Combination of travel time and delay measurements in an urban traffic controller

A case study of Zuidas

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I would like to dedicate this thesis to my older brother Fernando. You have been my role model throughout my whole student life and I would not be where I am right now if it was not for you. I would also like to dedicate it to my parents and my aunt for supporting me all these years and encourage me to follow this incredible adventure abroad.
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Abstract

Increasing traffic volume in the urban areas is leading to a series of negative effects such as congestion or emission of air pollutants. The city of Amsterdam is no exception to this trend and a sustainable solution is sought in the area of Traffic Management and Intelligent Transportation Systems. The goal of this study is to develop a traffic management strategy that enhances the traffic performance in distributor roads (Plus Network Auto in Amsterdam) during saturated conditions (AM and PM peak). After the analysis of the current state of the traffic management in the municipality of Amsterdam, an opportunity has been detected in which a combination of the different systems in place can be used to improve the traffic performance of the local road network. Travel time and delay measurements retrieved from inductive-loop detectors, automatic number plate recognition cameras and floating car data are used in a top-level urban traffic controller that combines the traffic responsiveness of a vehicle-actuated controller with the effective coordination of a fixed-time controller. The proposed controller can act locally when the delay measurements show congestion at a single intersection or along the whole corridor when the average speed drops below a specified threshold. A microscopic simulation model of the Zuidas district for the year 2030 and the PM peak has been used to evaluate the proposed top-level controller compared to the currently used vehicle-actuated controller and the coordinated fixed-time controller. The results show that the average speed in the main corridor has been increased by 28.5% and meets the desired speed set by the municipality for the Plus Network Auto. Overall delays at the intersections are reduced in average by 11.60% while the effect on the public transport modes remains similar. However, the coordinated fixed-time controller has shown even a better performance than the proposed top-level controller, for which a series of recommendations have been issued.
Sammanfattning

Ökande trafikvolymer i stortadsmiljöer leder till olika negativa effekter som trängsel eller utsläpp av luftföroreningar. Amsterdams stad är inget undantag till det här fakturet och en hållbar lösning eftersträvas i trafikförvaltningens och intelligenta transportsystemområde. Målet av denna studie är att utveckla en trafikförvaltningsstrategi som förbättrar trafikprestanda i utdelningsvägar (Plus Network Auto i Amsterdam) under intensiva trafikkon- 
ditioner (för- och eftermiddags trafik). Analysen av den nuvarande trafikförvaltningen i Amsterdams stad har visat att en kombination av olika innevarande system kan användas för prestandaförbättring av det lokala nätverket. Restiders- och fördröjningsmätningar från inductive loops, kameror med automatiserad igenkännande av registreringsskyltar samt floating car data används i en hög nivå tätorts trafikstyrning. Kontrollören kombinerar en vehicle-actuated controllers mottaglighet med en fixed-time controller’s effektiva samord- 
nings och kan fungera lokalt när fördröjningsmätningarna visar trängsel i en enda korssning eller längs en hel korridor när medelhastigheten är mindre än någon specifierad gräns. En mikroskopisk simuleringssmodell för Zuidas stadsdel i 2030 och förmiddagstrafik har använts för att utvärdera den presumtiva styrningen jämfört med den vehicle-actuated styrning som används i nuläget och den fixed-time styrningen. Resultatet visar att medelhastigheten i den principala korridoren har ökat med 28.5% och sammanträffas med den hastighet som önskas av staden för Plus Network Auto. Övergripande fördröjningar i korsningar minskas 11.6% medan påverkan på kollektivtrafiksfärdmedel är likadan. Emellertid har den samord- nade fixed-time kontrollören visat ännu bättre prestanda. På grund av detta har en serie rekommendationer utfärdats för den presumtiva kontrollören.
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Nomenclature

**Acronyms / Abbreviations**

ANPR Automatic Number Plate Recognition

ATB-A Automatic Traffic Builder - Amsterdam

DRIP Dynamic Route Information Panel

FCD Floating Car Data

FT Fixed time

HCM Highway Capacity Manual

ICT Information and Communications Technology

ITS Intelligent Transportation Systems

KiM Kennisinstituut voor Mobiliteitsbeleid (Netherlands Institute for Transport Policy Analysis)

MoCo Monitoring Corridors

NDW Nationale Databank Wegverkeersgegevens (National Data Warehouse for Traffic Information)

NMS Network Management System

NRM Nederlands Regionaal Model

P+R Park and Ride

PPA Praktijkproef Amsterdam (Practical Trial Amsterdam)

RVB Real-time Verkeerslicht Beïnvloeding (Real-time traffic light influence)

UTC Urban Traffic Controller
Nomenclature

VA  Vehicle Actuated

VMA  Verkeersmodel Amsterdam (Traffic Model Amsterdam)
Chapter 1

Introduction

This chapter presents an overview of the topic of this thesis. First, the background and motivation for this topic is detailed. The second section derives the research questions and goals of the study. Next, the scope and limitations of the thesis is portrayed, and finally the outline of the report is specified.

1.1 Background and problem statement

During the last decade, the traffic volume has increased in The Netherlands by 12% (KiM, 2016). The different factors that explain this change in the Dutch mobility are shown in Fig.1.1. Despite the world economic crisis, the traffic volume has managed to increase thanks to a reduction of oil prices and expansion of the road infrastructure.

Fig. 1.1 Evolution of traffic volume in the Dutch road network. Source: KiM (2016)
Introduction

Even though the traffic volume has increased steadily during this time, the total lost time on the roads has experienced an enormous variation, as seen in Fig. 1.2. On an aggregated level, the lost time has decreased by 1% since the last decade, achieved mostly by the construction of additional lanes in the roads. However, after a big drop during the 2010’s, a sharp boost is being experienced: 2015 lead to a rise of 22% in total lost travel time over the previous year, and this trend is expected to continue for the foreseeable future.

![Fig. 1.2 Evolution of traffic volume and lost travel time in the Dutch Road Network. Source: KiM (2016)](image)

The social costs of road congestion and delays, composed of lost travel time, unreliability of journey times and indirect effects is estimated in 3 billion euros, or 0.5% of the Dutch GDP (KiM, 2016). Thus, measures directed at tackling this problem are of great importance and a lot of effort from part of the local, regional and national administrations is put into it.

Amsterdam, as the capital of the Netherlands, is a good reflection of the trends occurring at the national level. By the year 2030, the city is expected to grow in almost 100,000 inhabitants, reaching the figure of 936,000 (Onderzoek, Informatie en Statistiek, 2016). Thus, the mobility will experience a steep rise in veh-km figures in the future, as well as the lost travel time on the network. Other factors such as an expected growth in employment over the national average and an extended growth in tourism (Gemeente Amsterdam, 2013), which already accounts for almost 60% of the visitors to the country, will definitely contribute to worsen the situation. Even though the share of car mode choice seems to be declining in the city (Onderzoek, Informatie en Statistiek, 2016), the total number of trips by this mode will keep increasing, and will be one of the main challenges to solve by the traffic engineers.
1.1 Background and problem statement

The municipality has published a mobility plan for the year 2030 (Gemeente Amsterdam, 2013), which outlines the policy and measures to be taken in order to ease the difficult situation that the city will have to face in the future. The main features are to optimize the use of the scarce public space available and adopt the latest innovations in the transport field to cope with the demand without the need to invest large sums of money.

Zuidas, in the southern part of Amsterdam, will be a crucial spot for the future development of the city. Currently under development, Zuidas will become by 2030 the main business centre of the city. But not only this, Zuidas will turn into a mixed-use, high density district in which local residents, workers, students, travellers and visitors will share the public space (Gemeente Amsterdam, 2016). Main trip attractors such as RAI convention centre, Zuid Station, Vrije Universiteit Amsterdam (VU) and the Vrije Universiteit medical centre (VUmc) will make this spot one of the busiest and most challenging areas of the city in terms of mobility. Zuidasdok, the main transport project of Zuidas, is the proposed solution for this challenge. Amsterdam Zuid station will increase its capacity in order to accommodate the growing number of passengers, and the A10 (Amsterdam ringroad) will be expanded and go underground to relieve the current and future congestion problems.

This research will focus on the knowledge quarter (Kenniskwartier, in the bottom left part of Fig.1.3), where the VU and the VUmc are established. Here, a solution is needed for the arterial streets De Boelelaan and Amstelveenseweg (part of the Plus Network Auto) during peak hours. A more detailed explanation about the Zuidas network will be provided during the case study chapter.

![Fig. 1.3 Map of Zuidas for the year 2030. Source: Gemeente Amsterdam (2016)](image-url)
1.2 Goal and Research Questions

The improvement of traffic management is a great alternative to building more infrastructure, as it makes more efficient use of the existing transportation resources in a low-cost and fast manner without the need to expand them. The traffic management loop can be divided into three different aspects, as shown in Fig.1.4: measurement or data collection systems, data processing systems (control strategy) and traffic measure systems.

Fig. 1.4 Control loop of an urban traffic network. Source: TrafficLab (2016)

In recent years, the surge of Information and Communications Technologies (ICT) has been applied to the traffic management sector, both in data collection and traffic measure systems. All these ICT systems applied in the transport field are called Intelligent Transportation Systems (ITS). ITS is defined by the World Road Association (World Road Association, 2017) as “the control and information systems that use integrated communications and data processing technologies for the purpose of”:

- Improving the mobility.
- Improving traffic flow by decreasing congestion.
- Increasing safety and managing accidents.
- Meeting transport policy goals and objectives.
1.2 Goal and Research Questions

Basically, the goal of ITS is to improve the overall performance of the entire transport system (in real time or even a predictive way) for the transport network users.

There is an extensive list of systems that are used in the field of transport. In this report, the ones that are currently used in the municipality of Amsterdam will be studied in the following chapter. There is also a broad range of applications for these systems, from traveller information systems to public transport management, emergency management, parking management or traffic control systems. The traffic control strategy depends greatly on the amount and quality of data obtained. Thus, combining different kinds of data sources can lead to a better course of action when managing the traffic on the network.

This study is focused on research about traffic management measures that can be taken to solve congestion problems in real-case scenarios. More precisely, how ITS can be used into a traffic control strategy in congested conditions. Detection and delay measurements from detector loops, as well as travel time measurements from either automatic number plate recognition cameras (ANPR) or floating car data (FCD) have been chosen as the data collection systems. This data mix will be used in a traffic control strategy that combines vehicle-actuated signal programs with a coordinated fixed-time controller to solve saturated conditions in urban artery roads.

The final objective of this thesis is to find a way in which the Intelligent Transportation systems currently used by the city can be adopted to improve the traffic performance of the road network.

The municipality of Amsterdam has an extensive list of Intelligent Transportation Systems displayed all around the city for traffic management purposes. The first goal of this research is to provide an overview of all the systems that are currently used by the municipality of Amsterdam, both for data collection systems and traffic measure systems.

The next goal is to combine the current traffic management strategy with the state-of-the-art knowledge to develop a traffic control strategy with the systems that are used at present, so that it is beneficial for the future traffic management of the city.

The last goal is to examine the possible performance of such traffic control strategy in a real study case in Zuidas. If such strategy is able to achieve a sufficient performance improvement this could lead to further studies in other areas of the city.

Thus, the research questions are listed below:

- What is the current state of traffic management in the municipality of Amsterdam?
- What are the Intelligent Transportation Systems that are in place in the city at present?
Introduction

• How can the traffic management of the city of Amsterdam be improved by using the systems that are currently in place?
  – Which system or group of systems can be applied to improve the traffic management?
  – Which control strategy could be used together with these systems in order to improve the performance in an urban traffic network?

• Could this proposed traffic signal control strategy be able to improve the performance of the default strategy in a real study case in the Knowledge quarter in the Zuidas district for the year 2030?

1.3 Scope and limitations of the Thesis

As the duration of the research period is limited, some assumptions need to be taken in order to reduce the complexity of the study, while maintaining the ability to represent the reality in the most exact way possible.

Development of ITS

For the purpose of this study, only current Intelligent Transportation Systems that are deployed in the municipality of Amsterdam will be considered. The field of ITS is rapidly evolving with plenty of innovative applications, making it very difficult to forecast how the situation will be for the goal year of 2030. Applications such as driverless cars, communication between vehicles and infrastructure or dynamic route guidance will completely change how the traffic is managed in an urban network (maybe even traffic lights will not be needed anymore). However, due to the uncertainty about how far the innovations in the ICT field will reach by the year 2030, this study has deemed suitable to maintain the current systems, even if this stance does not properly reflect the future situation.

Simulation environment

The road network used to test the improved urban controller will be an actual part of the city of Amsterdam, the Zuidas district. A very complex microsimulation model has been developed in Vissim by the Ruimte en Duurzaamheid team of Gemeente Amsterdam, in which pedestrians, bicycles, cars, heavy vehicles and public transport are all represented. The input data for the simulation is obtained from the traffic model of Amsterdam (VMA) for the year 2030. The size of the network, complexity of the intersections, parking spaces and variety of network users makes this model computationally expensive. However, it is necessary since the goal of the study is to test whether this new urban traffic controller could be used in a real traffic network.
One simplification of the model is that the A10, the highway that traverses the Zuidas district, is not represented in the model. This is because the expansion of the highway capacity will ensure that there are no spillbacks into the urban network.

The period of study will be the evening peak period, from 16:00 to 18:00, when the main movement is from the center of Zuidas to the A10. It is recommended that the same study is carried out for the morning peak, when the main traffic flow is in the opposite direction.

**Target group**

This study is aimed at motorized vehicles in the network (cars, motorbikes, light and heavy trucks), as this is the source of the problem in the streets of Zuidas. The selection of a fixed-time coordinated signal plan for this vehicles means that other network users such as pedestrians, bicycles and public transport lose the priority they had with the vehicle-actuated controller. An analysis will be performed to check whether the situation gets worse for these users. In such case, it may be in direct conflict with the local policy and its use should be restricted.

**Evaluation criteria**

The city of Amsterdam has defined a Surplus network for each road network category. For the Plus Network Auto, of which Amstelveenseweg and De Boelelaan are part of, the municipal policy establishes that the desired speed in these corridors is 20km/h. Thus, travel times from De Boelelaan to the A10 will be used as the criteria to determine if the objective performance is achieved. Besides, lost times at each intersection will be calculated. Other criteria, such as priority for slow modes, minimization of contaminant particles or minimization of stops will be disregarded in this research.

### 1.4 Outline of the Thesis

The thesis is structured according to the goals stated in section 1.2. In the first section of chapter 2, the architecture of the current traffic management strategy for the municipality of Amsterdam is described, including the data collection systems, data processing and traffic measure systems. The next sections consists of the review of a similar project in the city of Amsterdam and a literature review of the different urban traffic controllers that have been used through history. The result of this chapter will be the election of an urban traffic controller, including the traffic control strategy and the systems needed to perform that task. Chapter 3 displays the design of the chosen urban traffic controller from chapter 3, explaining the workflow of the control strategy. The case study will be reported in Chapter 4. First, there will be an introduction to the area where the study will be performed, Zuidas. Next,
the simulation environment and software interactions will be portrayed, as well as the data input for the model. This chapter will finish with an analysis of the results obtained from the simulation. In the last chapter, there will be a conclusion of the research and discussion of the achieved results, as well as the possibility of applying this controller in other environments and future research recommendations.
Chapter 2

Literature Study

In this chapter, all the literature needed for the thesis is arranged. First, the current state of traffic management in the city of Amsterdam is described, explaining all the Intelligent Transportation Systems deployed throughout the city. This includes data collection systems, data processing systems and traffic measure systems. A full overview of the system architecture can be found in Appendix A. Then, the RVB, an ongoing project in the city of Amsterdam that is used as the inspiration for the proposed traffic management solution is discussed. Finally, a literature review of the most known urban traffic controllers is portrayed.

2.1 Current state of Traffic Management

2.1.1 Data collection systems

The successful development of Traffic Management requires high-quality traffic information in real time. During the last decades, as a result of policies leaning towards the improvement of Traffic Management, data collection systems have evolved remarkably and the access to real-time traffic information is becoming the norm (Leduc, 2008). This data is the cornerstone of day-to-day network operation, responding to accidents and incidents and providing information to the network users.

Traditionally, on-road sensors such as inductive loops have been installed massively as the primary source of traffic data. These systems have proven to obtain considerable results, but insufficient due to its expensive cost of installation and maintenance, as well as its limited coverage (point-based data).
Thus, new data sources have been arising lately that not only collect data at a fixed point, but also in road segments and network-wise. This includes techniques such as ANPR or FCD, where new kinds of data are possible to obtain, such as travel times and OD flows.

Table 2.1 shows a classification of the most popular data collection methods and technologies by the network coverage and the kind of data collected. The full list of data collection systems is very diverse and includes many more methods, but it is not the purpose of this research to do a full review of each of them.

The city of Amsterdam currently employs the following data collection systems: Inductive loops, ANPR cameras, FCD and Parking data. These systems will be described in the following subsections.

**Inductive-loop detectors**

This is the most conventional technology to collect traffic data. It consists of one or more turns of insulated wire embedded in the road pavement in a square shape that generates a magnetic field. The loop detector notices the presence of a vehicle by inducing currents in the object, which reduces the loop inductance (Klein et al., 2006). The main use of these loops is to detect the presence of vehicles that drive over it and count its number. However, the main drawback of this technology is that it is quite expensive to install, but especially to maintain due to the damage caused by heavy vehicles.

Loop detectors are used by the municipality of Amsterdam at each signalized intersection of the city, both for motor vehicles and bicycles. As most of the signalized intersections in the city work with a vehicle-actuated signal timing plan, inductive loops are needed at each intersection leg. There are loops located at each lane just before the stop line of the intersection, in order to know that there are vehicles waiting for that signal group (otherwise it would be skipped) and some detectors placed some distance in advance, that are used for extending the green time of the stage.

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<td>Inductive loops</td>
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<td>Pneumatic tubes</td>
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<td>Cell-phone Tracking</td>
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<td>Airborne sensors</td>
<td>X X X</td>
</tr>
</tbody>
</table>
Apart from the intersections, loop detectors are also used at specific points of the urban network to collect site-based historical data of vehicle counts and speeds, but without use in real-time traffic management.

**Automatic Number Plate Recognition Cameras**

Video Image Processing cameras are currently used by traffic managers worldwide to obtain real-time traffic information. An ANPR system usually consists of one or more cameras, a microprocessor to digitalize the imagery and software to interpret the image and convert it into traffic data. ANPR cameras have several applications, ranging from travel time measurement, traffic counts and OD matrix acquisition to law enforcement or toll collection.

There are currently three kinds of cameras installed in the city. The travel time cameras are displayed in Fig.2.1 as yellow arrows. These cameras are part of the MoCo system, which stands for Monitoring Corridors. They are located about 1km from each other on the main distributor roads of the city (Plus Network Auto), as well as the ring road (A10). These are the roads with the largest intensities and serve as the main access links to the city.

Every time a vehicle is observed, the system collects the time stamp and associates it to a ciphered number that represents the license plate. When the same vehicle is observed in another camera, the same procedure is followed. The difference in time will provide the travel time of that vehicle. The main function of these cameras is to calculate the average travel time of the different corridors in real-time and show it on the DRIPS so users can make a better judgement at the time of selecting the route, as well as to function as a trigger for the scenarios of the NMS. A map showing all the MoCo routes where travel times are collected is portrayed in Appendix B.

The environmental cameras, shown in Fig.2.1 as green arrows, are ANPR cameras located in the border of central Amsterdam. They are mainly used for law enforcement, collecting the license plates of heavy vehicles that are forbidden to go into the city center. But, as they can also collect the license plates of the vehicles, these cameras are included as well in the MoCo system mentioned previously.

Finally, the trigger cameras, shown in blue in Fig.2.1, are part of a pilot study, in which the cameras are used to trigger a certain scenario when it detects a vehicle standing in the road.
Floating Car Data

One of the most promising advances of ICT in the transport field is the use of Floating Car Data (FCD) for Advanced Traveller Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS) applications (de Fabritiis et al., 2008).

The goal of FCD is to collect real-time traffic data by locating each vehicle equipped with FCD technology over the network. FCD complements the traditional data collection systems as a source of vast and high-quality data in an inexpensive way, as they do not require road-side devices to be installed (Rahmani et al., 2010). However, with the current state of development FCD is not good enough to replace fixed-location sensors. FCD can be used in a wide range of applications, such as improved incident management, traffic queue detection, improved OD matrices or dynamic network traffic control.
2.1 Current state of Traffic Management

The most important FCD technologies currently used are based on GPS or cellular based mobile phone devices (GSM/GPRS data). GPS benefits from a higher accuracy, especially with the future deployment of the Galileo Satellite system, but the sample of vehicles equipped with this system is still low. On the contrary, cellular based data presents a massive coverage, but its number of applications is weakened by the lower accuracy it provides (Leduc, 2008).

FCD is collected in the Netherlands at a national level by the National Data Warehouse for Traffic Information (NDW), established by an alliance of 19 public authorities. NDW has an agreement with 14 private companies to provide real-time data over 7100km of national, provincial and municipal roads (NDW, 2016). After two years of studying the possibilities and quality of FCD in different pilots and projects, the positive results has led to a tender for Be-Mobile to provide national FCD since March 1, 2017. This real-time information is shared by all the public administrations that are part of NDW as open data. The municipality of Amsterdam, as one of these public administrations, has also included the FCD as one of its data collection systems. FCD quality and reliability is currently being tested and it is expected to be used for the traffic management of the city soon.

Parking data

In the city of Amsterdam, when a car enters or leaves the parking garage, it is registered in the system, so it is possible to know the number of vehicles inside the parking lot at that moment. Then, this information is shown on a VVX display: vol (full), vrij (free) or not working. These displays are located both at the entry of the parking lot and on the streets leading to it. The number of available spots is not shown on the panels.

The parking system of the city is comprised by a set of parking lots deployed all over the city, 7 P+R facilities and two parking complexes for the main venues: the RAI convention center and the Amsterdam ArenA. These two main trip attractors of the city have a large number of parking garages in a reduced space. In order to coordinate them, the occupancy of each of these parking lots is reported to the NMS, with potential outcomes to the DRIP server, indicating the route to follow for the most suitable parking place. Another application of the parking data is to use it on the DRIPS of the highways leading to the A10 in order to recommend the best route to a P+R facility, bearing in mind their capacity and the congestion on the way leading to it.

2.1.2 Data management

Data management is a very important part of the traffic management process. A good source of data is not useful unless a good processing of the data is performed. Data acquired from
the different systems in the network needs to be pre-processed and cleaned before its use. After this, the data can be reduced, clustered or fused according to the needs of the traffic manager. Then, algorithm and techniques must be used to extract useful information out of the data, such as pattern recognition. Finally, the data that comes out as a result of the whole process needs to be transferred for using it in the traffic measure systems (Lopes et al., 2010).

The whole process of data management is shown in the sections Collecting, Processing and Distribution of Appendix A. As it can be seen from the diagram, the data from the different sensors are stored in local databases: data provided by external parties and other road managers is stored at the NDW server; data from the loop detectors provided by Siemens and Vialis are collected at the Kwaliteits Centrale; the data obtained from the ANPR cameras is stored in the MoCo database, also managed by Siemens; and the data from the parking lots is stored in the PVS (Parking Referring System), managed by Vialis. This large number of local data storages poses a problem for the potential combination and fusion of the data, so a central archive is soon expected to be built where all data from the different sources will be collected. This central archive will provide the municipality with great options to obtain a whole new level of knowledge.

Real-world sensor data is easily susceptible to outliers, missing data and inconsistent data because of measurement errors or sensor failures. Low-quality data will lead to a low-performance result no matter how good the data processing tool is. Thus, after the acquisition of the data, a pre-processing and cleaning process of the data is essential, improving the data quality through completeness, consistency and simplification.

All this data is then transmitted to the NMS (Network Management System), where it is processed. There are three levels of NMS for local, regional and national administration, which are connected among them by the DVM-exchange. This way, the different public administrations can work in a coordinated way. The way the data is processed in the NMS is based on scenarios. There is a base scenario, modelled for normal conditions. Depending on the data input from the different sensors, an alternative scenario can be automatically selected, with a certain set of traffic measures as the outcome.

As an example, the scenario where there is a queue downstream of IJtunnel southbound is shown in Fig.2.2. The average speed will be collected between the exit of the tunnel and the adjacent streets, and when this is below 17 km/h it will trigger the scenario. In this case, the response will be to modify the traffic control system of the adjacent intersections so that the vehicles coming from the tunnel have priority. Then, if the speed in the loop outside the tunnel is below 30km/h, one of the lanes in the tunnel will be closed to reduce the demand. Once the speeds on the different sections have gone back to normal, the scenario will finish, and the traffic control systems will operate again under the base scenario. In this case, only
the traffic control systems are used, but many more options are available, such as the use of DRIPS, ramp metering, operation of the bridges, and closing of road sections and tunnels.

Then, the generated information is distributed back to their respective servers, depending on the administration that is responsible for it. In the case of the city of Amsterdam, this includes the VBS, PVS and DRIP server.

### 2.1.3 Traffic measures

#### Ramp metering

Ramp meters are traffic signals installed on highways on-ramps in order to control the number of vehicles accessing the traffic flow of the highway. Vehicles coming from the lower network form a queue behind the merge line of the highway, and are released at a rate depending on the traffic flow of the mainline and the current speed. This allows the highway to carry the maximum volume at a uniform speed (Mizuta et al., 2014). Another benefit from using ramp
metering is the possibility to break platoons of vehicles released from a nearby intersection. When operating close to capacity, the mainline can accommodate one or two vehicles at a time, but when a whole platoon tries to squeeze in, turbulence and shockwaves are created.

In Amsterdam, ramp metering is installed on all entries to the A10. A strong cooperation between Rijkswaterstaat (Dutch Ministry of Infrastructure and the Environment) and the municipality of Amsterdam is needed for a correct work of the ramp metering system, since the management of the A10 falls under the jurisdiction of the national government, while the management of the adjacent intersections is performed by the local administration.

The PPA (Practical Trial Amsterdam) is a great example of this coordination. The PPA is an interesting and innovative field test in Amsterdam aimed at coordinated network-wide traffic management. Here, in-car technologies and road-side systems are combined in order to provide a seamless and efficient access to the highway network from the city. In the road-side track, ramp meters from the A10 are managed together with the traffic control systems at the adjacent intersections to store the excess of vehicles at buffer zones and avoid congestion (Hoogendoorn et al., 2013).

**Dynamic Route Information Panel**

A DRIP is an electronic panel displayed over the roads to give route information to the users. It is part of the larger group of Variable Message Signs (VMS). The information that can be provided by the DRIPS varies and can be divided into three different categories (SWOV, 2008):

- Route information, such as queue presence and its length or travel times.
- Route choice information. Information about the traffic distribution on two or more different alternative routes so users can optimize their route.
- Incident information, such as road crashes, future roadworks and advice about diversions.

DRIPS are part of the soft traffic control measures. This is, response to the measure is voluntary and not compulsory. Thus, the number of drivers that change their route choice due to the information shown on the DRIPS is moderate (Hoogendoorn, 1997).

DRIPS have been used in the Dutch motorways since 1990, and are increasingly placed in urban networks. There are many DRIPs currently located in the city of Amsterdam, mostly around the city center border, as well as the RAI convention center and Amsterdam ArenA. These DRIPs have different goals, such as showing the travel time in the corridors from the city center to the A10 and vice versa, giving advice about the best route choice or providing
2.1 Current state of Traffic Management

information about roadworks and accidents. The DRIPs are a specially useful tool for the scenario management explained in section 2.1.2.

Traffic Signal Control System

The objective of traffic signals is to increase the capacity of an intersection, its safety and provide a good level of accessibility to the road users by assigning the right-of-way for all users of the transportation network, including vehicles, bicycles and pedestrians (Waldstedt, 2014). Its use has proven to be very effective when the demand on the intersection legs is high.

A wide variety of traffic signal control systems is available, and they can be classified in different ways. A signal control mode can be isolated, when the signal timing is based only on the demand of the approaches for that intersection, or coordinated, when the signal timings are based on all the other adjacent traffic signals to improve the flow through them. A signal control mode can also be classified as fixed-time, when the cycle time and phase time is always the same and based on historical data, or vehicle-actuated, where the cycle time is variable and the green time is based on the detection of vehicles approaching the intersections. A more thorough study of the different urban signal control strategies will be carried out in the next chapter.

Traffic lights started operating in the city of Amsterdam in the year 1932 at Leidseplein (Linders, 2012). Since then, the number of signalized intersections has grown exponentially over the years, following the expansion of the city. Some of the intersections were actually removed, especially in the center, due to the decrease in the traffic demand.

There are currently 440 signalized intersections in Amsterdam, represented in Fig.2.3. They are divided in two systems, one controlled by Siemens and one controlled by Vialis. From these intersections, around 100 are part of Kwaliteits Centrale, a tool to analyze the performance of the intersections.

There are three different control modes under which the intersections in Amsterdam work: rigid (star), semi-rigid (half-star) and vehicle actuated. Most of these intersections work with an isolated vehicle-actuated control logic. Here, the green periods are related to the traffic demands detected at the inductive loops from each approach. When the vehicle is detected at one of the approaches, it gives a minimum green time that is then extended as more vehicles approach the intersection, up to a maximum green time. If there is no vehicle at one of the approaches, the controller will skip that stage. Thus, the cycle time of this strategy is variable.
Fig. 2.3 Location of the signalized intersections in Amsterdam. Source: Linders (2017)

The rigid scheme refers to the fixed-time controller defined previously. In the semi-rigid controller, the cycle time is fixed, but the green time of the main direction can be extended when there are no vehicles detected on the conflicting direction. These are mostly used in a coordinated way to create a green wave in an arterial road, as in Weesperstraat and Wibautstraat.

2.1.4 Discussion

The goal of this section is to determine which is the current state of traffic management in the city of Amsterdam in order to find possible improvements to it that can enhance the traffic performance of the urban network. After the study of each system that is in place, a recommendation is made.

As it has been explained before, the traffic signal control system provides three different control modes for the intersections: rigid, semi-rigid and vehicle actuated. So far, the only data input used to create the control logic is the detection of vehicles from inductive loops.
However, it is believed that this can be improved with travel measurements, obtained from ANPR cameras or FCD as well as delay measurements obtained from the inductive loops and characteristics of the controller. Thus, this would be the new input to develop the proposed urban traffic controller (from now on, UTC). In the next section, the RVB is detailed, an ongoing project in the city of Amsterdam which serves as the inspiration for the controller that will be developed in this thesis.

2.2 RVB project

RVB stands for Real-time Verkeerslicht Beïnvloeding, or Real-time Traffic Control System Influence in English. The RVB project came up as part of the Beter Benutten programme (Optimizing use), a national scheme involving the Dutch government, regions and businesses to improve the accessibility on roads, railways and waterways in the busiest regions of the country at the busiest hours (Ministerie van Infrastructuur en Milieu, 2016). The goal of RVB is to improve the accessibility in the city of Amsterdam by reducing the congestion and the travel times in the Plus Network Auto, shown in Fig.2.4.

Fig. 2.4 Plus Network Auto Amsterdam. Source: Verkeer en Openbare Ruimte (2016)
Table 2.2 Definition of the quality levels and measures to be taken in each of the levels. Source: Vialis (2016)

<table>
<thead>
<tr>
<th>Quality level</th>
<th>Travel Time</th>
<th>Intersection</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&gt; 30 km/h</td>
<td>Saturation &lt; 25%</td>
<td>Average waiting time &lt; 20 s</td>
</tr>
<tr>
<td>B</td>
<td>20 - 30 km/h</td>
<td>Saturation &lt; 25%</td>
<td>Average waiting time &gt; 20 s</td>
</tr>
<tr>
<td>C</td>
<td>15 - 20 km/h</td>
<td>Saturation 25 - 50%</td>
<td>Conflicting directions</td>
</tr>
<tr>
<td>D</td>
<td>10 - 15 km/h</td>
<td>Saturation 50 - 75%</td>
<td>Conflicting directions</td>
</tr>
<tr>
<td>E</td>
<td>5 - 10 km/h</td>
<td>Saturation &gt; 75%</td>
<td>Main direction</td>
</tr>
<tr>
<td>F</td>
<td>&lt; 5 km/h</td>
<td>Saturation &gt; 75%</td>
<td>Conflicting directions</td>
</tr>
</tbody>
</table>

The municipal policy establishes that these arterial roads must meet a quality requirement 'speed', which translates into an average speed of 15 km/h inside the ring road, while 20 km/h is desirable. In practice, this is speed is not reached during 12% of the time for the AM peak, 22% for the PM peak, and 25% during the rest of the day (Verkeer en Openbare Ruimte, 2016). Thus, the purpose of the RVB is to collect real-time information on the speed of traffic on the different sections of the Plus Network Auto, and automatically adjust the traffic control system when the speed rates do not meet the quality requirement (de Roos and Walstra, 2015).

The RVB collects data from two different systems: travel times from the MoCo cameras and saturation and waiting time from the inductive loops from the intersections. This data is gathered every minute and averaged every 5 minutes in the case of the traffic control system, or 10 minutes for the travel times. Then, a quality level is assigned to each of the data collection systems, ranging from A (best) to F (worst). Finally, depending on the quality level, a certain measure is applied to the traffic control system (Vialis, 2016). This measures can be applied per road segment, in the case of the travel time measurements, or individually in the case of the intersection measurements. This way, different kind of distortions of the traffic flow can be identified, and the right measure can be applied. The full explanation of quality levels and their respective measures is listed in Table 2.2.

This project has been tested in the corridors S100 (Stadshouderskade between Overtoom and F. Bolstraat) and S106 (Overtoom between Stadshouderskade and Overtoomse Sluis), with a total of 11 intersections, as shown on Fig.2.5.
After a simulation study that concluded with an improvement of 1.7% during the morning peak and 12.7% during the evening peak in terms of lost hours (Vialis, 2016), the field test was set to start in October 2016. The results from both the MoCo cameras and the intersections are analyzed in the following subsections.

2.2.1 Analysis from MoCo cameras

Travel time data from the MoCo cameras has been collected for the months of April 2016, November 2016 and April 2017 during three weeks each month. April 2016 represents the base scenario previous to the RVB project, while November shows the scenario where the RVB project is working while there were roadworks, and April 2017 represents the scenario where the RVB is fully operational. The travel time data has been collected for four road segments: Overtoom (S106) both inbound and outbound, and Stadshouderskade (S100) both eastbound and westbound.

The data has been pre-processed with the use of an algorithm to remove extreme outliers. For example, really long travel times can be a result of a detour or stop between two cameras, and they must be discarded, as well as negative or really low travel times that are not feasible. After that, the travel times are converted to speeds and averaged every five minutes. The results from the analysis are shown in Fig.2.6.

It must be mentioned that during the months of November '16 and April '17 data could not be retrieved in all road sections during some specific hours any day due to technical problems. For example, during the month of April '17 data was not collected from 14:45
Fig. 2.6 Comparison of the average speeds with and without the use of RVB to 17:00, so the analysis of the evening peak is incomplete and must be taken cautiously, as shown in 2.7.

Fig. 2.7 Example of speed counts from the MoCo system for the month of April in the Overtoom street. Some data is not recorded at certain periods of time.

As it can be seen from Table 2.3, there is not much difference in average speeds during the different months. Only in the case of Stadshouderskade Eastbound a certain improvement can be appreciated. The speed has also been aggregated for the different periods of the day. It is possible to observe that there is an improvement from 2016 to 2017 between 1% and 12% for all the cases studied except the Stadshouderskade Westbound during the evening peak.

The speed quality requirement of 15 km/h is met now for all the road sections, but still far from reaching the desired speed of 20 km/h during the rush hours, especially during the
Table 2.3 Average speeds (in km/h) on the Overtoom and Stadshouderskade for the different months and periods of the day.

<table>
<thead>
<tr>
<th>Street</th>
<th>Direction</th>
<th>Month</th>
<th>Whole day</th>
<th>AM peak (7:00 - 9:00)</th>
<th>PM peak (16:00 - 18:00)</th>
<th>Diff '17 - '16 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overtoom</td>
<td>Inbound</td>
<td>April ’16</td>
<td>19.42</td>
<td>16.63</td>
<td>14.79</td>
<td>7.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>November ’16</td>
<td>23.18</td>
<td>18.38</td>
<td>15.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April ’17</td>
<td>20.78</td>
<td>16.84</td>
<td>15.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diff ’17 - ’16 (%)</td>
<td>7.03</td>
<td>1.28</td>
<td>3.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outbound</td>
<td>April ’16</td>
<td>23.88</td>
<td>19.65</td>
<td>15.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>November ’16</td>
<td>24.66</td>
<td>19.49</td>
<td>17.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April ’17</td>
<td>25.11</td>
<td>19.86</td>
<td>16.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diff ’17 - ’16 (%)</td>
<td>5.13</td>
<td>1.08</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eastbound</td>
<td>April ’16</td>
<td>18.18</td>
<td>18.71</td>
<td>15.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>November ’16</td>
<td>18.08</td>
<td>16.83</td>
<td>12.65</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April ’17</td>
<td>20.26</td>
<td>19.96</td>
<td>16.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diff ’17 - ’16 (%)</td>
<td>11.48</td>
<td>6.67</td>
<td>3.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Westbound</td>
<td>April ’16</td>
<td>21.49</td>
<td>22.80</td>
<td>18.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>November ’16</td>
<td>21.79</td>
<td>23.84</td>
<td>16.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>April ’17</td>
<td>21.89</td>
<td>23.39</td>
<td>17.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diff ’17 - ’16 (%)</td>
<td>1.90</td>
<td>2.56</td>
<td>-9.17</td>
<td></td>
</tr>
</tbody>
</table>

evening peak. However, this desired speed is reached when the whole day is considered as the time period.

2.2.2 Analysis from Kwaliteitscentrale (delay measurements)

Kwaliteitscentrale was created with the goal of collecting, processing and analyzing traffic control systems’ data. So far, it has been installed in several intersections in the city of Amsterdam. The intersections that play a role in the RVB project and belong to the Kwaliteitscentrale are 541, 572, 576, 577, 578, 583 and 590 (see Fig.2.5 for location of the intersections). Similar as with the MoCo cameras, data has been collected for the months of April 2016 and April 2017, which represent the situation before and after the implementation of the RVB.

The output selected from the Kwaliteitscentrale to measure the performance of the intersections is the delay (wachttijd in Dutch), which is the difference in seconds between the driving time of the vehicle as it freely passes through the stop line and the estimated actual driving time of the vehicle up to the stop line. The result is shown in average waiting time per vehicle. From the intersections mentioned before, the Kwaliteitscentrale only provides reliable data of waiting times for the intersections 572, 576 and 577, all located on the Overtoom.
The results are shown on Table 2.4. Overall, the average vehicle delay is reduced in all of the intersections for the year 2017 with an improvement ranging from 2 to 13%. However, the results are generally worse if the delays are compared during the peak times, especially during the AM peak, where the average delays are increased in all of the intersections. These results are interesting, since the RVB project is intended to act during the periods of the day when there is more congestion (AM and PM peak), but it seems to achieve better results outside of these peak periods.

Table 2.4 Average vehicle delay (in s) per intersection for the whole intersection and the coordinated streams. The data is classified per month and period of the day

<table>
<thead>
<tr>
<th></th>
<th>All streams</th>
<th>Only coordinated streams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole day</td>
<td>AM</td>
</tr>
<tr>
<td>KR 572</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April '16</td>
<td>15.98</td>
<td>14.82</td>
</tr>
<tr>
<td>April '17</td>
<td>13.89</td>
<td>15.84</td>
</tr>
<tr>
<td>Diff (%)</td>
<td>-13.10</td>
<td>6.91</td>
</tr>
<tr>
<td>KR 576</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April '16</td>
<td>15.78</td>
<td>16.86</td>
</tr>
<tr>
<td>April '17</td>
<td>14.92</td>
<td>17.24</td>
</tr>
<tr>
<td>Diff (%)</td>
<td>-5.47</td>
<td>2.28</td>
</tr>
<tr>
<td>KR 577</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April '17</td>
<td>16.51</td>
<td>15.51</td>
</tr>
<tr>
<td>Diff (%)</td>
<td>-2.64</td>
<td>8.90</td>
</tr>
</tbody>
</table>

When the analysis is carried out for the streams that are coordinated (along the Overtoom for KR 572 and 576, and between Overtoom and Stadshouderskade for KR 577), the outcome is a mixed result. It should be expected that with the RVB the coordinated streams would considerably reduce their average delay at all times, and especially during the peak times. However, this results are in most cases remarkably worse during April 2017 than for the same month in the previous year, reaching in some cases an increase of 20% increased delay.

2.2.3 Discussion

The RVB is an interesting project in which both travel time measurements from the MoCo cameras and delay measurements from the Kwaliteitscentrale are used to influence the traffic light control system. However, the results from the field test are mixed and differ from the expected outcome. Even though the overall results are positive in terms of average speed and vehicle delays, these are generally worse when comparing the peak periods, exactly when the RVB should obtain the best results. Some reasons why the results are not as good as expected could be explained by the influence of change in vehicle intensities from one year to
another, the modification of the layout of the street or the errors and miscalibration of the
delay and travel time measurement systems.

The idea under which the RVB works is still believed to be effective and further analysis
during other months and in other arterial roads should be carried out to determine the
potential effects of the project. Thus, the development of the proposed controller of this
research will be based on the ideas from the RVB project. However, some modifications have
been done to improve the performance of the controller:

- When the speed drops below a certain critical value, the RVB decides to limit the
green time of all the conflicting directions to the minimum possible. Even though the
green split for the coordinated signal groups will be higher, the traffic signal control
system keeps controlling the intersections in an isolated way, which can result in vehicles
stopping at each of the intersections and increasing the delay. Thus, this controller
proposes to switch to a fully coordinated strategy that creates a green wave in the main
corridor once this speed threshold is reached.

- Instead of using the saturation ratio as a measure to influence the local intersections,
the delay will be the variable that will decide whether to activate the influence on the
controller. The delay is a more robust measure that includes more input parameters,
including the saturation ratio, to provide a better estimation of the congestion status.

In order to find a suitable coordinated strategy to combine with the default controller,
a literature study of the most important urban traffic controllers is developed in the next
section.

2.3 History of Urban Traffic Controllers

Traffic signals at intersections are the major control measure in urban road networks (Papa-
georgiou et al., 2003). Based on historical or real-time measurements they control the traffic
streams at urban intersections by determining the state of the traffic lights for each signal
group. The basic goal of these systems is to increase the traffic safety by separating conflicting
flows, but an additional performance objective must be set, which can be minimizing the
total delay, the delay for a specific user type (PT, bikes), maximize the intersection capacity,
etc. The optimal real-time control strategy faces a series of challenges, such as (Papageorgiou
et al., 2003):

- The size of the problem is very big for a whole network.

- There are many unpredictable disturbances that are difficult to measure.
• Measurements of traffic conditions are mostly done locally (point-based) and often noisy.

• There are real-time constraints for decision making in advanced controllers.

A detailed optimal control is unfeasible for more than one intersection with the current technology and hence one or more simplifications need to be taken into account, or only tackle part of the problem. Apart from this, traffic control in saturated conditions are currently being researched and most of the available strategies are only effective in undersaturated traffic conditions.

There are four possibilities for influencing traffic conditions via traffic lights operation (Papageorgiou et al., 2003):

• Stage specification: number of stages and its composition. This may seem trivial with a small amount of user types and streams, but it can turn into a difficult combinatorial problem in a complex intersection.

• Split: relative green duration of each stage. Increasing the green split of a stage will lead to a higher capacity for the streams included in that stage.

• Cycle time: duration of a signal cycle. This is, the time between the repetition of the same stage in a normal stage sequence. Increasing the cycle time leads to the increase in capacity of the intersection, but may increase the waiting times of vehicles at a red phase.

• Offset: time difference between the start of the green phases of two adjacent intersections. The offset is used to coordinate intersections and create green waves for the main traffic streams. The specification of the offset should take into account the existence of queues.

2.3.1 Isolated Fixed-Time Strategies

Fixed time strategies are characterized by performing the control based on historical demand data collected from the different systems at the intersection and running an offline optimized timing plan.

Isolated fixed-time controllers are the simplest of all the controllers and do not react to the current traffic situation. However, different plans can be arranged for the different periods of the day. There are two kinds of strategies in this category: stage-based or phase-based. Stage-based strategies determine the optimal splits and cycle time, while the phase-based strategies also determine the stage specification on top of that.
Examples of these strategies are: SIGSET, which minimizes the total delay at the intersection; and SIGCAP, which maximizes the intersection capacity (Papageorgiou et al., 2003).

2.3.2 Coordinated Fixed-Time Strategies

TRANSYT (Robertson, 1969) is the most known and frequently used coordinated fixed-time controller. It differentiates from the previous strategies as it does not look at a sole intersection but a set of them that need to be coordinated. TRANSYT has two main elements: a traffic model and a signal optimizer. As it can be seen in Fig. 2.8, the traffic model is fed with the network and demand data, as well as the pre-specified staging, the minimum green times and a starting choice of cycle time, splits and offsets.

Traffic control is optimized in TRANSYT by incremental changes of the decision variables (cycle time, splits and offsets) between the intersections until the objective function is minimized. This objective function is a linear combination of delays and stops (Muller et al., 2014). As these intersections are coordinated, the cycle time of each of them is equal to the network cycle or half of the time.

2.3.3 Isolated Traffic-Responsive Strategies

Instead of historical data, traffic-responsive strategies use real-time data to perform a vehicle-actuated strategy. They usually rely on inductive loop detectors located both at the stop line and some distance upstream of the stop line.

One of the simplest strategies for this category is the vehicle-interval method, that is used for isolated intersections. Minimum green times are assigned to each stage. If no vehicle is detected at the stop line at the start of the stage, the strategy proceeds to the next stage. After the minimum green time, a critical interval is created, in which an extra green time is added to allow the vehicle cross the intersection. If no vehicle is detected during the critical interval, the strategy advances to the next stage, otherwise creates another critical interval and so on until the maximum green time is reached. This is the strategy that is currently used in most of the intersections in the city of Amsterdam.
The main advantage of these strategies compared to the fixed-time ones is that they do not waste green time. As the green time depends on the passing on a vehicle over the detector, there is no unused green time.

### 2.3.4 Coordinated Traffic-Responsive Strategies

During the last decades, plenty of research has been done on coordinated traffic-responsive strategies, with a full scope of different controllers.

**SCOOT**

SCOOT (Hunt et al., 1982) is a British control system developed in the 1970's by TRL, and considered to be the traffic-responsive version of TRANSYT. It is one of the most famous coordinated traffic-responsive strategies and has been largely applied in cities in the UK and worldwide.

While TRANSYT receives the demand from historical traffic volumes, SCOOT receives data from inductive loops located upstream at the beginning of a link. The vehicle platoons are measured upstream of the link and a model of the platoon dispersion is used to estimate the arrival pattern at the intersection. The split rates are obtained from the turning flows on the intersection observed in the previous cycle (Muller et al., 2014).

Same as TRANSYT, SCOOT performs an incremental change iteration of splits, cycle times and offsets at a local level until it finds optimum and the signal states are submitted to the local controllers. The optimal offsets are calculated each cycle, while the optimal green split is calculated a few seconds before every stage change. These changes are done in small steps, so SCOOT cannot appropriately work when there are rapidly changing traffic conditions. Moreover, SCOOT’s performance is reduced when it works under saturated conditions.

**SCATS**

SCATS (Sims and Dobinson, 1980) is a popular Australian signal control system developed around the same time as SCOOT. Opposite to SCOOT, SCATS measures the traffic with inductive loops located before the stop line. For each cycle, SCATS measures the saturation flow (used green time divided by the total green time) at each traffic stream by measuring the unused green time. Based on this saturation flow, the optimal cycle times, green splits and offsets are calculated. Intersections are grouped together into an upper level controller that selects the strategy to follow and coordinates the local controllers.

**Model-based Optimization Methods**
During the 1980's and 1990's more rigorous strategies have been developed, including OPAC, PRODYN, CRONOS, RHODES and Utopia/Spot (Papageorgiou et al., 2003). The difference with these methods is that they do not consider the splits, cycles and offsets. Instead, they calculate in real-time the optimal phase switching times over a certain time horizon $H$. In order to get the optimal switching times, these strategies make use of dynamic traffic models with a small sampling time (2-5 s) that are fed by real-time traffic measurements to solve a dynamic optimization problem. The typical decision variable to optimize in these strategies is to minimize the total time spent by all vehicles.

The time horizon procedure consists in optimizing the problem in real time over a time horizon $H$ (e.g. 60 s), but applying the results only in a much smaller period $h$ (e.g. 4 s). After these period $h$, new measurements are collected and the optimization problem is solved over a new time horizon $H$. This poses a big computational problem, as the presence of discrete variables require exponentially-complex algorithms to solve the problem (Papageorgiou et al., 2003). Thus, decentralization of the controller is the usual solution in these cases.

Probably the most known of these strategies is the UTOPIA/SPOT. The UTOPIA/SPOT system is a network-wide traffic strategy that employs a bi-level controller for the urban networks.

The problem of the previous controllers (SCATS and SCOOT) is that they work as centrally controlled systems that have a limited and slow reaction to changing circumstances. This problem is solved with a decentralized controlled system such as UTOPIA/SPOT. The SPOT system was created in Turin and is a local intersection controller that optimizes the individual intersection, taking the adjacent intersections into account. This way, SPOT can react quickly to locally changing demand. The SPOT system is complemented with the UTOPIA system, a network-wide controller that can apply an overall strategy for the whole network.

Both UTOPIA and SPOT consist of an observer and a controller. The top level observer gets traffic data and state information from the local intersection level, and together with the predefined strategies influences the control actions on the local levels. The local intersection level, depending on this influence from the area controller, has more or less flexibility at the time of controlling its own intersection.

**Store-and-Forward based strategies**

The model-based strategies explained above had the problem of using exponentially complex algorithms to solve the optimization problem. Theoretically, they could be applied to a whole network, but this was not feasible in real-time operation for more than one intersection, so they needed from a double-level controller. These store-and-forward models are aimed at tackling that problem and its basic principle is to simplify the mathematical
description of the traffic flow process. Until now, all models had used discrete variables (red-green switching of traffic lights). The crucial simplification is introduced when the outflow \( u_i \) of a stream \( i \) is modelled as follows:

\[
    u_i(k) = (g_i(k)/c)s_i
\]  

(2.1)

where \( g_i(k) \) is the green time duration of signal group \( i \) and \( s_i \) its saturation flow. This means that the flow is averaged over all cycle time instead of \( s_i \) during the green phase and zero during the red phase. Even though this simplification has some drawbacks, this is of great importance because it leads to the application of highly efficient optimization methods with polynomial complexity, which allows for real-time coordinated control in large-scale networks. These are the first strategies that work on saturated traffic conditions.

TUC is a multivariable regulator approach to traffic-responsive urban control that was developed at the end of the last century (Diakaki et al., 2001). As a store-and-forward model approach, TUC uses a simplification of the traffic flow process that allows the efficient optimization of a network-wide control strategy, easy installation and management, and low requirements for real-time measurements.

In order to reduce the risk of oversaturation and the spillback on link queues, the model tries to minimize and balance the relative occupancies of each stream following the linear-quadratic criterion:

\[
    \mathcal{J} = \frac{1}{2} \sum_{k=0}^{K} (||x(k)||_Q^2 + ||\Delta g(k)||_R^2) \tag{2.2}
\]

where \( x(k) \) is the vector of the number of vehicles \( x_i \) in network links \( i \) for time \( k \), \( \Delta g(k) \) is the difference between vector of green times \( g(k) \) and the constant nominal green times \( g^N \) for each stage, and \( Q \) and \( R \) are nonnegative definite, diagonal weighting matrices. Only the green splits are optimized in the controller, while the cycle time and offsets need to be calculated by other algorithms.

**Back-Pressure Control**

The Back-Pressure control strategy (Ying et al., 2011) is another controller aimed at optimizing the network flow during congested conditions. Based on queue-length measurements from the adjacent intersections, the back-pressure strategy uses an algorithm to relieve the approaches with longer queues into approaches that are less loaded. This way, all approaches try to maintain a balanced queue length, avoiding spillback into the previous intersections.

One of the main drawbacks of this strategy is that the data needed for this algorithm is the queue length at each traffic stream, which is considerably difficult to estimate in real life.
Apart from this, the back-pressure strategy requires routers to maintain a separate queue for each destination, which is not always possible in real-life.

2.3.5 Integrated Traffic Control Strategies

Historically, control strategies for each type of traffic measure are designed and employed separately, which may lead to counter-productivity of the actions performed by each of them. The integrated control strategies correspond to an urban-freeway network controller which integrates different traffic measures such as traffic signal control, ramp metering, variable message signs and route guidance systems.

The main drawback of this strategy is the large number of variables that need to be taken into account for each measure and the complexity of the network size (Papageorgiou et al., 2003). Thus, this is currently available just with the use of store-and-forward models that have enough agility to calculate in real-time the application of the algorithm. The first integrated control strategies was IN-TUC, which includes the TUC strategy for signal control, ALINEA for ramp metering and a user-optimum route guidance strategy. The PPA project in Amsterdam is the best example of an integrated control strategy.

2.3.6 Discussion

As it was stated in Chapter 1, the aim of this study is to develop a traffic management strategy that is able to improve the traffic performance for the road network of Zuidas for the year 2030. The case study road network is characterized by:

- Arterial Road. The proposed controller must be adequate for its use in an arterial road. This means that a coordinated response is needed in the main stream of all the intersections.
- Saturated conditions. The controller must be able to perform its strategy during the peak hours, when there is heavy congestion in the network.

As a result from the discussion of the previous section, travel time in the main corridor has been selected as the input to measure the congestion on it. When the speed shows that there is no congestion, the VA traffic controller currently used by the municipality will be in place as it shows a good overall performance, especially in the case of public transport. However, during the peak hours the speed will drop showing signs of congestion, and here the VA traffic controller previously mentioned is not effective anymore.
Based on the characteristics of the Urban Traffic Controllers discussed in this section and the goals stated here, one of them will be selected to work with the travel time measurements and combine it with the VA traffic controller into a functional controller.

The strategies for isolated intersections are not useful in this study as an arterial road needs a coordinated response in order to maximize its throughput.

SCOOT cannot be used since there are no inductive loops located at the start of each link in the street network of Amsterdam. On top of that, SCOOT is a commercial traffic controller and the exact algorithm is not available.

SCATS is also a commercial traffic controller for which the control algorithm is not available and it does not perform well under saturated conditions.

The model based optimization strategies cannot handle saturated traffic conditions as they fail to consider the downstream traffic conditions in the real-time decision-making at individual intersections. On top of that, they rely on exponentially-complex algorithms that cannot be used in real-life for a whole network.

TUC and Back-Pressure are feasible controllers. They can manage the traffic in the network under saturated conditions and the control algorithm is available. However, in order to implement the back-pressure controller, each traffic stream needs a dedicated queue lane and this is not available in the case study. The complexity of the TUC control logic and its application in such a complicated road network makes it impossible to develop such controller during the short period of time of this study. Thus, none of these controllers will be used in this case.

Even though the fixed time controllers are not good at the time of working under saturated conditions, the peak hours are characterized by a stable great demand from all of the approaches without sudden changes, which makes it possible that all the effective green time is used. Apart from this, the creation of a coordinated fixed-time strategy is simpler than the traffic-responsive ones. Thus, this will be the strategy selected for this study. However, it must be noted that this strategy lacks from priority for public transport and cannot react to demand changing conditions.

Further research should include the study of the traffic controller TUC in this study case, which is expected to perform better during saturated conditions. This could be complemented with the study of the ramp metering control system ALINEA for the on-ramps to the A-10 and create an integrated traffic control strategy.
Chapter 3

Design of the Urban Traffic Controller

After the study of the RVB and the literature study of the urban traffic signal controllers, an opportunity to combine travel time and delay measurements in an UTC has been identified. The goal of this controller is to improve the performance of the traffic network for a main urban corridor during congested conditions. In this chapter the proposed top-level controller is explained in detail. First, the approach taken to develop the controller is laid out. Then, the functional description of the controller with the detailed steps are described.

3.1 Approach

The approach taken to develop this controller is that it fits seamlessly in the scenario management framework of the city of Amsterdam explained in Chapter 2. In this way, the measurements from the inductive loops, MoCo cameras and FCD would be stored in the central archive, where they would be combined and cleaned. The resulting data would be sent to the NMS, where it would be processed and a certain scenario would be triggered by the top level controller. After the selection of the scenario, the information
would be sent to the traffic signal control system, which would implement the selected strategy in the intersections that are part of the corridor.

The control logic of the proposed controller is depicted in Fig. 3.2. There are two inputs to the controller (travel time and delay) and three possible scenarios or strategies: VA strategy (default), FT coordinated control or VA strategy with maximum green time for the coordinated signal group. Every 5 minutes, the average travel time is collected for the main corridor and the mean speed is calculated, while the delay is estimated for the coordinated signal groups of each intersection. If the average speed drops below a certain threshold, the FT controller will be chosen to coordinate the main corridor of the network. Otherwise, if the delay is greater than the critical value at each of the intersections, a maximum green time will be applied for the coordinated signal group of that intersection only. If none of the scenarios are triggered, the VA strategy will continue to manage the intersections.

As it can be seen, travel times are used for the corridor as a whole, while the delays are used at a local level for each of the intersections. This way, the controller is able to recognize whether the congestion is located over the whole corridor or at a local intersection and act accordingly. The definition of the critical values for the speed and delays will be decided later in the report.

3.2 Functional description of the controller

This section provides a more detailed explanation on the controller steps to obtain the input, process it and generate the control logic.
3.2.1 Collection and preprocessing of travel times

As it has been previously said, both ANPR cameras and FCD can be used as travel time data collection systems, each with its advantages and disadvantages. The ANPR system uses two or more cameras located at a specific point, with the disadvantage that travel times can only be measured between these points. However, this is a mature technology which provides reliable data. On the other hand, the FCD has the advantage that it can be used to measure the travel time between any couple of locations in the network, but it is a rather new technology with a low penetration rate and lower reliability than the ANPR system. A study on how to merge the data from both systems and provide a better estimation of the travel times fall outside the scope of this thesis.

In order to use the collected travel time of an arterial road for the control of the traffic signals system, a correct estimation is needed in real time. Contrary to traffic flows on highways, which are considered as uninterrupted flows, traffic flows in an urban network are considered interrupted and their travel times are more difficult to study. Apart from the queuing delay that is also present in highways, signal delays and delays caused by vehicles from side streets also need to be taken into account, as well as the possibility of a vehicle to take an alternative route between the measuring points or to park the car for a long time between the spots. This leads to the existence of wrong measurements recorded in the system, so it is crucial that the travel times in urban networks are meticulously preprocessed before they can be used in traffic management.

The most important characteristic of a travel time data set is that it is a time series. This means that the data points are indexed in time order, and its analysis should take this into consideration. Another characteristic of travel time measurements is that its distribution does not follow a normal distribution, but is normally skewed to the congestion side. As an example, Fig.3.3 represents the distribution of travel time measurements recorded by the ANPR cameras for a corridor in the road network of Amsterdam, with more records towards the bigger travel time measurements.

There are several strategies that can be used to remove the outliers, being the ones from the article by Clark et al. (2002) some of the most cited in this field, and explained below:
Percentile Test

The Percentile Test sets an upper and lower pre-defined percentile value ($PT_u$ and $PT_l$) under which all the values in a certain time period that fall outside this range are considered outliers. Clark proposes the use of percentiles 10% and 90%.

Deviation Test

The Deviation Test dictates a critical distance $CD$ from the median of the $n$ travel times in the period. All the values $TT_i$ outside of this range $[TT_{median} - CD, TT_{median} + CD]$ are considered outliers. This $CD$ can be defined as:

$$CD = \delta_a \times \frac{\sum_{i=1}^{n}(|TT_i| - |TT_{median}|)}{n}$$

(3.1)

where $\delta_a$ is a given parameter.

Moving Grubbs’ Test

The previous tests to detect outliers present some drawbacks. Percentile test will be extreme, as the measurements outside of the percentiles will be eliminated no matter if they are valid or not. On top of that, most of the outliers for travel time measurements in urban networks will be found for high values of travel times, as a result of choosing alternative routes or making a big stop along the route. The deviation test fails to recognize that the distribution of the travel times is usually skewed to the congestion side, while the same $CD$ is applied equally to the upper and lower part of the median.

Grubbs’s test for outliers is a test to detect whether a single value is an outlier in a data set. It does so by comparing the furthest data point from the mean to the test statistic critical value. As there is a possibility that more than one measurement can be an outlier, an iterative process takes place in which one outlier is eliminated each time until there are no measurements over the critical value. This way, the first measurements to be tested are the ones in which a detour or a long stop has been made. These will have an abnormally high value of travel time and they will eliminated first. As the test is applied to a time series, it is called Moving Grubbs’ Test. The steps needed to implement test in the controller are detailed below.

Step 1: Initiate a time window $T_w$

A time window $[t - t_w, t]$ is selected, for which the set of travel time measurements $N$ that fall within it will be selected. This time window must be selected carefully. If the window is too large, some of the travel times that are not outliers will be removed, while if it is too narrow some of the outliers will not be recognized. In this case, the time window chosen for the study is equal to the decision period of the proposed controller, 5 minutes.
Step 2: Calculate the G-value for the time window

\[ G = \frac{\max|\mu - T_i|}{\sigma_i} \]  \hspace{1cm} (3.2)

Where:
\( \mu \) = mean of the travel times in the time window;
\( \sigma_i \) = standard deviation of the population;
\( T_i \) = travel time measurement \( i \) of set \( N \);

\( G_i \) is considered an outlier if

\[ G_i \geq \frac{N - 1}{\sqrt{N}} \sqrt{\frac{(t_{\alpha/(2N),N-2})^2}{N - 2 + (t_{\alpha/(2N),N-2})^2}} \]  \hspace{1cm} (3.3)

Where:
\( N \) = population size for the time window;
\( t_{\alpha/(2N),N-2} \) = critical value of the t-distribution with \((N-2)\) degrees of freedom and a significance level of \( \alpha/(2N) \);

Step 3: Repeat the Grubb’s test until there are no outliers

In order to get the new mean and standard deviation for the new population without the outlier, the following formulas are used:

\[ \mu_2 = \frac{N\mu_1 - o}{N - 1} \]  \hspace{1cm} (3.4)

\[ \sigma_2 = \frac{(N - 1)\sigma_1^2 + N\mu_1^2 - o^2 - (N - 1)\mu_2^2}{N - 2} \]  \hspace{1cm} (3.5)

Where \( o \) is the value of the outlier removed. After all the outliers have been removed in the time window, the mean value of the travel time is calculated and sent to the controller as an input to select the strategy. Then, the time window is moved to the next period and all the steps are repeated.

An example on how this test removes the outliers from a set of travel times obtained from the ANPR cameras is shown in Figs.3.4 and 3.5. The distance between both ANPR cameras is 1698 m. In the case of Fig.3.4, some of the travel time records are much higher than the rest, even reaching 4500 s, which would be an average speed of 1.36 km/h. The Grubbs’ test is able to recognize and eliminate all these outliers as shown in Fig.3.5, providing a more coherent distribution of travel times where the deviation of travel time records is within a normal range for urban travel times.
3.2.2 Estimation of delays

Delays at the coordinated signal groups of the different intersections in the main corridor must be estimated in order to detect the congestion at a local level. The Highway Capacity Manual 2010 (TRB, 2010) will be the method selected to estimate the delay at the intersections. Although there are other methods available to predict the delay, the HCM has been selected as it is the most recognized worldwide and a thorough investigation of these methods is outside the scope of this thesis.

The values calculated with the HCM correspond to the average control delay experienced by all the vehicles of a traffic signal group during the analysis period, including movements at slower speeds or stops due to signal control or queues at an intersection. The input to calculate this delay is divided into three categories: geometric conditions, traffic conditions and signalization conditions.

Geometric conditions include parameters such as area type, number of lanes, average lane width, existence of parking spots, etc. With these parameters as an input, the saturation flow (in veh/h) is calculated for the coordinated signal groups of the intersection. Due to the limited time available for this thesis, a standard value of 1800 veh/h/lane has been selected.
as the saturation flow. A more profound estimation of the saturation flow would provide more accurate results at the time of calculating the delay, and thus is highly recommended. The method to calculate the saturation flow is also detailed in the HCM (TRB, 2010).

Traffic conditions relate to the vehicle demand at each coordinated signal group. This demand will be calculated by the inductive loops placed at the intersections and it will provide aggregated values in periods of 5 minutes to the central computer. Apart from this, other data such as the arrival type, proportion of vehicles arriving on green or approach speed will be needed.

The signalization conditions refer to the type of signal controller that is in place, the analysis period, the cycle time of the intersection and the green time of the coordinated streams. In case of a fixed-time (FT) controller, the green times and cycle times are fixed and thus possible to set offline. However, the VA controllers have variable cycle times and green times, so the average must be calculated and sent to the central computer in order to use it in the HCM formula.

The HCM calculates the average delay as show in Equation 3.6:

\[ d = d_1 + d_2 + d_3 \]  

(3.6)

Where:
\[ d = \text{control delay per vehicle (s/veh)}; \]
\[ d_1 = \text{uniform control delay (s/veh)}; \]
\[ d_2 = \text{incremental delay (s/veh)}; \]
\[ d_3 = \text{initial queue delay (s/veh)}; \]

The first term corresponds to the uniform delay, which is the delay assuming uniform arrivals and no initial queues. Its formula is:

\[ d_1 = \frac{0.5 C \left( 1 - \frac{g}{C} \right)^2}{1 - \left[ \min(1, X) \frac{g}{C} \right]} \]  

(3.7)

Where:
\[ d_1 = \text{uniform control delay (s/veh)}; \]
\[ C = \text{cycle time (s)}; \]
\[ g = \text{effective green time for the signal group (s)}; \]
\[ X = \text{lane group v/c ratio}; \]
The second parameter of the equation is the incremental delay, taking into account the stochasticity in traffic demand, temporary cycle failures and oversaturation. This equation assumes that there is no unmet demand that generates initial queues at the start of the analysis period. The random delay is calculated as:

\[
d_2 = 900T \left[ (X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right]
\]  

(3.8)

Where:
- \(d_2\) = random arrival delay (s/veh);
- \(T\) = duration of analysis period (h);
- \(k\) = incremental delay factor;
- \(I\) = upstream filtering/metering factor;
- \(c\) = lane group capacity (veh/h);
- \(X\) = lane group v/c ratio;

The incremental delay factor \((k)\) depends on the type of controller. It has a value of \(k = 0.5\) for fixed time controllers and a variable value for vehicle-actuated controllers that depends on the v/c ratio. The upstream filtering factor includes the effect of metered arrivals from upstream intersections. It has a value of 1 for isolated intersections and depends on the v/c ratio of upstream intersections for non-isolated intersections.

Finally, the last term of the delay is the one that accounts for the existence of an initial queue at the start of the analysis period. The value of this parameter depends on the size of the initial queue, the duration of the analysis period and the v/c ratio during this period. The parameter is calculated as:

\[
d_3 = \frac{3600}{vT} \left( t_A Q_b + Q_c - Q_{eo} + \frac{Q_c^2 - Q_{eo}^2}{2c_A} - \frac{Q_b^2}{2c_A} \right)
\]  

(3.9)

With:

\[
Q_c = Q_b + t_A(v - c_A)
\]  

(3.10)

If \(v \geq c_A\), then:

\[
Q_{eo} = T(v - c_A)
\]  

(3.11)

\[
t_A = T
\]  

(3.12)
3.2 Functional description of the controller

If \( v < c_A \), then:

\[
Q_{eo} = 0 \tag{3.13}
\]

\[
t_A = \frac{Q_b}{(c_A - v)} \leq T \tag{3.14}
\]

Where:
- \( Q_b \) = initial queue at the start of period \( T \) (veh);
- \( v \) = demand flow rate (veh/h);
- \( c_A \) = average capacity (veh/h);
- \( T \) = duration of analysis period (h);
- \( t_A \) = duration of unmet demand in \( T \) (h);
- \( Q_e \) = queue at the end of the analysis period (veh);
- \( Q_{eo} \) = queue at the end of the analysis period when \( v \geq c_A \) and \( Q_b = 0 \) (veh);

After adding all these terms, the average delay is obtained per signal group. The HCM continues to calculate the average delay at the intersection, but since this study is focused on the delay at the coordinated signal groups, this step is not necessary. The HCM defines six levels of service according to the average delay obtained from the formula, as shown in Table 3.1.

<table>
<thead>
<tr>
<th>LOS</th>
<th>Control delay (s/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( \leq 10 )</td>
</tr>
<tr>
<td>B</td>
<td>10 - 20</td>
</tr>
<tr>
<td>C</td>
<td>20 - 35</td>
</tr>
<tr>
<td>D</td>
<td>35 - 55</td>
</tr>
<tr>
<td>E</td>
<td>55 - 80</td>
</tr>
<tr>
<td>F</td>
<td>( &gt;80 )</td>
</tr>
</tbody>
</table>

A description is provided for each of the levels. A represents a situation in which traffic flows freely without any restriction from neighbouring vehicles, while F represents a situation in which the vehicle demand is higher than the capacity and the traffic flows under saturated conditions. For this study, level E (\( >55 \) s/veh) has been chosen as the level where the actuation at the local intersections must be done. This level represents an unstable flow that is operating close to capacity. Thus, it is the right moment to include the maximum green time for the coordinated signal groups.
3.2.3 Selection of strategy

Every period of 5 minutes the travel times are collected, merged, preprocessed, averaged and sent to the top-level controller, while the delays at the local intersections are estimated as explained before. Based on this input, the central computer can select between three possible strategies:

- FT coordinated controller (FT)
- VA controller (VA)
- VA controller with maximum green time for the coordinated signal group (VAx)

The base scenario starts with the VA controller managing all the intersections of the network. The control logic followed by the central computer is specified below:

```plaintext
for i=1:n
    if \( v_i < v_t \)
        choose FT
    else
        for j=1:N
            if \( d_{ij} > d_t \)
                Choose VAx for intersection j
            else
                Choose VA
        end
    end
end
```

Where:
- \( i \) = period of study;
- \( n \) = number of control periods;
- \( v_i \) = average speed for period \( i \);
- \( v_t \) = speed threshold;
- \( j \) = intersection of study;
- \( N \) = number of intersections;
- \( d_{ij} \) = delay for period \( i \) and intersection \( j \);
- \( d_t \) = delay threshold;
3.2.4 Transition between controllers

In order to change between the VA controller and the FT controller, a transition step is needed. When the fixed-time coordinated controller begins to operate, a new cycle length and offset must be established.

There are three ways in which an offset transition can be achieved: dwell, lengthen and shorten. Dwell is a transition technique in which the coordinated phase is extended until the new offset is achieved. The second technique also increments the cycle time, but the additional time is distributed over all phases. Finally, the last technique consists in shortening the cycle time, reducing the time of all phases as long as the minimum green time is guaranteed (Koonce et al., 2015). All these techniques can limit the amount the cycle time is extended or shorten to a certain percentage so that cycle times during transition are not extremely long or short. An overview of all these techniques is shown in Fig. 3.6.

In this case, a Max Dwell (+25%) strategy has been selected for the transition of the controller. As the nature of the controller is to prioritize the traffic flow of the coordinated direction, the 'Add' or 'subtract' technique is not useful since it treats all phases as equal importance. The Dwell technique is also not suitable in this case, as the cycle time of the coordinated controller is considerably high.

Fig. 3.6 Different transition modes between two different control strategies. Source: Koonce et al. (2015)

In this case, a Max Dwell (+25%) strategy has been selected for the transition of the controller. As the nature of the controller is to prioritize the traffic flow of the coordinated direction, the 'Add' or 'subtract' technique is not useful since it treats all phases as equal importance. The Dwell technique is also not suitable in this case, as the cycle time of the coordinated controller is considerably high.
The offsets will be compared to the leading intersection, which is the first upstream coordinated intersection. The current and desired offset will be obtained for each intersection in relation to the leading intersection, and the difference will be calculated. With this difference and the maximum dwelling time, the number of cycles needed to adjust the offset will be determined for each intersection. The logic followed by the controller to process the transition time is detailed below:
3.2 Functional description of the controller

\[ g_e = 0.25c \]

for \( i = 1:N \)

\[ \Delta T_i = tc_i - tf_i \]

\[ n = \text{ceil} \left( \frac{\Delta T_i}{g_e} \right) \]

\[ g_l = \text{mod} \left( \frac{\Delta T_i}{g_e} \right) \]

for \( j = 1:n \)

\[ \Delta T_{i,j} = \Delta T_i - (n - 1)g_e \]

if \( \Delta T_{i,j} \geq g_e \)

\[ g_{i,j} = g_{i} + g_e \]

else

\[ g_{i,j} = g_{i} + g_l \]

end

end

end

Where:

\( g_e \) = green extension for the coordinated signal group;

\( i \) = intersection of study;

\( N \) = number of intersections;

\( tc_i \) = current offset between intersection \( i \) and first intersection;

\( tf_i \) = desired offset between intersection \( i \) and first intersection;

\( \Delta T_i \) = difference between the current and desired offset for intersection \( i \);

\( n \) = number of transition cycles;

\( g_l \) = green extension for the last cycle;

\( j \) = cycle of study;

\( \Delta T_{i,j} \) = difference between the current and desired offset for intersection \( i \) and cycle \( j \);

\( g_{i,j} \) = green time for the coordinated signal group of intersection \( i \) and cycle \( j \);
Chapter 4

Case Study: Zuidas

In this chapter, the proposed controller from Chapter 3 is tested in a simulation environment of the Zuidas district in Amsterdam. First, an introduction is given about the characteristics of the area and its evolution for the year 2030. After this, the simulation environment is detailed, including the software structure and the interaction between the different programs. Finally, the results obtained from the simulation are analyzed.

4.1 Introduction

Zuidas, located in the south of Amsterdam, is currently one of the most ambitious urban developments that the city has ever experienced. Conceived as a high-density mixed-use district, Zuidas is meant to be a top-level international business centre with over 700 companies established there, as well as a main spot for public institutions and housing, all merged to create a dynamic urban hub (Gemeente Amsterdam, 2016).

The district currently hosts 2,000 inhabitants, over 31,000 workers and more than 30,000 students (Gemeente Amsterdam, 2016). These numbers are expected to sharply increase for the year 2030, when the whole project is expected to be realized. This growth can be appreciated in Fig.4.1 where all the construction projects that will be developed until the completion of the district are shown. Once the whole district is finalized, a total of 2,100,000 $m^2$ will be available, of which 1,400,000 $m^2$ will be used for services, 800,000 $m^2$ for residential purposes and 1,200,000 $m^2$ for office space. This will result in a total of 7,000 dwellings, with capacity for around 13,000 - 15,000 inhabitants and 56,000 working places.

This increasing demand in a high-density neighbourhood will pose a serious challenge in terms of mobility. Zuid station is currently under pressure with 80,000 daily passengers (Ingenieursbureau Zuidas, 2016b), and the forecast suggests that it will increase up to
130,000 train passengers and 118,000 metro passengers, especially after the completion of the North/South line, making it one of the busiest stations in the country. Apart from this the traffic flow on the A10, the highway that traverses the district, is already being problematic and the congestion is expected to increase by the year 2020. This route is not only essential for the accessibility of Zuidas, but for the whole northern part of the Randstad area. As part of the national policy, the A10 has a top-level priority, meaning that the traffic should flow smoothly and no congestion should occur at any time.

This mobility problem will be tackled with the project Zuidasdok, shown in 4.2, which consists on the whole remodelling of the south axis (Ingenieursbureau Zuidas, 2016a). The A10 will be expanded in the configuration 2-4-4-2 with 4 inside lanes for through movements and 2 parallel outside lanes for accessing the local network, and will be moved for a distance of approximately 1 kilometer where the train station is located.

This case study will focus on the Kenniskwartier (Knowledge Quarter in English), a special part of Zuidas that contains the Vrije Universiteit Amsterdam and the VU medical center.
4.1 Introduction

Located between the center of Zuidas and the exit 8 of the A10, the Kenniskwartier receives a lot of through traffic that is funnelled through the distributor roads Amstelveenseweg and De Boelelaan, which are part of the Plus Network Auto. As it could be expected the biggest intensities are found during the peak hours, especially since the center of Zuidas is the main business district of the city, with a lot of workers sharing the same travel patterns. Thus, the main traffic stream during the morning peak goes from the exit 8 of the A10 through Amstelveenseweg and De Boelelaan to the center of Zuidas, and vice versa during the evening peak. Currently heavy congestion is observed during the peak hours with large queues in Amstelveenseweg and De Boelelaan that can spill back to the adjacent roads, with the possibility of affecting the A10 and diminishing the attractiveness of Zuidas. Thus, it is of essential importance that the traffic problems are tackled for the future situation.

The solution proposed is to implement the urban controller developed in this study to coordinate the intersections on the way from the center of Zuidas to the A10 and vice versa whenever there is congestion in the road. The goal is to create a green-wave arterial road that increases the accessibility of the district. This study will examine the following intersections:

- 687: De Boelelaan / Buitenveldertselaan
- 695: De Boelelaan / Gustav Mahlerlaan
- 683: De Boelelaan / VOP VU medisch centrum
- 688: De Boelelaan / Amstelveenseweg
- 689: Amstelveenseweg / A10 Zuid buitenring
- 699: Amstelveenseweg / A10 Zuid binnenring

Due to the complexity of the intersections and the different distances between them, coordination can only be done in one of the directions. The direction of the coordination will be chosen depending on the time of the day: inbound for the AM peak and outbound for PM peak, as shown in Fig.4.3. As the microscopic model developed by the municipality is only available for the evening peak, this will be the period of time considered for the simulation. The simulation with the demand for the AM peak should be included in a further research, studying the feasibility of the controller for the opposite direction.

4.1.1 Traffic Information

Even though the car modal share is expected to decrease from the current 41% to 30% for the year 2030, traffic intensities will increase in most roads next to exits 8 and 9 of the A10.
during this period of time because of the overall increase in mobility. Traffic volume in the Kenniskwartier will increase by 22% compared to 2015 and travel times are expected to be longer in 2023 than 2013 according to dynamic traffic models (Pelgrim, 2017).

The intensities and V/C values of the intersections for the area of the study have been modelled for the years 2015 and 2030 in the VMA, and are shown in Appendix B. The traffic intensity increases in the majority of the road stretches of the Kenniskwartier, especially on De Boelelaan and Amstelveenseweg towards the A10. This comes mostly because of the development of the area around Gustav Mahlerlaan, which will undergo a complete change from a sports field to a series of highrise buildings.

From the V/C maps it can be observed that most of the intersections are currently almost reaching its capacity, with V/C values over 0.80 in most of the cases, especially in the intersection De Boelelaan / Gustav Mahlerlaan (695) and Amstelveenseweg with both entries to the A10 (689 and 699). The situation will improve slightly for the year 2030 in the Kenniskwartier due to the improvement of the access to the A10. However, the intersection De Boelelaan / Buitenveldertsealaan (687) will pose a serious challenge due to the addition of the tram tracks coming from the western leg of De Boelelaan.
4.2 Simulation environment

The traffic network model has been developed in Vissim by the team Ruimte en Duurzaamheid of the municipality of Amsterdam. This network represents the whole area of Zuidas for the year 2030, shown in Fig. 4.4. This is a large and considerably complex network, including the following different vehicle classes: car, taxi, heavy vehicles, buses, trams, pedestrians and bikes. This makes it especially difficult at the time of designing the traffic control systems for the intersections, as all this different users have to be taken into account.

![Fig. 4.4 Zuidas network in Vissim for the year 2030. Source: Ruimte en Duurzaamheid (2017)](image)

The duration of the simulation is 2 hours, representing the evening peak, from 16:00 to 18:00. The demand input has been obtained from the VMA for the forecast model of 2030. The distribution of the intensities throughout this period can be observed in Table 4.1. First, there is a 10 minute warm-up period in which the vehicles are loaded into the network, followed by two periods of inflow, the busiest hour, and two periods of exiting flow. The percentages correspond to the data obtained by the municipality of Amsterdam for the current distribution of intensities during the peak hour.

Table 4.1 Distribution of traffic during the peak hours

<table>
<thead>
<tr>
<th>Start time</th>
<th>End time</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0:10</td>
<td>0:00</td>
<td>5.5</td>
</tr>
<tr>
<td>0:00</td>
<td>0:15</td>
<td>12</td>
</tr>
<tr>
<td>0:15</td>
<td>0:30</td>
<td>12.4</td>
</tr>
<tr>
<td>0:30</td>
<td>1:30</td>
<td>50</td>
</tr>
<tr>
<td>1:30</td>
<td>1:45</td>
<td>13.2</td>
</tr>
<tr>
<td>1:45</td>
<td>2:00</td>
<td>11.3</td>
</tr>
</tbody>
</table>
Fig. 4.5 shows a detailed view of the Kenniskwartier network, with the corridor that needs to be coordinated highlighted in yellow. Travel times in this section will be collected to measure the performance of the strategy implemented, as well as the delay observed at the intersections 687, 695, 683, 688, 689 and 699. It must be noted that intersections 689 and 699 are managed by a fixed-time controller already in the base scenario, although these intersections are not coordinated. Intersection 683 is an actuated pedestrian crossing at the VUmc and intersections 687, 695 and 688 are managed by VA controllers. Under the fixed-time strategy, all these intersections will be operated by fixed-time controllers that will be coordinated.

![Fig. 4.5 Close-up view of the Kenniskwartier, with the highlighted coordinated corridor. Source: Ruimte en Duurzaamheid (2017)](image)

### 4.2.1 Simulation workflow

In this section, the software programmes used for the simulation are presented, including the interaction between them. Fig. 4.6 represents the workflow of the simulation, with the black boxes representing the main processes and the coloured boxes the program under which these processes are carried out.

**OTTO**

OTTO is a Dutch software program used to calculate the intergreen matrix of an intersection. The input needed for this software is an intersection drawing in which the stop
lines and the lanes are shown. Then, OTTO calculates all the possible conflict situation distances and clearance times according to the CEOW guideline for the Dutch roads.

COCON

Once the intergreen times are calculated in OTTO, this are included in COCON together with the demand input, the minimum green times and yellow times, the design conflicts and the desired coordination to create the fixed time signal controller (DTV, 2017).

COCON provides two kinds of intersection analysis. The classical method calculates conflict groups, internal loss times and the cycle times based on the Webster formula. The critical signal group is entered in the interactive phase diagram, where the rest of the signal groups are adjusted from the base scheme. The second method employs graph theory to calculate all possible arrangements for an intersection. Every arrangement has an associated cycle time, lost time, flexibility, critical stream and critical load. The best arrangement is selected and the phase diagram is filled in automatically, but all the different arrangements can be checked.

ATB-A

ATB-A stands for Automatic Traffic Builder - Amsterdam. This software is used to create the vehicle actuated signal control programmes for the intersections of the municipality. ATB-A works with the fixed-time control programme developed in Cocon as a base reference.
The loop detectors from the Vissim traffic network provide the ATB-A with the detector occupancy, which applies in real-time a certain algorithm to increase the green times based on the incoming flow to the intersections. This algorithm is property of Vialis and is not available.

**Vissim**

Vissim is a microscopic, behavior-based multi-purpose traffic simulator developed by the PTV Group (PTV Group, 2016). Contrary to the macroscopic simulation models (i.e. PTV Visum), where the traffic situation is represented as averaged variables such as speed, flow and density, the microscopic traffic models simulate single entities (vehicles and pedestrians), where complex traffic conditions are visualized in high level of detail supported by realistic traffic models. The microsimulation models are more accurate at the time of representing the traffic, but they are more complex and require from a bigger number of parameters.

Within all the microscopic traffic simulators, Vissim is chosen because of its ease of use and the flexibility it offers. First of all, Vissim provides with a lot of freedom at the time of setting up the traffic signal controllers with plenty of different options, and the possibility to use external programs, such as the one used by the municipality to create the vehicle-actuated signal program. Apart from that, Vissim is also very useful as it offers dynamic simulation control from external software through its COM-server. This is, all the data from Vissim can be accessed through the COM interface, and this can be used to modify the parameters of the simulation before or during the simulation.

**Matlab**

Matlab is a numerical analysis environment for engineers and scientists and a programming language, with a diverse range of applications in the fields of science, engineering and finance. Matlab has been used in this study to create the upper-level controller that selects between the vehicle actuated or fixed time strategy.

Matlab is able to interact with Vissim through the COM interface. It can be used to enter the input parameters of the simulation, obtain parameters before or during the simulation and use them to influence it, and collect and analyze the output from the simulation. It has to be noted that while most of the parameters can be manipulated before the start of the simulation, the list of the ones that can be changed during the simulation is significantly reduced, complicating the dynamic interaction.

Vissim does not allow on its own to change the parameters while the simulation is running. In the specific case of this study, it means that only one traffic signal strategy can be selected per intersection in a simulation run, without the possibility to switch between a fixed-time
4.2 Simulation environment

and vehicle actuated control. Thus, Matlab is needed in order to change between the different strategies.

In order to implement this controller, the signal heads of all the intersections in Vissim need to be duplicated, one for each signal control strategy. The signal controllers can be set to active or inactive, but only before the simulation starts. Thus, both signal controllers need to be active during the simulation. The problem is solved by controlling the signal heads of the controller that needs to be inactive through the COM interface by giving permanent green, while the signal heads of the other controller remains working as it is supposed to. Once there is a change of strategy, the opposite situation occurs.

**Simulation Steps**

1. The intergreen times are calculated in Otto (offline)

2. The fixed-time signal control strategy is created in Cocon, and transfer to Vissim as .sig files (offline)

3. The traffic network is created in Vissim, including the dynamic demand (offline)

4. Matlab activates Vissim and sets the simulation parameters (offline)

5. Matlab starts the simulation during one simulation step. It starts with the VA controller, so Matlab controls the FT signals by giving them permanent green (online).

6. Vissim provides ATB-A with detector occupancy at each intersection leg in order to determine the traffic light states (online)

7. After each control step, Vissim sends the average speed in the corridor and delay of the coordinated signal groups at the local intersections to Matlab (online)

8. Based on the average speed, Matlab decides whether to keep the VA strategy or switch to the FT one. If the speed does not drop below the threshold but the delays at the local intersection do, a maximum green time is applied to the coordinated signal group. In case of switching between controllers, a transition period is needed (online)

9. If the FT controller is chosen, the traffic signals are controlled by the .sig files in Vissim created in step 2, and the VA signals are controlled by Matlab by giving permanent green. If the VA controller is chosen, refer to steps 5 and 6.

10. Repeat step 7 until the end of the simulation is reached.

11. Matlab closes Vissim and saves the output (offline)
4.3 Results

The following section presents the results from the simulations that have been carried out in the environment described before. First, the calibration of the speed threshold to change between strategies has been calculated. Then, the calibration of the delay estimation method has been accomplished. Finally, the evaluation of the proposed controller has been performed, taking the speed in the main corridor and the delays at the intersections as the performance indicators.

4.3.1 Calibration of the speed threshold

The goal of this section of the study is to identify which speed should be selected as the threshold to change between the vehicle actuated controller and the coordinated fixed time controller in order to achieve the best outcome in terms of speed in the coordinated corridor (Fig.4.5). In order to perform this simulations, the delay actuation at the local intersections has not been included yet to avoid the alteration of the results.

Thresholds from 12 km/h up to 24 km/h with increments of 1 km/h have been tested in the simulation environment. 5 simulations with different random seeds have been run for each threshold for a duration of 2 hours between 16:00 and 18:00.

As it can be seen from Fig.4.7, the deviation between the time for the change of strategy in a single speed is remarkable, especially for the lower speed thresholds. This is due to the big variation of travel times in urban environments, as it was stated in Section 3.2.1. However, it is clear to see that there is a trend to change between controllers sooner when the speed threshold is set higher. From 25 km/h and higher, the controller is always changed after the first 5 minutes of the simulation, so it can be considered as the FT controller.

![Fig. 4.7 Change between the VA and FT strategies for the different speed thresholds](image-url)
The mean value of the speed throughout the 2 hour simulation has been obtained and it has been averaged over the 5 simulations for each speed threshold. The results are shown in Fig. 4.8. There is a positive trend between the speed threshold for the change of strategy and its average speed in the coordinated corridor. The bigger the threshold is set, the faster the vehicles drive in the main corridor, reaching average speeds over 20 km/h in many cases, which is the desired speed set by the municipality for the Plus Network Auto.

Fig. 4.8 Average speed in the corridor during the evening peak hour for different speed thresholds

According to this results, choosing the coordinated fixed-time controller during the whole evening peak would be the best solution to achieve the fastest average speed in the main corridor, and thus prioritize the vehicle flow from the center of Zuidas to the A10. However, using the coordinated controller for the whole of the evening peak might have a negative impact in the conflicting directions and the public transport.

Apart from the current VA controller and the FT controller, a speed threshold must be selected in order to test the performance of the proposed controller. Thus, the speed threshold of 15 km/h will be selected, which corresponds to the speed requirement from the municipality for the Plus Network Auto. These three strategies will be evaluated in Section 4.3.3 for the speed in the main corridor and Section 4.3.4 for the delays at local intersections.

Further research should include the simulation of a longer period of time to test whether a change of strategy previous to the start of the evening peak would provide better results in terms of average speed in the corridor and delays at the intersections. As well, this study should be performed during the morning peak in the opposite direction (A10 to the center of Zuidas), ideally with a longer simulation period.
4.3.2 Calibration of the delay estimation method

The goal of this section is to calibrate the delay estimation method proposed by the HCM and explained in Chapter 3 so that the delays used as an input for the top level controller are as similar to reality as possible. For this purpose, the I-parameter needs to be calibrated for the FT controller, and both the I-parameter and k-value need to be adjusted for the VA controller.

The mean squared percentage error (MSPE) will be used as the outcome to compare the effectiveness of the calibration. Its formula is written as:

\[
MSPE = \frac{100}{n} \sum_{i=1}^{n} \left( \frac{\hat{Y}_i - Y_i}{Y_i} \right)^2
\]  

(4.1)

Where:
- MSPE = mean squared percentage error;
- n = number of time stamps;
- \( \hat{Y} \) = estimated parameter;
- Y = measured parameter;

The relative error is used since different intersections will be taken into account. The coordinated signal groups from the different intersections will provide different delay values. The squared error is used as the consequence of a large error between the delay estimation and its measured value is much more important than a small error.

**Calibration of I-parameter for the FT controller**

The I-parameter, or upstream filtering adjustment factor includes the effects of the arrival pattern from upstream signals. This parameter value ranges between 0 and 1, where 1 represents Poisson-distributed arrivals to the intersections. This is the pattern that Vissim chooses for the creation of vehicles in the network and would work in isolated-intersections. However, the existence of other intersections upstream of the intersection that is studied may have an effect on the arrival pattern.

A simulation has been run in the Vissim model with the FT controller operating the intersections during the whole simulation period. Delays have been collected every 5 minutes at the coordinated signal groups of each intersection.

The delays have been calculated using the HCM formula for each coordinated signal group time period with I-parameters ranging between 0 and 1. These delays have been compared to the measured values obtained from Vissim and the MSPE values have been obtained. The results are shown on Fig.4.9.
Fig. 4.9 Calibration of I parameter for the estimation of delays with the HCM method for fixed-time control

An I-parameter with a value of 0.52 obtains the best results with a MSPE value of 6.08%. This will be then the parameter used to for the estimation of delays with the FT controller.

Fig.4.10 shows how the HCM model fits the measured delay from Vissim at the coordinated signal groups of the different scenarios with the proposed I-parameter. As these signal groups are coordinated, the delays remain quite low during the whole period for intersections 688, 689 and 699. The results show that the HCM-method gives a better estimate when the value of these delays is rather high (intersection 695), but it is not able to represent correctly the delays when the values are close to 0 (intersection 699). This is not a problem for the proposed controller, since it is only important to check the situation when the traffic is close to saturation, this is, when there are big delays.

**Calibration of I-parameter and k-value for the VA controller**

The k-value, known as incremental delay calibration factor, is a term included in the second term of the delay equation to incorporate the effect of the controller type on the delay. While this value is set at 0.5 for fixed time controllers, the possibility to adapt the green time to the demand makes it possible to reduce this incremental delay, an hence reduce the parameter. The k-value wis calculated by the following formula:

$$k = (1 - 2k_{min})(X - 0.5) + k_{min}$$

(4.2)

Where X is the v/c ration and $k_{min}$ is a parameter that depends on the unit extension of the VA controller.
Same as with the FT controller, a simulation has been run with the VA controller and delays have been collected every 5-minute period at each of the coordinated signal groups of the intersections.

The delays have been calculated as well with the HCM formula with values from the I-parameter between 0 and 1 and values of $k_{min}$ between 0 and 0.5. The results show that an I-value of 0.20 and a $k_{min}$ value of 0.5 provide the best overall performance, with a MSPE of 12.98%. The $k_{min}$ of 0.5 means that the k-value is independent of the saturation degree in the coordinated signal groups. Thus, the only difference between the calculation of the delays for the FT and the VA controller is the value of the I-parameter.

Fig 4.11 shows how the HCM formula fits the measured delays from Vissim using the calibrated parameters. The results show that the estimation of the delays is worse when the VA controller is used. In the case of intersection 695 the estimation of delays is completely different from the measured ones. Even though the HCM estimates correctly the delay during the first 30 minutes of the simulation, the difference during the rest of the time is immense. The reason behind this difference is that the HCM is not able to estimate the spillback delay created by the next intersection. The queue at intersection 688 starts to grow during the simulation, until the point that it reaches intersection 695 and affect the flow of the different
4.3 Results

Fig. 4.11 Comparison between estimated delay by HCM and measured delay in Vissim for the coordinated signal groups of the intersections with the VA controller

signal groups. While this is recorded in Vissim, the HCM formula does not have a term to take this into account.

However, this could result in a positive effect. The idea of the controller is that when the delay recorded at the coordinated intersection reaches the threshold, a maximum green time is applied to it in order to relieve the congestion on it. However, if there is a spillback from the next intersection, this extension of the green time is not going to have any effect on the congestion of the lane.

Table 4.2 summarizes the values adopted for the calibration parameters of the HCM delay estimation method.

Table 4.2 Calibration of the parameters chosen for each signal strategy and MSPE associated.

<table>
<thead>
<tr>
<th>$I$</th>
<th>$k_{min}$</th>
<th>MSPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT</td>
<td>0.52</td>
<td>-</td>
</tr>
<tr>
<td>VA</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>
4.3.3 Evaluation of the speed in the coordinated stream

As a conclusion from Section 4.3.1, three different strategies have been selected to evaluate the speed in the main corridor: the current vehicle-actuated controller, the coordinated fixed-time controller, and the proposed controller with a speed threshold of 15 km/h. 20 simulations have been run for the evening peak for each strategy with different random seeds. Travel time has been collected for the vehicles in the main corridor (between intersection 687 and exit to the A10, see Fig.4.5) and averaged every 5 minutes. Fig.4.12 shows the average of the 20 simulations for each strategy, aggregating the mean speed of the corridor in 5-minute intervals.

Fig. 4.12 Average speed in the corridor during the evening peak hour for different control strategies

Over all, the FT controller shows an improvement in total average speed of 36.5\% (21.61 km/h) compared to the current VA controller, with a mean value of 15.83 km/h. Besides, the mean speed is 28.5\% higher (20.34 km/h) when the proposed controller is the one managing the traffic, as it is shown in Fig.4.13

It is possible to see that the VA controller fails to manage the traffic in the corridor during the evening peak, as the average speed steadily decreases since the start of the simulation, reaching almost average speeds of 10 km/h. By not providing enough green time to the main stream going from Zuidas to the A10, queues start to build up at the intersections and increasing with each cycle, thus explaining the decreasing speed. This is especially significant between intersections 695 and 688, where the big demand creates such big queues that it sometimes spillback into the operation of intersection 695. It is only at the end of the simulation, when the demand starts to decrease, that the speed starts to recover again.

Fig. 4.13 Average speed for the evening peak
4.3 Results

As it was shown in Section 4.3.1, the FT controller is the one that gets the best performance in terms of average speed. Here it is more clear to see the need for a further research in which a longer simulation period is chosen, since the average speed is reasonably higher already at the beginning of the evening peak. With a longer simulation period, it would be possible to observe when the FT performs worse than the VA controller and hence the optimal change between strategies.

The proposed controller gives a mixed result between both previous controllers. As it starts the evening peak with the VA controller, the speed is lower than with the FT strategy, but as the strategy change is done, the speed in the main corridor increases considerably with respect to the base scenario. In Fig.4.12 the proposed controller never shows an average speed below 15 km/h. This does not mean that the speed threshold is not reached, and is due to providing the average of 20 simulations, since the time deviation of the change of strategy makes that each simulation can get very different results for the same time stamp.

Fig. 4.14 shows the first two simulation runs with the proposed controller. Both simulations keep a fairly similar average speed until 16:35, when the first one changes its strategy to the FT controller. From there, the difference between both simulations starts growing until the change of strategy of the second simulation, with a speed difference of almost 15 km/h at 17:05. Finally, both simulations reach a similar final speed around 25 km/h.

![Simulation examples for the proposed controller](image)

Fig. 4.14 Examples of two different simulation runs with different random seeds while using the proposed controller. The dot represents the change between the VA and FT strategies.

4.3.4 Evaluation of delays at intersections

Apart from the speed in the main corridor, delays at local intersections will be studied in order to determine what effects the proposed controller has on the intersection as a whole, as well as its effect in conflicting flows with the main corridor. Same as with the speed evaluation, 20 simulations have been run with different random seeds for each strategy and...
the average vehicle delay has been obtained in intervals of 5 minutes for all the streams of the intersections that play a role in the study case.

Table 4.3 Intersection delays per vehicle for the different control strategies (in seconds) and difference with the vehicle actuated strategy

<table>
<thead>
<tr>
<th>Intersection</th>
<th>VA (s)</th>
<th>FT (s)</th>
<th>FT VA %</th>
<th>Controller (s)</th>
<th>Controller VA %</th>
</tr>
</thead>
<tbody>
<tr>
<td>687</td>
<td>49.92</td>
<td>41.47</td>
<td>-16.94%</td>
<td>46.49</td>
<td>-6.87%</td>
</tr>
<tr>
<td>688</td>
<td>38.13</td>
<td>28.05</td>
<td>-26.43%</td>
<td>32.05</td>
<td>-15.94%</td>
</tr>
<tr>
<td>689</td>
<td>27.51</td>
<td>27.30</td>
<td>-0.74%</td>
<td>29.79</td>
<td>8.30%</td>
</tr>
<tr>
<td>695</td>
<td>56.55</td>
<td>49.48</td>
<td>-12.50%</td>
<td>45.69</td>
<td>-19.20%</td>
</tr>
<tr>
<td>699</td>
<td>33.07</td>
<td>28.08</td>
<td>-15.11%</td>
<td>26.22</td>
<td>-20.72%</td>
</tr>
</tbody>
</table>

Table 4.3 shows the average vehicle delay at each intersection for the whole simulation period. The values range from 27 to 57 s/veh for the current VA strategy, with intersection 695 (De Boelelaan / Gustav Mahlerlaan) as the most congested one. Both the FT coordinated controller and the proposed controller present substantial improvements compared to the base situation, in many cases reaching a reduction of 15% in the average vehicle delay. Intersection 689 is the only one where the proposed controller performs worse than the VA controller, increasing 8.30% the average delay. Overall, the FT controller is the one that achieves the best result, with a decline of 14.92% in the global average delay, while the proposed controller reaches a drop of 11.60%.

Fig. 4.15 Average vehicle delay at each intersection during the evening peak hour for the VA controller

Fig.4.15 displays the evolution of the delay at each intersection during the evening peak for the VA controller. As the simulation starts, all the intersections show a similar average delay between 20 and 30 s/veh. As the simulation goes on, intersection 695 keeps increasing its delay to almost 100 s/veh and reaching saturation, while the rest of the intersections keep the delay within normal limits. Thus, a further analysis of the intersection 695 will be carried out.
4.3 Results

The problem at intersection 695 is the great amount of vehicles turning westbound to intersection 688 from all directions, as it can be seen in Fig. 4.16. A total of 2417 vehicles from 3 conflicting signal groups merge into a two-lane stretch of road towards Amstelveenseweg. As the cycle time is variable with the VA strategy, when that cycle time is small the intersection will operate close to capacity and a sudden increase in demand can cause that the amount of green time for each signal group is not enough to accommodate the coming vehicles.

The cycle time of the FT controller is set at 100 seconds, which gives enough capacity for all 3 signal groups to keep a regular flow. Thus, with the FT and the proposed controller, the average delay at this intersection is controlled within the limits of admissible values. The results can be observed in Fig. 4.17. During the first part of the simulation the FT controller performs worse than the other two controllers, as the demand is still increasing and the cycle time is too large for it. However, when the demand at the intersection is maximum the FT controller manages to keep the delay within the limits while the delay with the VA controller is not controlled. Here the proposed controller is the one with the better performance, as it takes the advantage of the adaptability to the coming demand from the VA controller during the first part of the simulation, and the effectiveness of a large fixed cycle time during the last part of the simulation.

![Fig. 4.17 Average vehicle delay at intersection 695 during the evening peak hour for the different control strategies](image)

When the delays are evaluated for the coordinated signal groups in the main corridor, the results are clearly advantageous for the FT and the proposed controller, as Table 4.4 shows. In all cases (except kr695) the delay for these signal groups drops at least 20%, and much more in some of the cases. The case of intersection 699 is very interesting, with reductions.
Case Study: Zuidas

of over 90% in the delay. This is because the flow of vehicles approaching the intersection from the south comes exclusively from a single signal group of intersection 689 with a similar green time, making it possible to coordinate both intersections perfectly.

Table 4.4 Delays per vehicle in the coordinated signal groups of each intersection for the different control strategies (in seconds) and difference with the vehicle actuated strategy

<table>
<thead>
<tr>
<th>Intersection</th>
<th>VA</th>
<th>FT</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>688</td>
<td>53.96</td>
<td>28.06</td>
<td>-48.01%</td>
</tr>
<tr>
<td>689</td>
<td>30.47</td>
<td>13.56</td>
<td>-55.51%</td>
</tr>
<tr>
<td>695</td>
<td>48.75</td>
<td>46.95</td>
<td>-3.69%</td>
</tr>
<tr>
<td>699</td>
<td>24.12</td>
<td>2.19</td>
<td>-90.94%</td>
</tr>
</tbody>
</table>

Finally, the delays for the public transportation vehicles have been evaluated. Several lines of buses and trams run through De Boelelaan and Amstelveenseweg. It would be expected that the delay for these modes of transport would increase as a consequence of using a FT coordinated controller that does not provide priority for public transport movements. However, the results obtained from the simulations show a mixed outcome, as it can be seen in Table 4.5. While the buses performance is generally lower with the FT and the proposed controller, with increases of up to 44% in the average delay, the average delay for the trams drops remarkably for intersections 688 and 695.

The tram delay at intersections 689 and 699 remains constant as the tramway is inbunded from the rest of vehicle movements.

Table 4.5 Delays per vehicle for buses and trams at each intersection for the different control strategies (in seconds) and difference with the vehicle actuated strategy

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Vehicle</th>
<th>Amount</th>
<th>VA</th>
<th>FT</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>688</td>
<td>Bus</td>
<td>58</td>
<td>29.49</td>
<td>42.34</td>
<td>43.55%</td>
</tr>
<tr>
<td></td>
<td>Tram</td>
<td>44</td>
<td>41.50</td>
<td>23.16</td>
<td>-44.19%</td>
</tr>
<tr>
<td>689</td>
<td>Bus</td>
<td>120</td>
<td>31.34</td>
<td>25.98</td>
<td>-17.10%</td>
</tr>
<tr>
<td></td>
<td>Tram</td>
<td>24</td>
<td>55.09</td>
<td>55.09</td>
<td>0.00%</td>
</tr>
<tr>
<td>695</td>
<td>Bus</td>
<td>108</td>
<td>31.12</td>
<td>38.49</td>
<td>23.69%</td>
</tr>
<tr>
<td></td>
<td>Tram</td>
<td>24</td>
<td>55.61</td>
<td>13.90</td>
<td>-75.00%</td>
</tr>
<tr>
<td>699</td>
<td>Bus</td>
<td>64</td>
<td>39.48</td>
<td>52.70</td>
<td>33.48%</td>
</tr>
<tr>
<td></td>
<td>Tram</td>
<td>24</td>
<td>24.45</td>
<td>24.45</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Taking into account the number of buses and trams that traverse each intersection, the total lost time has been calculated for each mode of transport, and the results are presented.
in Fig. 4.18. The VA controller has the best performance for the buses and the worst for the trams, while the FT controller has the best performance for the trams and the worst for the buses. The proposed controller scores in between both controllers for both modes of transport. The VA controller total lost time for the public transport (buses and trams) is 4.56 hours for the whole evening peak. The FT controller reduces this value in 0.39% to 4.54 hours, while the proposed controller shows a total lost time of 4.55 hours and a reduction of 0.27%. Thus, the difference in the total lost time for the three strategies is almost unnoticed.
Chapter 5

Conclusions and Recommendations

The goal of this thesis is to find a way in which the Intelligent Transportation Systems currently used by the city of Amsterdam can be combined and adopted into a new strategy to improve the traffic performance of the local road network. An opportunity has been spotted in which the travel time and delay measurements retrieved from inductive-loop detectors, automatic number plate recognition cameras and floating car data are combined into a traffic strategy. These measurements will serve as an input to the proposed traffic signal controller, which is a top level controller that combines the adaptive allocation of green time from the vehicle-actuated controllers and the effective coordination from the fixed-time controllers. The proposed controller has been tested in a simulation environment in the Zuidas district for the year 2030, and has shown significant improvements to the base scenario situation. In this chapter, the conclusions of the study are drawn, and the recommendations and further studies are specified.

5.1 Conclusions

In this section the research questions listed at the beginning of the report will be recalled and answered.

What is the current state of traffic management in the municipality of Amsterdam? What are the Intelligent Transportation Systems that are in place in the city at present?

Chapter 2 gives a clear picture of what the current state of traffic management is in the municipality of Amsterdam. First, the data collection systems in place have been listed, including their locations and the purpose of its use in the city. This list consists of inductive-
Conclusions and Recommendations

loop detectors, automatic number plate recognition cameras, floating car data and parking data.

After this, the data is pre-processed, archived and sent to the Network Management System. This data serves as the input to trigger different management scenarios that have been tailored for specific traffic situations in the city.

Finally, the traffic measures that are used by the city of Amsterdam are explained. This consists of ramp metering on the on-ramps of the A10, dynamic route information panels and traffic signal control systems located at all signalized intersections of the city. A schematic view of the current traffic management framework is available in Appendix A.

Which system or group of systems can be applied to improve the traffic management?

As it was stated in Chapter 2, most of the signalized intersections work with an isolated vehicle-actuated control logic. This logic gives minimum green time to each stage and extends it on the basis of vehicle detection at each stream by inductive loops. Thus, this is the only system required for the operation of the traffic controllers.

At the end of this chapter, a possibility to include travel time and delay measurements in an urban traffic controller has been observed. The ANPR cameras currently installed in the city, FCD or a combination of both technologies can be used to retrieve the travel time data. The inductive loops can also be used to get the count of vehicles per stream, and with this input the delays can be estimated with the use in this case of the HCM delay estimation method.

The idea of this study is that by combining the data from the different systems that are already installed in the local network (ANPR, FCD and inductive-loop detectors) a better performance of the signalized intersections can be achieved.

Which control strategy could be used together with these systems in order to improve the performance in an urban traffic network?

During chapter 2, a series of different urban traffic controllers that have been developed through time are described. This lists includes both isolated and coordinated traffic strategies, as well as fixed-time and traffic-responsive strategies.

The result of this chapter is the combination of the current isolated vehicle-actuated strategy when there is no congestion in the network and a coordinated fixed-time strategy so that a green wave is created along the corridor and the congestion is dissipated.

The idea of this top-level controller is that it fits seamlessly within the Network Management System of the municipality. For that, scenarios are created for situations in which local
intersections or the corridor as a whole are congested, with the use of travel times as the trigger to coordinate the whole corridor with the FT strategy, and the delays as the trigger at the local intersections. The whole strategy has been detailed in Chapter 3.

Could this traffic signal control strategy be able to improve the performance of the default strategy in a real study case in the Knowledge quarter in the Zuidas district for the year 2030?

The proposed controller has been tested in a simulation environment of the Zuidas district for the year 2030 during the evening peak. The coordinated stream corresponds to the streets De Boelelaan and Amstelveenseweg in the direction Zuidas-A10. The results from the simulation show that the controller is indeed able to improve the base scenario situation.

The average speed is increased in the coordinated corridor by 28.5% during the evening peak, reaching 20.34 km/h and fulfilling the municipality desires of average speed for the Plus Network Auto. The delays at the intersections are reduced by a total of 11.60% compared to the base scenario, and only in the case of intersection 689 (Amstelveenseweg - A10 Zuid Buitenring) the average delay is higher than with the VA controller. The delays for the coordinated streams of the intersections are reduced between 20% and 90%. In terms of public transport performance, the delays for the trams are fairly reduced, while the bus delays slightly increase. Overall, the total lost time for the public transport modes is reduced by 0.27%.

However, the FT controller gives even a better performance than the proposed controller in terms of average speed (increase of 36.5% compared to the VA controller) and average delays (reduced by 14.92% compared to the VA controller). Thus, this is the controller with the best performance during the evening peak.

5.2 Recommendations and future research

This section summarizes the recommendations that have been issued throughout the whole study.

Proactive measure to trigger the change of controller strategy

This study makes use of a reactive measure to trigger the change between the VA controller and the FT controller. The travel time measurements are collected in the main corridor and averaged every 5 minutes. This means that some of the measurements are almost 5 minutes old at the time of activating the change of strategy, so the traffic demand and hence the travel time can be completely different by then. Thus, a proactive measure that predicts what the travel time will be in the future seems a better choice.
In his doctoral thesis, Liu (2008) develops a neural network based traffic flow model for urban route travel time prediction. The approach is an hybrid of data-driven and model-based approaches, with the traffic control strategy and traffic demand as the input. Travel time collection systems provide only arrival travel times, this is, the travel time when the vehicle reaches the second measuring point. However, departure travel times are far more interesting, which is achieved with travel time prediction. Further studies could include this travel time prediction model in order to anticipate the congestion of the main corridor and trigger the new traffic control strategy.

Apart from a proactive measure that predicts the travel time, a method that predicts the delays could be used to estimate the future congestion. In his master thesis, van Eijk (2014) proposes the use of Vehicle Route Guidance Systems to obtain the intended routes and destinations of the vehicles. These systems can be used to obtain the future location of the vehicle in the local network and predict the traffic delays for each stream taking into account the signal control strategy that is in place. The proposed strategy evaluates the future expected delays for different strategies (VA and FT) and selects the one with the lowest total delay. This controller was tested in a small simple network with positive results. Thus, it could be interesting to evaluate the controller for a big and complex model such as the one from this study.

Improvement of the Coordinated Signal Control Strategy

For the purpose of this study, a fixed-time coordinated controller has been used in order to prioritize the vehicle flow in the main corridor when congestion is detected by means of the average speed. However, this strategy is rather simple and more effective and complex solutions can be put in place. Some of the problems the fixed-time controller faces is the lack of adaptation to changing demands, poor performance under saturated conditions or the inability to give priority to certain modes of transport. None of the signal controller variables (stage specification, split, cycle time or offset) can be modified throughout its operation. Thus, this creates a very rigid traffic operation where the green time is not always allocated where it is most needed.

New strategies with more complex algorithms would be expected to provide better performances in terms of total delay. Specially those controllers who can handle situations under saturated conditions should be studied carefully and applied in the same case study. In Chapter 2, several control strategies were analyzed to see their potential benefits for the proposed network. As an outcome, the TUC controller was deemed feasible for the characteristics of the traffic demand and network. According to (Diakaki et al., 2001), this controller can give considerable reductions in total travel time, total time spent and total fuel consumption when compared to a fixed-time controller, with bigger improvements for higher-saturation scenarios. Thus, further research should include the results of using such
controller on its own, or in combination with the current VA controller. Following this, a study of the IN-TUC controller could be performed, which consists of the TUC controller for the urban signalized intersections complemented with the study of the ramp metering control system ALINEA for the on-ramps to the A10 and create an integrated traffic control strategy.

**Incorporation of the highway A-10 in the simulation model**

The microsimulation model that has been used in this study case includes all the local streets of the Zuidas district, but does not incorporate the highway A-10 under the assumption that it will not affect the management of the network. However, it is possible that the increased demand in the highway and its new layout for the year 2030 may lead to congestion in some cases, and even possible spillbacks into the local network. Thus, it is recommended that the highway is included in the model to evaluate its potential effects on the network and the proposed controller in the study. The addition of the A10 would be a necessary requirement to study the effects of the IN-TUC controller, as it includes the ramp metering control system.

**Test of the controller for the AM peak and in other areas of the city**

The proposed controller has been tested in a study case in the streets De Boelelaan and Amstelveenseweg during the evening peak. As it was stated during the results section, the coordinated FT controller option was the one that achieved the best results in terms of average speed in the main corridor and average delay at the local intersections. Thus, this controller should be the chosen one during the whole evening peak. A longer period should be considered before the start of the evening peak to detect when the optimal change between the strategies should take place.

Apart from this, the study should be replicated for the morning peak period, with a coordination in the same corridor but different direction. In this study, the major vehicle flow goes from the exit of the A10 towards the center of Zuidas. Results should be analyzed to see whether the expected results are as positive as with the study that has been carried out.

Further studies should be carried out in other parts of the city of Amsterdam to test its possible improvement with the current situation. This controller is mostly indicated for the urban roads that are part of the Plus Network Auto of the city of Amsterdam. These roads serve as the main channel between the center of the city and the A10, and a steady and seamless flow would be a benefit for the urban network as a whole.
References


References


SWOV (2008). SWOV Fact Sheet: Road safety effects of Dynamic Route Information Panels (DRIPs).


Vialis (2016). Simulatie RVB.


Appendix A

Traffic management system architecture
Appendix B

Maps
MoCo Routes
Traffic intensity in Zuidas West for the PM peak. 2015
Traffic intensity in Zuidas West for the PM peak. 2030
V/C ratios of the intersections in Zuidas for the PM peak. 2015
Legend
Kruispuntbelasting
Onbelast
Kruispuntbelasting in toes
Bekleed
Onbekleed
Zuidas 2015acorr
kruispuntbelasting avondspits 2015 maximum
VMA 5.1
Voor voetverkeer en fietsers
In beweging
Auto verkeer
V/C ratios of the intersections in Zuidas for the PM peak.
2030