experiment. The variables to be adjusted for the MPC were control interval, control horizon and prediction horizon. The results of these experiments will be discussed in chapter 5 and will be judged on basis of the following performance indicators: Total cost, average travel time per user class and robustness. It is explained before that the main performance indicator of the control methods is total (economic) cost. The total cost is calculated by counting the time each vehicle spends in the network, multiplied by the value of time of the specific vehicle class. The second performance indicator, travel time by user class, is measure by letting virtual vehicles travel through the traffic state on the main road. This performance indicator therefore mostly measures how the traffic state on the A15 improves by applying either TMS or MPC. Finally there will be looked at how the different control methods score on these first two performance indicator for each demand level so there can be assessed how robust the control methods are.

Table 4.2: Experiment overview

	Heavy peak hour				**Regular peak hour**				**Accident**			
	No control	TMS	SC MPC	MC MPC	No control	TMS	SC MPC	MC MPC	No control	TMS	SC MPC	MC MPC
90%												
95%												
100%												
105%												
110%												

5 Results and discussion

In this chapter the results of the different experiments described in chapter 4 will be evaluated. Here the Traffic Management Scenario and the Model Predictive Controller will be scored with the performance indicators set in chapter 4. The first paragraph will evaluate the heavy peak hour case, paragraph 5.2 will then evaluate the low peak hour case and in paragraph 5.3 the accident will be described.

5.1 Case 1: Heavy peak hour

On December 15th 2011 a heavy evening peak hour occurred and was used for this case, as was described in paragraph 4.4. First in subparagraph 5.1.1 the outputs of the model will be described, then the outputs of the TMS and the MPC. In 5.1.2 the total cost of the output of the control methods will be described. Then 5.1.3 and 5.1.4 will discuss the travel time per user-class and the robustness of these travel times respectively.

5.1.1 Description

December 15th 2011 was a winter day with some sleet in the afternoon. This resulted in a heavy evening peak hour. In Figure 4.1 the traffic state of the evening peak hour (from 15:00 until 19:00) can be seen.

Prediction

The predicted traffic state on the A15 and the alternative route for 17:00 can be seen in Figure 5.1. What we can see from the figure is the daily congestion at Charlois (km 56) is propagating upstream and two stop-and-go-waves from bottleneck Spijkenisse (km 44) are dissolving. At the right hand side we can see the traffic state of the alternative route (the Vondelingenweg). In this picture two small heavy stop-and-go-waves can be seen. These are the result of the half-hourly Botlek bridge openings. Aside from these bridge openings the road is clear as we can conclude from the figure.

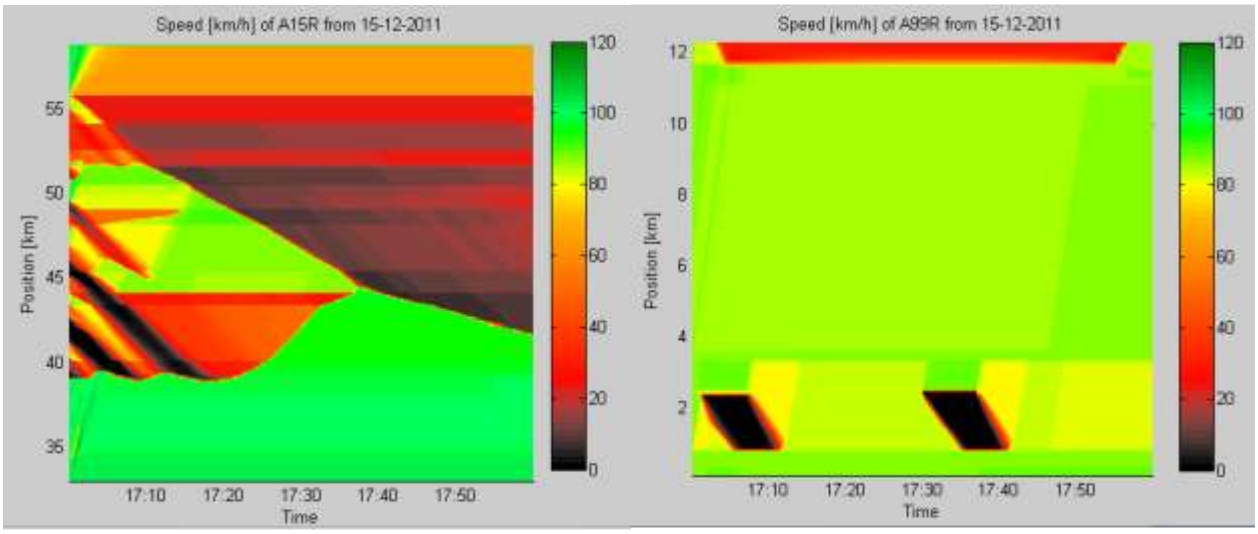

Figure 5.1: Predicted traffic state on the A15 and alternative route on 15-12-2011 at 17:00

Traffic management Scenario

The resulting traffic state when traffic was rerouted to the alternative route according to the TMS is shown in Figure 5.2. The triggers for the TMS to be turned on are the availability of the alternative route and the speed in the bottleneck at Charlois. As we can see from Figure 5.1 the speed at bottleneck Charlois is during the whole hour below 50 km/h. The availability of the alternative route is a bit more complex, the speed is during the whole hour above 30 km/h, but the Botlek bridge opens twice. This means that the TMS is turned off every time the bridge opens. These openings are scheduled and can therefore be predicted. In this case the TMS reroutes 60% of the traffic. In preliminary experiments it showed that at a 70% rerouting percentage the bridge opening at the alternative route causes a spillback to the main route. Since there can be assumed that road users will not choose a congested off-ramp over a free flowing main route even if they are advised to do so, the rerouting percentage will be 60%.

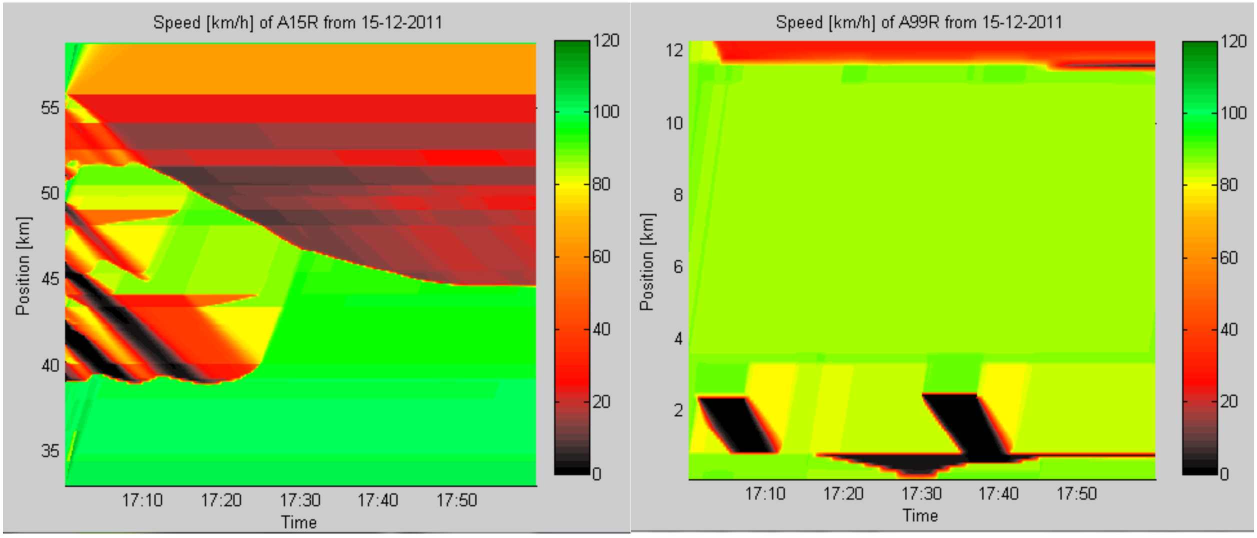

Figure 5.2: Predicted traffic state on the A15 and alternative route on 15-12-2011 at 17:00 with the application of the TMS

When comparing Figure 5.2 with Figure 5.1 it can be noticed that the TMS causes a better visual traffic state for the A15. The congestion at the bottleneck at Charlois does not spill back to the bottleneck at Spijkenisse. There is still congestion at bottleneck Spijkenisse, but this is caused by the bottleneck itself. Overall can be concluded that the traffic jam length is shorter and the traffic state on the A15 improved. Since the TMS lets the traffic use the alternative route more, it can be expected that the traffic state there deteriorates. As can be seen on the right in Figure 5.2 there is no effect downstream of the Botlek bridge (in the picture above the black stop-and-go-waves), since the visual traffic state is identical as that depicted in Figure 5.1. There is a short queue starting at the bridge at 17:15 but this has no major consequences for the main road.

Single-class Model Predictive Control

The resulting traffic state when traffic was rerouted to the alternative route according to the MPC is shown in Figure 5.3. What can be concluded from this figure is that compared to Figure 5.1 the MPC shortens the congestion on the A15 from bottleneck Charlois. It is about one kilometer shorter than the congestion in the case of the TMS (Figure 5.2). On the right hand side can be seen that also in the case of the MPC there is some spillback on the alternative route after the first opening of the Botlek bridge. Note that the MPC lets congestion from the alternative route spill back to the main route in the first half hour.

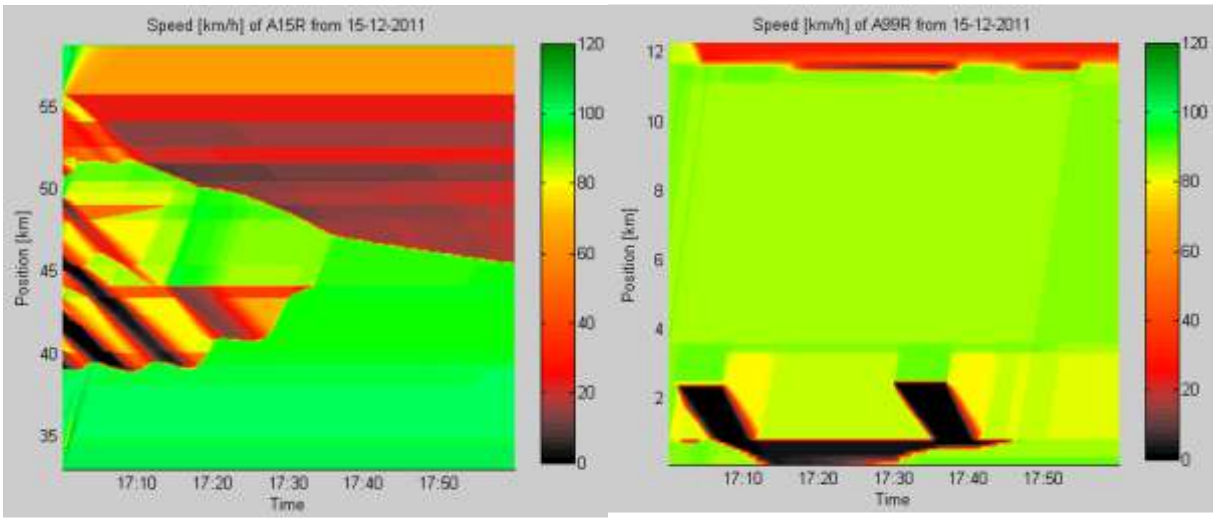

Figure 5.3: Predicted traffic state on the A15 and alternative route on 15-12-2011 at 17:00 with the application of the single-class MPC

In conditions where no multi-class measures are possible, this is the optimal solution. The optimized control signal can be seen in Figure 5.4. This Matlab figure created by the BOS-HbR framework shows two graphs. The upper graph is the control signal at Spijkenisse and the bottom graph is a signal that reroutes traffic back to the main route before Charlois. This last signal is in this research never activated. In the figure can be seen that in the first 15 minutes around 65% of the traffic is rerouted and after that 30%.

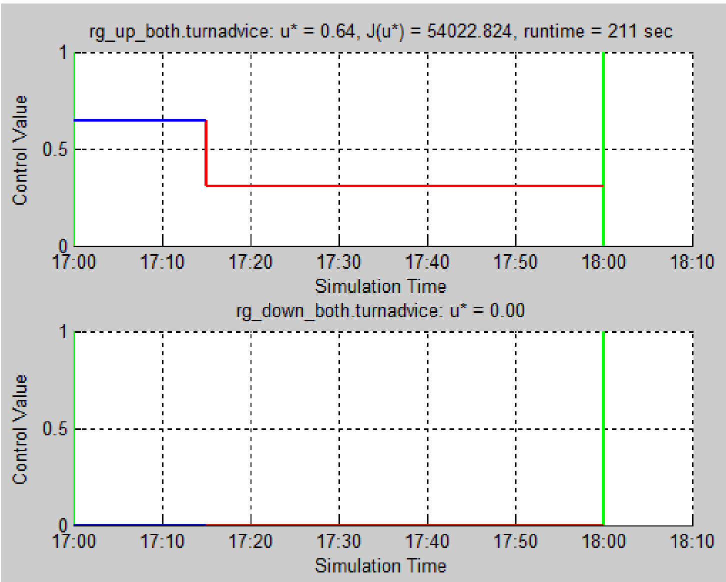

Figure 5.4: Control signal of the single-class MPC for 15-12-2011 at 17:00

Multi-class Model Predictive Control

The resulting traffic state when traffic gets rerouted to the alternative route according to the multi-class MPC is shown in Figure 5.5. What can be concluded from this figure is that compared to

Figure 5.3 the multi-class MPC has little difference in traffic state with the single-class one and thus also shortens the congestion on the A15 from bottleneck Charlois.

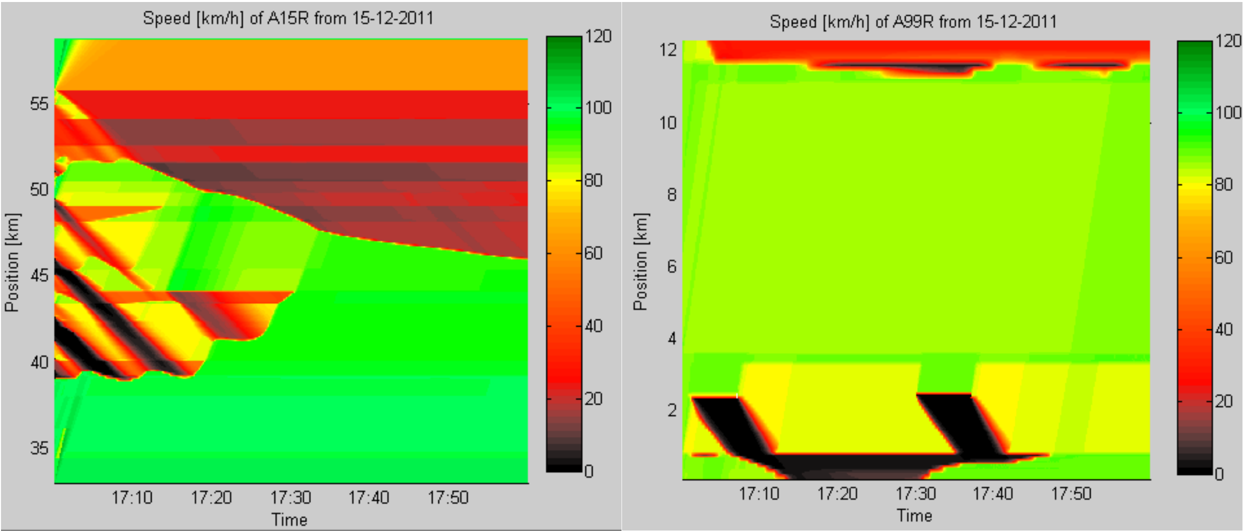

Figure 5.5: Predicted traffic state on the A15 and alternative route on 15-12-2011 at 17:00 with the application of the multi-class MPC

The MPC optimizes on total cost and congestion (traffic standing still) has a high influence on costs. As was mentioned before, truck traffic standing still with its high value of time has great influence on total cost. The multi-class MPC therefore is likely to optimize to get the shortest travel times for the trucks. The optimized control signal can be seen in Figure 5.6. The figure consists of four small graphs. The upper two graphs show the control signal of the route guidance on the A15 at the bottleneck Charlois (the network can be seen in Figure 3.5). As can be seen from the figure, 82% of the re-routable passenger car traffic is rerouted from 17:00 until 17:15, from 17:15 until 18:00 52% of the passenger car traffic is rerouted. Note that in this case the MPC never reroutes truck traffic. The shortest and, if congestion-free the fastest, route is the main route. If the MPC can keep the main road free of congestion by rerouting passenger car traffic, there is no reason for the trucks to be rerouted.

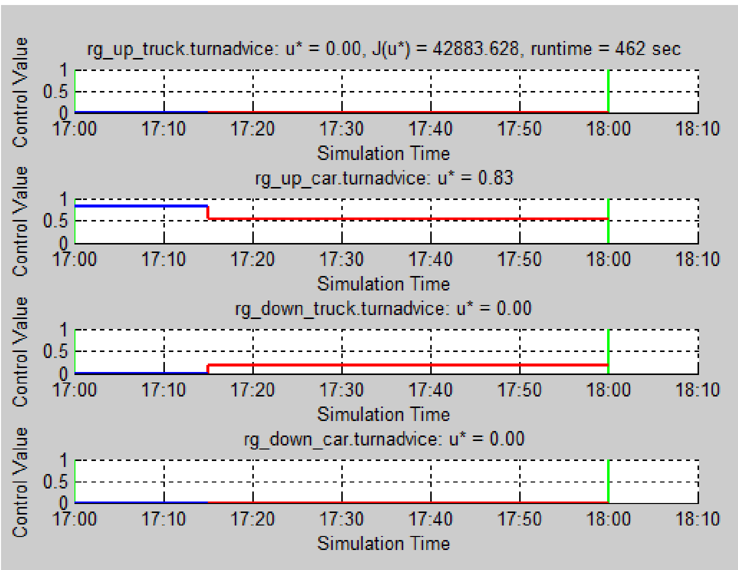

Figure 5.6: Control signal of the multi-class MPC for 15-12-2011 at 17:00

The lower two figures show the route guidance on the alternative route where traffic can be rerouted back to the A15. As was mentioned before these lower two figures however can be ignored, as experiments have shown that they never have an effect on the traffic flow. From the figure can be seen that truck traffic is routed back to the A15 at this route guidance signal. But since the only traffic that can be rerouted (in this case non-background traffic) is traffic that has to be rerouted to the alternative route in the first place, there will be no truck traffic rerouted at this signal.

To conclude, the TMS and the MPC show different control inputs and therefore different outcomes according to the traffic state. In the next paragraphs will be shown how the both methods will score on performance indicators.

5.1.2 Total cost

In Table 5.1 the total cost of the different methods is shown. The table is the result of the calculation shown in 4.7.1. Both control methods do very well compared to the situation where no traffic control is applied. During one hour of the evening peak there can be 5.6% saved by the TMS and 7.2% by the MPC. Applying user-class specific MPC wins another 0.8% on the total cost.

Table 5.1: Total cost case heavy peak hour

Control method	Total cost (1000 €)	Total cost ratio
No control	57.6	100%
TMS	55.5	96.4%
Single-class MPC	53.4	92.8%
Multi-class MPC	52.9	92.0%

The Model Predictive Controller optimizes its control signal based on this criterion. Therefore, the total cost value of this method can be considered as the optimal value for this case. This was known beforehand, but now it can be seen how good TMS scores. It can be concluded that it causes a large improvement in cost.

5.1.3 Travel time per user class

In Table 5.2 the average travel time per class is shown as well as the relative improvement to the original travel time of that class. The calculation of these values was described in 4.7.2. It can be seen that the travel times of both cars and trucks do not differ very much. This is due to the heavy congestion in the peak hour in this case. In congestion cars and trucks move just as fast. So the heavier the congestion, the higher the likelihood of travel times of passenger cars and trucks to lie closely together. From this table it cannot be concluded that the MPC scores better on the travel time of trucks than the TMS what would be expected, since the MPC can reroute based on user-class.

Table 5.2: Travel times per user class case heavy peak hour

Control method	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	51.18	100%	52.39	100%
TMS	48.30	94.3%	49.36	94.2%
Single-class MPC	43.28	84.6%	44.63	85.2%
Multi-class MPC	42.10	82.3%	43.44	82.9%

What can be concluded from the table is that both control methods lead to better travel times than in the no control case. Applying the TMS wins more than 5% in travel times for both user-classes, but applying MPC gains an extra 10% in travel times. If the MPC is applied user-class specific travel times of trucks but also for passenger cars decrease with 2.3% compared to the single-class variant.

5.1.4 Travel time robustness

As was mentioned in paragraph 5.6, each experiment was performed five times, each with a different demand level. This was to research how the traffic system and the control would respond to changes in the predicted demand. In Figure 5.7 and Figure 5.8 the different traffic states of the A15 and the alternative route are shown. In the cases of overestimation of the demand (the two left most graphs in the two figures), the congestion of the bottleneck at Charlois does not spill back to the bottleneck at Spijkenisse. In the cases of the current predicted demand and underestimation of the demand the congestion spills back from Spijkenisse to Charlois and this results in standstills represented by the black areas, meaning the traffic has very low speeds. Since this is the location where the traffic is rerouted it will be more difficult to gain travel time by traffic control, as can be seen from Figure 5.7. The traffic state of the alternative route does not change much. In the bottom of the figures it can be seen that the bridge openings cause slightly longer queues as the demand increases.

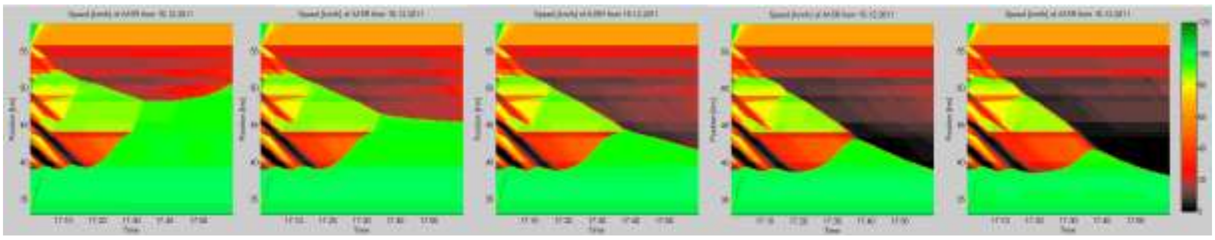

Figure 5.7: Speed contour graphs for the A15 of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

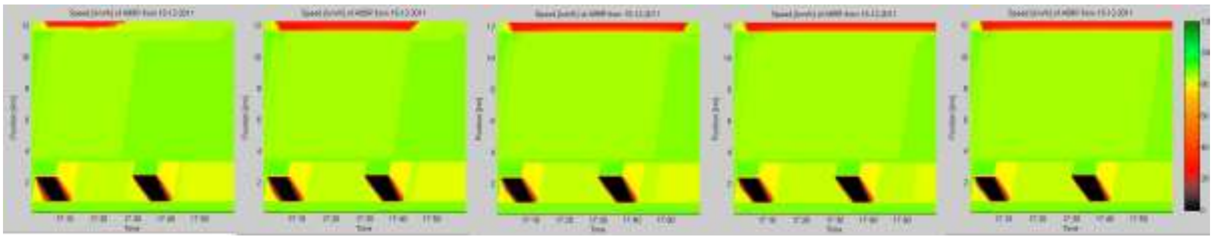

Figure 5.8: Speed contour graphs for the alternative route of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

In Figure 5.9 and Figure 5.10 the different traffic states for the A15 and the alternative route for each demand level can be seen after the application of the TMS. From the figures can be concluded that the TMS improves the traffic state in all cases. In the 90%, 95% and 100% cases the queue on the main route at bottleneck Charlois shortens where if no control applied this happens only in the 90% case. In Figure 5.7 can be seen that if the congestion from bottleneck Charlois spills back to bottleneck Spijkenisse traffic comes to a standstill at the latter bottleneck. Applying the TMS prevents this from happening in the 105% demand case. Overall can be concluded that in all demand cases the traffic state improves.

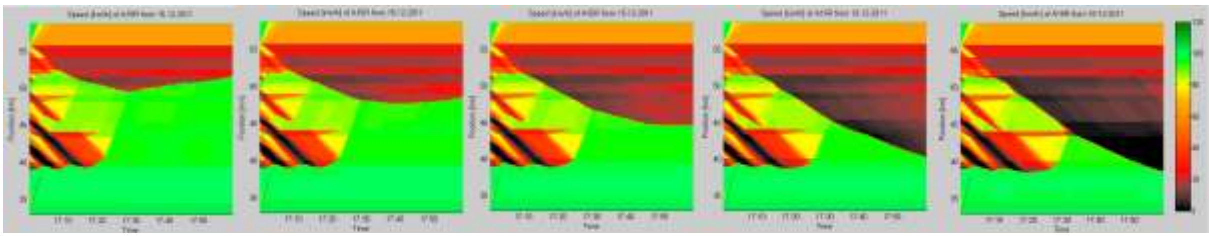

Figure 5.9: Speed contour graphs for the A15 of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

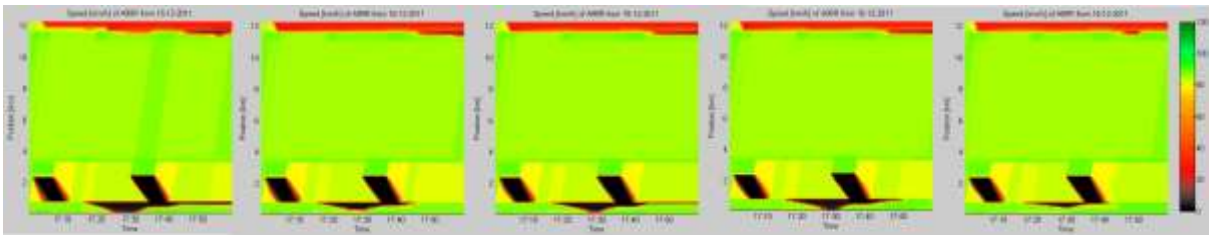

Figure 5.10: Speed contour graphs for the alternative route of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

In Figure 5.11 and Figure 5.12 the traffic state results for the MPC can be seen. If we compare this to the figures above we can conclude first that the overall congestion is shorter. The stop-and-go-waves on the alternative route are heavier and the off-ramp to the alternative route (bottleneck Spijkenisse) suffers from that in the two high demand cases. However the queue at bottleneck Charlois grows slower than when TMS is applied.

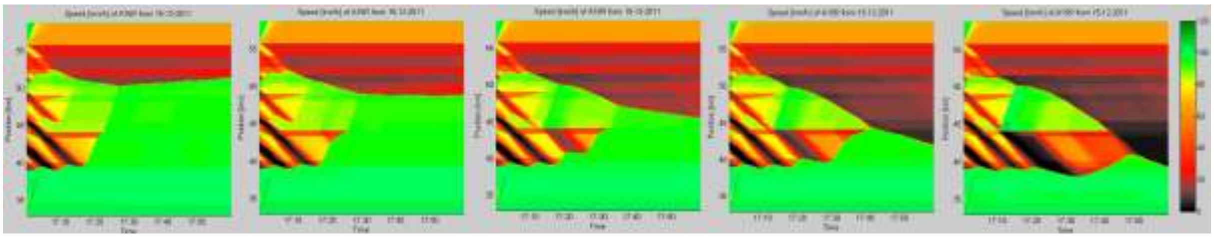

Figure 5.11: Speed contour graphs for the A15 of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

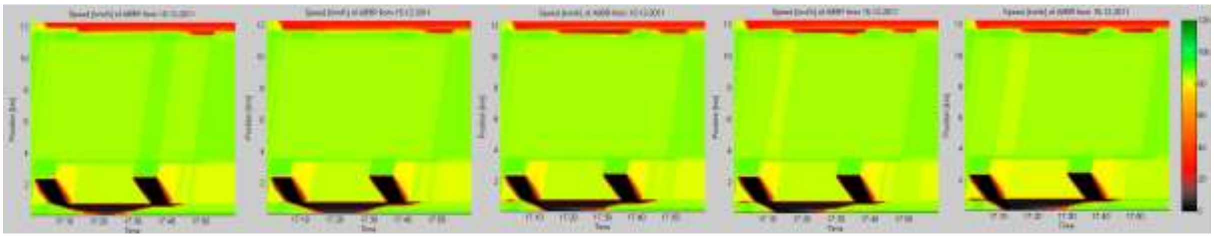

Figure 5.12: Speed contour graphs for the alternative route of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

Applying multi-class MPC improves the traffic state on the main route further. The congestion length is shorter and the surfaces of the dark and black areas, which mean traffic travelling at slow speeds become smaller. The differences with single-class MPC are subtle but present.

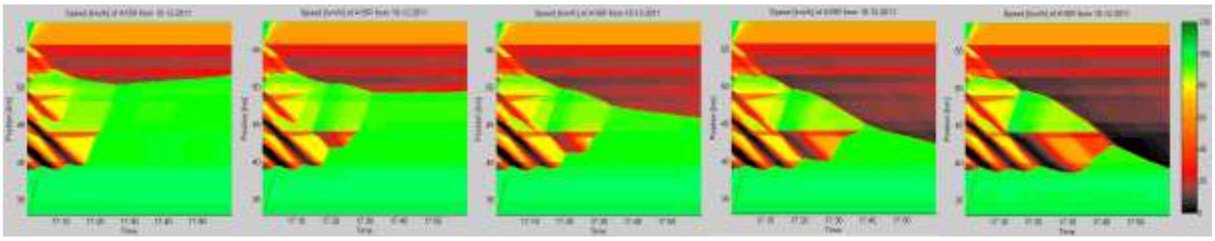

Figure 5.13: Speed contour graphs for the A15 of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

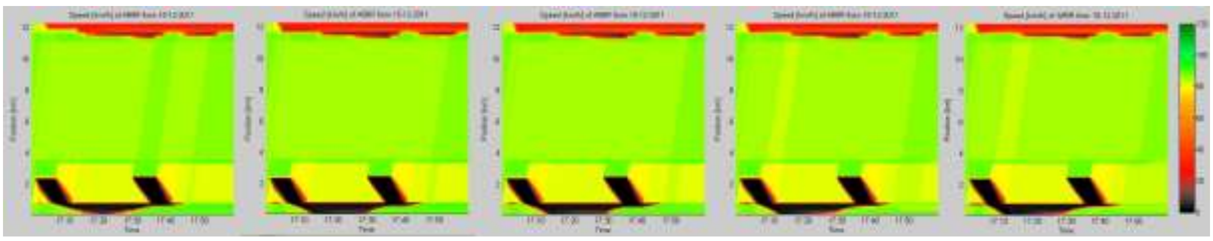

Figure 5.14: Speed contour graphs for the alternative route of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 15-12-2011

In paragraph 5.7 was shown how virtual vehicles travel through speed contour graphs to create average travel times. As was mentioned before, vehicles that do not reach the top of the figures before the end of the hour are not counted. Therefore travel times of virtual vehicles early in the hour are weighed relatively heavy to vehicles that would travel later in the hour. The resulting average travel times can be seen in Table 5.3. In this table one can see that as was concluded in 5.1.3 that the MPC results to lower travel times than the TMS and that multi-class MPC leads to lower travel times for both passenger cars as trucks. However, with lower travel times comes also greater sensitivity to demand fluctuations in the case of the single-class MPC. The multi-class MPC seems more resistant to demand fluctuations than the single-class MPC although the differences are minimal. In Table 5.4 the total costs for each demand level are shown. Here can be concluded that in terms of total cost all control methods respond similar.

Table 5.3: Travel time per user class for each demand level case heavy peak hour

Control method	Demand case	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	90%	38.49	0.75	39.86	0.76
	95%	45.31	0.89	46.44	0.89
	100%	51.18	1.00	52.39	1.00
	105%	56.90	1.11	58.24	1.11
	110%	>60		>60	
TMS	90%	35.51	0.74	36.96	0.75
	95%	41.61	0.86	42.89	0.87
	100%	48.30	1.00	49.36	1.00
	105%	54.81	1.13	55.90	1.13
	110%	>60		>60	
Single-class MPC	90%	32.99	0.76	34,58	0,77
	95%	37.42	0.86	38,88	0,87
	100%	43.28	1.00	44,63	1,00
	105%	49.53	1.14	50,95	1,14
	110%	58.23	1.35	59,64	1,34
Multi-class MPC	90%	32.18	0.76	33.79	0.78
	95%	36.57	0.87	38.12	0.88
	100%	42.10	1.00	43.44	1.00
	105%	48.49	1.15	49.87	1.15
	110%	56.24	1.34	57.60	1.33

Table 5.4: Total cost for each demand level case heavy peak hour

Control method	Demand case	Total cost (€)	Total cost ratio
No control	90%	45028	0.78
	95%	51260	0.89
	100%	57565	1.00
	105%	64119	1.11
	110%	70241	1.22
TMS	90%	43774	0.79
	95%	49283	0.89
	100%	55531	1.00
	105%	61915	1.11
	110%	68405	1.23
Single-class MPC	90%	43121	0.81
	95%	47892	0.90
	100%	53435	1.00
	105%	59302	1.11
	110%	65468	1.23
Multi-class MPC	90%	42909	0.81
	95%	47467	0.90
	100%	52947	1.00
	105%	58938	1.11
	110%	65302	1.23

5.1.5 Conclusion

Applying the TMS, the single-class or multi-class MPC lead to better travel times but are slightly more sensitive to demand changes. Compared to the costs and travel time the control methods save this unreliability is negligible. Applying MPC over TMS leads to large improvements in cost and travel times in the case of the heavy peak hour. Applying multi-class improves cost and travel time even more.

5.2 Case 2: Regular peak hour

On December 13th 2011 a relatively quiet evening peak hour occurred compared to the heavy peak hour of the previous case. First in subparagraph 5.2.1 the outputs of the model will be described. First the outputs of the prediction will be described, then the outputs of the TMS and the MPC. In 5.2.2 the total cost of the output of the control methods will be described. Then 5.2.3 and 5.2.4 will discuss the travel time per user-class and the robustness of these travel times respectively.

5.2.1 Description

December 13th 2011 was a regular winter day with a regular peak hour. This resulted in the evening peak hour shown in Figure 4.2 where the traffic state of the evening peak hour (from 15:00 until 19:00) can be seen. In this subparagraph the traffic state of the prediction will be discussed first. Then the same will be done for the traffic states after the application of the TMS and the MPC respectively.

Prediction

The predicted traffic state on the A15 and the alternative for 17:00 can be seen in Figure 5.15. In the left figure we can see the traffic state for the A15. The bottleneck Charlois (km 56) shows a slightly growing queue. It grows from around 4 to 5 km from 17:00 to 17:30 and from 17:30 until 18:00 this queue remains constant. There is no congestion at the bottleneck at Charlois, so the traffic exiting the A15 to the alternative route will not be hindered. At the right hand side we can see the traffic state of the alternative route (the Vondelingenweg). In this picture two small heavy stop-and-go-waves can be seen. These are the result of the half-hourly Botlek bridge openings. Aside from these bridge openings the road is clear as we can conclude from the figure.

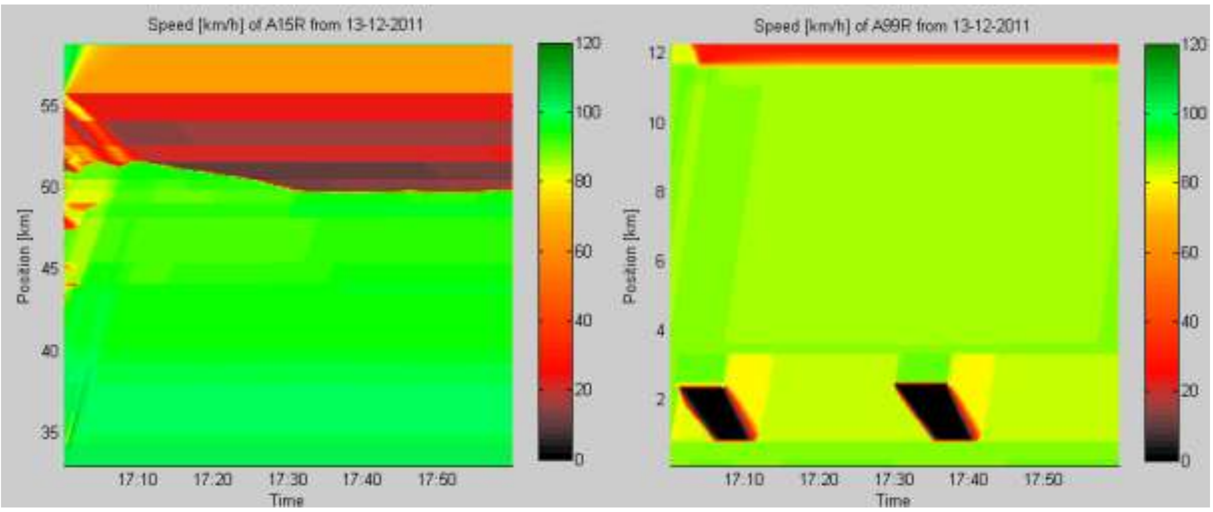

Figure 5.15: Predicted traffic state on the A15 and alternative route on 13-12-2011 at 17:00

Traffic Management Scenario

The traffic state after the application of the TMS can be seen in Figure 5.16. In paragraph 4.2 the conditions for which the TMS is turned on were described. These comprise the speed on the main route and the availability of the alternative route. The traffic state in Figure 5.15 shows that at bottleneck Charlois the traffic travels below 50 km/h for the whole hour. In 5.1.1 was described that the availability of the alternative route is a little bit more complex. The speed on the alternative route is constant above 30 km/h except for the two openings of the Botlek bridge. As was described before the TMS thus is turned on during the whole hour, except during the openings of the bridge. The rerouting signal for this experiment was 90%, the way this percentage was determined was described in 4.2.

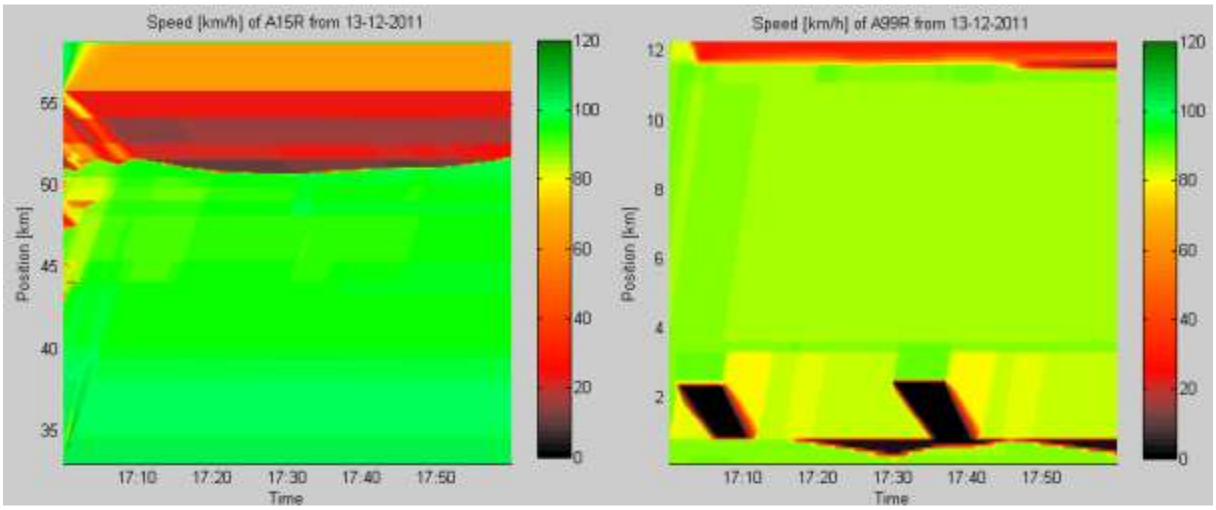

Figure 5.16: Predicted traffic state on the A15 and alternative route on 13-12-2011 at 17:00 with the application of the TMS

We can compare the traffic state after the implementation of the TMS from Figure 5.16 and the original prediction from Figure 5.15 and conclude an improvement in traffic state on the A15. The congestion is around 1 km shorter and decreases after 17:30 instead of increasing. Since traffic is being rerouted to the alternative route, one can see that the traffic state there slightly deteriorates. This is caused mostly by the fact that the congestion for the bridge openings leave a stop-and-go wave (the horizontal black line in the figure on the right) which does not dissolve before the next opening.

Single-class Model Predictive Control

When we look at the traffic state after implementing the MPC in Figure 5.17 one can see that the traffic state has improved compared to the situation with no control in Figure 5.15. If we compare the application of the MPC to the application of the TMS in Figure 5.16 it can be seen that Figure 5.17 shows a shorter queue than Figure 5.16. On the right hand side the first Botlek bridge opening shows some spillback on the alternative route. However, there is no stop-and-go wave after the second opening.

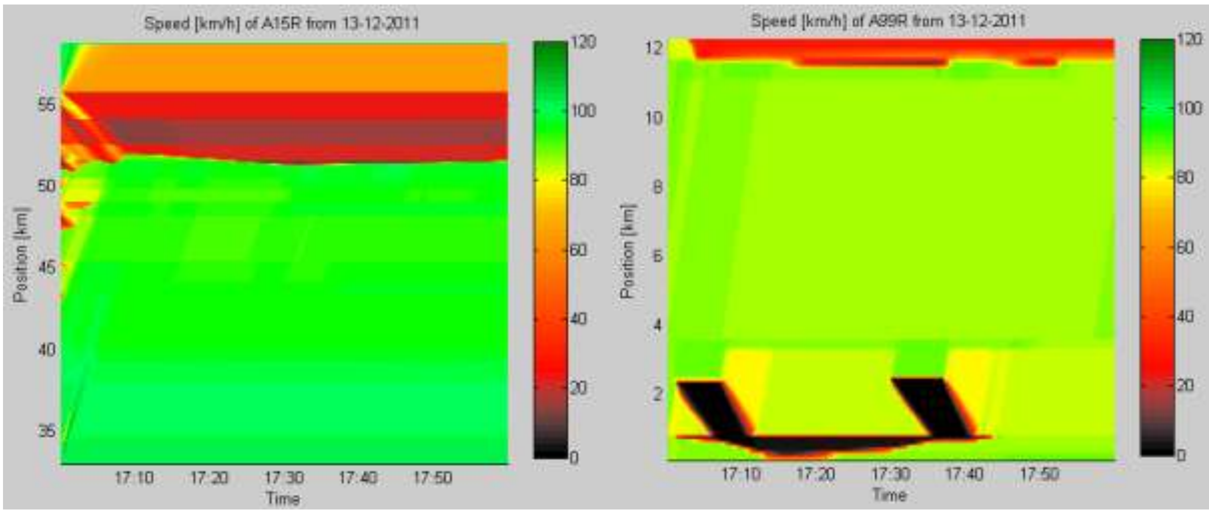

Figure 5.17: Predicted traffic state on the A15 and alternative route on 13-12-2011 at 17:00 with the application of the single-class MPC

Also here the optimization of the control signal leads to a visually better traffic state. The optimized control signal can be seen in Figure 5.18. There can be seen that for the first 15 minutes 70% of the traffic gets rerouted and for the rest of the hour 40%. This is a little more than in the heavy peak hour case, where the signals were set on 65% and 30% respectively. This is due to the fact that the alternative route gets congested when re-routing too much traffic.

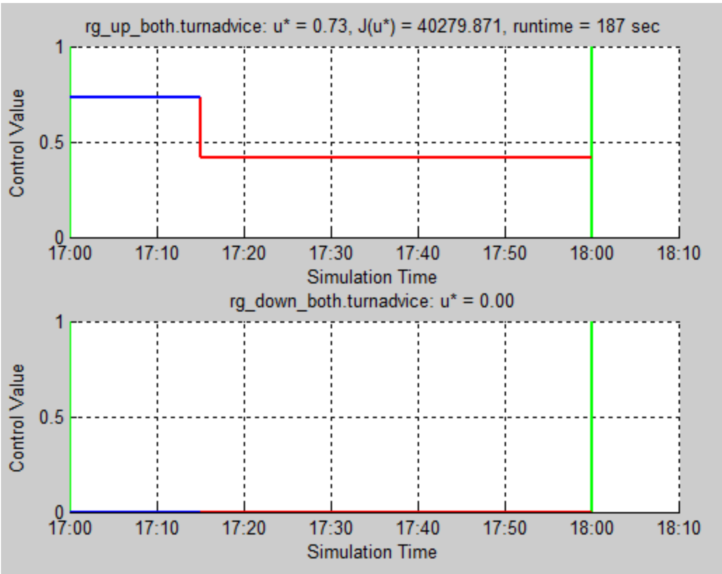

Figure 5.18: Control signal of the single-class MPC for 13-12-2011 at 17:00

In this case the MPC reroutes less traffic than the TMS. Therefore can be assumed that the TMS reroutes too much traffic to the alternative route.

Multi-class Model Predictive Control

Compared to Figure 5.17 the traffic state when the MPC uses multi-class route guidance in Figure 5.19 looks very similar. The queue on the main route is however slightly shorter.

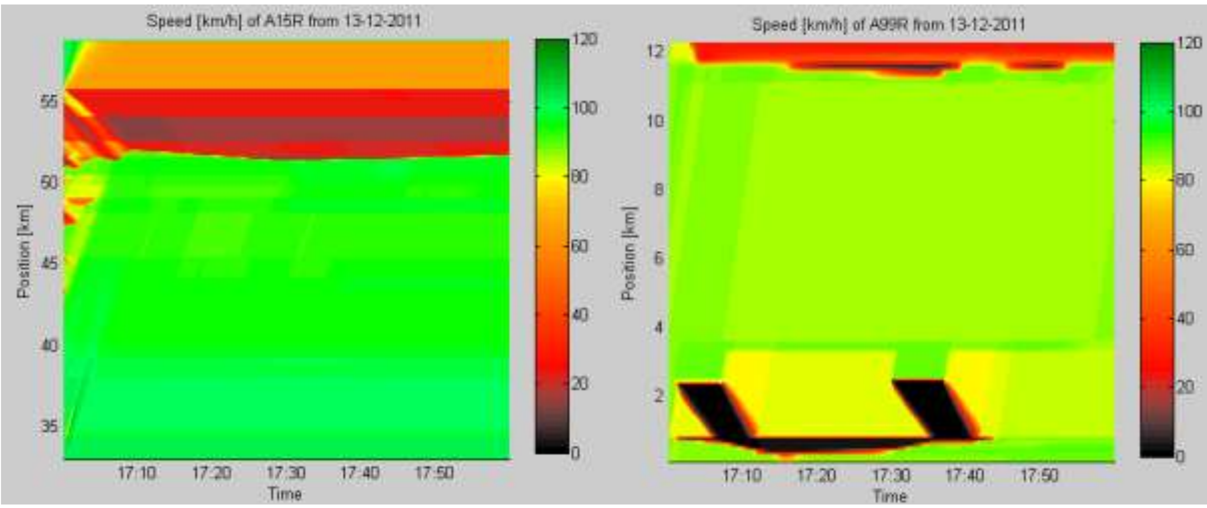

Figure 5.19: Predicted traffic state on the A15 and alternative route on 13-12-2011 at 17:00 with the application of the multi-class MPC

The optimized control signal for the multi-class MPC can be seen in Figure 5.20. What strikes here is that contrary to the signal in the heavy peak hour case truck traffic gets rerouted here. In the first 15 minutes all the passenger car traffic (the second graph in the figure) gets rerouted and 14% of the truck traffic gets rerouted. The travel time gain for trucks by entering the alternative route is relatively higher in this case compared to the heavy peak hour case.

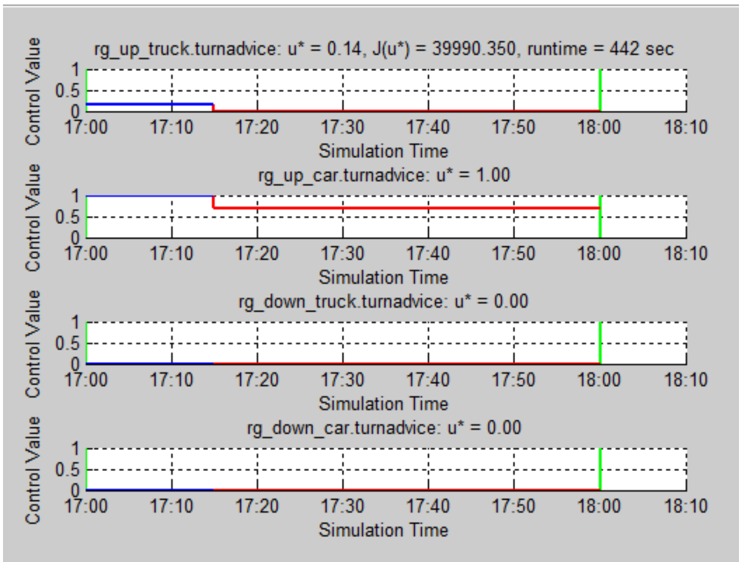

Figure 5.20: Control signal of the multi-class MPC for 13-12-2011 at 17:00

To conclude both control methods seem to have positive effects on the traffic state. The application of multi-class rerouting seems to be minimal. In the next sub-paragraph the scores on the performance indicators will be discussed.

5.2.2 Total cost

In Table 5.5 the total cost of the different methods is shown. The table is the result of the calculation shown in 4.7.1. Also in this case both control methods save significant costs. The TMS saves 3.3% and the MPC saves 6% when single-class rerouting is active and 6.5% when multi-class rerouting is applied. Note that the MPC saves almost twice as much than the TMS.

Table 5.5: Total cost case regular peak hour

Control method	Total cost (1000 €)	Total cost ratio
No control	42.5	100%
TMS	41.1	96.7%
Single-class MPC	40.0	94.1
Multi-class MPC	39.8	93.5%

It can be concluded that both control methods lead to a large improvement in cost.

5.2.3 Travel time per user class

In 4.7.2 was described how travel times per user-class were determined. Table 5.6 is the result of this method. The travel times of the different classes are listed and the relative improvement compared to the original travel time of the classes without traffic control applied. Compared to Table 5.2, where the same data is shown for the heavy peak hour, the travel times of the passenger cars and the trucks differ more. This is due to the fact that in this case there is less congestion and therefore a larger relative difference in speeds. Also in this case the MPC has a larger improvement compared to the TMS. For the passenger cars this is 10% and for the trucks 8.5%. Applying MPC in regular peak hours improves travel times much. The improvement of multi-class here is less (1% versus a little more than 2%) than it was for the heavy peak hour. In the heavy peak hour case this difference was smaller, but here the differences in travel time matter.

Table 5.6: Travel times per user class case regular peak hour

Control method	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	32.41	100%	37.73	100%
TMS	30.45	94.0%	32.67	86.6%
Single-class MPC	27.27	84.1%	29.46	78.1%
Multi-class MPC	26.86	82.9%	29.04	77.0%

What can be concluded from the table for both control methods is that they lead to better travel times than in the no control case.

5.2.4 Travel time robustness

As was mentioned before, each experiment was performed five times, each with a different demand level. This was to research how the traffic system and the control would respond to changes in the predicted demand. The traffic states for the prediction in the situation of no control can be seen in Figure 5.21 and Figure 5.22. What can be seen from Figure 5.21 is that with less demand the congestion gets a little shorter, but with 5% or 10% extra demand the congestion at bottleneck Charlois gets a lot longer. In the two graphs most right it can be seen that the congestion grows to 5 to 10 kilometers length. We can also assume that if there will be extra demand this congestion would have been there from the start of the time interval. In the case of 110% demand the queue grows to the bottleneck at Spijkenisse and could hinder the off-ramp to the alternative route. In Figure 5.22 can be seen that the traffic state on the alternative route hardly changes with increased or decreased demand.

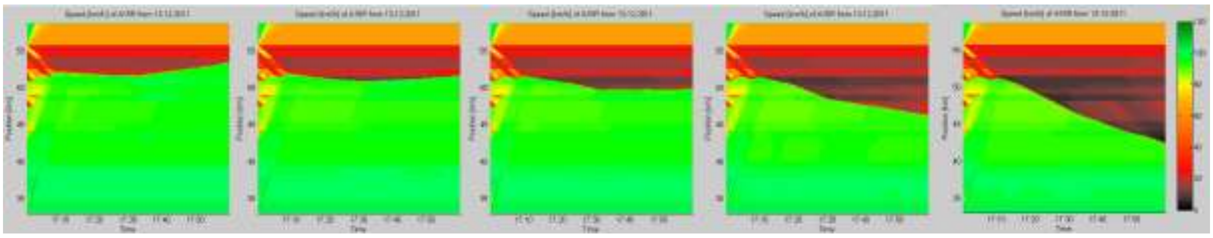

Figure 5.21: Speed contour graphs for the A15 of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

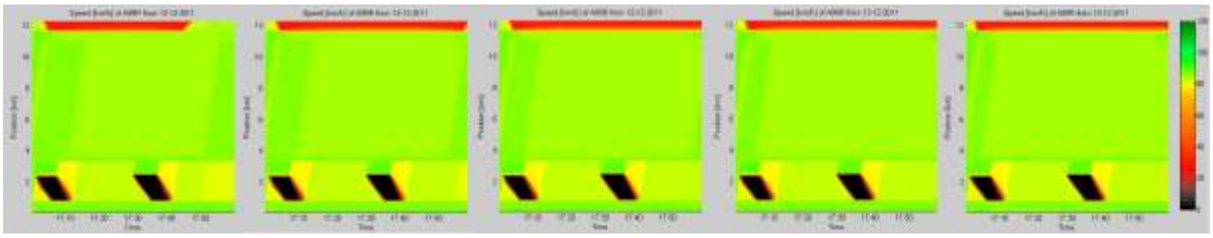

Figure 5.22: Speed contour graphs for the alternative route of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

In Figure 5.23 and Figure 5.24 the traffic states of the A15 and alternative route respectively can be seen when the TMS is applied. If the traffic state of the A15 is compared to the traffic state before the application of the TMS in Figure 5.21, it can be seen that there is a large improvement regarding the queue length. In the 110% demand case the congestion does not spill back to the bottleneck at Spijkenisse anymore. The queue growth in the experiment interval is relatively small in this case when the TMS is applied, compared to the 105% case where it grew to about 5 km. On the alternative route however the queues that originate from the Botlek bridge openings leave a stop-and-go wave that lasts until the next opening of the bridge. The traffic state at the alternative route deteriorates thus at the Botlek bridge and at the on-ramp back to the A15 at the top of the figures, but the rest of the road remains clear. Therefore it can be concluded that applying the TMS in this case at first sight leads to good results.

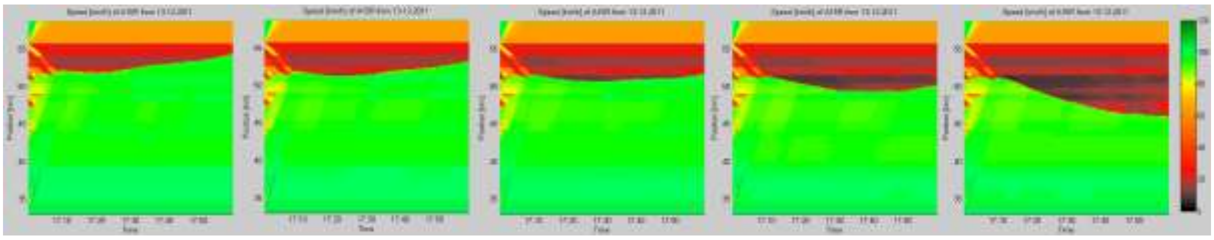

Figure 5.23: Speed contour graphs for the A15 of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

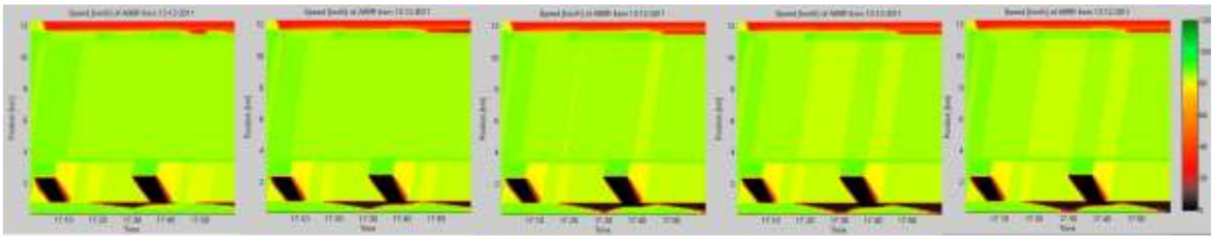

Figure 5.24: Speed contour graphs for the alternative route of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

In Figure 5.25 and Figure 5.26 the traffic states of the A15 and alternative route after application of the single-class MPC can be seen. On the A15 the queue length in the four left most cases is shorter than after the application of the TMS. On the alternative route the first bridge opening causes a short stop-and-go-wave which dissolves after the second bridge opening. This stop-and-go-wave happens also in the case of the TMS, but due to the TMS being activated around the bridge openings it happens there later. In the 110% demand case the stop-and-go-wave of the bridge-opening spills back to the main route and causes a short congestion there. The congestion here at bottleneck Charlois is shorter than after applying the TMS. The traffic state in this demand case does not look intuitive since the congestion at Spijkenisse could have been prevented by the MPC by rerouting a lower percentage of the traffic. Apparently the total cost this way is lower. The control signal for this case can be found in Appendix B.

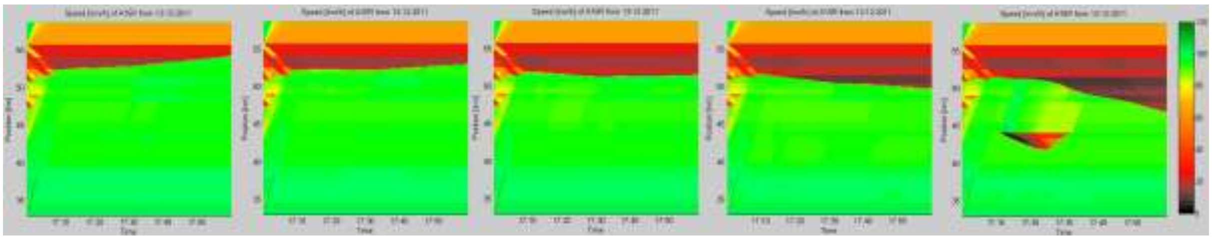

Figure 5.25: Speed contour graphs for the A15 of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

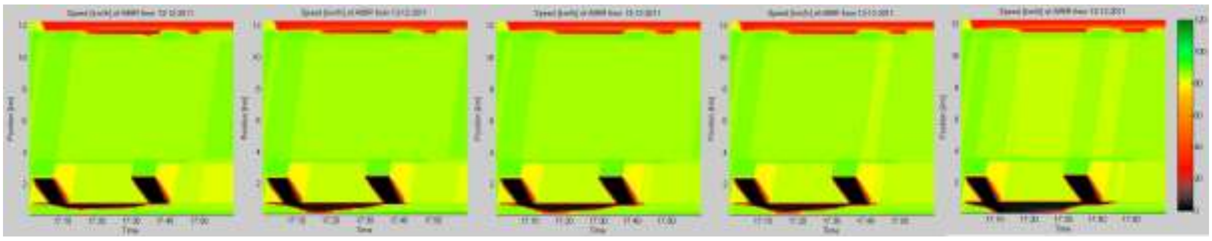

Figure 5.26: Speed contour graphs for the alternative route of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

When the multi-class MPC is applied on this case with different demands the traffic state improves even more, as can be seen in Figure 5.27 and Figure 5.28. Compared to the traffic state after applying the single-class MPC, the multi-class MPC can keep the congestion at Spijkenisse in the 110% demand case stop from occurring. It can be concluded that the MPC leads to a better traffic state than the TMS. Multi-class rerouting appears to have minimal added value compared to single-class rerouting with the exception of the 110% demand case.

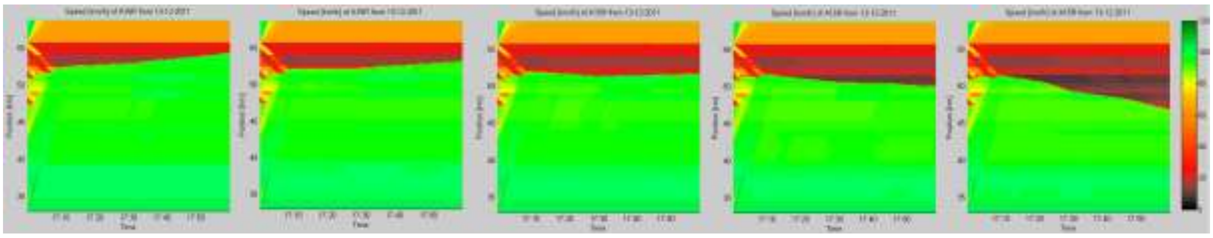

Figure 5.27: Speed contour graphs for the A15 of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

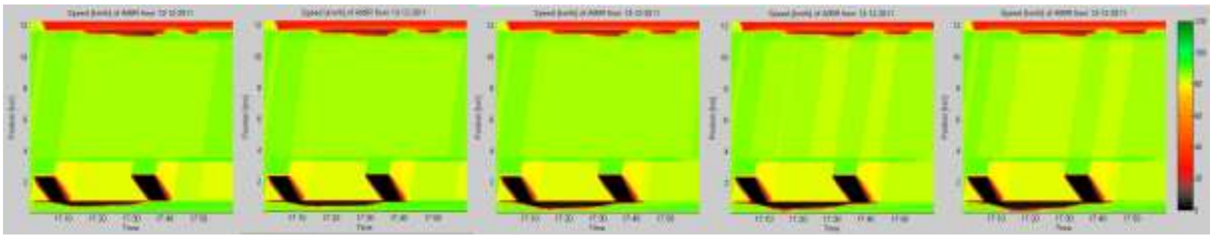

Figure 5.28: Speed contour graphs for the alternative route of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 13-12-2011

In paragraph 4.7 was shown how virtual vehicles travel through speed contour graphs to create average travel times. In Table 5.7 the average travel times for each class and their ratios compared to the 100% case are shown. From this table it can be seen that the TMS shows a good improvement in travel times for both classes and that the MPC performs even better on this indicator. The multi-class in turn has a slight improvement over de single-class MPC. With a less heavy peak hour the control methods are less sensible to demand fluctuation than in heavy peak hour case. The control methods also have similar sensitivity to these demand fluctuations. In total cost all methods show large improvements in the high demand cases compared to the situation with no control, as can be seen in Table 5.8. Both MPC variants show a smaller variance in total cost than the TMS does in this case.

Table 5.7: Travel time per user class for each demand level case regular peak hour

Control method	Demand case	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	90%	25.70	0.79	27.91	0.80
	95%	28.94	0.89	31.17	0.90
	100%	32.41	1.00	34.73	1.00
	105%	35.28	1.09	37.64	1.08
	110%	38.28	1.18	40.76	1.17
TMS	90%	24.27	0.80	26.48	0.81
	95%	26.68	0.88	28.87	0.88
	100%	30.45	1.00	32.67	1.00
	105%	34.53	1.13	36.88	1.13
	110%	38.17	1.25	40.92	1.25
Single-class MPC	90%	22.93	0.84	25.18	0.85
	95%	25.00	0.92	27.25	0.93
	100%	27.27	1.00	29.46	1.00
	105%	30.92	1.13	33.19	1.13
	110%	34.94	1.28	37.15	1.26
Multi-class MPC	90%	22.70	0.85	24.96	0.86
	95%	24.79	0.92	27.02	0.93
	100%	26.86	1.00	29.04	1.00
	105%	30.53	1.14	32.78	1.13
	110%	33.65	1.25	36.22	1.25

Table 5.8: Total cost for each demand level case regular peak hour

Control method	Demand case	Total cost (€)	Total cost ratio
No control	90%	34125	0.80
	95%	38316	0.90
	100%	42528	1.00
	105%	48001	1.13
	110%	54178	1.27
TMS	90%	33704	0.82
	95%	37314	0.91
	100%	41147	1.00
	105%	45155	1.10
	110%	51237	1.25
Single-class MPC	90%	33187	0.83
	95%	36259	0.91
	100%	40003	1.00
	105%	43736	1.09
	110%	48548	1.21
Multi-class MPC	90%	33062	0.83
	95%	36091	0.91
	100%	39776	1.00
	105%	43519	1.09
	110%	48228	1.21

5.2.5 Conclusion

All methods seem to improve the traffic state, total cost and improve travel times for both passenger cars and trucks. Model Predictive Control performs overall better than the Traffic Management Scenario, and has especially for the total cost phenomenal results. Applying multi-class rerouting has less gain in travel time and costs than in the heavy peak hour case.

5.3 Case 3: Accident

On November 17th 2011 an accident occurred at 14:50. The road cleaning activities after this accident lasted for an hour; the road thus got cleared at 15:50. In this paragraph the results in traffic state of the different control methods will be discussed. In this subparagraph 5.3.1 first the outputs of the prediction will be described, then the outputs of the TMS and the MPC. In 5.3.2 the total costs will again be described. Then 5.3.3 and 5.3.4 will discuss the travel time per user-class and the robustness of these travel times respectively.

5.3.1 Description

The resulting traffic state from loop detector data from the accident and thereafter can be seen in Figure 4.3. The predictions ran with Fastlane here will go from 15:00 until 16:00.

Prediction

The predicted traffic state after the accident happened can be seen in Figure 5.29. The accident causes a very long queue on the A15 (the left graph) almost until the end of the used network. The daily congestion that should start around this time is therefore also not present. This queue is primarily traffic standing still. At 15:50 when the road gets cleared it can be seen that the daily congestion at bottleneck Charlois arises. At the right hand side we can see that due to the accident the first bridge opening on the alternative route causes a shorter queue due to the lack of traffic flowing in.

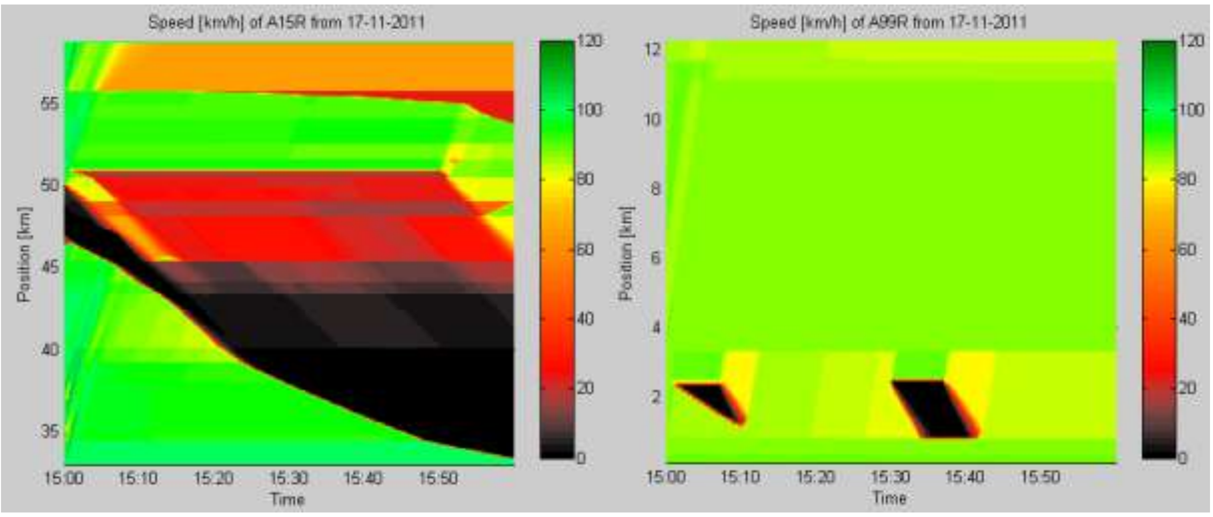

Figure 5.29: Predicted traffic state on the A15 and alternative route on 17-11-2011 at 15:00

Traffic Management Scenario

The traffic state after rerouting the traffic can be seen in Figure 5.30. After the accident is noticed by the controller the TMS will be activated. The TMS will then reroute all traffic possible to reroute to the alternative route.

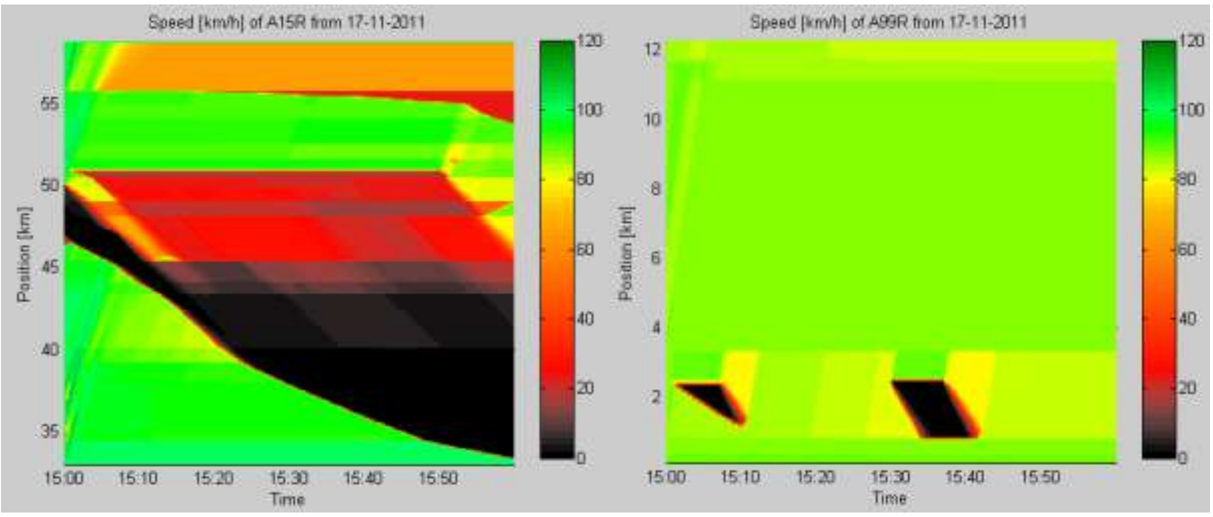

Figure 5.30: Predicted traffic state on the A15 and alternative route on 17-11-2011 at 15:00 with the application of the TMS

When Figure 5.30 is compared to Figure 5.29 we can see that the traffic state on the A15 due to rerouting at km 44 slightly improves. The black area changes there to grey, which means that the traffic is flowing at low speeds instead of standstill.

Single-class Model Predictive Control

Figure 5.31 depicts the traffic state after the application of the single-class MPC. The graph on the right, which shows the traffic state of the A15, looks similar to the graph of the traffic state of the TMS. The graph of the MPC shows a more grey area below the 45km line where the TMS had a more black area there. On the right can be seen that the traffic state on the alternative route after application of the MPC is similar to the one after the application of the TMS.

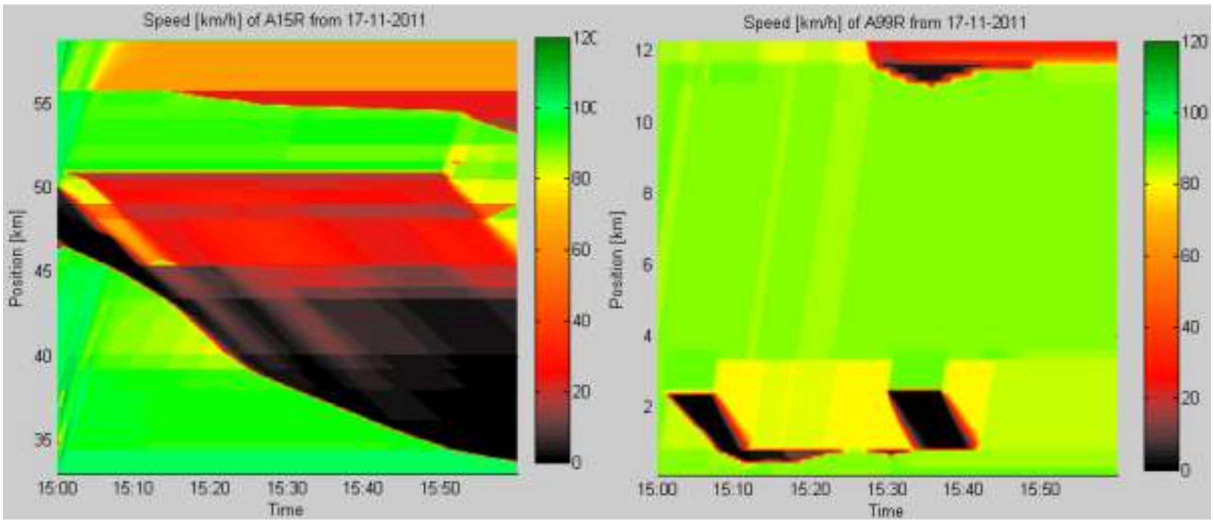

Figure 5.31: Predicted traffic state on the A15 and alternative route on 17-11-2011 at 15:00 with the application of the single-class MPC

The control signal in Figure 5.32 is set to 100% rerouting for the whole hour. The MPC reroutes as much traffic as possible to mitigate the main route.

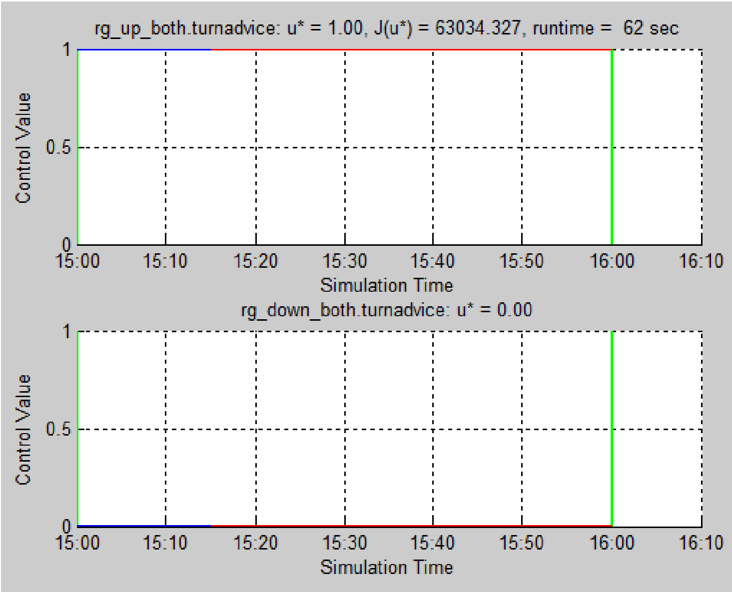

Figure 5.32: Control signal of the single-class MPC for 17-11-2011 at 15:00

Multi-class Model Predictive Control

Figure 5.33 depicts the traffic state after the application of the multi-class MPC. It is very similar to the traffic state of the single-class controller, which is due to the fact that the control signal for both rerouting signals is very similar, as is explained below.

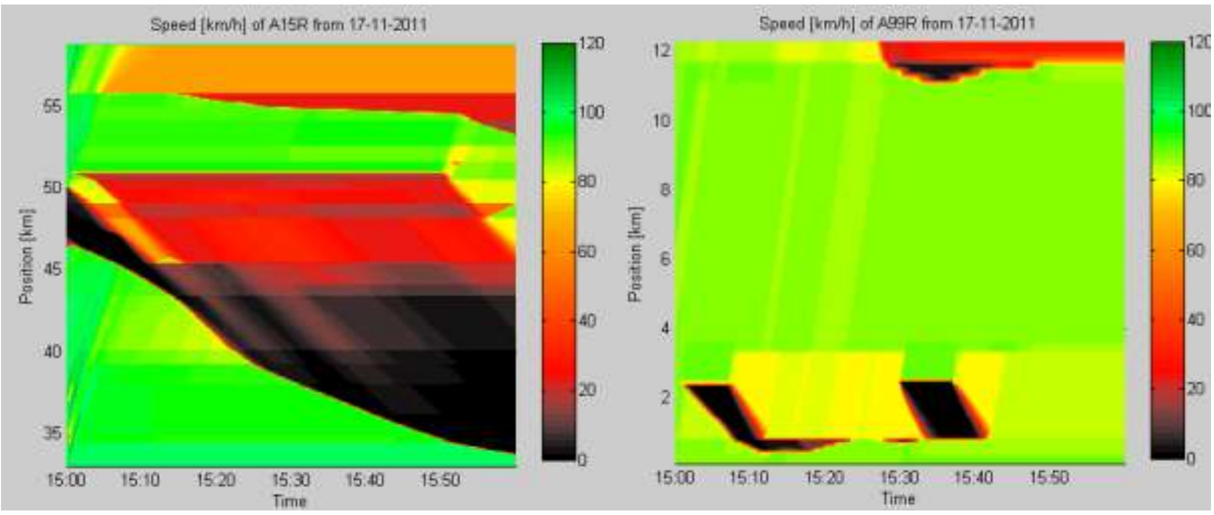

Figure 5.33: Predicted traffic state on the A15 and alternative route on 17-11-2011 at 15:00 with the application of the multi-class MPC

The control signal that was the result of the optimization of the MPC is shown in Figure 5.34. Due to the severity of the accident the MPC reroutes all traffic in the first 15 minutes. After 15 minutes the control signal for the trucks changes to 90%. The control signal for cars stays on 100%. It can thus be concluded that single-class MPC as well as multi-class MPC almost reroute the same amount of traffic in this case.

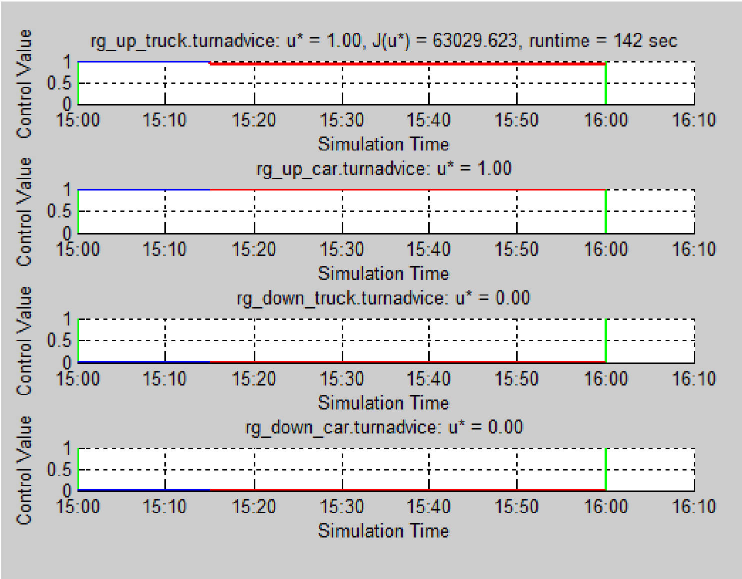

Figure 5.34: Control signal of the multi-class MPC for 17-11-2011 at 15:00

As one can see, when a heavy accident happens the control methods seem to improve the traffic state, but not as much as with a regular peak hour. Both the control methods get the traffic moving again, but they do not shorten the queue. But as was stated before, traffic standing still has a great influence on cost. Class specific rerouting seems to have little influence here. In the next subparagraphs will be described how the control methods perform on cost and travel time.

5.3.2 Total cost

In 5.3.1 was concluded that the queue lengths after application of the control methods did not diminish. In **Fout! Verwijzingsbron niet gevonden.** can be seen that the total cost decreases ith 4.5%. This is a good result despite the queue length not diminishing.

Table 5.9: Total cost case accident

Control method	Total cost (1000 €)	Total cost ratio
No control	65.3	100%
TMS	62.4	95.5%
Single-class MPC	62.4	95.5
Multi-class MPC	62.4	95.5%

What strikes here is that despite the traffic states in 5.3.1 the TMS and both MPC approaches score the same on total cost. In this accident situation the best option is to reroute as much traffic as possible and that is what TMS and both MPC's do here. This leads to similar performance.

5.3.3 Travel time per user class

In **Fout! Verwijzingsbron niet gevonden.** the average travel time per class is shown as well as he relative improvement to the original travel time of that class. However these are the travel times of the vehicles on the main route. Since all traffic that enters the main route at the start of the network and exits at the end gets rerouted, the travel times shown are averages for background traffic. Therefore in this case this performance indicator has less weight.

As with the heavy peak hour case, it can be seen that the travel times of both cars and trucks do not differ very much. All methods win about 6% in travel time for both classes although they win more for the trucks and the MPC scores slightly better. In absolute numbers the travel time gain for the cars is about 2 minutes and the travel time gain for the trucks is 2.5 minutes. Since the multi-class MPC does not send all traffic to the alternative route where the single-class MPC does the travel times from the main route are lower for the single-class MPC than for the multi-class MPC.

Table 5.10: Travel times per user-class case accident

Control method	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	40.82	100%	43.29	100%
TMS	39.01	95.6%	41.04	94.8%
Single-class MPC	38.84	95.1%	40.77	94.1%
Multi-class MPC	38.91	95.3%	40.83	94.3%

5.3.4 Travel time robustness

To measure travel time robustness also this experiment was performed five times with a different demand level. In Figure 5.35 and Figure 5.36 the different traffic states of the A15 and the alternative route are shown. These figures do not differ very much from each other. In the upper right hand corner of the graphs of the traffic states of the A15 the start of the daily congestion after the road gets cleared can be seen. At the higher demand levels this congestion grows faster. Another small difference is the speeds in the queue, at lower demands they are a bit higher, depicted by the grey areas instead of black areas.

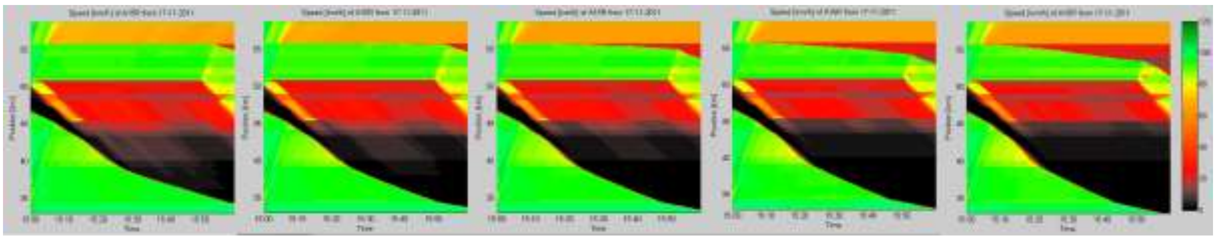

Figure 5.35: Speed contour graphs for the A15 of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

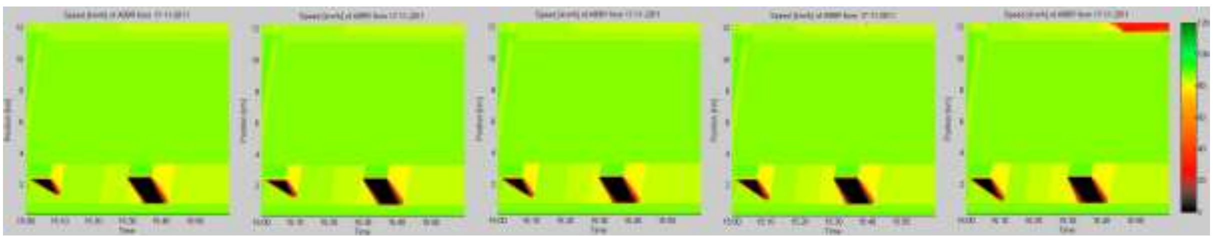

Figure 5.36: Speed contour graphs for the alternative route of the prediction for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

After the application of the TMS the traffic states of the A15 and alternative route improve, as can be seen in Figure 5.37 and Figure 5.38. If the two most right graphs are compared to the ones in

Figure 5.35 one can conclude that there is little to no improvement. The accident and the demand cause the off-ramp to the alternative route to be blocked.

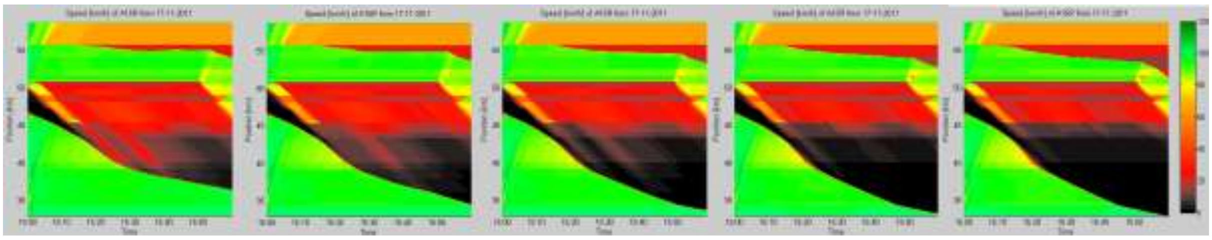

Figure 5.37: Speed contour graphs for the A15 of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

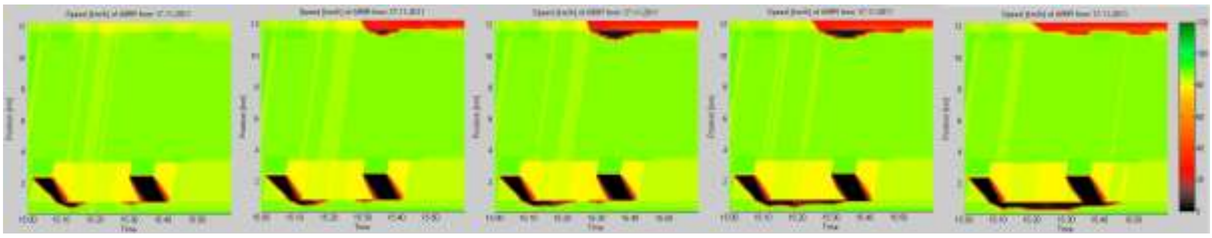

Figure 5.38: Speed contour graphs for the alternative route of the application of the TMS for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

In Figure 5.39 and Figure 5.40 the traffic state after the application of the single-class MPC can be seen. These figures are similar to Figure 5.37 and Figure 5.38.

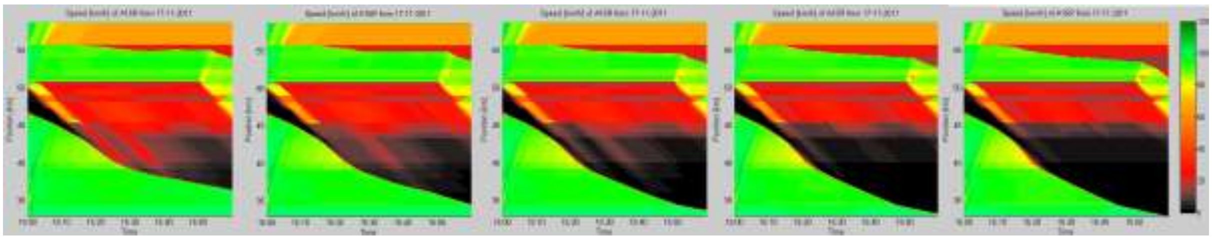

Figure 5.39: Speed contour graphs for the A15 of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

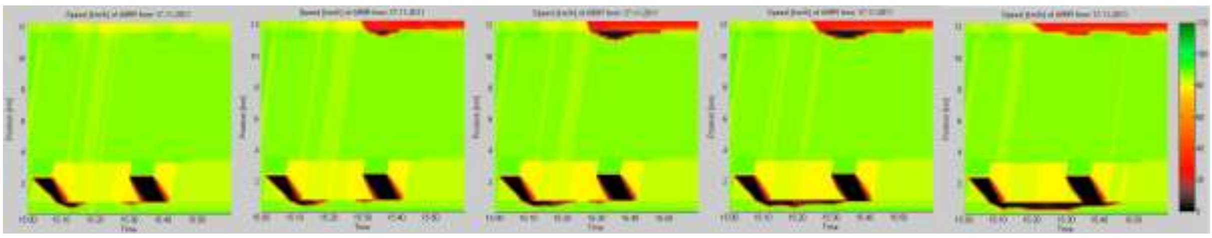

Figure 5.40: Speed contour graphs for the alternative route of the application of the single-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

Also the figures (Figure 5.41 and Figure 5.42) from the multi-class MPC show little difference with the single-class MPC.

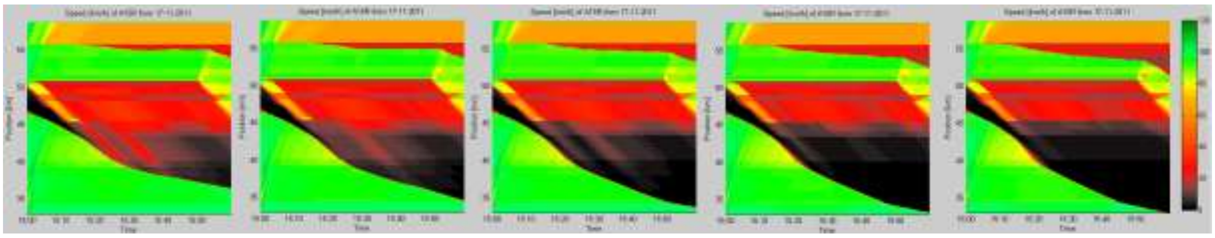

Figure 5.41: Speed contour graphs for the A15 of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

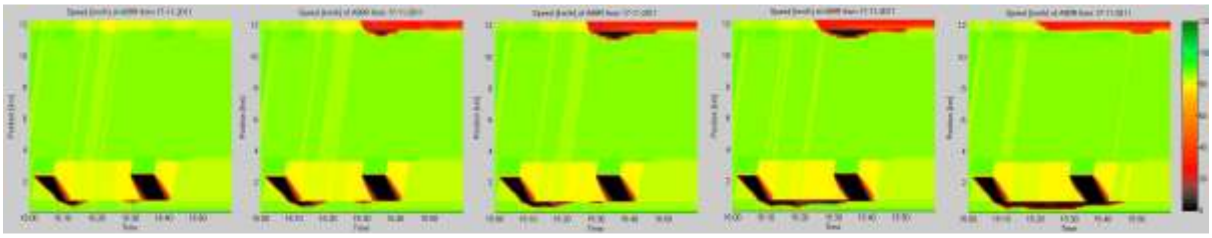

Figure 5.42: Speed contour graphs for the alternative route of the application of the multi-class MPC for 90%, 95%, 100%, 105% and 110% of the original estimated demand on 17-11-2011

It can be concluded that the traffic states for the TMS, the single-class and multi-class MPC all look similar; they improve slightly with increasing demand level.

As was mentioned before since in this case almost all the traffic gets rerouted for all three control methods. The travel times in Table 5.11 of the passenger cars and trucks only give an estimation on how the MPC performs for these classes. In the table can be seen that correspondingly with the results on traffic state and total costs the control methods do not differ much in performance here. The control signals of the MPC can be seen in the appendix, it can be seen that the control signal of the MPC is very similar to the control signal of the TMS, which reroutes all traffic. This explains the fact that there are little to no differences between the total costs of the application of both control signals.

Table 5.11: Travel time per user class for each demand level case accident

Control method	Demand case	Average travel time passenger cars (min)	Average travel time passenger cars ratio	Average travel time trucks (min)	Average travel time trucks ratio
No control	90%	37.75	0.92	39.95	0.92
	95%	39.36	0.96	41.69	0.96
	100%	40.82	1.00	43.29	1.00
	105%	41.48	1.02	44.11	1.02
	110%	43.37	1.06	46.03	1.06
TMS	90%	34.74	0.89	36.41	0.89
	95%	37.60	0.96	39.39	0.96
	100%	39.01	1.00	41.04	1.00
	105%	39.72	1.02	42.96	1.05
	110%	41.73	1.07	43.85	1.07
Single-class MPC	90%	34.28	0.88	35.88	0.88
	95%	36.47	0.94	38.65	0.95
	100%	38.84	1.00	40.77	1.00
	105%	40.07	1.03	42.15	1.03
	110%	41.05	1.06	43.07	1.06
Multi-class MPC	90%	34.28	0.88	35.88	0.88
	95%	36.47	0.94	38.65	0.95
	100%	38.91	1.00	40.83	1.00
	105%	40.07	1.03	42.15	1.03
	110%	41.29	1.06	43.34	1.06

Table 5.12: Total cost for each demand level case accident

Control method	Demand case	Total cost (€)	Total cost ratio
No control	90%	54959	0.84
	95%	59941	0.92
	100%	65324	1.00
	105%	70706	1.08
	110%	75743	1.16
TMS	90%	50912	0.82
	95%	56585	0.91
	100%	62395	1.00
	105%	68383	1.10
	110%	74203	1.19
Single-class MPC	90%	50743	0.81
	95%	56504	0.91
	100%	62387	1.00
	105%	68444	1.10
	110%	74083	1.19
Multi-class MPC	90%	50743	0.81
	95%	56504	0.91
	100%	62426	1.00
	105%	68444	1.10
	110%	74203	1.19

5.3.5 Conclusion

In this case can be concluded that applying traffic control gains travel time and cost in a situation with an accident. However with a heavy accident that occurred on November 17th 2011 the TMS and the MPC, applied single-class or multi-class have no significant differences in performance.

5.4 Discussion

The model study consisted of three cases discussed in the previous paragraphs. These cases will be discusses here.

5.4.1 Heavy peak hour

The case of the heavy peak hour made clear that applying traffic control with a rerouting signal to the A15 shows good results. If a TMS designed based on traffic model runs is applied to this traffic system, good cost reductions can be made. Travel times of both passenger cars and trucks improver after the implementation. Applying MPC shows an even better performance, both in cost as in travel times. The TMS – designed based on experience – saves around half of the costs the MPC – the optimal control signal - saves. That is a good result for the TMS, but not one without improvement possible. The multi-class MPC shows even better results. Since the control signal here is optimized by total cost on which travel times of trucks have high influence, the difference in travel times of passenger cars and trucks are smaller, where passenger cars will always have shorter travel times due to their higher free-flow speed. This difference can be appointed to the control signal, where the MPC in this case reroutes only passenger car traffic. The A15 is sensitive to demand fluctuations during a high peak hour. If the traffic demand would be 5% higher, the total cost will be around 11% higher. Both the TMS and the MPC have an equal sensitivity for this.

5.4.2 Regular peak hour

In a peak hour that is less heavy the relative performance of both control methods change. Both methods still show increasing performance. The TMS has a similar improvement as in the heavy peak hour (around 4% gain in total cost) where the MPC has less gain over the TMS as in the former case. The difference between the single-class MPC and the multi-class MPC is also smaller on total cost than in the heavy peak hour case.

5.4.3 Accident

The accident in the third case TMS and MPC were applied was a heavy one. Applying the both control methods, the MPC single-class and multiclass, showed less gain than in the regular peak hour cases. Both methods score equal on total cost. Also demand fluctuations would have lesser impacts on this accident than they have on the peak hours described above. At 10% more demand the travel times become 6-7% higher. This can be explained by the fact that most traffic is standing still already and therefore the travel time is high and the added travel time by the extra demand becomes relatively less. What strikes the most is that applying traffic control had the largest influence on travel times of trucks. It seems that traffic control in general has most beneficial results for truck traffic on the A15.

5.5 Synthesis

In this chapter the results of the experiment described in chapter 4 were presented and discussed. In the first paragraph the case of the heavy peak hour was evaluated, where first a description of the visual traffic state for each of the four modes of control – no control, TMS, single-class MPC and multi-class MPC – were given. In this description also the signals the control methods used to manage traffic were discussed. In the subparagraphs that followed the total cost, travel time per user class and the robustness of travel times were presented and the paragraph was closed with a short conclusion on the case. This process was repeated for the regular peak hour in the second paragraph and the accident in the third paragraph. Finally in the discussion the results were put into perspective. In the case of the heavy peak hour applying traffic control in general has great benefits in terms of total cost and travel time per user-class. What can be seen in 5.1 is that the single-class MPC has twice the gain the TMS has and the multi-class MPC gains almost a percent more in costs. These costs should be interpreted as travel time costs and the cost gain of the control methods in a heavy peak hour are between around two and five thousand Euros. The overall gain in the case of the regular peak hour on all these performance indicators is less. The MPC's have less gain over the TMS in this case and the range of gain here is between 1.5 and 2.5 thousand Euros and in the accident case it does not matter which traffic control method there is used since they all gain around 3 thousand Euros per peak hour, which is relatively less to the original costs compared to the peak hour cases. Regarding travel times on the main road, truck traffic benefits most from traffic control in general. Applying multi-class MPC shortens travel times of trucks but also of passenger cars on the A15. In none of the cases either one of the traffic control methods proves to be significantly more robust than the others, there are differences but they are small. In the next chapter final conclusions will be drawn.

6 Conclusions and recommendations

This thesis will be ended with conclusions on the results of the model study and thus answering the research questions from the first chapter. Then recommendations and suggestions for further research are made.

6.1 Conclusions

In the introduction of this research the main research goal was stated:
To make a quantitative comparison based on economic costs among Traffic management Scenarios, Single-class Model Predictive Control and Multi-class Predictive Control.
To achieve this goal research questions were formulated. These answer will be summarized here.

6.1.1 How can control methodologies be categorized?

Firstly a literature study mapped the two traffic control measures that were compared in the current study. This resulted in a chart (Figure 2.4). The graph shows the difference among control methods on the properties of adaptability and the prediction horizon. What can be seen from Figure 2.4 how Model Predictive Control is a more advanced method over Traffic Management Scenarios, because Model Predictive Control has a longer prediction horizon and uses an algorithm to find the optimal control signal. The graph also showed that the latter, already applied in practice, is a great step in the direction of adaptive traffic control.

6.1.2 Which relevant Dynamic Traffic Management (DTM) measures that can be applied to the A15 can be found in literature?

The traffic management measures, which can be controlled by TMS and MPC, discussed in the state of the art (chapter 2) were multi-class ramp metering and route guidance. Dynamic speed limits and peak-hour lanes were not discussed since they are not feasible in the case of the A15. For the current study only the effect of route guidance was researched since the application of route guidance is the state of the practice. Route guidance is currently applied single-class but user-class specific route guidance was applied for the multi-class Model Predictive Controller.

6.1.3 How can Traffic Management Scenarios and Model Predictive Control be compared?

Because Traffic Management Scenarios are put into practice currently and Model Predictive Control is not, the models cannot be compared with a data study. Traffic Management Scenarios are designed based on experience there are no traffic models with the scenarios implemented, while Model Predictive Control is a widely researched traffic control method. To compare them in a fair way a method of comparison was designed. This method is a simulation experiment using a traffic model with a changeable control module in it. This module can be turned off to simulate a base case; it can be the Traffic Management Scenario, the single-class Model Predictive Controller or the multi-class Model Predictive Controller in the current study.
The current study used the framework BOS-HbR (Schreiter et al. 2011b) that fulfills these requirements. The framework uses the eastbound part of the A15 in the Port of Rotterdam Region

as its network. The traffic model used in this framework is the multi-class model Fastlane (Lint et al. 2008) which is necessary to model traffic correctly for this highway, due to its high truck share, and to model multi-class route guidance.

6.1.4 What Traffic Management Scenarios are currently in use?

The Traffic Management Scenario currently used in practice on the A15 is the 'A15 Haven Uit' (Houtriet 2011) Scenario. BOS-HbR was designed with Fastlane as its prediction component, but the translation of the Traffic Management Scenario had to be done separately for this research. The Traffic Management Scenario used for this research was designed with the activation and de-activation triggers from the original scenario. The applied control signal is a result of a set of experiments in order to find the highest compliance to the signal from the traffic on the road that realistically can be assumed. By implementing the Traffic Management Scenario in a traffic model, the human controller is taken out of the feedback loop. Therefore the implementation of 'A15 Haven Uit' is not a perfect representation of the Traffic Management Scenario used in practice but this implementation is done to resemble the practical scenario well enough to be representative.

6.1.5 What are good performance indicators for judging Traffic Control?

The results of the comparison are judged by a set of performance indicators. The performance indicators for this comparison are: total cost, travel time per user-class and travel time robustness. The total cost, which is in this case also the economic cost, is the travel time of the user-classes multiplied by their Value of Time. The Port of Rotterdam region is of high economical value for The Netherlands and is therefore a fit performance indicator. Because the current study also researched the influence of multi-class Model Predictive Control over single-class Model Predictive Control it is necessary to measure how the travel times of both user-classes are affected. Finally the robustness of the control methods is measured by using different demand levels to control the uncertainties created by the assumptions made in the predicted traffic demand.

6.1.6 What is the gain of applying Model Predictive Control in comparison to applying Traffic Management Scenarios in terms of total cost and travel time per user-class?

Both traffic control methods gain a lot of economic value. However the Model Predictive Control method doubles the gain in both total cost as travel times per user class than the Traffic Management Scenario. This is consistent with the findings of previous research (Deo et al. 2009) which also concluded that (multi-class) Model Predictive Control has large benefits. Contrary to expectation was that both control methods performed similar in the accident case. It was expected that Model Predictive Control, the more adaptive method of the two, would perform better to a sudden change in traffic state. A possible explanation for this is that the accident used in the current study was too heavy for traffic control to have significant effect. It was expected on beforehand that Model Predictive Control would perform better than Traffic Management Scenarios, however the difference between them was smaller than expected.

The gain of Model Predictive Control is expected to be higher when more types of signals are included, such as a ramp meter. The traffic control system then becomes more complex, and will be more difficult to handle for a human controller. Model Predictive Control is more capable of doing so.

6.1.7 What influence has the division of traffic into two user-classes on the performance of the Model Predictive Controller?

As was concluded in chapter 5, applying multi-class Model Predictive Control causes an improvement compared in total cost. This improvement is relatively small and is mostly gained due to the fact that the multi-class Model Predictive Controller improves the travel times of trucks. The control signal reroutes in peak hours only passenger car traffic and thus separates the two different user-classes. This leads to an increase in travel times for both passenger cars and trucks.

6.1.8 How do Model Predictive Control and Traffic Management Scenarios respond to changes in the predicted demand?

Both these methods react equal to demand changes in comparison with the base (100%) demand case. So where in total cost and the travel time for each user class the Model Predictive Controller has better results, it does not react relatively better on demand changes than the Traffic Management Scenario.

6.2 Recommendations and further research

To finish this master thesis recommendations for the future will be made and suggestions for future research will be formulated.

6.2.1 Recommendations

Continue applying Traffic Management Scenarios to appropriate traffic situations

One of the conclusions that can be drawn from this thesis is that applying Traffic Management Scenarios lead to cost gains and better travel times. Traffic Management Scenarios with route guidance can achieve these results also on other locations with an alternative route available for a road stretch with bottlenecks which can cause congestion. It is therefore recommended to find other locations where Traffic Management Scenarios can be used. This can also clear the road for future implementation of Model Predictive Control by investing in the Dynamic Traffic Management systems.

Implement multi-class Dynamic Traffic Management in the Port of Rotterdam area

Both previous research and this research have shown that a multi-class traffic management approach lowers travel cost and travel time in areas with a high share of truck traffic. In this research was chosen for route guidance since the infrastructure for route guidance (i.e. the traffic control center, alternative route signs and DRIP's) is present. Therefore multi-class route guidance can be implemented and it is recommended to do so.

Design Traffic Management Scenarios based on a simulation study with a traffic model

There is an increase in use of Traffic Management Scenarios in the Netherlands, which is a positive development as this research has shown that traffic control can lead to good results. However the

Traffic Management Scenario 'A15 haven Uit' used in practice by Regiodesk was designed based on expertise. The scenario used in this research was designed in a model study. This scenario has shown good results and in some cases approached the performance of the Model Predictive Controller, which is considered an optimal approach. Therefore designing a Traffic Management Scenario with a traffic model is highly recommended.

6.2.2 Further research

Rerouting around bridge openings

In this research the Model Predictive Controller could not, due to its control horizon of 15 minutes, accurately reroute traffic 'around' the bridge openings. The Traffic Management Scenario was designed this way and showed benefits from it. Since the bridge openings are scheduled it is interesting for the Model Predictive Controller to reroute around these bridge openings. This can be an interesting follow-up research.

Behavioral research on the respond to DRIP signals

The maximum compliance of traffic to the Traffic Management Scenario was based on the appearance of congestion on the off-ramp to the alternative route. Other factors than this congestion affect compliance as well (e.g. habits). And since the current study took multi-class traffic it is interesting how different user-classes respond to Dynamic Route Informal Panels (DRIP's) signals and see how compliant these road users are.

Feasibility study on other multi-class traffic management measures in the Port area

In the conclusion was mentioned that ramp metering and peak-hour lanes were not considered as possible traffic management measures. When the constructions on the A15 are finished, the possibilities for these measures return. Multi-class ramp metering is being researched for this network (Schreiter 2012), however multi-class peak hour lanes are not. Using peak hour lanes on the A15 as truck lane is an interesting topic for research.

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Appendix: Control signals

Appendix A: Compliance to the control signals of the TMS

Appendix B: Control signals of the MPC's

Appendix A: Compliance to the control signals of the TMS

Table A1: Compliance to the signals of the TMS

Demand Level	Heavy peak hour	Regular peak hour	Accident
90%	70%	90%	100%
95	60%	90%	100%
100%	60%	90%	100%
105%	60%	90%	100%
110%	50%	90%	100%

Appendix B: Control signals of the MPC's

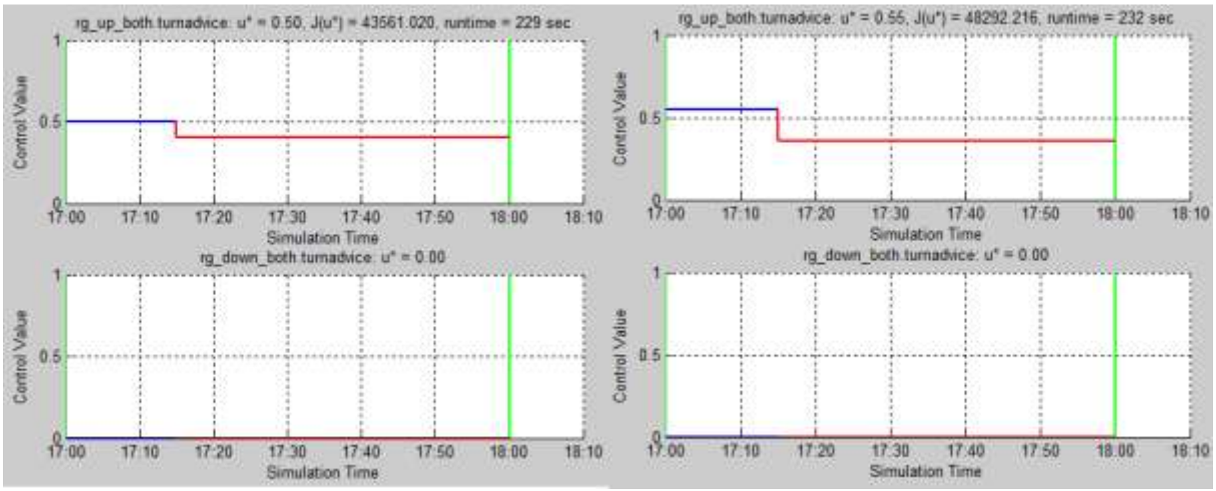

Figure B1: Control signals of the single-class MPC on 15-12-2011 for demand levels 90% and 95%

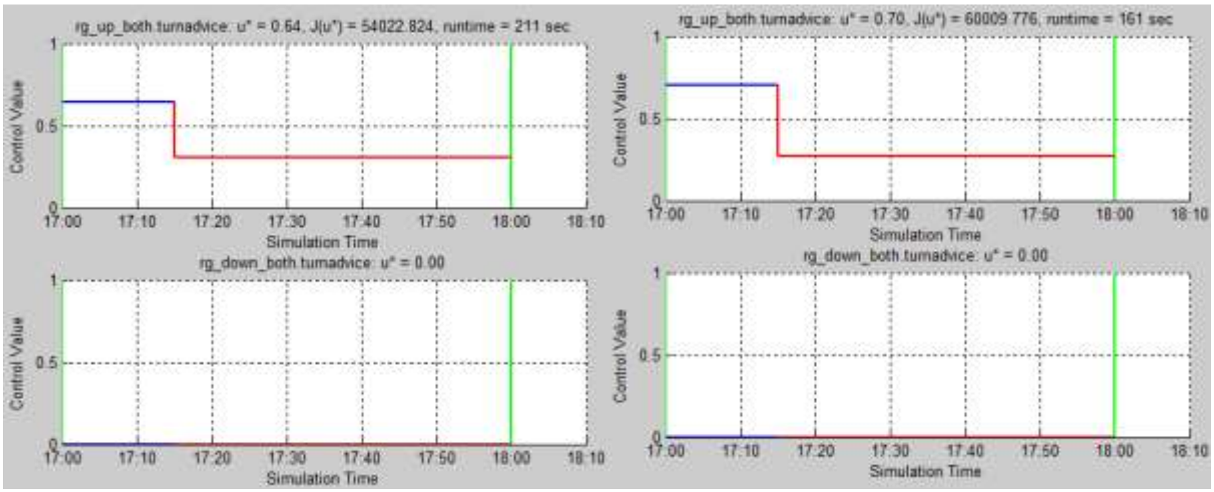

Figure B2: Control signals of the single-class MPC on 15-12-2011 for demand levels 100% and 105%

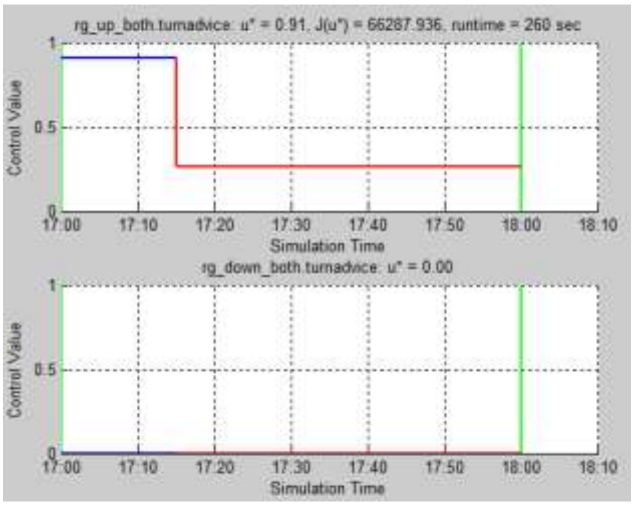

Figure B3: Control signal of the single-class MPC on 15-12-2011 for demand level 110%

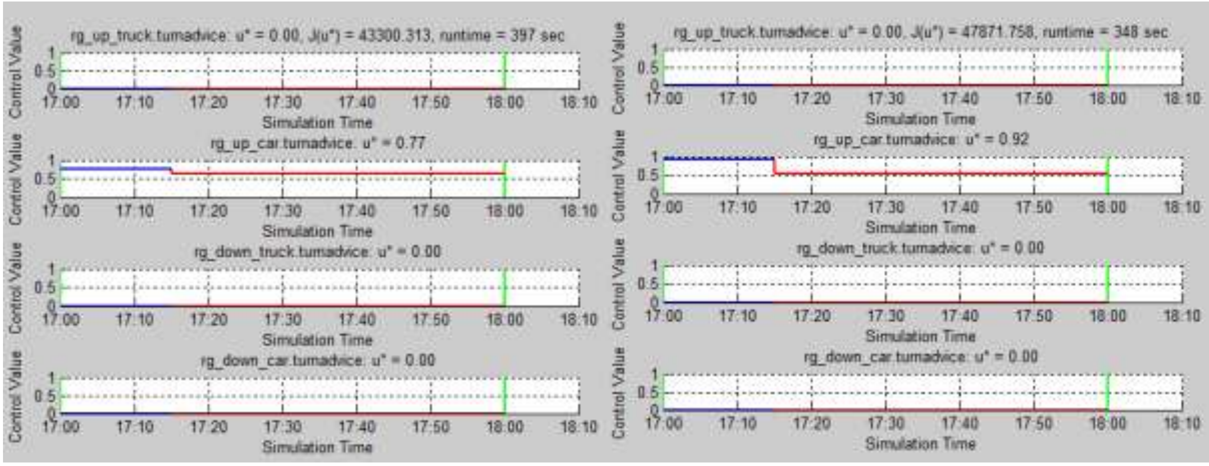

Figure B4: Control signals of the multi-class MPC on 15-12-2011 for demand levels 90% and 95%

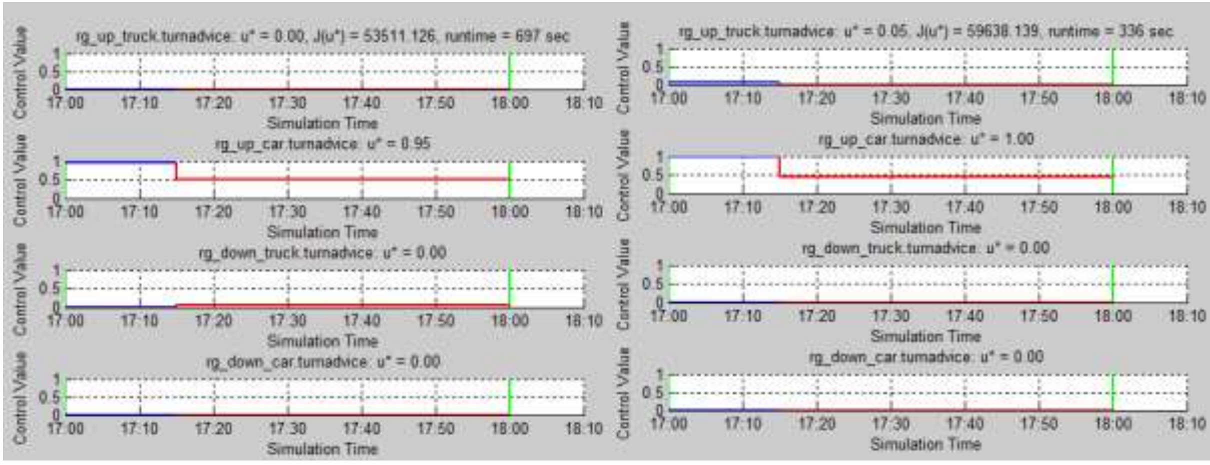

Figure B5: Control signals of the multi-class MPC on 15-12-2011 for demand levels 100% and 105%

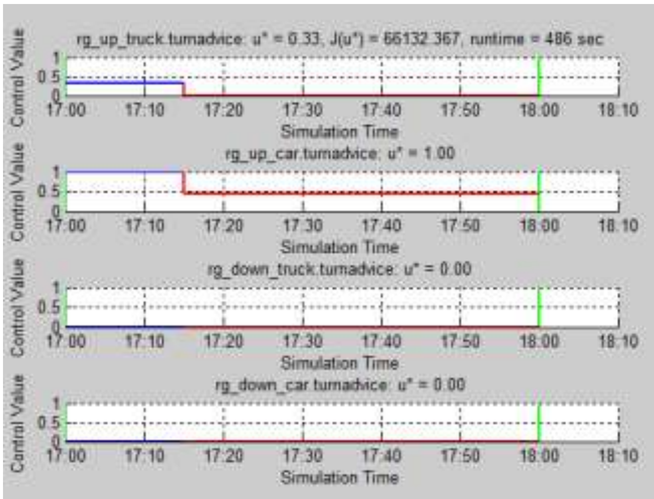

Figure B6: Control signal of the multi-class MPC on 15-12-2011 for demand level 110%

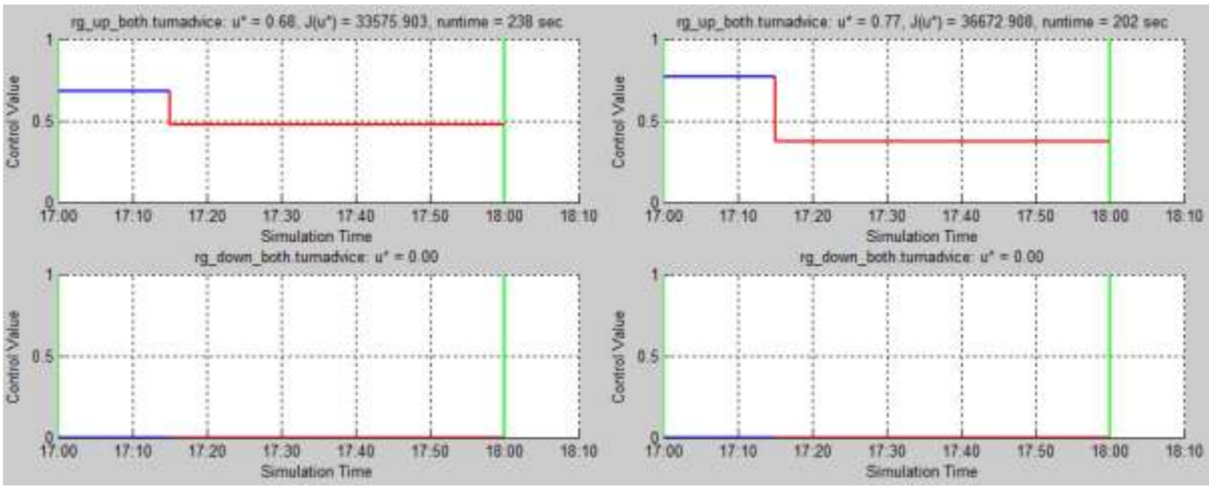

Figure B7: Control signals of the single-class MPC on 13-12-2011 for demand levels 90% and 95%

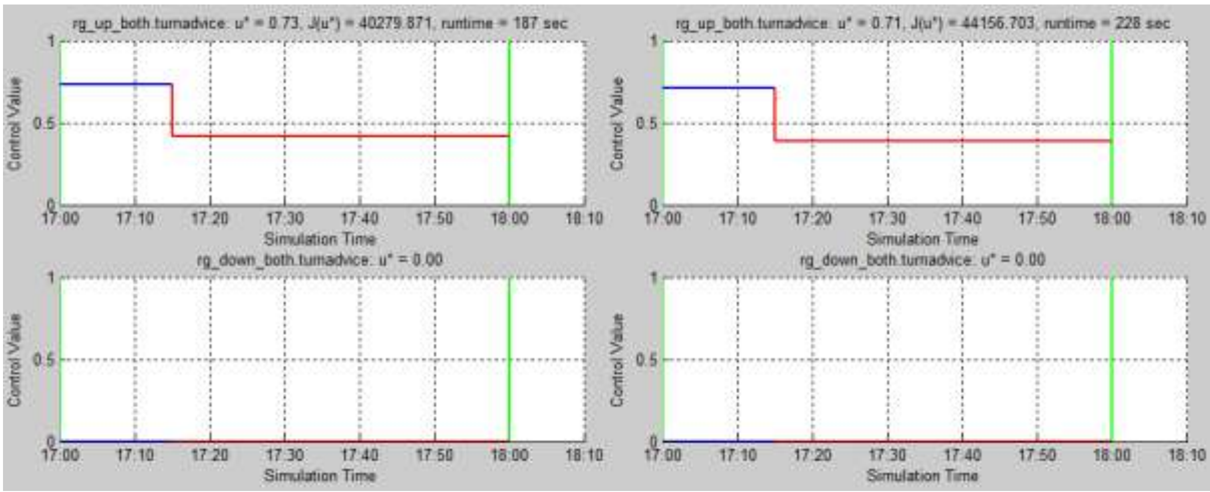

Figure B8: Control signals of the single-class MPC on 13-12-2011 for demand levels 100% and 105%

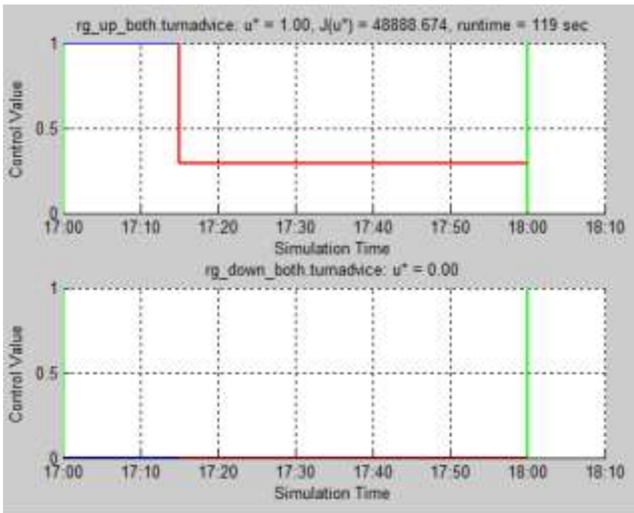

Figure B9: Control signal of the single-class MPC on 13-12-2011 for demand level 110%

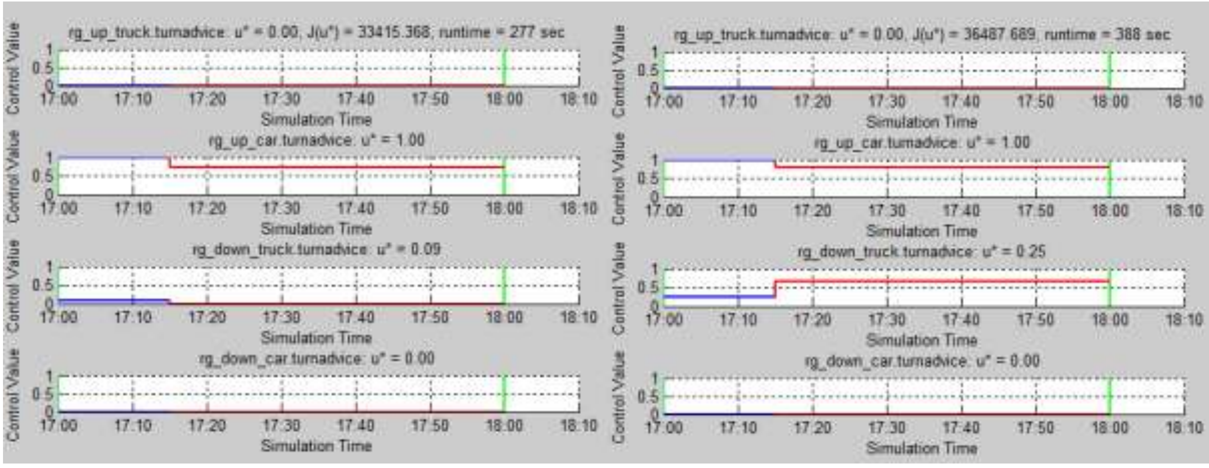

Figure B10: Control signals of the multi-class MPC on 13-12-2011 for demand levels 90% and 95%

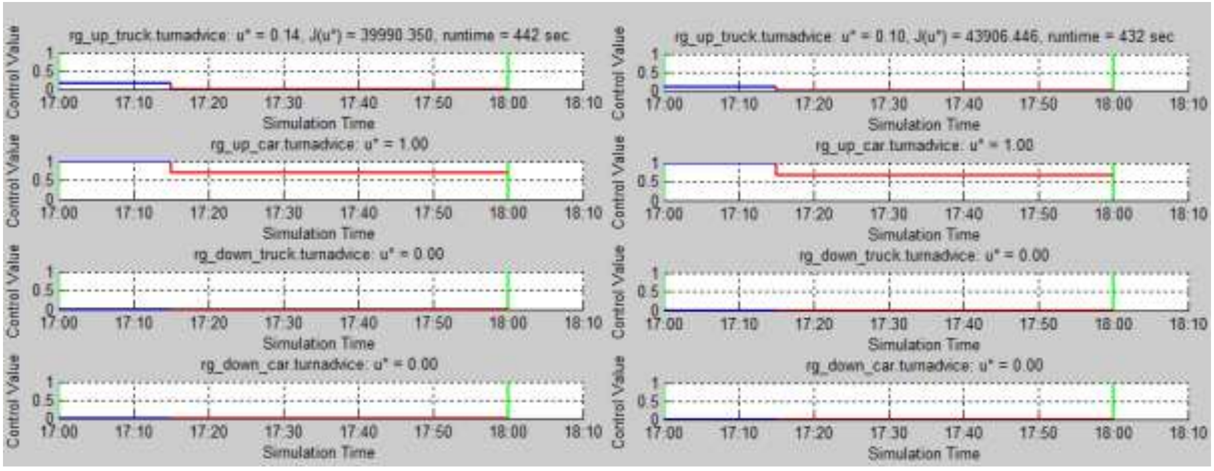

Figure B11: Control signals of the multi-class MPC on 13-12-2011 for demand levels 100% and 105%

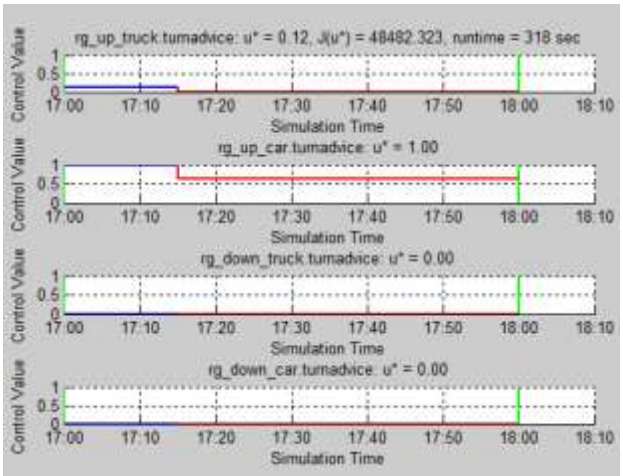

Figure B12: Control signal of the multi-class MPC on 13-12-2011 for demand level 110%

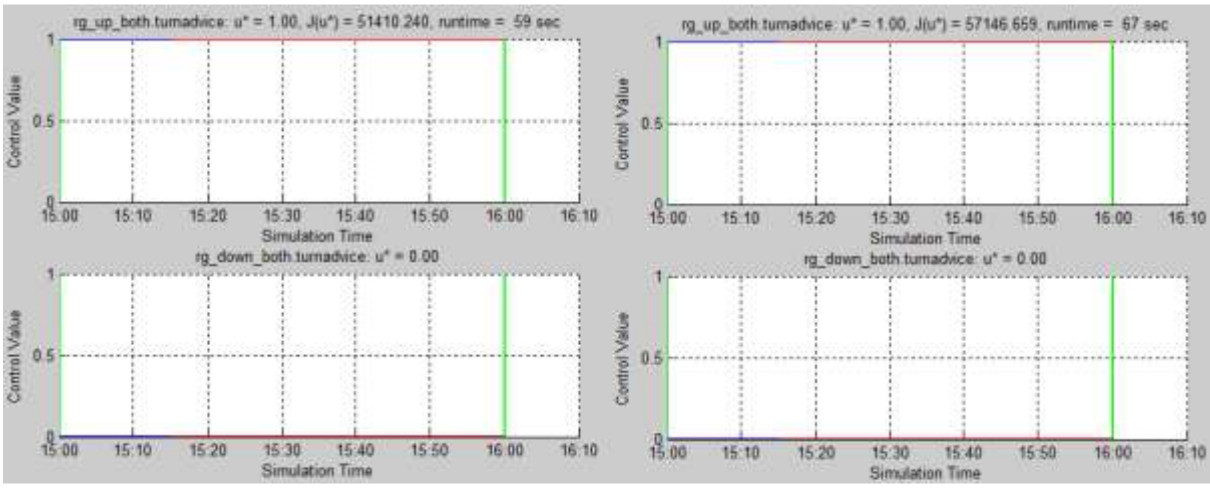

Figure B13: Control signals of the single-class MPC on 17-11-2011 for demand levels 90% and 95%

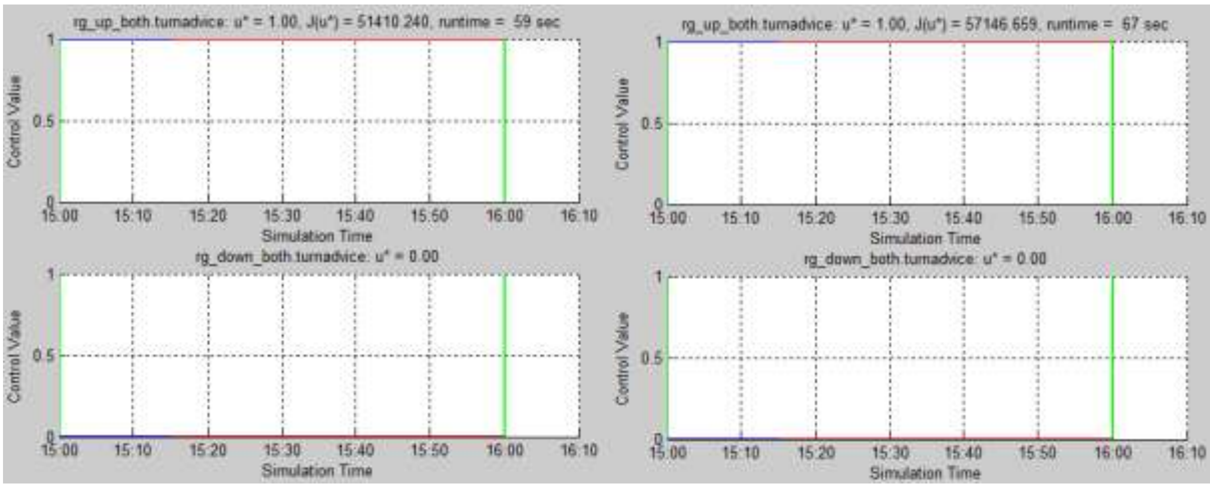

Figure B14: Control signals of the single-class MPC on 17-11-2011 for demand levels 100% and 105%

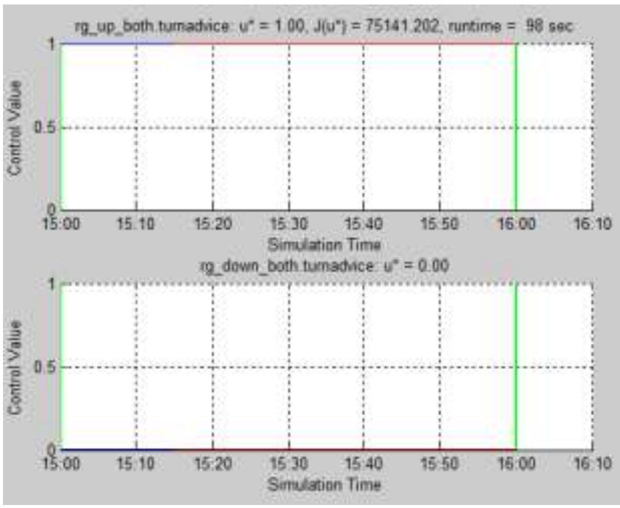

Figure B15: Control signal of the single-class MPC on 17-11-2011 for demand level 110%

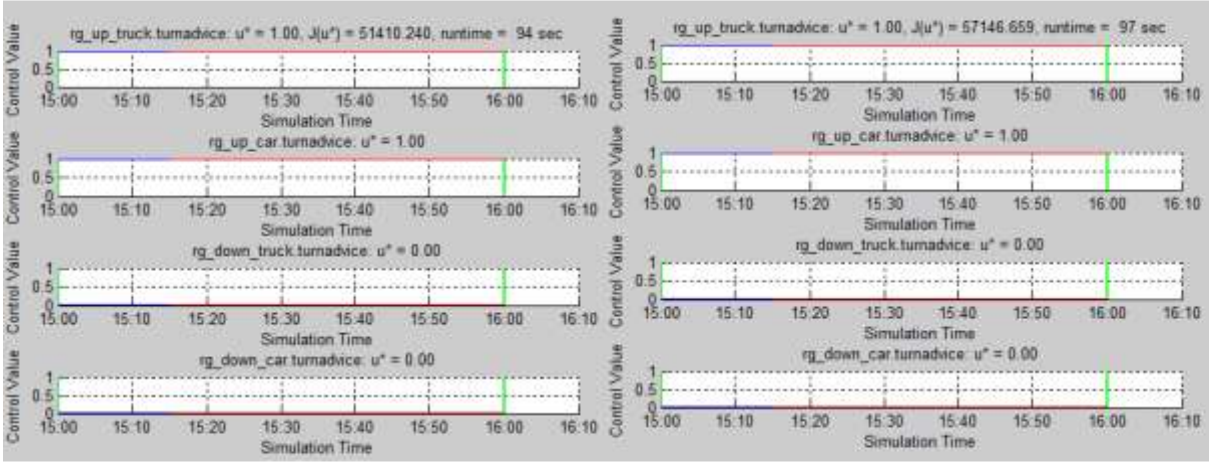

Figure B16: Control signals of the multi-class MPC on 17-11-2011 for demand levels 90% and 95%

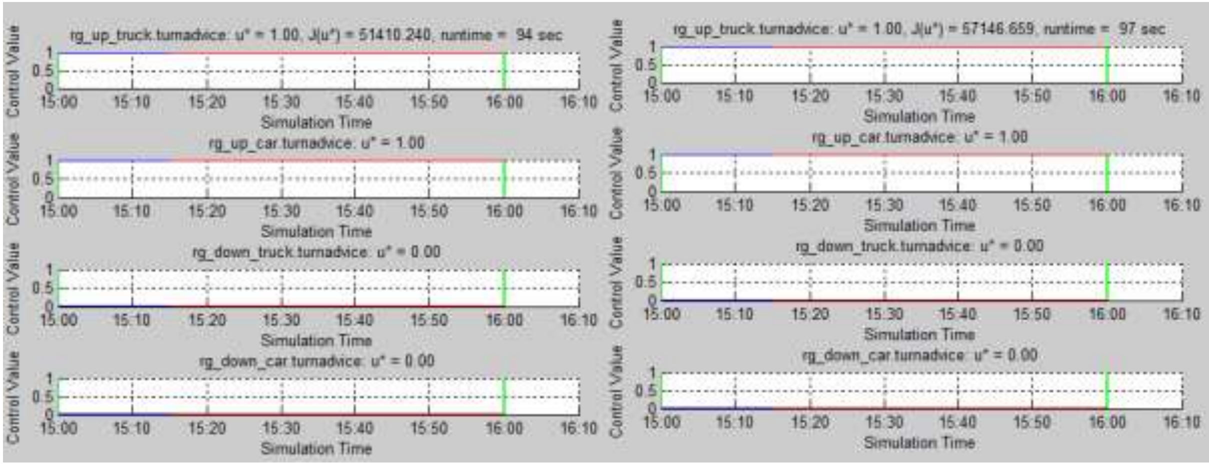

Figure B17: Control signals of the multi-class MPC on 17-11-2011 for demand levels 100% and 105%

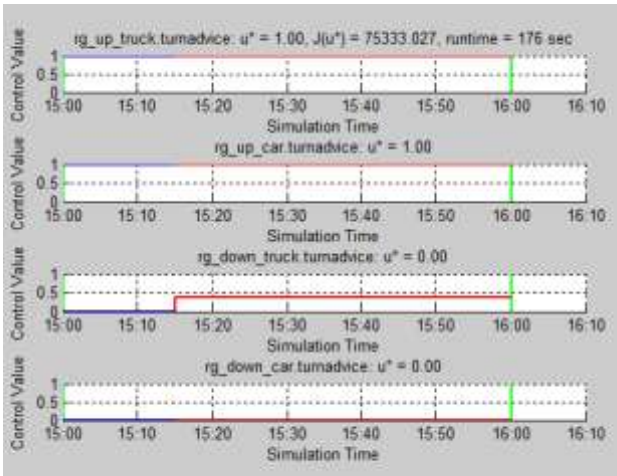

Figure B18: Control signal of the multi-class MPC on 17-11-2011 for demand level 110%