MASTER

Prioritizing areas for the iomplementation of an adaptive traffic management system within the municipality of Copenhagen

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Prioritizing areas for the implementation of an adaptive traffic management system within the municipality of Copenhagen

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TU/e KØBENHAVNS KOMMUNE PEEK Imtech

Content

Preface

This document is the final report of the multi criteria evaluation I performed within the scope of my graduation in the master Construction Management and Engineering at the University of Eindhoven. The research took place from February till June 2013 at the municipality of Copenhagen.

About one and a half year ago a newspaper article got my interest about a new intelligent traffic management system in the city of Copenhagen. After reading many articles my intention was to perform a research in the field of Smart Mobility within urban areas.

What I liked most about my research was the interviews with experts from Peek traffic, and to notice the different views from the several departments within the municipality of Copenhagen Every interviewee was expert in some field, and my goal was to gain a lot of knowledge. This knowledge would be required to get an overall understanding, and to perform a good research.

The first semester of the school year 2012/2013, I followed an exchange semester at the Danish Technical University(DTU) in Lynby. Already before going abroad, I was thinking about the possibilities of performing my graduation thesis in Denmark (Copenhagen). In this period from September till December 2012, I followed 3 courses (in total 20ects) and had enough time to investigate the possibilities for my graduation in Copenhagen. The possibilities were to perform the final thesis at the university in Lyngby (DTU), a company or a public authority.

Besides the 3 courses I took in college, I had some time to work. I came in contact with the general manager of Peek traffic Denmark and agreed on working 1 day in the week at the office. Peek traffic Denmark belongs to the Imtech concern, and started early 2012 in Denmark. Peek is a European company that is located in several countries and that offers solutions for mobility issues of today and the future. Currently, Peek carries out several big projects for the municipality of Copenhagen. The high-tech traffic management solutions from Peek in Copenhagen represent an contribution to making the Danish capital completely CO2 neutral by 2025. While working for Peek, I came in contact with several experts within the company. During this period, I read a lot about the different projects and the different intelligent traffic systems(ITS). I also had several meetings with the general manager of the Traffic design department (Technical and Environmental department) of the municipality of Copenhagen where we discussed interesting topics to investigate. We decided to focus on adaptive traffic management systems within the municipality of Copenhagen.

I also would like to take this opportunity to thank a few people. First of all I would like to thank Kees den Hollander for his support during my stay in Denmark and giving me the opportunities to perform my thesis in Denmark. Along with Kees, I would like to thank Steffen Rasmussen and Anders Madsen for assisting and giving feedback to my work. I would also like to thank my supervisor Peter van der Waerden for his comments and advice during my research.

Management summary

In recent years, governments are facing the challenges of climate change. Traffic is responsible for several environmental problems in urban areas. Traffic congestion poses a challenge for all large and growing urban areas.

Especially Carbon Dioxide has become an increasingly serious problem due to its negative impacts on the climate change. Because of this, the municipality of Copenhagen wants to become completely CO2 neutral by 2025. Within the area of mobility, budgets have been set for the coming years. A part of this budget is reserved for the implementation of ITS solutions in Copenhagen, which among other things will contribute to a CO2 reduction.

One of the solutions is to implement adaptive traffic management systems (ATMS) in several areas of the city. One attraction of ATMS is the potential to achieve a better performance off an existing traffic network infrastructure without having to build expensive extra lanes or change the physical geography of a city's street network.

The main objective of this thesis is to identify the most important criteria for implementing an ATMS and to rank the most suitable areas. As each area has its own characteristics and unique elements, it is important to know which criteria (or characteristics) are seen as the most important while considering implementation of an ATMS in the area. Therefor a pair-wise comparison was constructed and completed by six ATMS experts. Twelve criteria (or characteristics) were evaluated in this pair-wise comparison. The presence of changing traffic conditions is considered as the most important characteristic.

The alternatives (or areas) are chosen by a group of experts and are characterized by using an online questionnaire. In this questionnaire the five alternatives were presented and 26 experts gave their judgements for each criterion for each alternative. The standardized average values (or scores) were used to calculate the overall dominance score for each alternative. The final result is a ranking of the five alternatives.

Central station gets the highest score, and therefore is the most preferred alternative for implementing an ATMS. Nørreport area has nearly the same score as Central station and is ranked as number two. The next step for the municipality of Copenhagen should be to test the Central station and Nørreport area in a simulation environment (e.g. Vissum) and compare the performance of the traffic network with the current situation.

1 Introduction

1.1 General introduction

More than half of the world's population lives in cities, and that number is only increasing. Urban residents are responsible for 75% of the emissions of the greenhouse gas Carbon Dioxide CO_2 worldwide. Road transport is responsible for about one fifth of the EU's emissions of the CO_2 emission(European Cyclist' Federation).

In addition to this, traffic is responsible for several environmental problems in urban areas. First of all, deteriorating of air quality by traffic is mainly caused by emissions of air pollutants. Secondly, acidification of the natural environment is caused by the emission of NO_x and Sulfur Dioxide (SO_2). Thirdly, traffic is a major source of noise pollution in urban areas.

The most problem concerns the emission of the greenhouse gas Carbon Dioxide CO_2, which contributes to a negative climate change. Because of the adverse effects of CO_2, the municipality of Copenhagen wants to be completely CO_2 neutral by 2025. In August 2009, a unanimous city council passed the Copenhagen Climate Plan. This plan is summarized under the name: CPH 2025 Climate plan, and includes 50 specific initiatives which should help Copenhagen to achieve the target of a 20 percent reduction of CO_2 from 2005 to 2015 and carbon neutrality by 2025.

The goal of a 20% reduction of CO_2 by 2015 was already achieved in 2011, when CO_2 emissions were reduced by 21% compared to 2005. In order to become carbon neutral by 2025, the city must use less energy than it does today, and at the same time change energy production to green energy. In addition, a surplus of green energy must be produced to offset the emissions that will continue to be generated by for example transport.

The CPH 2025 Climate Plan is a holistic plan as well as a collection of specific goals and initiatives within four areas – **energy consumption, energy production, mobility** and the **city administration**.

Figure 1 gives an overview of the distribution of CO_2 reduction in 2025 caused by the 50 initiatives of the climate plan in the different areas. As shown figure, 11% of the CO_2 reductions should be achieved by making the traffic greener.

At present, traffic is responsible for 21% of the city's overall CO_2 emissions, but it is intended that this will be reduced to **11%** by 2025. The allocation of the reduction of CO_2 within the area of mobility can be seen in figure 2. In total 135,000 tons of CO_2 should be reduced by several initiatives in the four fields of mobility.

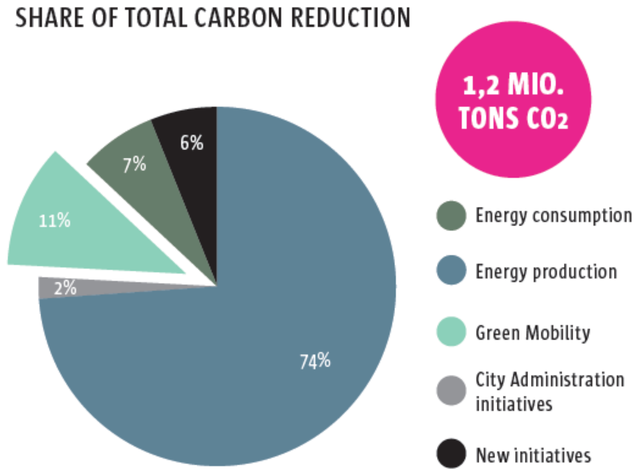


Figure 1: Share of total carbon reduction in 2025 (CPH 2025 Climate plan, 2001)

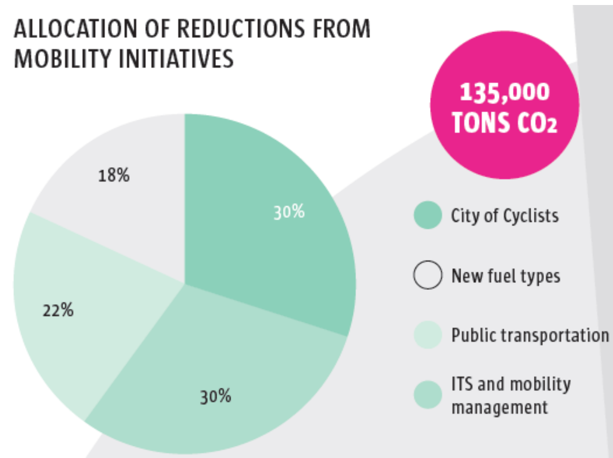


Figure 2: Share of total carbon reduction in 2025 (CPH 2025 Climate plan, 2001)

Reduction will be achieved through further improvement of the bicycle infrastructure, better public transport as well as through implementing a congestion charge for road transport in the city. Also, the municipality's vehicle fleet will be replaced with hydrogen cars and electric cars. The aim is to achieve optimal traffic flow with as few CO2 emissions as possible. Copenhageners are encouraged to travel by bike, walk or take public transport when getting around in the city.

Over the past years, Intelligent Transportation Systems (ITS) have been used increasingly to manage and control road traffic in many cities. ITS can reduce traffic emissions through a better demand management and through better traffic flow. With ITS there are many possibilities to improve the traffic flows within the existing infrastructure which will result in a CO2 reduction. ITS and mobility management should account for 30% of the total reduction of CO2 (approximately 40.500 TONS) within the context of mobility in Copenhagen. An Intelligent Transportation System (ITS) involves a much closer interaction between all of its components: cars, pedestrians, public transportation, and traffic management systems.

In urban areas like Copenhagen, policy objectives and measures may conflict with each other and themselves. For example, optimal accessibility and air quality are difficult to combine, as well as optimal flow for cars and priority for public transport, cyclists and pedestrians. Translating policy objectives into an operational system is very complex given the dynamic nature of traffic in urban areas. To cope with this complexity, local adaptive control systems (an example of an ITS system) are necessary to achieve a balance between the different modes of travelling. By means of rapid communication technology, these systems can interact with the conditions in the network and automatically switch to the optimal control strategy for the network based on the given political objectives/priorities.

This optimization can decrease the number of stops of buses, heavy trucks, and cars which results in less accelerating and decelerating. These actions are most harmful for fuel consumption and emissions. A study done to investigate energy-efficient management and control for urban networks outlines the most important waste factors (Jaap Vreeswijk; 2009). Inefficient deceleration and/or lack of anticipation (and thus stops) accounts for 22% of all fuel unnecessarily wasted in traffic. Congestion (also stops) is responsible for another 15%, whereas speedy driving, inefficient traffic light control (again stops), and construction sites and/or traffic accident each account for 11%. An adaptive traffic management system (ATMS) can substantially decrease several waste factors in a dense urban area, and therefore might be a good solution in some areas in Copenhagen. In recent years ATMS are becoming more effective and popular, mainly by improved communication and detection technologies.

At this moment, the Traffic design department of the municipality of Copenhagen is testing an real time ATMS which uses a 'policy based' adaptive traffic control system (see appendix A). This system (named Imflow) c – for example by promoting climate friendly solutions such as walking, cycling, and public transport. A preferred vehicle such as a bus or a cyclist may be located and identified on the road. With that information, the traffic lights in that area may be changed to give priority to these green modes of transport. This is the first system of that kind that will be implemented in the municipality of Copenhagen.

1.2 Structure of the thesis

This thesis contains 7 chapters, and the introduction makes the first chapter of this thesis. Chapter 2 describes the research framework. Chapter 3 is a literature research and the theoretical background on this research topic. Chapter 4 gives describes the research area. In chapter 5, a pairwise comparison is established based on the most important criteria for an ATMS. In chapter 6, the data collection will be described including the selection of alternatives and the actual execution of the questionnaire. The conclusions and recommendations can be found in chapter 7.

2 Research framework

2.1 Problem Statement

Carbon Dioxide has become an increasingly serious problem due to its negative impacts on the climate change. Because of this, the municipality of Copenhagen wants to become completely CO2 neutral by 2025. Within the area of mobility, budgets have been set for the coming years. A part of this budget is reserved for the implementation of ITS solutions in Copenhagen, which among other things will contribute to a CO2 reduction.

Alongside the limited budget, the municipality has to deal with the 'old' fixed time traffic technologies in the city and the limited possibilities for expansion of the infrastructure. Because of that, the municipality aims to optimize the current traffic network. One of the solutions is to implement adaptive traffic management systems (ATMS) in several areas of the city. One attraction of ATMS is the potential to achieve a better performance off an existing traffic network infrastructure without having to build expensive extra lanes or change the physical geography of a city's street network.

But one of the most difficult challenges is to find out which areas are (most) suitable for implementing an adaptive traffic management system (ATMS). This level of suitability depends on several criteria with various importance's that characterize an area. Obtaining this knowledge is the first step in selecting areas for implementing these ATM-systems.

2.2 Research aim/objective

The main objective of this research is to show a ranking of areas that are (most) suitable for implementing an adaptive traffic control systems within the municipality of Copenhagen.

In order to achieve this main objective, the following goals are formulated:

• The first goal is to provide a clear understanding on today's traffic light control, research area, and in particular adaptive traffic management systems. This will give the reader a sound basis for understanding the key component in this research;

• The second goal is to construct a list of most important criteria for implementing an ATMS, and set the weights/priorities of each criterion;

• The third goal is to characterize the different (relevant) areas within the municipality of Copenhagen by means of the chosen criteria;

• The final goal is to deliver a method by which municipalities can compare the suitability of areas for implementing an ATMS.

The end result of this research by applying a Multi-Criteria Evaluation will show a ranking of areas that are (most) suitable for implementing an adaptive traffic control systems within the municipality of Copenhagen. As budget is limited, this insight is of major importance to take decisions on investing in ATMS for some areas in the city.

2.3 Scope

This research focuses on the application of 'policy based' adaptive traffic control systems within the area of Copenhagen to improve the flow of transport modes, such as public traffic, pedestrians, cars and cyclists.

The payoff of these systems depends on several criteria, which will be explicit researched. However the information flows within the area of urban traffic are very extensive. To make the research feasible it will be limited by some boundary conditions:

- No attention is paid to the impact of the ATM-system on the complete network;
- Some human factors, such as behaviour adaption are not considered (e.g. number of people that switch to use PT/bicycle instead of taking the car);
- Increase of usage of cars due to improvement of average waiting time/average speed is not taken into account;
- Reduction of noise pollution is not taken into account.
- The exact payoff of an ATMS in an area is not taken into account. This requires extensive and expensive research.

2.4 Research design

To achieve the main goal, this thesis is composed from four parts (see figure 3). Each part contains a number of steps are described in this chapter.

Part I

To obtain an extensive understanding about ATMS, a literature study took place covering several articles and case studies. Evaluating a decision requires that both its benefits and its costs are considered. Because of that the several cost components and operational benefits of ATMS through years will be defined. The information required for the research was collected from scientific journals, reports, books and relevant internet websites. This first part is described in Chapter 3 and 4 and contains the following steps:

- Evaluate various case studies;
- Define all requirements and cost components for implementation of an ATMS;
- Define all benefits that can be obtained from an ATMS;
- Gain knowledge and understanding of the research area.

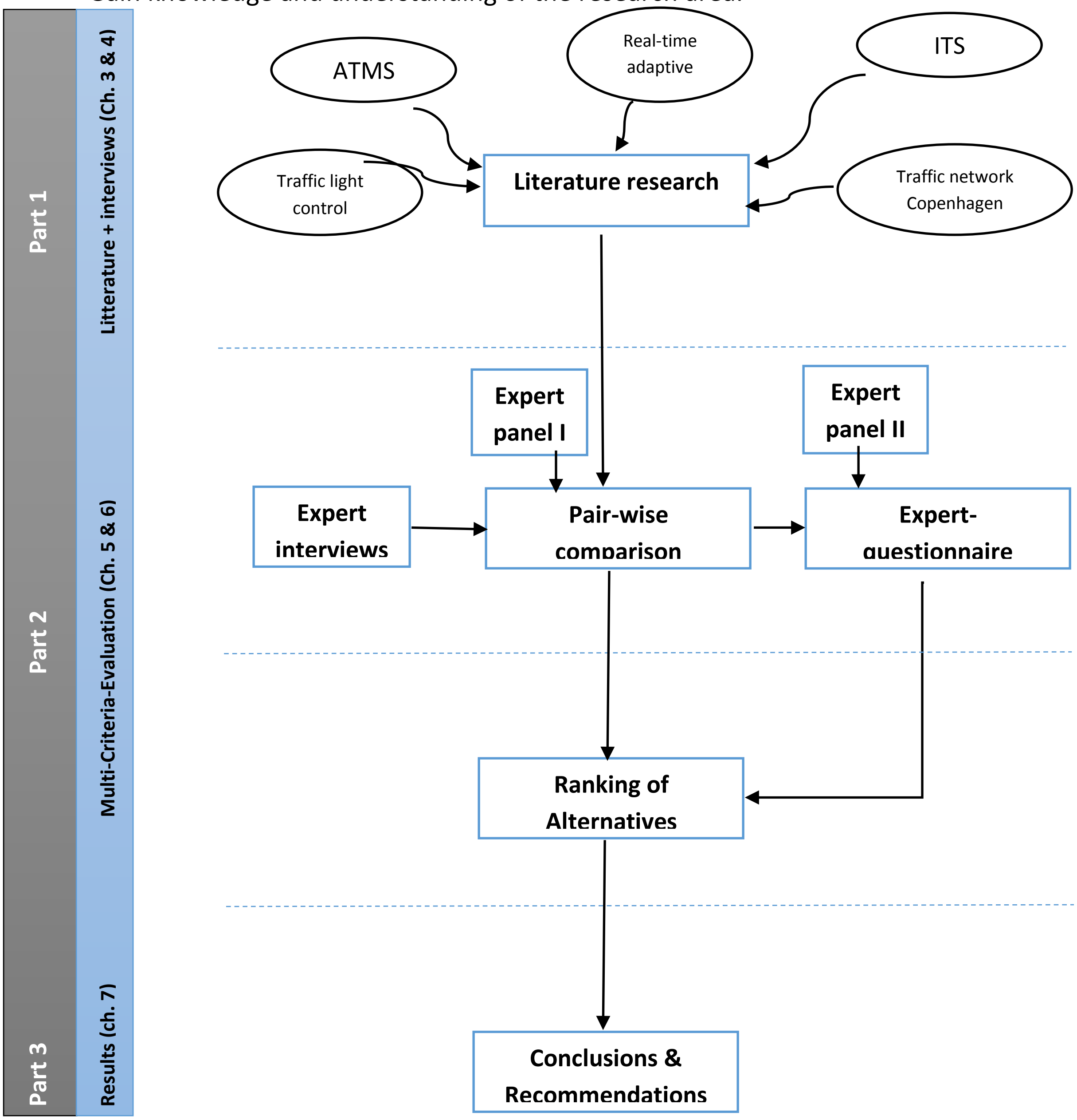


Figure 3: Research design

Part 2

There are several scientifically research methods available. After extensive exploration of qualitative and quantitative methods, the decision is made to use a Multi-Criteria Evaluation (MCE). The MCE is a qualitative research method, used for comparing several independent alternatives based on various criteria. The complexity is caused by the multiplicity of criteria that are important in the strategic choice: ranking the areas for implementing an ATMS. A multi-criteria evaluation approach is suitable when an intuitive approach is not appropriate, for example because the decision-maker(s) feel the decision is too large and complex to handle intuitively, because it involves multiple objectives, or multiple stakeholders.

This research uses the application of the Analytic Hierarchy Process (AHP), a specific research method of the Multi-Criteria Decision Analysis (MCDA). The AHP method makes it possible to decompose the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analysed independently.

The next step after obtaining all necessary knowledge in Part I is to define and select the various criteria. The composition of the entire set of criteria that play a role in the strategic choice between alternatives, is examined by in-depth **interviews** with experts in the field of ATMS.

To compare areas with the AHP method, it is important to know which criteria are more important. One of the major strengths of the AHP is the use of pair-wise comparisons. In this research the **pair-wise comparison** is applied to obtain the weights of the elements. **Expert panel I** (see figure 3) consisting of experienced consultant in the field of ATMS is used for the completion of the pair-wise comparison. This method results in a weight for each criterion.

The next important step in a AHP is defining the alternatives (or choice-possibilities). The alternatives represent the 'different possibilities to solve the problem'. In this study, the alternatives are the different areas in Copenhagen and will be selected in a group session with **expert panel II**. Expert panel II consist of several decision makers from different departments within the municipality of Copenhagen.

The criteria applied in a MCE serve as a tool to test the various decision alternatives from a particular point of view. After defining the areas, an online **questionnaire** is constructed to characterize the alternatives. The characterization of the areas is conducted by experts from 3 different departments of the municipality of Copenhagen. This characterization includes all criteria selected in the previous step.

The final step is to rank the chosen alternatives by using the characterization of the alternatives and the obtained weights. Saaty (1990) proposes an simple weighting and summing process in the AHP to calculate the overall score for each alternative. Another method with a more sound theoretical basis, is the overall dominance method. In this research we will use this method to calculate the quantitative dominance score for each alternative. The quantitative dominance overall scores will be used to rank the alternatives. The second part is described in Chapter 5 and 6 and contains the following steps:

- Select the set of criteria and rate the criteria by using pair-wise comparison (AHP);
- Select the different alternatives with use of experts input (AHP);
- Set-up an online questionnaire for experts to characterize the selected alternatives;
- Rank the various areas by calculating the overall dominance scores.

Part 3

The third part and last part of the research contains the conclusions and recommendations. The results from part 2 will be discussed and the research objective is evaluated. Also recommendations concerning further research are described.

2.5 Research relevance

This research is relevant for the Faculty of The Built Environment as well as the master Construction Management and Engineering. The central topic in the graduation of the CME-master program is: 'Increasing the sustainability in urban areas and achieving energy neutrality'. One of the sub-topics is: 'Research into energy restriction on mobility of people and goods'.

The energy consumption in urban districts, related to traffic and mobility, consists of almost 30 % of the total of energy use in the urban environment. Recent years the topic of smarter mobility is increasing popularity and there will be increasing interest in energy management, related to 'urban traffic' in the future.

Eindhoven University of Technology sees many opportunities to use technology for solving mobility problems. Technology can be used to solve the negative effects of mobility. Traditionally, the TU/e has a lot of expertise in areas including automotive technology, logistics, planning and ICT/ embedded systems. This is why Smart Mobility has been designated as one of the three strategic areas of the university (Peels et al, 2011). This research will focus on the mobility & traffic area.

Smart Mobility also has a close relation with reduction of energy consumption in urban areas, which has been one of the main pillars in this master program. By optimization of traffic in dense urban areas like Copenhagen, energy consumption and the CO_2 footprint will be decreased. This contributes to a more sustainable environment and is embraced by the Copenhagen Climate Plan.

This research may contribute in developing a decision making tool for municipalities who are considering to implement an adaptive traffic management system. Insight in the various criteria of ATMS is crucial for making decisions. This research is also interesting for the KENWIB, Kenniscluster energieneutraal wonen in Brainport program of chair holder prof. dr.ir. W.F. Schaefer. Adaptive traffic management systems are a hot topic at this moment and developments in recent years went fast. The information from this research can be used for identical problems in other municipalities.

3 Theoretical background

3.1 Intelligent traffic systems and mobility management

Intelligent transport systems (ITS) are advanced applications which, without embodying intelligence as such, aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated, and 'smarter' use of transport networks (DIRECTIVE 2010/40/EU).

Interest in ITS comes from the problems caused by traffic congestion and the development of information technology for simulation, real-time control, and communications networks. Traffic congestion has been increasing worldwide as a result of increased motorization, urbanization, population growth, and changes in population density. Congestion reduces efficiency of transportation infrastructure and increases travel time, air pollution, and fuel consumption.

ITS involve a much closer interaction between all of its components: cars, pedestrians, public transportation, and traffic management systems.

Intelligent transport systems vary in technologies applied, including all types of communications in vehicles, between vehicles (car-to-car), and between vehicles and fixed locations (car-to-infrastructure). Applications vary from basic management systems such as car navigation; traffic signal control systems; variable message signs; automated number plate recognition or speed cameras, and to more advanced applications such as parking guidance and information systems; weather information; and so on. These systems are being developed to increase the efficiency of the actual systems and to contribute to a cleaner, safer and more efficient transport system, especially in urban areas.

Technology has been developed very rapidly in recent years, creating new opportunities for traffic planning and traffic management which can improve traffic flow and reduce CO_2 emissions. Through traffic planning and traffic management, the City of Copenhagen will reduce carbon emissions from traffic by optimizing conditions for bicycles, busses and cars. Travelling time on busses will be cut by 10% and their frequency improved by 20%.

The city has set the following objectives of the operation and maintenance of ITS and traffic signals: ‘Operation and maintenance of ITS and traffic signals must be high standard and work effectively; Technology choices must be ‘’green’’ and have a long term perspective – it should support the municipality’s vision for green growth and green mobility; and the system must be flexible towards concrete political traffic priorities – for example promote climate friendly solutions such as walking, cycling and public transport’.

One of the ITS-applications which gained a lot of popularity in recent years and meets the municipality's objectives best concerns: adaptive traffic management systems (ATMS). An adaptive system would be able to respond quickly to the changes in the traffic/road conditions, modifying signal policies, and gives priority to different road users. Where the adaptive approach really scores in comparison to traditional 'fixed-time' systems is in dense urban networks with a high level of traffic and congestion. The reward comes from travel times savings for vehicles, whether they are cars, buses or trucks, and the wider economic advantages that flow from this. Adaptive solutions are particularly effective where traffic patterns are evolving or likely to be subject to unpredictable demands.

A crucial component in an ATMS is the traffic light controller. Currently, all intersections within the municipality of Copenhagen use old fixed-time traffic light controllers. The step from fixed-time controlled lights to adaptive traffic flow controlled lights will reduce waiting time and increase the traffic flow.

3.2 Traffic light control and coordination

Traffic lights block people from reaching their destination faster, they make cars burn more fuel, and they force them to brake and accelerate several times on their trip.

But beyond these disadvantages, people also have to accept that traffic lights are playing a key role in our infrastructure networks, not only for the safety of traffic, but also for pedestrians who want to cross a road without putting their life to risk. Traffic lights include complicated control and coordination to ensure that the traffic moves smoothly and safely.

Although in some regions authorities and various companies have started testing innovative traffic light control systems, there are usually two different modes adopted by most nations on the planet: fixed time and dynamic control. Besides these two modes, adaptive control , which can be seen as a form of dynamic control, gained much popularity recently.

3.2.1 Fixed time control

In traffic control, simple and old forms of signal controllers are what are known as electro-mechanical signal controllers. A fixed time traffic light control system is an old-fashioned way in which traffic lights are configured to turn on the green colour after a given period of time, usually between 30 and 120 seconds, but this may very well vary depending on traffic values and region.

A fixed time controller uses dial timers that have fixed signalized intersection time plans. Since a dial timer has only one signalized intersection time plan, it can control phases at a signalized intersection in only one way. Time plans for each intersection are pre-calculated or pre-determined signal plans. So there is a fixed cycle time and a given order of green phases. The green-light duration serving each direction is fixed, no matter how the traffic conditions changes. Disadvantages of this system are pretty clear, as queues can be resolved in less time than given by the fixed time controller. And traffic lights can switch to green light while there is no queue at all. This type of old-fashion control causes much irritation among road users. Furthermore, as traffic patterns change with the passage of time, fixed time plans become outdated. This requires the area to be resurveyed, and new signal timing plans calculated every few years. The problems of most fixed-time systems make it clear that a more responsive approach to changing traffic conditions is needed.

3.2.2 Dynamic time control (semi-adaptive control)

Dynamic traffic light control systems are programmed to adjust their timing and phasing to meet changing traffic conditions. These control systems run on top of existing traffic light controllers, and require detection to measure traffic conditions and a communication network. These control systems are more appropriate for the crowded traffic we are facing in urban areas. The system adjusts signal phasing and timing to minimize the total delay on each intersection. Dynamic traffic light systems can also create green waves by synchronizing the offset times for the different following intersections, to maintain the flow. It is also normal to alter the control strategy of a traffic light based on the time of the day and the day of the week. With this feature the intersection can better handle the morning and afternoon rush hour, where there is an increased amount of traffic from different directions.

As compared to fixed time control systems, the foundation of a dynamic system is actually a detector, which is nothing more than a simple device that communicates with the traffic light and informs it about traffic conditions in real time. The sensors inform whether vehicles or other road users are present, to adjust signal timing and phasing within the limits set by the controllers programming. It can give more time to an intersection approach that is experiencing heavy traffic, or shorten or even skip a phase that has little or no traffic waiting for a green light. The green light for one approach can also be terminated if the gap-time between two vehicles is longer than the pre-set threshold, indicating the presence of non-continuous traffic flow.

There is considerable similarity between the operations of a responsive signal system and an adaptive traffic control system. The main difference between the two is that adaptive systems typically do not select from a menu of signal timing plans; they make more complex adjustments. However, most ‘adaptive systems’ still operate in a responsive mode in which they collect data, calculate what to do and then implement timing changes a short time later.

An adaptive system can therefore be seen as an advanced form of dynamic time control, where changes instantaneously will be implemented based upon real-time demand.

3.2.3 Adaptive time control (real-time adaptive)

Adaptive time control does not use any pre-calculated or pre-determined signal plans. It is more based on self-organized red and green phases. So, there is no fixed cycle time or a given order of green phases. The green phases are determined by the actual queue lengths, if no more vehicles have to be served, the light turns into red and other directions will be served.

Traffic lights that act locally real-time can improve traffic globally. By reducing unnecessary stopping and starting of traffic, congestion will be minimized, emissions, travel time and fuel consumption will be reduced. Adaptive systems can save money. By measuring vehicle inflow and outflow through intersections as it occurs and coordinating lights with only their nearest intersections, network optimization can take place. If the systems knows what is coming towards an intersection, it is better able to deal with or anticipate incoming traffic and do an optimization. These control systems strive to get the most out of the current system, by reacting immediately to current traffic conditions.

The traffic flow controls the traffic light rather than the other way around. This system makes use of two sensors at each intersection: One measures incoming flow, and one measures outgoing flow. Each intersection communicates with every neighbouring intersection, such that the next intersection knows how many vehicles are coming through. The whole point of these kinds of adaptive systems is to avoid stopping incoming platoon and maintain the flow of vehicles. Maintaining the flows decreases collision and accelerating and braking and accelerating and braking contribute significantly to emissions and fuel consumption. Adaptive systems encourage maintaining speed within the limits to meet green lights. The gap between the platoons of cars gives opportunities to serve flows in other directions.

3.2.4 Policy based adaptive control

The latest generation of adaptive control is the policy based adaptive control, which uses real-time information in combination with a set of policies for the different modes of traffic to optimize the network. Policy based adaptive control supports multi-criteria optimization at network, route, and intersection levels. Policy objectives can be defined for each level, with local policy also being awarded a certain 'weight'. This introduces balance in prioritizing the various traffic streams, such as slow-moving traffic, public transport, car traffic, heavy goods traffic and emergency services. So, the user can set the importance of the different transport modes, and also have the possibility to change these policies.

The whole set of policies represent a scenario. A policy based adaptive control system tracks all vehicles within the networks and predicts the arrival and departure of public transport vehicles at signalized intersections and stops. A public transport vehicle receives conditional priority based on the configured policies and its current status. Conditional priority means for example that late buses are given priority and early buses are not. It is also possible to give absolute priority to public transport vehicles, which simple means that all public transport vehicles will receive full, active, unconditional priority. A policy based adaptive control system can also provide information to pedestrians and cyclist about their remaining waiting time. Figure 4 shows an overview of the development of traffic light control systems discussed so far in this paragraph.

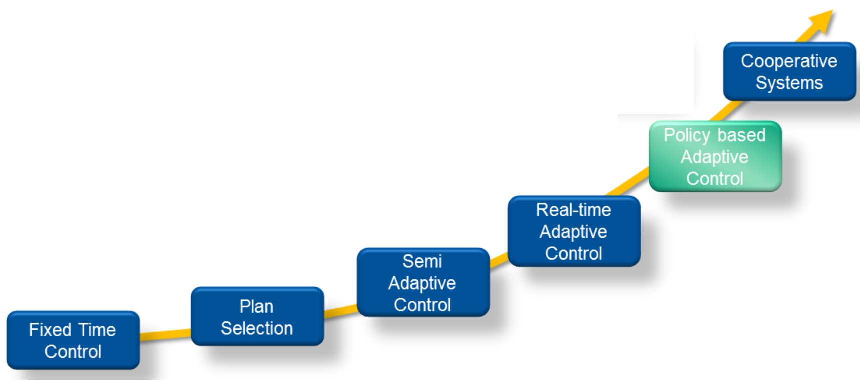


Figure 4: Overview of development of traffic light control systems (Imflow, 2012)

The latest development in traffic light control systems is the development of cooperative systems.

3.2.5 Cooperative systems

Cooperative systems are the newest development in the traffic and transport sector. These systems make it possible for vehicles to communicate with other vehicles (V2V) and with traffic management systems (V2I or I2V). With these new systems, information will be available about the locations of other vehicles and the surroundings. It is initially developed to improve safety but can also lead to a faster and cleaner traffic.

Because every vehicle broadcasts its own speed, location and direction, it is easier to avoid potential collisions. V2V is often discussed as a potential component of future "driverless cars", but it can also be helpful in human-driven cars. The received data from other vehicles can be used to automatically take action, such s braking or speeding up.

The vehicle to infrastructure (V2I or I2V) can be used to communicate with the surroundings, such as street signals, signs, and traffic lights. This allows cars to react automatically to red lights, school zones, maximum speed limits, and green waves. V2I information can be used to send detailed information about vehicles characters such as vehicle type, weight/load, and direction. This information can be used by traffic signal controllers to optimize the green times settings for different approaches. Car drivers in their turn can receive real-time traffic information from signal controllers, such as time-to-red (TTR) or time-to-green (TTG). The in-vehicle system compares this information with an estimated time-to-travel to an intersection. The system can inform the driver to prepare a stop, and therefore smoothly decrease decelerate or to maintain or accelerate. Unnecessary braking and acceleration will be reduced and traffic management at signalized intersections will greatly improve.

The cooperative system also aim to avoid traffic accidents by notifying drivers of the information obtained through communications between the vehicles and sensors installed on the road, or among vehicles. I2V will significantly improve traffic control and safety via effective and reliable transmission of data fully adapted to the local situation of the vehicle.

These systems are especially valuable in regions of dense traffic, which are characterized by increased accidents and frequent traffic jams. The new generation of Vehicle Infrastructure Cooperative Systems uses direct communication between vehicles and pedestrians or among vehicles for continuous information exchange in order to prevent frontal collision accidents between vehicles and pedestrians at intersections difficult for drivers to see. These systems are still in development and are tested in several countries in Europe.

Cooperative systems should be seen as an addition to existing systems like traffic lights, vehicle sensors and the internet.

In the next chapter we will outline the state of the art of available adaptive systems.

3.3 Adaptive traffic management systems

There are several adaptive systems in the market. Each system has its own installation and maintenance costs. In an effort to gain a greater understanding of the cost components of adaptive technology, field research is done to identify these components. This chapter focuses on the most common or well-known adaptive systems and which are installed and running at many locations worldwide.

The goal of this field research was to identify general installation and maintenance costs of adaptive systems, and thereby understand the main costs components. The research 'Adaptive Traffic Control Systems in the United States' in 2009 and the updated summary and comparison in 2010, both by Selinger resulted in a comparison of seven specific adaptive technologies. These surveys give a good insight in the main costs components, maintenance costs and operational benefits of the several ATMS.

3.3.1 Cost components

Research by Selinger in 2009 on the cost, maintenance, and reliability of popular adaptive traffic control technologies showed a great variation in costs. Four adaptive systems (ACS-Lite, OPAC, SCOOT, SCATS) were investigated and based on information provided by 19 respondents. The overall average cost for an adaptive system was $55,000 per intersection. This cost includes an average cost of $20,000 for intersection upgrades to implement an adaptive system. An upgrade consists of upgrading controllers, installation of detectors and interconnection between the intersections.

There is not a good rule of thumb to estimate the costs per intersection for implementing adaptive systems. This is because both the costs per intersection for the various systems and per system can vary greatly. The research showed e.g. that the cost per intersection for implementing SCATS varies between $23.000 and $118.000. These great differences are caused by several variables (see below).

When examining system cost there are many variables to consider. There are the clear costs for system hardware and software, installation time, and upgrades to the intersections necessary to make the system work. These upgrades can include new detection. Especially when the intersection didn't use any detection in the old situation, new detection (loop, video and/or radar) can cover a significant part of the total cost. In other cases only an upgrade of the current loop detection is required. Some systems require advanced detection, while for some adaptive systems it is not a requirement. And there is also a variation in the number of detection necessary to make the various system works.

Other key cost components are interconnection between the controllers if not previously installed, controller upgrade and communication changes. The interconnection between the various controllers is crucial to make the adaptive system work. In some cases the interconnection is previously installed, but might contain old cables which are unsecure and therefore have to be replaced.

There is also a wide range of time required to install an adaptive system and fine tune it. The research by Matt Selinger in 2010 shows that there is no direct correlation between the number of intersections per system and the implementation time.

There are also other costs that are not so easy to identify. These costs can include licensing fees, costs for training, and digging activities.

The high variability in system costs was one of the concerning findings of the surveys of Selinger. It can be concluded that an estimation of adaptive system costs on a 'per intersection' basis not feasible/achievable.

3.3.2 Maintenance costs

The research showed no direct correlation between the basic system size and the installation and fine tuning effort. One of the key advantages of an adaptive system is that it can change signal timing to address demand, so that there is less involvement by engineering and technical staff to manage the system. This statement however does not hold upon the information provided by the survey. Some other components which come along with an adaptive system are the costs of training and ongoing maintenance.

Training:

Training cost is also one of the cost components of an adaptive system. This also shows one of the disadvantages of adaptive systems. Most systems are complex and require extensive training of staff of agencies. If agencies choose not to train their staff, they will be fully dependent on the vendor or consultants for making changes to the system or solving failures. This will lead to additional costs after implementing the system.

Ongoing maintenance:

Ongoing maintenance is also an important component to consider in the evaluation of the several adaptive systems. How much effort and money does it really cost to keep the system running smoothly?

One of the selling points for adaptive systems is that maintenance should be minimal since the system adjusts to traffic conditions, removing the need for periodic signal timing updates. It is important to have insight in the hours the systems take for maintenance per week. The average maintenance effort based on all systems investigated by Matt Selinger was 10 hours per week. The ongoing maintenance effort and costs is difficult to quantify beforehand. In recent years some newer technologies have merged in the industry, which in general show lower maintenance costs.

3.3.3 Reliability

When looking at the reliability of adaptive systems, researches by Matt Selinger and Curtis show that the newer systems are more reliable and have less down time of the system. The down time is the time that a system is not operational (offline). The survey shows that most systems operate with a least 90% up time. This value may be viewed as acceptable, however, 10% downtime still equates to about 2.5 hours of down time per day. When averaging the more reliable installation, the average downtime was 5%, which equates to more than 8 hours of offline time per week.

There are many factors that influence the reliability of an adaptive system. The factors that affect an adaptive system´s operational reliability are: Installation and Setup, Interface between Detection and Adaptive System, Detection Problems (Loop, Video, or other), Adaptive Software Issues, and Communication (Ethernet, Fiber, or other). Results from the research show that detection and communication are the main causes of reliability problems.

3.3.4 Operational benefits

There are several operation benefits that can be considered as a result of implementing an adaptive system. The operational goals are established before installation of the adaptive system and are extensively tested in a simulation environment (e.g. Vissum). The operational goals can be:

- Improving network travel time;
- Decreasing the number of stops;
- Decrease specific intersection delays;
- Minimizing queue lengths;
- Prioritizing public transport, cyclers, trucks;
- Increasing average speed;
- Improving travel time for certain routes in the network.

Installation of an ATMS also provides the municipality with valuable traffic management information. After implementing an ATMS in a specific network a huge variety of data will be available to the city. This traffic information can be: number of stops, number of cars on each link, CO_2 footprint, waiting time, queuing information.

It is clear that newer, more innovative technologies provide significantly better operational efficiency than the more traditional responsive adaptive systems. The survey of Selinger also showed sufficient evidence to show that real-time adaptive technology provides greater benefit than responsive adaptive approaches. So where is adaptive technology heading? It will continue to change and get better, and more and more systems will be developed that will operate with limited need for maintenance. The systems will be autonomous, and will be adapting to traffic in real-time on a second by second basis.

4 Research area

4.1 General info Municipality of Copenhagen

Copenhagen Municipality is the largest of the municipalities making up the city of Copenhagen(see figure 5). It is located at the center of Copenhagen and contains the old historic city. The municipality covers 91.3 km² (88.25 km² of which is land), and has a population of 549,050 in 2012 (Statistics Copenhagen City and Statistics Denmark).

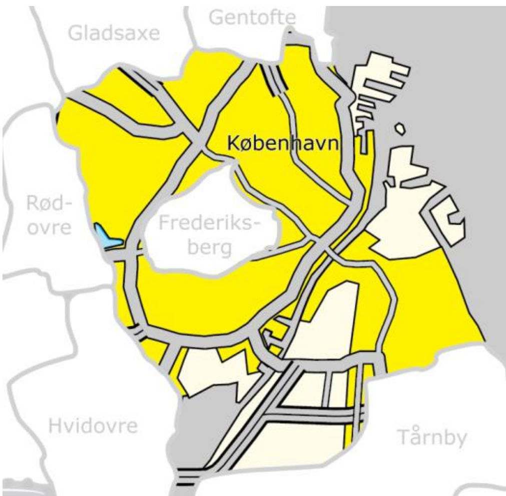


Figure 5: Map of Municipality of Copenhagen

Figure 6: 10 official districts of Copenhagen

It is a fairly small part of the actual city which falls within the municipality, both because it covers a confined area and because the enclave of Frederiksberg is an independent municipality. Since a reform in 2006–08, Copenhagen is divided into the following 10 official districts as shown in figure 6.

1. Indre By
2. Østerbro
3. Nørrebro
4. Vesterbro/Kongens Enghave
5. Valby
6. Vanløse
7. Brønshøj-Husum
8. Bispebjerg
9. Amager Øst
10. Amager Vest

In the municipality of Copenhagen, the local government of Copenhagen consists of a governing body, called the City Council, and an administrative branch. The City Council is divided into seven committees: the Finance Committee and six standing committees, each of which has its own specialized field of responsibility.

The Finance Committee is an overarching committee, which coordinates and plans the total management of the City of Copenhagen. It comprises the chairmen of each of the standing committees plus six other members of the Council, and is chaired by the Lord Mayor. Each committee is linked to a particular section of the administrative branch of Copenhagen's local government.

The seven administrations are:

1. The Finance Administration
2. The Culture and Leisure Administration
3. The Children and Youth Administration
4. The Health and Care Administration
5. The Social Services Administration
6. **The Technical and Environmental Administration**
7. The Employment and Integration Administration

This research is done in cooperation with the traffic departments, which is subject to the technical and environmental administration. More information about the technical and environmental administration can be found in appendix B.

4.2 Traffic network

Copenhagen offers various types of transportation and has an extensive public transportation network. The network is used by many modes of travelling and also contains metro and train lines. The train and metro lines are out of the scope and will not be described in this research.

4.2.1 Signalized intersections

The traffic network in Copenhagen consists of 364 signalized intersections. The 364 signalized intersections are divided into 52 signal groups. Figure 7 shows signal group 28 (purple dots) which is located in the south west of Copenhagen and consists of ten intersections.

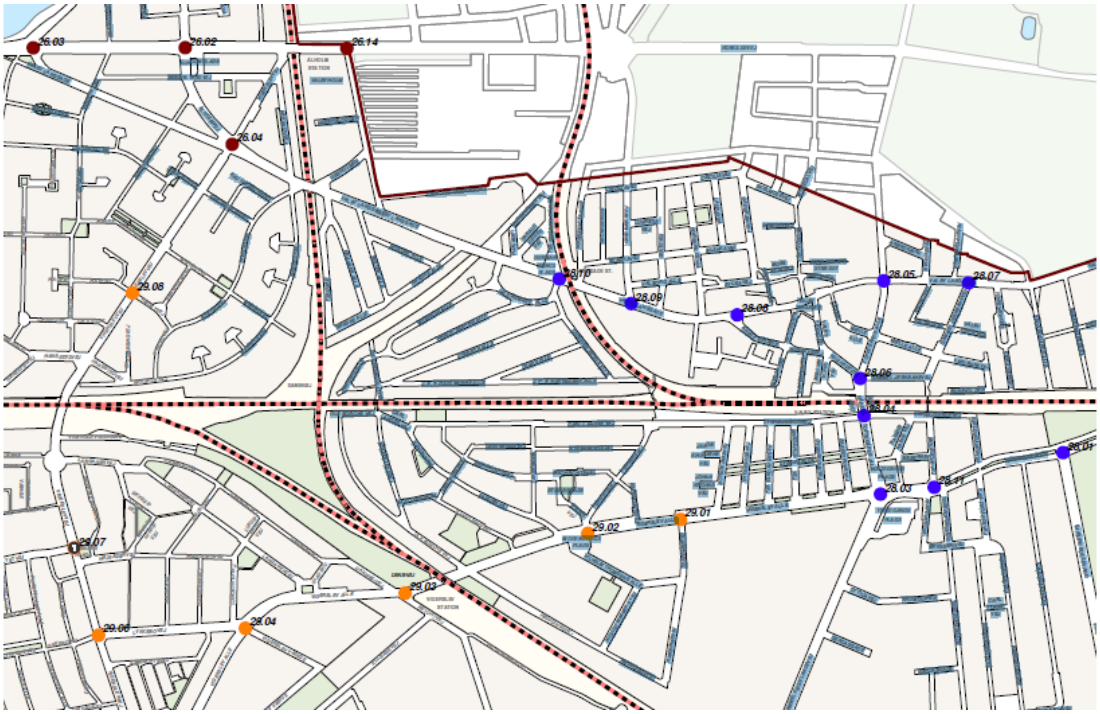


Figure 7: Valby area with 10 intersections indicated by purple dots. (Bosch, 2012)

4.2.2 Bus lines

The municipality of Copenhagen operates different types of bus lines, indicated by a letter and a number. There are 8 main bus lines (the A-lines) active in the municipality of Copenhagen. These A-lines are characterised by their high frequency; they run every few minutes, and they contain most passengers compared with the other bus lines. The A-lines are seen as the backbone of bus transport in central Copenhagen.

The minor bus lines are indicated by the letters S & E. These lines are served by express buses that operate on longer lines, with fewer stops. These lines have a lower frequency, approximately every 30minutes and drive further into the suburbs of Copenhagen. Figure 8 shows the A-lines, and figure 9 illustrates the S & E-lines.

Bus lines are a key component in many ATMS. Certain bus lines within an area can be detected and given priority at signalized intersections. This may reduce the travel time and improve the punctuality of the chosen bus lines in the area. It also possible to give conditional priority for buses at signalized intersections. This means that for example late buses are given priority and early buses are not.

Figure 8: A-bus lines in Copenhagen. Retrieved from http://kbhkort.kk.dk/.

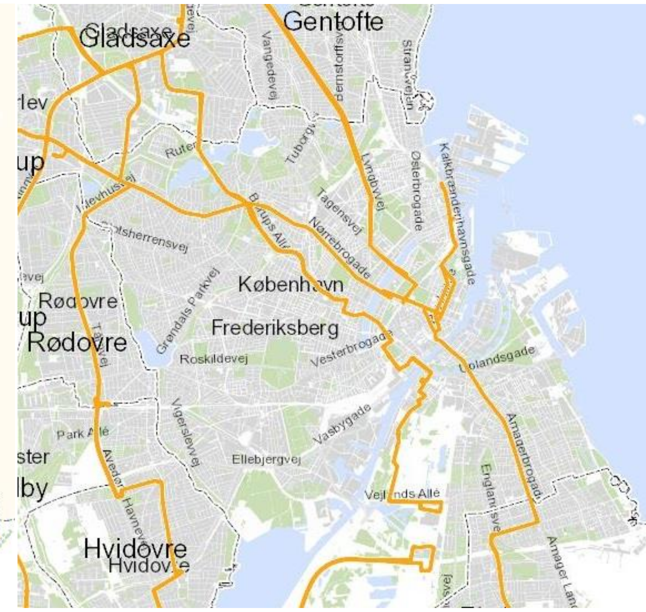


Figure 9: S & E bus lines in Copenhagen. Retrieved from http://kbhkort.kk.dk/.

4.4.3 Heavy trucks

Certain routes in the city are appointed as heavy truck routes. An ATMS system can cooperate with a built-in module (e.g. FREILOT) which gives priority to heavy trucks and therefore it can be interesting if a certain area handles a lot of heavy traffic. Minimizing accelerating and braking of heavy trucks will reduce the emission of air pollutants.

4.4.4 Cyclist

One of the pillars of the vision of the municipality of Copenhagen CO2 reduction will be achieved through further improvement of the bicycle infrastructure. In the coming years the bicycle infrastructure will be improved and bicycle super highways will be created. Travelling by bike will be encouraged in the municipalities vision. This bicycle super highways make use of green waves on arterial roads. There is 300km of super highways planned for the near future. Figure 10 shows the current and planned bicycle super highways in the municipality of Copenhagen. Figure 11 shows the bicycle 'Plusnet' infrastructure in Copenhagen. The purple dotted lines show the bicycle plans that are planned. Adaptive traffic management systems can give priority to cyclers on specified intersections, so that waiting time and travel time will be reduced.

Figure 10: Bicycle super paths (or highways) in municipality of Copenhagen. Retrieved from http://kbhkort.kk.dk/.

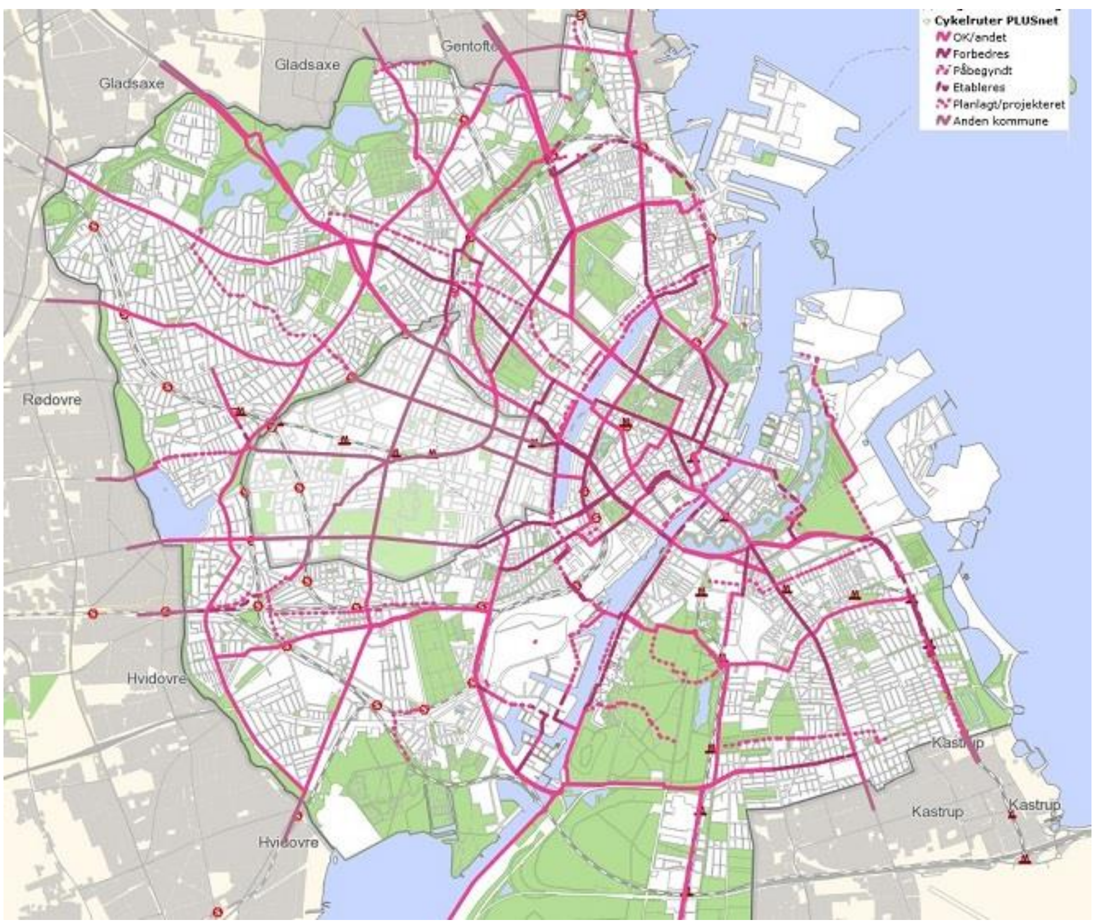


Figure 11: Bicycle Plusnet in municipality of Copenhagen. Retrieved from http://kbhkort.kk.dk/.

5 Identifying and weighting the various criteria

5.1 Introduction

The previous chapters described the current state of the various ATMS, cost components, maintenance, reliability, and the research area. As seen in chapter 4, the research area is huge with a total of 364 signalized intersections. Each area has its own characteristics and unique elements. The complexity to create a priority list of suitable areas for an ATMS is caused by the multiplicity of criteria that are important in this strategic choice.

The first step in prioritizing the different areas within the municipality of Copenhagen is to find the various criteria which play a role in the suitability of an ATMS. To compare areas within Copenhagen in an early stage, it is more efficient to define the criteria which contribute to a successful implementation of an ATMS.

The methods used for identifying the criteria, designing the questionnaire, surveying respondents and the results of the survey are described in this chapter. The objective of this survey is to set the weights of the criteria found in the literature research and the in-depth interviews with experts. Therefore, the result of this chapter shows the priorities/weights of the criteria for implementing an ATMS.

To compare alternatives/areas in Copenhagen, it is not realistic to focus on the cost of implementing a certain ATMS or to focus on the operational benefits. As noticed before, the cost of installing and maintenance are very volatile and difficult to predict. Also the operational benefits resulting from implementing an adaptive system depend on many factors and are difficult to predict in an early stage. Although simulation can give a way better view, there might always be disparities between the simulation and the real world implementation. Simulations are also expensive and time consuming.

5.2 Identifying and selecting of criteria

The purpose of identifying criteria is to develop a hierarchical tree (AHP tree), and develop the means by which the set of alternatives can be tested and compared. A list of 19 criteria retrieved from the literature research can be found in appendix C.

However some of the criteria may be are overlapping / non distinguishing or not relevant. Some criteria are pre-conditions to selecting alternatives or are difficult to judge. These criteria are not included in the AHP structure and therefor are out of scope of this research. After in-depth interviews with ATMS experts from the Netherlands and Denmark table 1 is constructed. Table 1 shows the 13 most relevant criteria for implementing an ATMS.

Criteria	Short Description
Network complexity (1)	The Complexity of a network is caused by several characteristics. Complexity of the network can be caused by the structure of the network, which can have different forms. Besides the structure, the variation of the distances between the intersections plays a role. Also the variety of road users can make a network more complex, as well as conflicting urban, local and traffic plans. ATMS systems can better deal with complex networks compared to fixed time control.
Network robustness (2)	The robustness of a network is a characteristic of the system. It is the ability of function retention under changing conditions. Changing conditions include the fluctuations in supply and demand of road users. Fragility is the opposite of robustness. A network that is fragile is not robust. When the network is fragile, unexpected flows can't be handled by the 'fixed time controllers' which result in congestion and queuing. A fragile network leads to unreliable travel times.
Limited expansion possibilities (3)	If expansion of the current infrastructure is limited, optimal usage of the current traffic network is required. This is also one of the reasons why road authorities and other traffic departments are currently investing in intelligent traffic systems for these areas. These ITS or ATMS utilize the traffic capacity to its absolute max.
Special lanes (4)	Special lanes for buses and bicycles may be an advantage for an ATMS. With separated lanes it is easier to detect bicycles, cars or buses instead of detecting them when they are among the rest of the traffic. This way it is easier to separate the several user groups and give them a priority.
Network Congestion (5)	Network congestion depends on the carrying capacity and traffic intensity. A network which is heavily congested and have many queues might be more interesting for implementing an ATMS than an area where is no congestion at all. If a network isn't congested at all, the benefits of installing an ATMS often do not outweighs the cost.
Changing traffic conditions (6)	With this criteria we consider the predictable traffic flow variations/fluctuations of the network on the day itself and day to day. When a network has traffic flow variations, it can still be a robust network. A network can for example have high traffic flow in one direction at several intersections in the morning rush hour and the contrary direction in the evening rush hour.
Unpredictable traffic patterns (7)	With this criteria the unpredictable traffic flow variations/fluctuations of the network on the day itself and day to day are considered. These are traffic patterns which are practically impossible to predict and put a lot of pressure on a network. Some networks experience more unpredictable traffic patterns then others, and it is impossible to adjust signal timing plans.
Red light violation (8)	Red light violation is a serious safety problem in high density areas, as it increases the number of collisions. One of the main reasons of red light violation is caused by the irritation of 'waiting for nothing'. By implementing an ATMS system an maximum waiting time for each direction can be set, which reduces the red light violation.
Conflicting modalities/traffic flows (9)	Depending on the different modes that are present in the network, several conflicts can occur between modalities and traffic flows. In a network with fixed time controllers it is very hard to prioritize different modes within the same network, also because the fixed time controllers don's use any input from the current traffic conditions. On some intersections bus routes, bicycle routes, heavy vehicle routes are contrary to each other which results in conflicting situations. An ATMS will control these modalities based on the current traffic situation, time of the day, importance etc.
Importance of Heavy vehicle priority (10)	In Copenhagen some routes are appointed as preferred heavy vehicles routes. The number of heavy vehicles on these routes is higher compared to other roads. ATMS systems have the possibility to attach cooperative functionality to the traffic light system, and give priority to heavy vehicles.
Importance of Public transport priority (11)	In some networks there are more bus lines or are specific bus routes with high priority. An ATMS can give priority under certain circumstances to specific bus lines or routes. In the specific situation of Copenhagen, there are many bus lines indicated by letters and numbers. Especially the A and S bus lines in the networks are considered as important bus lines which should receive priority at intersections.
Importance of Bicycle priority (12)	Increasing the use of bicycles is one of the main focusses of the city of Copenhagen, and has many advantages. To make it more attractive for cycling, priority at intersections would be a great improvement. An ATMS can detect bicycles and give priority depending on the time of the day and other variables. In some networks within Copenhagen the need for prioritizing bicycles is higher than other areas.
Importance of Car priority (13)	Although the city of Copenhagen want to discourage car use, some of the roads within our research area are important to cars for entering or leaving the city. On some of the arterial roads car priority can be relevant and important for the city. An ATMS system can detect cars and give them priority under certain circumstances.

Table 1: Selected criteria and descriptions

5.3 Analytical Hierarchy Process

Developed by Thomas L. Saaty (1990), the AHP is a widely used Multi-Criteria Decision method (MCDM), allowing for the structuring of complex decisions. One of the major strengths of the AHP is the use of pair-wise comparisons to derive accurate ratio scale priorities, as opposed to using traditional approaches of "assigning weights" which can also be difficult to justify. AHP decomposes a decision problem into a hierarchy of smaller, easily comprehendible sub-problems, each of which can be analysed independently (Saaty,1990). These independent elements of the hierarchy can relate to any aspect of the bigger decision problem, tangible or intangible, measured or estimated. Once this hierarchy is built, the various elements/criteria are evaluated by pair-wise comparison, with respect to their impact on an element above them in the hierarchy. The decision makers can use concrete data, or use subjective judgments about the elements' relative meaning and importance. This possibility, to implement human, subjective, judgment in a decision model, is an important feature of AHP.

AHP converts these judgments into numerical values that can be processed and compared with other, more objective, criteria. A numerical weight is derived for each element of the hierarchy allowing for this comparison between diverse criteria of different scale.

As a final step, priorities are calculated for each of the decision alternatives. These numbers represent the ability of alternatives to reach the decision goal. The alternative with the highest value is seen as the best option. The procedure for using the AHP can be stated as:

1. Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives;
2. Establish priorities among the elements of the hierarchy by making a series of judgments based on pair-wise comparisons of the elements. Each criteria in an upper level is used to compare the criteria in the level below with respect to it;
3. Synthesize these judgments to yield a set of overall priorities for the hierarchy;
4. Check the consistency of the judgments;
5. Obtain the global priority for sub criterion by multiplying the weight of the parent node (main criteria) with the weight of the sub criterion.

4.3.1. AHP structure

Modelling the problem provides the decision maker with a better understanding of the decision to be made. After identifying all the different criteria, it is important to construct main criteria, sub criteria and alternatives. After discussions with several experts within the municipality of Copenhagen the final AHP structure is designed and shown in figure 12.

The AHP structure is based on the problem discussed in the research context and is built of three levels.

- Goal: Implement an ATMS in Copenhagen
- Criteria: The 3 main criteria: Network composition, Network usage,. Conflicts & priority.
- Sub-criteria: These are the characteristics that describe an area (each are of interest in achieving the goal)

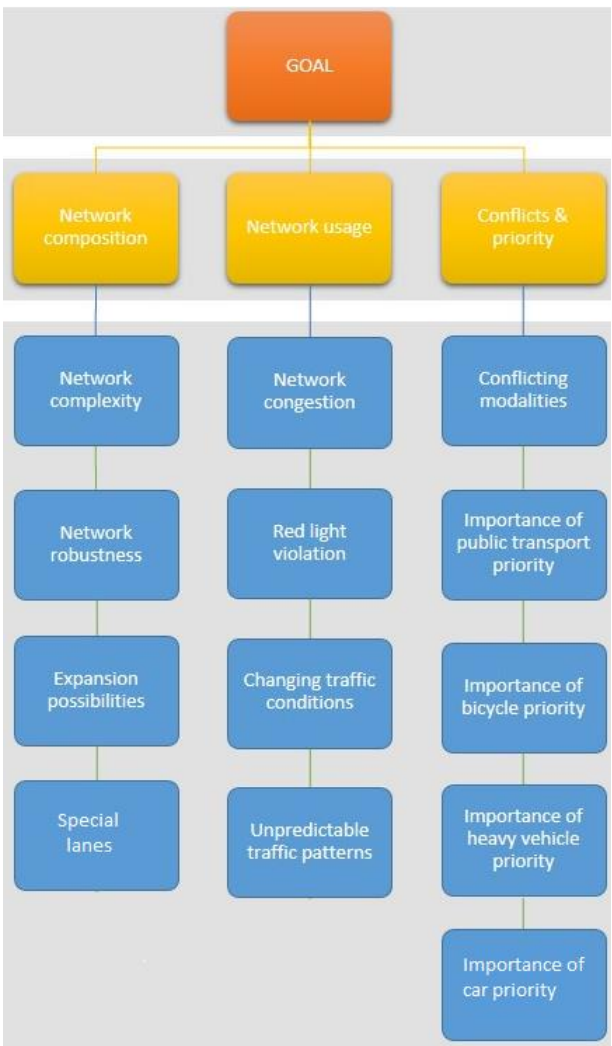


Figure 12: Analytical Hierarchy Process structure of criteria.

In order to find the most suitable alternatives (areas) for implementing an ATMS in Copenhagen, it is important to know what the relative importance is of these criteria in experts perspective. This will be step 2 of the procedure: Establish priorities among the criteria of the hierarchy by making a series of judgments based on pair-wise comparisons of the criteria.

5.4 Questionnaire Design & Respondents

The next step is the weighting of the defined criteria. Each criteria has a different importance degree, and this degree (or weight) is relevant to determine which criteria should be selected for evaluating the various alternatives.

What is the relative importance of these criteria in perspective of ATMS experts? To know the relative importance there is a need to quantify the criteria against each other which requires calculating the priority weights. Evaluation of these criteria can only be done by specific ATMS experts, as they are qualified to implement these systems in the real world.

"Human beings are not good at processing large streams of new data and information... the most we can hold in short-term memory, without forgetting something, is six or seven pieces of data."
Peters & Waterman Jr., 1982

The relative importance of the criteria are derived by pair-wise comparison. This limits complex decision making. The paired comparison allows the problem to be diluted in simple comparisons without having to pay attention to other elements (Saaty, 1990).

Based on the defined main and sub-criteria the questionnaire is designed. The questionnaire is designed to find the weights of the performance criteria using the pair wise comparison approach which was proposed by Saaty (1990). In this approach the respondent has to express his opinion about the value of one single pair wise comparison at a time. The comparisons are made using a scale of absolute judgements that represents, how much more, one element dominates another with respect to a given criteria. The absolute numbers and their explanation are shown in table 2. A nine point scale is provided to quantify pair-wise importance (or preference).

When performing the pair-wise comparison, the respondents should always keep the goal in mind. This goal is: Prioritization of areas in Copenhagen for implementing an ATMS. In other words, which criteria are most important to determine the suitability of an ATMS in a certain area?

Value	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak or slight	slightly favor one criteria over another
5	Moderate importance	Moderately favor one criteria over another
7	Strong importance	Strongly favor one criteria over another
9	Very strong importance	An criteria is favored very strongly over another

Table 2: Fundamental scale of absolute numbers

The number of paired comparisons in the questionnaire depends on the number of criteria in each hierarchy. If there are 'n' criteria in a hierarchy, there must be n(n-1)/2 number of paired comparisons. Using this method a total number of 22 questions are set up for this questionnaire. For example, the main category 'Conflicts & priority' includes 5 sub-criteria. Using this formula, 10 pair-wise comparisons are required for evaluating this sub-criterion.

The questionnaire is created as a word-document and sent to the members of expert panel I. This expert panel only contains experts in the field of ATMS, because specific knowledge is required to compare these criteria. However, ATMS experts are very scarce and therefor this questionnaire is only sent to 10 ATMS experts from Peek traffic/Imtech, Copenhagen municipality and a Danish consultancy firm. Along with the questionnaire, a document containing the description and explanation of the research goal and criteria is sent. The respondents can use this document while answering the questionnaire. A short version of this document can be found in appendix D. In total six out of ten questionnaires were completed.

5.5 Analysis and results

5.5.1 Reciprocal and normalized matrices

In this paragraph, the weights of the criteria will be calculated. The responses from the questionnaire are worked out in an excel spread sheet. The weight of the criteria and sub-criteria are calculated based on the assigned values of the experts. The values of the pair-wise comparison are already in numerical form, so they don't have to be converted for making the calculations.

There are four pair-wise comparison matrices. One for the main criteria with respect to the goal, which is shown in Table 3. For instance, table 3, criterion 'Conflicts & priorities' states that it is 1,42 times more important than criterion 'Network usage'. This value is the geometric mean of the 6 judgements.

Table 3 is also known as an judgement or confrontation matrix. Since the pair-wise comparison matrix satisfies a_{ij}= 1/ a_{ji}, the matrix is also called a reciprocal matrix (Saaty, 1977). Pair-wise comparison of criteria only have to be done once per pair, as it can be assumed that if criterion

A is four times larger than criterion B, criterion B will be four times smaller than criterion A (Saaty, 1990).

To calculate the weights using the AHP the eigenvalue method is predominantly used by Saaty, which is also used to calculate the consistency of the judgements. Table 4 shows the normalized matrix for the same main criteria. The normalized matrix is calculated by dividing each cell by column total for that cell. For instance, as stated before 'Conflicts & priorities' is 1,42 times more important than criterion 'Network usage'. Dividing this score by the column total for that cell (3,73) gives a normalized score of 0,38.

The 'relative weight' or eigenvalue is the calculated by dividing the sum of the row by the size of the matrix *n.* For the criteria 'Conflicts & priorities' this results in a 'relative weight' of 0,39. The sum of the row (1,18) is divided by the size of the matrix *n* (3,00).

	Network usage	Conflicts & priorities	Network composition
Network usage	1,00	0,70	0,76
Network conflicts & priorities	1,42	1,00	1,20
Network composition	1,31	0,83	1,00
Sum	3,73	2,53	2,97

Table 3: Reciprocal matrix of the main criteria with respect to the goal.

	Network usage	Conflicts & priorities	Network composition	SUM (EV)	Norm. Eigenvector
Network usage	0,27	0,28	0,26	0,80	0,27
Network conflicts & priorities	0,38	0,39	0,40	1,18	0,39
Network composition	0,35	0,33	0,34	1,02	0,34
Sum	1,00	1,00	1,00	3,00	1,00

Table 4: Normalized matrix of the main criteria with respect to the goal with the 'Normal eigenvector' (weight).

Similarly the reciprocal & normalized matrices are calculated for all of the remaining sub criteria and their weights are calculated. These reciprocal & normalized matrices can be found in appendix E.

5.5.2 Eigenvalue and consistency ratio

Knowledge of the eigenvalue method and consistency ratio is necessary to apply pair-wise comparisons. If criterion A is twice as important as criterion B and criterion B is three times as important as criterion C, a simple algebraic calculation would find criterion A to be six times more important than criterion C.

The problem of accepting/rejecting matrices has been greatly discussed in many articles, especially the relation between the consistency and the scale used to represent the decision maker's judgements. As priorities make sense only if derived from consistent or near consistent matrices, a consistency check must be applied. Saaty (1977) has proposed a consistency index (CI), which is related to the eigenvalue method. The standards rule by Saaty (1990) states that if CR <= .10, consistency is acceptable.

However Lane and Verdini (1989) have shown that by using a 9-point scale, Saaty's consistency ratio (CR) threshold is too restrictive due to the standard deviation of CI for randomly generated matrices being relatively small. In this study, we took 0.15 as the allowable threshold (Lane and Verdini, 1989), and employed only those matrices whose CRs were equal to or smaller than 0.15.

In this research the consistency is calculated based on Alonso and Lamata (2006). They have estimated the Random Index(RI) using 100,000 matrices of each dimension. The consistency ratio (CR), the ratio of CI and RI, is given by: CR = CI/RI. In the AHP, the quotient of this difference divided by (n-1) is defined as the consistency index (CI), which is the index of the consistency of judgements across all pair-wise comparisons (Lootsma, 1991).

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1},$$

where λ_{max} = maximal eigenvalue

If the CR is below the chosen threshold α , the decision matrix is considered as having an acceptable consistency. One specific matrix is either consistent or not (i.e. either accepted or not as a consistent matrix). The CRs are calculated for each matrix for each respondent. The ratios of matrices satisfying this threshold were 95,8% (23/24).

	Consistency Ratio (CR)			
Respondent	Criteria	Sub-criteria 1	Sub-criteria 2	Sub-criteria 3
1	14%	10%	9%	15%
2	0%	5%	14%	4%
3	14%	4%	4%	11%
4	14%	7%	28%	6%
5	4%	10%	11%	11%
6	14%	7%	7%	6%

Table 5: Consistency Ratios for all matrices.

Table 7 shows the CRs for all the constructed matrices. Respondent 4 has one inconsistent matrix, which is excluded from the dataset. Overall can be concluded that the data may be considered as consistent.

5.5.3 Geometric mean

An aggregation of each individual's resulting priorities can be computed using either a geometric or arithmetic mean. When calculating the geometric average of the judgments the respondents are considered as equal important. Geometric mean is a type of mean or average in mathematics, which indicates the central tendency or typical value of a set of number. To calculate the geometric mean, the numbers are multiplied and then the nth root of the resulting product is taken (n is the number of respondents in the set). The geometric mean of a data set {a1, a2, …, an} is given by:

$$\left(\prod_{i=1}^{n} a_i\right)^{1/n} = \sqrt[n]{a_1, a_2, \ldots, a_n}$$

The basis for using this method has been justified mathematically by (Saaty, 2001).

5.5.4 Priority weights of criteria

The table 5 shows the ranking and priority weights of the main criteria and the priority weights of the sub criteria. These weights are calculated from the 6 responses obtained from the ATMS experts.

Main criteria	Priority weights	Sub-criteria	Priority weights
Network usage	0,27	Network robustness	0,36
		Expansion possibilities	0,31
		Network complexity	0,25
		Special lanes	0,08
Network composition	0,34	Changing traffic conditions	0,37
		Unpredictable traffic patterns	0,28
		Network congestion	0,29
		Red light violation	0,06
Network conflicts & priorities	0,39	Public transport priority	0,30
		Conflicting modalities	0,26
		Car priority	0,20
		Heavy traffic priority	0,13
		Bicycle priority	0,11

Table 6: Weights of the main criteria and sub criteria calculated from the questionnaire responses.

The vision of the municipality of Copenhagen is focused on the priority of public transport, bicycles and discouraging of car use. Therefor car priority was not included in the pair-wise comparison. However later on this research, car priority turned out to be important in some areas of the city. Especially major roads entering or exiting the city can benefit from car priority, which can also lead to a reduction of CO2 emissions. Car priority is appointed the average weight of the other sub-criteria within the main criteria: 'Network composition'.

In table 6 the final weights of the sub-criteria have been calculated by multiplying the relative score of the sub-criterion within their respective category with the score of the parent criterion, e.g. the score of 'Network robustness' is calculated by multiplying the criterion score of 'Network usage' (0,27) with the score of 'Network robustness' (0,41), resulting in a score of 0,11. The total score of all calculated final weights of the sub-criteria equals 1,00 when added together.

Sub-criteria	Global weight
Changing traffic conditions	0,124
Public transport priority	0,118
Conflicting modalities	0,102
Network congestion	0,099
Network robustness	0,097
Unpredictable traffic patterns	0,095
Expansion possibilities	0,082
Car priority	0,079
Network complexity	0,067
Heavy traffic priority	0,050
Bicycle priority	0,044
Special lanes	0,022
Red light violation	0,020
Sum	1,00

Table 7: Final weights of all sub criteria.

5.6 Conclusion

A pair-wise comparison was constructed and completed by six ATMS experts. Their consistent judgements have been used to calculate the weight of each of the defined criteria.

With respect to the main criteria, the experts prefer the criterion Network conflicts & priorities with an average relative weight of 39 %. Corresponding average weights for the network composition and network usage main criteria are 34 % and 27%, respectively.

As can be seen in table 6 , changing traffic conditions (0,124) has assigned the highest weight. The presence of this characteristic in an area is seen as the most important characteristic while considering implementation of an ATMS in the area. All the extracted weights will be used to analyse and compare several alternatives (areas) in the municipality of Copenhagen.

6 Multi-criteria evaluation and ranking of alternatives.

6.1 Introduction

After obtaining the weights for all the relevant criteria, the next important step in a AHP is defining the alternatives (choice-possibilities) in term of the included criteria. The alternatives represent the 'different possibilities to solve the problem'. In general, the alternatives should be selected from the research area. In this study, the alternatives are synonyms for the areas within municipality of Copenhagen. This research area contains 364 signalized intersections which are divided into 52 signal groups (areas).

After defining the alternatives, the final step of the AHP is to compare and evaluate the alternatives. The criteria applied in a MCE serve as a tool to test the various decision alternatives from a particular point of view. All criteria get a score on a 9-grade value scale, and therefore become an abstract unit, valid across all scales. These abstract units are converted to ratio scores and all are compared in pairs of the evaluated alternatives. This will result in so-called dominance scores. After standardization of these scores, the overall dominance scores per alternative will be calculated. These overall values represent the relative ability of alternatives to achieve the decision goal: implementation of an adaptive traffic management system in the area. The end result will be a ranking of alternatives based on their overall dominance score.

6.2 Selection of the alternatives

Five decision makers from different departments are selected in order to form a panel of experts. This expert panel (II) will express their judgments and opinions concerning the selection of alternatives. Because the decision makers belong to different department within the 'Centre of Traffic', their values and preferences are different.

As said before, the municipality of Copenhagen consists of 364 signalized intersections. It is therefore practically impossible to analyse all possible areas within the municipality of Copenhagen. In a group meeting with the five decision makers consensus was reached regarding the choice of five alternatives (areas). Each area consist of 6-12 intersections and is located in a different part of the city. A short description of each alternative is given in table 8.

Area	Short Description
Nørreport	The area of Nørreport is a network consisting of 9 intersections (05.01 / 05.02 / 05.03 / 05.04 / 05.05 / 05.06 / 05.07 / 18.08) and is located at the center of Copenhagen. In the area around Nørreport are many bicycle lanes. Most of the bike paths belong to the Plusnet, some are designated to the green bicyle network. There is also planned a super bicycle path in this area. The area is also characterized by several major bus lines driving to or leaving from Nørreport station. The most important bus lines are: 5A / 6A / 11A / 150S / 350S / 173E.
Corridor Jagtvej	The Corridor Jagtvej consist of 6 intersections in a line(20.07 / 20.09 / 18.06 / 16.01 / 16.05 / 14.09). The corridor Jagtvej crosses several important roads that are crucial for traffic entering or leaving the city center. Jagtvej has seperated bicycle lanes and crosses Norrebrogade and Tagensvej, which both also contain many cyclist. The corridor is characterized by several major bus lines crossing Jagtvej. The corridor itself has busline, which is line 18. At intersection 18.06 (Jagtvej/Norrebrogade) the bus lines 5A and 350S cross Jagtvej. At intersection 16.05 (Jagtvej/Tagensvej) the bus lines 6A and 43 cross Jagtvej.
Central station	This are consist 9 intersections (02.01 / 02.02 / 02.03 / 02.04 / 02.05 / 02.06 / 02.07 / 02.12) One of the intersections is an important pedestrain crossing. The area is characterized by many major and minor bus lines driving to or leaving from Central station. There are also many pedestrians in this area, leaving or entering the amusement park: Tivoli. The major bus lines that drive through or cross the network are: 1A / 2A / 5A / 6A / 9A/ 11A / 250S. The minor bus lines are: 10 / 12 / 30 / 40 / 66 / 68.
Corridor Nørre Alle / Lyngbyvej	This corridor consist of 11 intersections and is an important entrance way for all traffic entering or leaving Copenhagen center from/to the north. The corridor is also an important route for many buslines and entering and leaving the city from/to the North. Besides that the route also contains many cyclist. Several major bus lines driving through this corridor leave from Nørreport station. The most important bus lines are: 173E / 150S & 184. These bus lines follow the corridor till Lyngbyvej goes over into Helsingørmotorvejen. The bus lines 6A / 96N and 350S all leave from Nørreport station and drive through this network till they leave the corridor at the intersection Tagensvej/Nørre Alle, where these bus lines stay on the Tagensvej into the direction of Nørrebro. Bus line 95N & 4A are crossing the corridor.
South Copenhagen	This area is located in the south part of Copenhagen and consist of 12 intersections. This network is an important entrance route from traffic coming from the Øresundsmotorvejen (highway south Copenhagen). The network also contains bicycle paths. The most important bus lines are: 3A & 4A. Other buslines that go through this network are : 10 / 30 / & 97N.

Table 8: Alternatives and short description.

6.3 Online survey

To create the characterization of the alternatives with respect to the defined criteria and sub criteria, an online survey is set up. Each alternative is extensively described for the respondents. Subsequently they are asked for each criteria to characterize the alternatives on a numeric 1-9 scale. The definition of each number is shown in table 9. The online questionnaire is placed on the following URL link: http://www.its-survey.eu. Screenshots of this online questionnaire for the 'Norreport' alternative can be found in Appendix F.

Experts are required to evaluate the alternatives, as their judgments possess deeper knowledge about traffic management and they are familiar with the different areas in Copenhagen. For this online survey 50 invitations for participation are sent to experts of three departments of the municipality of Copenhagen (København kommune). These departments are: Traffic design, Traffic plan, and the Cycling department.

scale	1	2,3,4	5-6	7,8,9	10
Network comlexity	very simple nework	↔	normal network	↔	very complex network
Network robustness	fragile network	↔	normal network	↔	very robust network
Expansion possiblities	none	↔	normal	↔	extreme many
Red light violation	no red violation	↔	normal percentage	↔	extreme high percentage
Unpredictable traffic patterns	100% predictable	↔	normal traffic patterns	↔	extreme unpredictable
Changing traffic conditions	never change	↔	normal changes	↔	extreme many changes
Conflicting modalities / traffic flows	no conflicts	↔	average nr. of conflicts	↔	extreme many conflicts
Bicycle priority	no priority	↔	average priority	↔	extreme high priority
Heavy traffic priority	no priority	↔	average priority	↔	extreme high priority
Public traffic priority	no priority	↔	average priority	↔	extreme high priority
Car priority	no priority	↔	average priority	↔	extreme high priority

Table 9: Linguistic values

As can been seen in table 9, the respondents are asked to characterize each area based on these eleven selected criteria. In chapter 5.2 thirteen criteria were defined and used for the pair-wise comparison. The criterion: 'Special lanes' was initially included in the pair-wise comparison , but hindsight is decided to remove it from the online questionnaire. This is done after feedback from experts, who suggest that this criterion is too vague and doesn't play an important role in the implementation of an ATMS.

Also the criterion: 'Network congestion' was initially included in the pair-wise comparison, but is excluded from the online questionnaire. This criterion is considered as a pre-condition for selecting the alternatives in chapter 6.2. The result is that this criterion is not sufficiently distinguishing. Thus, eleven criteria are considered in this online questionnaire.

6.4 Analysis and results

The response rate of the 50 invited persons for the online survey is about 50 % (i.e. 26 completed questionnaires). The individual judgments of 26 respondents for each criterion for the alternatives are received. The complete dataset retrieved from the online questionnaire can be found in Appendix G. The next step is the aggregation of the individual judgments, which is calculated by averaging all the 26 judgments.

Table 10 shows the average judgment for each criteria for each alternative. The red shading indicates the lowest average judgment , where green indicates the highest average judgment for each criteria.

		Alternatives				
		Nørreport	Jagtvej	Central station	Lyngbyvej	South CPH
Sub criteria	complexity	6,4	4,7	6,9	6,0	5,8
	robustness	4,4	4,1	4,1	2,6	3,1
	Expansion possibilities	6,0	5,5	4,7	3,1	3,3
	Red light violation	5,6	5,6	6,0	5,0	4,8
	Unpredictable traffic patterns	4,9	4,1	5,4	4,5	3,9
	Changing traffic patterms	5,9	5,0	6,0	5,5	5,3
	Conflicting modalities	7,0	5,9	7,1	6,1	5,6
	Bicycle prio	8,0	7,3	7,1	6,8	5,3
	Heavy traffic prio	4,23	4,2	4,7	6,6	7,5
	PT prio	8,4	7,5	8,7	8,5	6,8
	Car prio	4,8	5,3	5,1	7,6	8,3
	Average	6,0	5,4	6,0	5,7	5,4

Table 10: Average judgement of each criteria for each alternative.

Before constructing table 10 , all criteria need to have the same direction. The robustness and expansion possibilities criterion need to change direction. A low score on these criteria means that these areas have characteristics that are favourable for implementing an ATMS. A very fragile area has a higher need for an ATMS. The same applies to an area with very limited expansion possibilities. Therefore ‘Network robustness’ and ‘Expansion possibilities’ have changed direction.

As we can see in table 10, the area of Central station scores most frequently the highest average score on the criteria, followed by Nørreport area. If all criteria had the same weight Central station and Nørreport would be ranked as number 1 & 2. In general the average score on all of the criteria are close for all alternatives. However the weight of each criterion is calculated in the previous chapter and should be applied. The next step is to standardize the scores into the unit [0,1] interval.

6.4.1 Standardization

The standardization technique used in this research is the standardization to ratio scores. The formula for this technique is given below:

$$e_{ik} = \frac{(E_{ik} - E^{-}_{k})}{(E^{+}_{k} - E^{-}_{k})}$$

E_{ik} *is the score on criterion k*

E^{-}_{k} *is the minimum score on criterion k*

E^{+}_{k} *is the maximum score on criterion k*

Table 11 shows the scores for all criteria after standardization and transformation to ratio scores.

		Alternatives				
		Nørreport	**Jagtvej**	**Central station**	**Lyngbyvej**	**South CPH**
Sub criteria	**complexity**	0,93	0,68	1,00	0,86	0,83
	robustness	1,00	0,93	0,94	0,59	0,69
	Expansion possibilities	1,00	0,93	0,79	0,52	0,55
	Red light violation	0,93	0,94	1,00	0,83	0,79
	Unpredictable traffic patterns	0,90	0,77	1,00	0,84	0,72
	Changing traffic patterns	0,99	0,83	1,00	0,93	0,88
	Conflicting modalities	0,98	0,83	1,00	0,85	0,78
	Bicycle prio	1,00	0,91	0,89	0,84	0,66
	Heavy traffic prio	0,56	0,56	0,62	0,88	1,00
	PT prio	0,97	0,86	1,00	0,98	0,78
	Car prio	0,58	0,64	0,62	0,92	1,00
	Average	0,89	0,81	0,90	0,82	0,79

Table 11: Standardized ratio-scores.

Each criterion holds a different level of importance (or weight). The research objective is to identify the most referred alternative. Based on these data from the online survey concerning the five alternatives , the score for each of the alternatives can be calculated.

6.5 Ranking of the areas

After obtaining the weights in Chapter 5 , and the selection and characterization of the alternatives in Chapter 6, the last step in the AHP is the ranking of the alternatives. The result from both steps are combined to calculate the final ranking. Figure 13 visualizes the process of ranking the areas.

The weighted summation method, also known as the multi-attribute value (MAV), is the simplest and most widely used summation method. Saaty (1990) proposes this simple weighting and summing process in the AHP to calculate the overall score for each alternative. Another method with a more sound theoretical basis, is the overall dominance method. In this research we will use this method to calculate the quantitative dominance score for each alternative. The quantitative dominance overall scores will be used to rank the 5 area's that are characterized by experts.

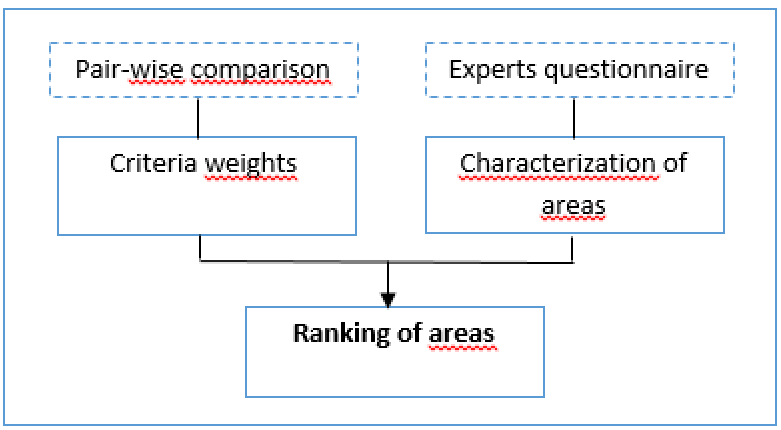


Figure 13: Process model: ranking areas

6.5.1 Quantitative dominance scores

The quantitative can be conducted in four consecutive steps.

Step 1:

Standardized scores of each criteria are compared in pairs of the evaluated alternatives resulting in so-called dominance scores. For calculating these scores per criteria the equation as stated on the next page is used.

Equation: $W_k(e_{ik} - e_{jk})$

e_{ik} = Score of alternative 'i' on criteria 'k'
e_{jk} = Score of alternative 'j' on criteria 'k'
W_k = Weight of criteria 'k'

Each cell is created by multiplying the weight (W_k) by the difference between e_{jk} *and* e_{ik}.

Applying this equation for e.g. the pair A1-A2 criteria 1 (Complexity) results in a score of 0,016. Table 13 illustrates the first out of five steps.

k	Description
1	complexity
2	robustness
3	Expansion possibilities
4	Red light violation
5	Unpredictable traffic patterns
6	Changing traffic patterms
7	Conflicting modalities
8	Bicycle prio
9	Heavy traffic prio
10	PT prio
11	Car prio

Table 12: Table.. criteria and their description.

k	1	2	3	4	5	6	7	8	9	10	11	∑kϵC
A1-A2	0,016	0,007	0,006	0,000	0,013	0,020	0,016	0,004	0,000	0,013	-0,005	0,089
A1-A3	-0,005	0,006	0,017	-0,001	-0,009	-0,001	-0,002	0,005	-0,003	-0,004	-0,003	-0,001
A1-A4	0,004	0,040	0,040	0,002	0,006	0,007	0,013	0,007	-0,016	-0,002	-0,027	0,075
A1-A5	0,006	0,030	0,037	0,003	0,018	0,014	0,020	0,015	-0,022	0,023	-0,033	0,110
A2-A3	-0,021	-0,001	0,011	-0,001	-0,022	-0,021	-0,018	0,001	-0,003	-0,016	0,001	-0,089
A2-A4	-0,012	0,033	0,034	0,002	-0,006	-0,012	-0,003	0,003	-0,016	-0,014	-0,022	-0,014
A2-A5	-0,010	0,023	0,031	0,003	0,005	-0,006	0,005	0,011	-0,022	0,010	-0,029	0,021
A3-A4	0,009	0,034	0,022	0,003	0,015	0,009	0,015	0,002	-0,013	0,002	-0,023	0,075
A3-A5	0,011	0,024	0,020	0,004	0,027	0,015	0,022	0,010	-0,019	0,026	-0,030	0,110
A4-A5	0,002	-0,010	-0,003	0,001	0,012	0,006	0,007	0,008	-0,006	0,024	-0,006	0,035

Table 13 : Standardized scores of each criteria(1-12) compared in pairs of the alternatives(A1-A6).

Step 2:

The last column of table.. illustrates the summation of the row. This and the previous step can be combined to the following equation and results in the dominance scores (A_{ij}).

$$A_{ij} = \sum_{k \epsilon C} W_k(e_{ik} - e_{jk})$$

C = The set of quantitative criteria

A positive score implies dominance of one alternative in relation to another while a negative value implies submission. A dominance measure of 0 implies an indifference between the compared alternatives.

Table 14 illustrates the dominance scores (A_{ij}). As can be seen in the table e.g. alternative 1 dominates alternative 2.

i↓ j→	A1	A2	A3	A4	A5
A1	0,000	0,089	-0,001	0,075	0,110
A2	-0,089	0,000	-0,089	-0,014	0,021
A3	0,001	0,089	0,000	0,075	0,110
A4	-0,075	0,014	-0,075	0,000	0,035
A5	-0,110	-0,021	-0,110	-0,035	0,000

Table 14: Dominance scores Aij

i↓ j→	A1	A2	A3	A4	A5
A1	0,000	0,072	0,000	0,061	0,089
A2	-0,072	0,000	-0,072	-0,011	0,017
A3	0,000	0,072	0,000	0,061	0,089
A4	-0,061	0,011	-0,061	0,000	0,028
A5	-0,089	-0,017	-0,089	-0,028	0,000

Table 15: Standardized dominance scores Aij

Step 3:

Standardize quantitative dominance scores (D_{ij}). This is done by dividing each dominance score by the summation of the absolute term of all dominances scores (A_{ij}). The equation below is used to construct table 15 with the standardized dominance scores.

$$D_{ij} = \frac{A_{ij}}{\sum_{i'} \sum_{j'}} \left| A_{i'j'} \right|$$

Step 4:

The last step in the method is the calculation of the total scores (Si) The following equation is used for this step:

$S_i = \sum_j D_{ij}$ / N

$N = \text{Number of alternatives}$

Table 16 shows the total scores for each alternative. Alternative 'A1' gets the highest overall dominance score.

i↓ j→	A1	A2	A3	A4	A5	Si
A1	0,000	0,072	0,000	0,061	0,089	0,044
A2	-0,072	0,000	-0,072	-0,011	0,017	-0,028
A3	0,000	0,072	0,000	0,061	0,089	0,045
A4	-0,061	0,011	-0,061	0,000	0,028	-0,016
A5	-0,089	-0,017	-0,089	-0,028	0,000	-0,045

Table 16: Dominance scores Dij

6.5.2 Final ranking

Si	Alternative	Name	Ranking
0,045	A1	Central station	1
0,044	A3	Nørreport	2
-0,016	A4	Jagtvej	3
-0,028	A2	Lyngbyvej	4
-0,045	A5	South CPH	5

Table 17: Total scores Si and final ranking.

Table 17 shows the final ranking of the five alternatives. Central station area gets the highest score and therefore is the most preferred alternative for implementing an ATMS. However, Nørreport area has nearly the same score as Central station.

7 Conclusions and recommendations

In this final chapter, conclusions of the findings in this thesis are provided together with recommendations for further research. In the first paragraph, a summary and conclusion about this research are given. The second paragraph includes the discussion of the results. The third paragraph includes recommendations for further research.

7.1 Conclusions

This year the first real-time ATMS is implemented in the area of Valby, six kilometres south west of Copenhagen centre. Implementation of an ATMS leads to a much closer interaction between all of its components: cars, pedestrians, public transportation, heavy trucks etc. At this moment all 364 signalized intersections within the municipality of Copenhagen are managed by fixed time controllers. Compared to fixed time control , an ATMS can significantly improve traffic flows for different road users. Simulation reports of the Valby area show a strong reduction of the delay time of the buses in the area. But also the other modalities benefit from implementing an ATMS. The simulations show an overall decrease in delay time of 30% in the morning rush hour compared with the current situation. Comparable or even better results are possible in many other areas of the municipality of Copenhagen.

However, some areas are more suitable for implementation of an ATMS then others. As budget is limited, this insight is of major importance to take decisions on investing in ATMS for some areas in the city. As each area has its own characteristics and unique elements, it is important to know which criteria (or characteristics) are seen as the most important while considering implementation of an ATMS in the area. The first goal in this research:

1) Construct a list of most important criteria for implementing an ATMS, and set the weights/priorities of each criteria.

Therefore a pair-wise comparison was constructed and completed by six ATMS experts. Twelve criteria (or characteristics) were evaluated in this pair-wise comparison. The presence of changing traffic conditions (0,124) is considered as the most important characteristic, while public transport priority (0,118) and conflicting modalities (0,0102) are considered as second and third most important characteristics.

The second objective in this research was:

2) Characterize the different (relevant) areas within the municipality of Copenhagen by means of the chosen criteria;

After defining the weights of the criteria , five areas are selected by an expert panel. This expert panel consists of decision makers from different departments of the municipality of Copenhagen.

To get insight into alternatives scores regarding the defined criteria, an online questionnaire was constructed to collect data. In this questionnaire the five alternatives were presented and 26 experts gave their judgements for each criterion for each alternative. All the experts are familiar with the evaluated areas.

The main objective of this research was:

3) Show a ranking of areas that are (most) suitable for implementing an adaptive traffic control systems within the municipality of Copenhagen.

The standardized average values (or scores) were used to calculate the overall dominance score for each alternative. Central station area gets the highest score and therefor is the most preferred area for implementing an ATMS. Nørreport area has nearly the same score as Central station and is ranked as number two.

7.1.1 Reflection of results:

1) Changing network conditions is considered as the most important characteristic for implementing an ATMS. This is not surprising , because a network with a high degree of changing traffic conditions is difficult to manage with fixed time control. A network managed with fixed time control can work with several timing plans changed based of the time of the day. However when traffic conditions change frequently, the adaption of fixed time is limited. Partly because of these reasons, a high degree of 'changing traffic conditions' is considered by experts as the most important characteristic. An ATMS can adapt to changing traffic conditions in real time.

2) For Copenhagen 5 areas area evaluated and the Central station and Nørreport area are ranked as the most suitable areas for implementing an ATMS. Compared to the other areas evaluated in this research, these two areas are located in the centre of the city and contain all modes of travelling. These areas are both characterized by the many major and minor bus lines driving to or leaving to the Central station or Nørreport station. Together with the many cyclist and pedestrians this results in many conflicting situations. Considering the criteria it is not surprising that these two areas are ranked as number one and two.

7.2 Discussion

- In this thesis, the information from the pair-wise comparison was obtained from six ATMS experts. Because it is such a specific part of the ITS, experts are scarce. However a higher number of respondents would increase the reliability of the data;

- The success of an ATMS in a certain area of the city also depends on the costs of implementation and the operational benefits. As noticed before, the cost of installing and maintenance are very volatile and difficult to predict. Also the operational benefits resulting from implementing an adaptive system depend on many factors and are difficult to predict in an early stage. Because of these reasons, these factors are left out of this research. Simulation may give a better view of the costs and operational benefits, but is due to costs not effective to evaluate all areas in a city;

- Initially the criterion 'car priority' was not included in the pair-wise comparison. This choice was made because of the municipality's vision towards green mobility. However at a later stage in this research, car priority turned out to be a criterion that should have been included pair-wise comparison. Therefore 'car priority' got appointed an average weight of 0,20 within the parent node (conflicts & priorities);

- The method used in this thesis may be considered as an backward approach. In traditional procedures an municipality decides to achieve certain goals in various parts of the city. Consequently, experts are employed to determine what suitable tools (ATMS or otherwise) can be applied to achieve this. However the method applied in this thesis gives an insight in the important characteristics of areas and what kind of areas are most suitable for an ATMS.

7.3 Recommendations

The personal ideas and knowledge gained from this thesis are presented as recommendations.

- In my opinion, the next step should be to test the Central station area and the Nørreport area in a simulation environment (e.g. Vissum). Although there will always be some disparities between the simulation and the real world implementation, the simulations give a good view of the operational benefits. Simultaneously a cost estimation can be made for both areas. The last step before implementation is to carefully consider if the costs and benefits outweigh each other.

- The list of thirteen criteria constructed in this research can be applied to other municipalities. It can be helpful for making a selection of suitable areas and will save them a lot of time.

- An evaluation of the implementation of the real-time ATMS in the area of Valby should be performed. Disparities between the real operational improvements and the data from the simulation should be compared. Also the obstacles and difficulties during the implementation need to be defined. This evaluation will improve the implementation in other areas of the city.

- A close interaction between the various departments and involved actors is crucial for an successful implementation of an ATMS. Each involved actor has its own interest and cooperation is necessary to construct the objectives for a certain area.

7.4 Further research

For further research, it could be interesting if the various objectives for each area of the city will be determined. In some areas there is need for reducing the average waiting time for buses, in other areas the number of stops of cars should be reduced. There may be objectives concerning minimizing queue lengths, or prioritizing public transport, cyclers, trucks etc. To reach consensus between all involved actors and define the various objectives for each area is the basis for the implementation of ITS (e.g. ATMS).

8 References

Articles:

- Alonso, J.A., Lamata, M.T. (2006) Consistency in the analytical hierarchy process: A new approach. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems Vol. 14, No. 4 (2006) 445−459*
- Apostolou, B. (1993) An empirical examination of the sensitivity of the analytical hierarchy process to departures from recommended consistency ratio's. *Mathl. Comput. Modelling Vol. 17, No. 415, pp. 163-170, 1993*
- Broersen, C. (2011) A complex model for generating sustainable land use plans: Determining the spatial location allocations of energy sources in urban planning. *Graduation program - Construction Management and Urban Development 2011-2012 Process Engineering*
- Curtis, E. (2007) ACS Lite. The Next Generation of Traffic Signal Control. *ITS- CT Student Research Project Spring 2012.*
- Ehrenberg, R. (2010) Adaptive traffic lights could achieve 'the green wave'.
- Gier, J.de(2011) Traffic flow on realistic road networks with adaptive traffic lights. *Journal of Statistical Mechanics: Theory and Experiment Volume 2011, April 2011.*
- Ishizaka, A. (2009). Analytic Hierarchy Process and Expert Choice: Benefits and Limitations. *ORInsight, 22(4), p. 201–220*
- Koning, A. de (2011) EcoFLEX: Het verbeteren van de luchtkwaliteit met behulp van Groen Dynamisch VerkeersManagement, gebaseerd op real time luchtkwaliteitsmetingen.
- Lane E.F. & Verdini W.A.(1989) A consistency test for AHP decision makers. *Decision Science 20 (1989) pp.575-590*
- Lootsma F.A. (2009) Scale Sensitivity and Rank Preservation in a Multiplicative Variant of the Analytic Hierarchy Process. *Proceedings of the 2nd International Symposium on The Analytic Hierarchy Process, (Pittsburgh, PA, 1991) pp 71-83.*
- NCHRP Synthesis 403 (2010). Adaptive Traffic Control Systems: Domestic and Foreign State of Practice A Synthesis of Highway Practice. *National cooperative highway research program: Transportation research board of the national academies.*
- Peels, A., Duijn, H., Ham, J., Roumen, H. (2011). Eindhoven university of technology master plan 2020. *Retrieved March 5, 2013, from Eindhoven university of technology: http://www.tue.nl/universiteit/over-de-universiteit/profiel-en-missie/strategie-2020/*
- Peters, T. & Waterman Jr., R. (1982). *In search of Excellence.* USA: Harper & Row, Publishers, Inc.
- Saaty, T. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15, p 234-281*
- Saaty, T. (1990). How to make a decision: the analytical hierarchy process. *European Journal of Operational Research, 48, p 9-26*

  Saaty, T. L., (2001) Decision Making with Dependence and Feedback: The AnalyticNetwork Process, Pittburgh: RWS Publications, 2001, pp.84-136

- Selinger, M (2009) Adaptive Traffic Control Systems in the United States: A review of the cost, maintenance and reliability of popular adaptive traffic control technologies.
- Shelby, S. G., D.M. Bullock, D. Gettman, R.S. Ghaman, Z.A. Sabra, and N. Soyke (2008). An Overview and Performance Evaluation of ACS Lite- A Low Cost Adaptive Signal Control System. . In Proceedings of the Annual Meeting of the Transportation Research Board, Washington, D.C., 2008
- Teo, K. T. K. (2010) Optimization of traffic flow within an urban traffic light intersection with genetic algorithm. *2010 Second International Conference on Computational Intelligence, Modelling and Simulation*
- Turksma, S. (2001) An overview of UTOPIA-SPOT deployment in Northern Europe. *Proceedings of 6th ITS World Congress, New York.*
- Vreeswijk, J. (2009) Energy-efficient traffic management and control for urban networks. *Paper prepared for POLIS Conference 2009.*
- Wismans, L.J.J., Berkum, E.C., Bliemer, M.C.J. (2009) Multi objective optimization of traffic systems using dynamic traffic management measures. *In: G. Fusco (ed.) Models and technologies for intelligent transportation systems. Proceedings of the international conference, Rome, Italy, pp. 29-34.*
- Wong, J.K.W. (2005) Intelligent building research a review
- Zhou, X.Z.B. (2010) Adaptive traffic light control in wireless sensor network based intelligent transportation system

Books:

1) J.D. Sterman (2000), Business Dynamics, System thinking and modeling for a complex world, Mc Graw Hill, Boston.
2) Richard Newton (2006), Project Management, Step by Step, how to plan an dmanage a highly successful project.
3) Bosch, N. (2012) CPH, Valby bus priority, functional specification.
4) Bosch, N. (2012) CPH, Valby bus priority, simulation report.
5) M.K.M. Mahmod (2011) Using Co-operative Vehicle Infrastructure Systems to Reduce Traffic Emissions and Improve Air Quality at Signalized Urban Intersections
6) N. van den Bosch (2012) Functional/Simulation Report ImFlow CPH, Valby bus priority
7) CPH 2025 Climate plan (2012) A green, smart and carbon neutral City. *The city of Copenhagen – Technical and environmental administration, edition September 2012.*
8) Imflow (2012) Next generation policy based adaptive control. *Imtech traffic & Infra.*
9) Kittelson & Associates, Inc. (2008) Signal timing manual. *U.S. Department of Transportation-Federal Highway Administration.*

Websites:

1. http://www.peektraffic.com
2. http://iopscience.iop.org/1742-5468/2011/04/P04008/figures
3. http://en.wikipedia.org/wiki/Sydney_Coordinated_Adaptive_Traffic_System_(SCAT)
4. http://www.scats.com.au/product_adaptive_control.html
5. http://www.trafficforum.ethz.ch
6. http://en.wikipedia.org/wiki/Traffic_light_control_and_coordination
7. http://www.autoevolution.com/news/how-do-traffic-light-control-systems-work-41839.html
8. http://rhythmtraffic.com/index.php/insync/
9. http://www.bolagsfakta.se/pressreleaser/visa/pressrelease/488673/imtech-breakthrough/10BC9D4D-4E48-25B9-AAC4-57EA3FACFB67
10. http://www.swarco.com/en/Products-Services/Traffic-Management/Urban-Traffic-Management/Urban-Traffic-Systems/UTOPIA
11. http://www.wegenwiki.nl/Adaptieve_regeling
12. https://www.educate-sustainability.eu/portal/content/copenhagen
13. https://subsite.kk.dk/sitecore/content/Subsites/CityOfCopenhagen/SubsiteFrontpage/LivingInCopenhagen/~/media/2E76B083C02740F69F288D9FDD6F3BAE.ashx
14. https://subsite.kk.dk/sitecore/content/Subsites/CityOfCopenhagen/SubsiteFrontpage/LivingInCopenhagen/~/media/2E76B083C02740F69F288D9FDD6F3BAE.ashx
15. http://en.wikipedia.org/wiki/Multi-criteria_decision_analysis
16. http://en.wikipedia.org/wiki/Social_return_on_investment
17. http://www.autoevolution.com/news/how-do-traffic-light-control-systems-work-41839.html
18. http://www.wired.com/wiredscience/2010/09/traffic-lights-adapt/

APPENDIX

Appendix A – Case study: CPH, Valby bus priority (Imflow)

In the south-western corner of Københavns Kommune, the area of Valby is located. Valby is mainly a residential district about 6 km from the city centre. The project area is delineated by three main roads, the Vigerslev Alle, the Toftegårds Alle and the Valby Langgade, and consists of ten signalized intersections. These ten intersections can be seen below in figure 14.

Name of the project:
CPH, Valby bus priority

Organization Client:
Københavns Kommune

Contact person Client:
Anders Boye Torp Madsen

Figure 14: Valby area with ten signalized intersections

In the project area there are 3 main bus lines active and three minor bus lines. There are 8 main bus lines (A-lines) active in the municipality of Copenhagen. These A-lines are characterised by their high frequency; they run every few minutes, and they contain most passengers compared with the other bus lines. The A-lines are seen as the backbone of bus transport in central Copenhagen.

The minor bus lines are indicated by the letters S & E. These are express buses that operate on longer lines, with fewer stops. These lines have a lower frequency, approximately every 30minutes and drive further into the suburbs of Copenhagen.

Policies

In the vision of the Københavns Kommune, green growth and green mobility are guidance for the implementation of ITS systems. Encouraging public transport is a key policy objective for Københavns Kommune in achieving their environmental goals. An important pre-condition to implementing a successful public transport strategy is a perceived high quality level by the general public. Key success factors are travel time and punctuality of the public transport service, as well as the accuracy of predicted waiting times. For travellers, the public transport alternative should enable them to reach their destination faster, cheaper and less stressful than alternative modes of transport.

Based on intelligent traffic light optimization, public transport can be prioritized throughout the road network. One of the major advantages of this solution is conditional priority as well as system flexibility. This allows the system to be expanded to support temporary optimization for other modes of transport (e.g. cyclists or pedestrians) as well as event management.

Policy Objectives

The key focus in this project is to establish a direct link between the municipality's policy objectives and signal timings at intersections. The main objective is to improve the travel time of the bus lines. Line 18 has the highest priority in the network, together with lines 1A and 4A. In addition to this main objective there is a secondary objective to achieve green growth and green mobility by improving the waiting time for pedestrians and cyclists in the network.

Public Transport

For bus priority the following objectives are defined:

- Increasing the average speed of line 18 during rush hours with 5 percent.
- Reducing the average waiting time of line 18 during rush hours with 5 seconds per intersection.
- Increasing the average speed of line 1a and 4a during rush hours with 5 percent.
- Reducing the average waiting time of line 1a and 4a during rush hours with 5 seconds per intersection.

During the simulation phase a comparison is made between the situation with the new designed controller applications without ImFlow and the situation with ImFlow. PT objectives in this phase are:

- Reducing average delay
- Average travel time

Pedestrians and Cyclists

For pedestrians and cyclists the following objectives are defined:

- Maximum average waiting time of the pedestrians on pedestrian priority crossings is 55 seconds.
- Maximum average waiting time of the cyclist on cyclists' priority crossings is 55 seconds.

At the moment there is no detection for pedestrians and cyclist, so there are no reports about the waiting times of pedestrians and cyclists.

Besides the objectives for the public transport, pedestrians and cyclist there are also objectives concerning the total network:

- No structurally growing queues on side directions excluding the shortcut routes.
- Total network performance will be the same

With no performance indicators of the current traffic flow it's hard to measure these objectives on street. Although in the simulation models it is possible to measure these performance indicators. So the Performance is determined by the model. The results of the simulation study are presented briefly below.

Results

The simulations show that the performance of ImFlow on network level is much better than the currently used fixed time programs. Figure 15 and 16 below show the average delay time for the current and the future situation with ImFlow during the morning and afternoon rush hour for the different modalities within the network.

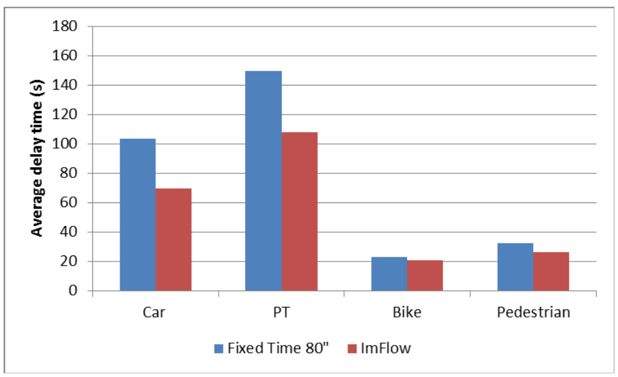


Figure 15: Network performance morning rush hour

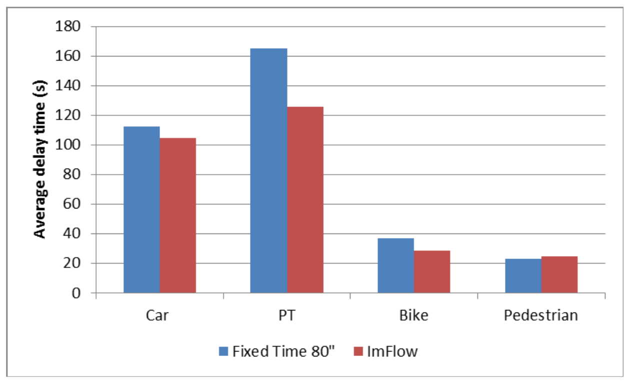


Figure 16: Network performance afternoon rush hour

Especially in the morning ImFlow is performing very well with every work day 139 hour less delay time. In the morning rush hour ImFlow is able to improve the average travel time of the bus lines but also to get rid of most of the queues on the main directions. Also the low speed traffic modalities share in this good result by lowering the average delay time and as a result the travel time.

In the evening the percentage difference is a bit lower, but still a reduction of 67 delay hours.

Zooming in on the main objective, improving the travel time of the bus lines in the area, there are some differences between the bus lines. Overall there is a strong reduction of the delay time of the busses, according to the pictures below this reduction is due to the lines 18, 1A and 4A, the three main lines in the Valby area. The other 3 minor bus lines are performing quite different. Overall de average delay time is lower with ImFlow. The performance of bus line 26 is slightly worse compared with the old situation.

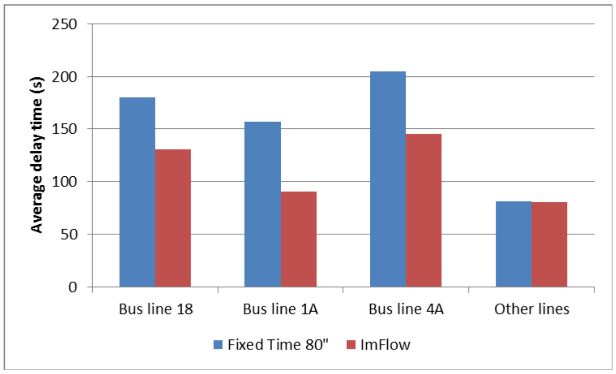


Figure 17: Network performance morning: bus lines

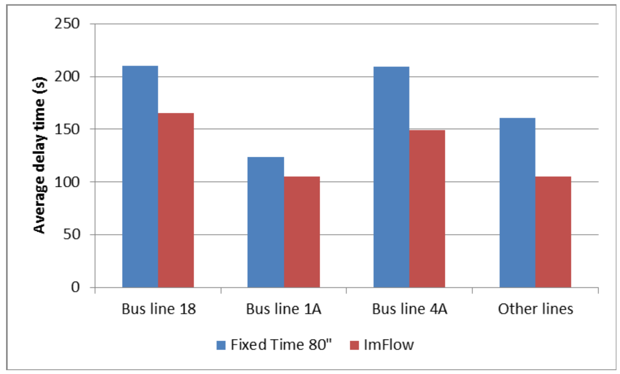


Figure 18: Network performance afternoon: bus lines

From the PT operator MOVIA there is a report available of the performance of the busses during the first quarter of 2012. This report concerns the lines 18, 1a and 4a. To evaluate the PT objectives after implementation a similar report will be made by Movia. A comparison of both reports results in a review of the objectives. The complete implementation of Imflow at the 10 intersections will be ready around March 2013.

Conclusions

The decrease in delay time during the morning rush hour can be up to more than 30% of the current delay time.

In the afternoon the results are slightly lower but still a very good result for the motorized traffic and also the cyclists. With Imflow the waiting time for pedestrians in the afternoon is almost the same as in the old situation with the fixed time controllers. Due to the enormous gains in network performance the social costs caused by delays in the network will also decrease.

Based on the results of ImFlow and having in mind the traffic policies of the municipality it turns out that ImFlow is a traffic control system that can improve the traffic situation in the Valby area. Implementing ImFlow will result in buses with less delay, but also the other modalities benefit from implementing ImFlow.

Appendix B - The Technical and Environmental Administration

The essential tasks of the Administration are authorities processing within the environmental and the roads and traffic field, district planning, urban renewal and processing of building projects. In addition, the Administration handles the cleaning and maintenance of the roads and parks of Copenhagen as well as parking control. The City's cemeteries also belong under the Technical and Environmental Administration. The vision of Copenhagen is that they should have the world's best city environment and a unique urban life, and their values focus on trust, openness and a comprehensive view. The Technical and Environmental Administration consists of eleven smaller departments.

1. Center for public construction
2. Urban Design
3. Center for construction
4. Center for Cemeteries
5. Centre for Environment
6. Parks and Nature
7. Centre for Parking
8. Centre for Cleaning
9. Centre for Resources
10. **Centre for Traffic**
11. Copenhagen Business Services

Center for Traffic

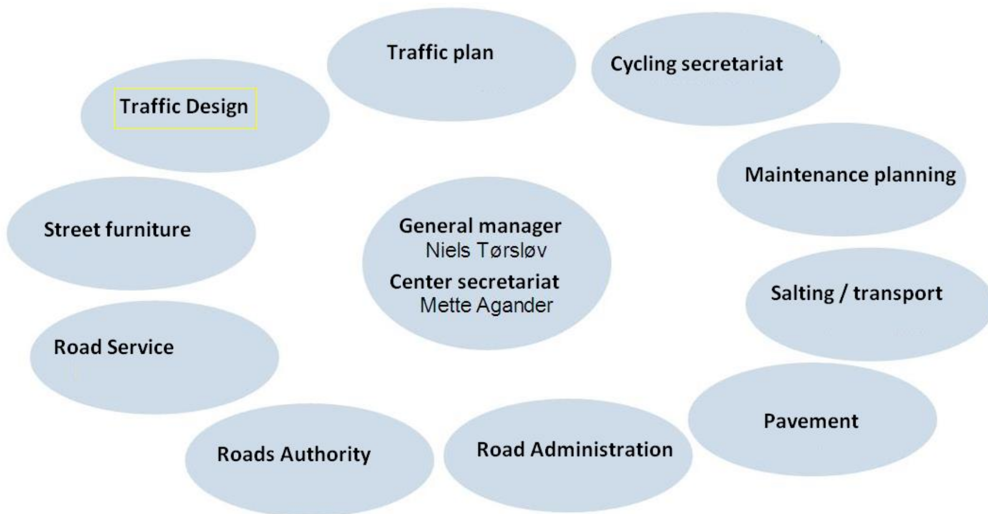
The Centre for Traffic is responsible for the traffic and road network. They plan traffic with particular focus on cycling, school, roads, public transport and road safety. The tasks of this department include:

- Maintenance of the road network
- signaling,
- signage,
- striping,
- traffic counts,
- clearing of snow / salting of the roads
- Managing the private roads and street lightning
- Giving permits for containers, scaffolding and excavations.
- Ensure that everyone - including children, the elderly and the disabled - can move freely, comfortable, safe and secure in Copenhagen.

The center of Traffic contains of 10 smaller departments, as can be seen in this figure below.

Center for Trafik

Organisation pr. 1. januar 2013



Appendix C - List of all criteria and their descriptions.

1. Complexity of the Network
   The more complex a network is, the more added value an ATMS can offer. Complexity of the network can be caused by the structure of the network. A network can be of the form: arterial/grid/ring-radial etc. Besides the structure, the variation of the distances between the intersections plays a role. An ATMS doesn't need to control with a fixed time cycle, an ATMS is very useful when the distances show a high variation.
2. Density of Network
   With this criterion we mean the density of the network itself. How far are the several intersections away from each other? Distances from down and upstream intersections. "A higher density has an advantage for implementing an ATMS" A low network density will lead to platoon dispersion. The further intersections are away from each other the higher the platoon dispersion will be, this has negative impact on the functionality of an ATMS. Also it will require additional detection between the intersections to predict the arrival of the vehicles.
3. Network congestion
   A network which is heavily congested and have many queues might be more interesting for implementing an ATMS. If a network isn't congested at all, the need for an investment in ATMS is low.
   Network congestion depends on the carrying capacity and the traffic intensity.
4. Network saturation
5. Network robustness
   The robustness of a network is a characteristic of the system. It is the ability of function retention under changing conditions. Changing conditions include the fluctuations in supply and demand of road users. This fluctuations include all 'normal' fluctuations: the difference in demand between peak and off-peak, or between holidays/weekends and weekdays, but also the influence of weather conditions, accidents, planned closures (major road works), or extreme events. Fragility is the opposite of robustness. A network that is fragile is not robust. When the network is fragile, unexpected flows can't be handled by the fixed time controllers which result in congestion and queuing. Here an ATMS might offer a solution.
6. Traffic Flow Variations
   A timing plan is developed for a specific set of traffic conditions. When these changes substantially, the timing plan loses effectiveness. With this criterion we consider the traffic flow variations/fluctuations of the network on the day itself and day to day. When a network has traffic flow variations, it can still be a robust network. A network can for example have high traffic flow in one direction at several intersections in the morning rush hour and the contrary direction in the evening rush hour. When this occurs every day the fixed time control can work with several timing plans and adapt to this situation. A fixed time plan is mostly changed based on the time of the day. However when there is a huge variation in the day itself and day to day, the adaption of fixed time is limited. In these networks it might be interesting to install an ATMS, because the system will adjust directly to the actual situation.
7. Network geometrics
   Width of lanes and approaches of the several streets in the network)
8. Limited expansion capacity current infrastructure
   If expansion of the current infrastructure is limited, optimal usage of current traffic network is required.
9. Conflicting modalities/traffic flows

Bus routes / bicycle lanes / heavy vehicle routes / main roads are contrary to each other in the network which results in conflicting situations. An ATMS will control these modalities based on the current traffic situation.

10. Separated bus lanes
    Separated bus lanes might be an advantage for an ATMS, as it is easier to give priority to buses in the network compared to a fixed time controlled network.
11. Separated bicycle lanes
    It is easier to detect bicycles on separated lanes instead of detecting them when they are among the rest of the traffic. This way it is easier to separate the several user groups and give them a priority.
12. Conflicting main roads
    It is more difficult to synchronize intersections with crossing main roads compared with a crossing of one main road and minor road. It is also difficult when you it is hard to tell which one is the main road. The advantage of an ATMS is that the system will create a balance.
13. The presence of Green bicycle lanes / bicycle super lanes / bicycle PLUS net lanes.
    The presence will probably not be significant. An ATMS is suitable when this green bicycle lanes conflict with other modalities. On the other hand it might be easier to give priority to these cyclers on intersections which are part of an ATMS.
14. The presence of heavy vehicle routes in the network
    In Copenhagen some routes are appointed as preferred heavy vehicles routes. The number of heavy vehicles on these routes is higher compared to other roads. ATMS can cooperate with a module (FREILOT) which gives priority to HGV and therefor it can be more interesting to install an ATMS here
    ATMS systems have the possibility to attach cooperative functionality. With the ATMS you must be prepared for future developments.
15. Disturbing elements/factors
    In a network there can be a number of disturbing factors which make it more difficult to configure an ATMS. Some of these disturbing factors can be: side streets, parking places alongside of the streets, supermarkets, shopping centres, event halls, stadiums, fuel stations, zebra crossings, roundabouts, varying speed limitations in the network etc. The more disturbing elements, the better you have to think about handling these elements. An ATMS haves some filters for this, and is better in handling the disturbing elements. We also have to distinguish negative disturbing elements, this are elements which make it more difficult to install an ATMS compared to other areas where these elements are not present.
16. Total number of vehicles entering network
    This might be an important criteria cause making improvement by installing an ATMS for a network of 5000 daily users or 15000 users makes a difference. The trade-off (total operational benefits) for a network with more users is higher (not taken into account the costs).
17. Conditional public transport priority in the network
    This criterion depends on the number of A and S bus lines in the network and the importance of each line. An ATMS can give priority under certain circumstances to specific bus lines or routes.
18. Necessity/need of traffic management data
    After implemeting an ATMS in a specific network a huge variety of data will be available to the city. This traffic information can be: number of stops, number of cars on each link, CO2 footprint, waiting time, queeing information. For some areas it might be more relevant to obtain traffic management information than for others.
19. Complains from road users
    If a network/area get many complains from road users, this might be an indication of the quality. These complains are very relevant. Complains about traffic lights are mostly send to the municipality.

Appendix D - Pair-wise comparison survey:

Each network has its own characteristics/criteria and unique elements. Some area are more suitable for implementing an adaptive traffic management system (ATMS). After identifying the different criteria that influence the implementation of an adaptive traffic management system (ATMS), it was important to construct main categories and sub categories. The final structure consist of 3 main criteria and 12 sub-criteria:

Main criteria:	**Network composition (1)**	**Network usage (2)**	**Conflicts & priority (3)**
Sub criteria:	Network complexity	Network congestion	Conflicting modalities
	Network robustness	Red light violation	Importance of PT priority
	Expansion possibilities	Changing traffic conditions	Importance of bicycle priority
		Unpredictable traffic patterns	Importance of heavy vehicle priority

Each criteria of the first (main) and second (sub-criteria) hierarchy needs to be compared in pairs, using individual pair-wise questions.

Purpose: The purpose of these comparisons is to determine the relative importance of the criteria/characteristics for implementing an ATMS. So in other words: which presence of criteria in a network are most interesting for installing an ATMS. These weights extracted from the judgements by experts will be used to analyse and compare several areas in Copenhagen for implementing an adaptive traffic management system.

In the current situation all networks are controlled by fixed time controllers.

For example: Network 1 is less interesting for implementing an ATMS , where it might be very interesting for implementing it in Network 2.

Network 1	**Network 2**
Simple arterial network	Complex network
Many expansion possibilities	No expansion possibilities
No network congestion	Heavy network congestion
Traffic conditions are fixed	Traffic conditions change a lot
No conflicting modalities	Conflicting modalities (cars, buses, bicycles)
No priorities	Bicycle priority is very important

This pair-wise questionnaire consists of 20 comparisons, which will not take more than 15 minute to complete. **However the pair-wise comparison method demands careful considerations**. To indicate the importance of one criteria over another, we use the following 1-9 scale. A description of each criteria is shown under the pair-wise comparison. It is recommended to read every criteria description before filling in the ‘answer’. The value (answer) can be chosen by pressing the little square. Please save the document when completed and sent it back to l.v.d.heijden@student.tue.nl.

Value	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak or slight	slightly favour one criteria over another
5	Moderate importance	Moderately favour one criteria over another
7	Strong importance	Strongly favour one criteria over another
9	Very strong importance	An criteria is favoured very strongly over another

Example:

Goal: Determine the most suitable areas to implement an adaptive traffic management system (which criteria are most important to determine the suitability of an ATMS in a certain area)

<u>Of the 2 criteria given below which one influences more and how much more?</u>

A	9	7	5	3	1	3	5	7	9	B
Network composition	☐	☐	☐	☐	☐	☐	☒	☐	☐	Network usage

Answer: The experience and judgement of the respondent shows that 'Network usage' is moderately more important the network composition with respect to the abovementioned goal.

START

Sub criteria:

A	9	7	5	3	1	3	5	7	9	B
Network complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Network robustness**

A	<u>Network complexity</u> *The Complexity of a network is caused by several characteristics. The more complex a network is, the more added value an ATMS can offer. Complexity of the network can be caused by the structure of the network. Networks can have different forms: arterial/grid/ring-radial etc. Besides the structure, the variation of the distances between the intersections plays a role. A network is also more complex when urban plans, local plans and traffic plans are in conflict with each other. The more complex a network, the more useful a ATMS will be.*
B	<u>Network robustness</u> *The robustness of a network is a characteristic of the system. It is the ability of function retention under changing conditions. Changing conditions include the fluctuations in supply and demand of road users. This fluctuations include all 'normal' fluctuations: the difference in demand between peak and off-peak, or between holidays/weekends and weekdays, but also the influence of weather conditions, accidents, planned closures (major road works), or extreme events. Fragility is the opposite of robustness. A network that is fragile is not robust. When the network is fragile, unexpected flows can't be handled by the fixed time controllers which result in congestion and queuing. A fragile network leads to unreliable travel times. An ATMS can decrease the fragility of an network and therefor improve the robustness.*

A	9	7	5	3	1	3	5	7	9	B
Network complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	**Expansion possibilities**

A	<u>Network complexity</u> *The Complexity of a network is caused by several characteristics. The more complex a network is, the more added value an ATMS can offer. Complexity of the network can be caused by the structure of the network. Networks can have different forms: arterial/grid/ring-radial etc. Besides the structure, the variation of the distances between the intersections plays a role. A network is also more complex when urban plans, local plans and traffic plans are in conflict with each other. The more complex a network, the more useful a ATMS will be.*
B	<u>Limited expansion capacity current infrastructure</u> *If expansion of the current infrastructure is limited, optimal usage of current traffic network is required. This is also one of the reasons why road authorities and other traffic departments are currently investing in intelligent traffic systems for these areas. An adaptive traffic management system utilize the traffic capacity to its absolute max.*

Appendix E - Reciprocal & normalized matrices for all sub-criteria.

	Network Complexity	Network Robustness	Expansion possibilities	Special lanes
Complexity	1,00	0,55	0,79	3,93
Robustness	1,83	1,00	1,09	3,93
Expansion possibilities	1,27	0,92	1,00	3,56
Special lanes	0,25	0,25	0,28	1,00
Sum	4,36	2,72	3,16	12,41

Table 18: Reciprocal matrix for subcriterion 'Network composition'.

	Complexity	Robustness	pansion possibilit	Special lanes	SUM (EV)	Norm. Eigenvector
Complexity	0,23	0,20	0,25	0,32	1,00	0,25
Robustness	0,42	0,37	0,34	0,32	1,45	0,36
Expansion possibilities	0,29	0,34	0,32	0,29	1,23	0,31
Special lanes	0,06	0,09	0,09	0,08	0,32	0,08
Sum	1,00	1,00	1,00	3,00	4,00	1,00

Table 19: Normalized matrix for subcriterion 'Network composition' with the 'Normal eigenvector' (weight).

	Network Congestion	Red light violation	Changing traffic conditions	Unpredictable traffic patterns
Network congestion	1,00	6,21	0,52	1,25
Red light violation	0,16	1,00	0,23	0,19
Changing traffic conditions	1,93	4,43	1,00	1,16
Unpredictable traffic patterns	0,80	5,16	0,86	1,00
Sum	3,90	16,81	2,60	3,60

Table 20: Reciprocal matrix for subcriterion 'Network usage'.

	Network Congestion	Red light violation	Changing traffic conditions	Unpredictable traffic patterns	SUM (EV)	Normalized Eigenvector
Network congestion	0,26	0,37	0,20	0,35	1,17	0,29
Red light violation	0,04	0,06	0,09	0,05	0,24	0,06
Changing traffic conditions	0,50	0,26	0,38	0,32	1,47	0,37
Unpredictable traffic patterns	0,21	0,31	0,33	0,28	1,12	0,28
Sum	1,00	1,00	1,00	1,00	4,00	1,00

Table 21:Normalized matrix for subcriterion 'Network usage' with the 'Normal eigenvector' (weight).

	Conflicting modalities	Public transport priority	Bicycle priority	Heavy truck priority
Conflicting modalities	1,00	0,92	2,84	1,55
Public transport priority	1,09	1,00	2,47	2,76
Bicycle priority	0,35	0,41	1,00	1,01
Heavy truck priority	0,64	0,36	0,99	1,00
Sum	3,09	2,69	7,29	6,32

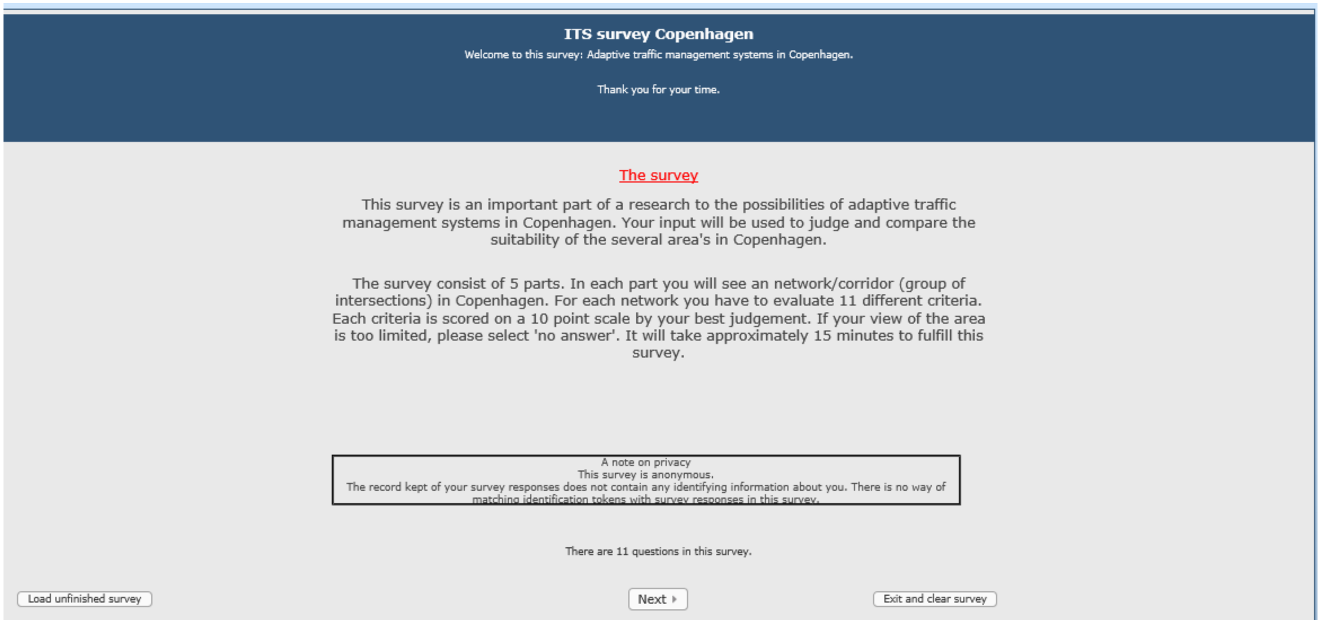
Table 22: Reciprocal matrix for subcriterion ‘Conflicts & priorities’.

	Conflicting modalities	Public transport priority	Bicycle priority	Heavy truck priority	SUM (EV)	Normalized Eigenvector	Corrected
Conflicting modalities	0,32	0,34	0,39	0,25	1,30	0,33	0,26
Public transport priority	0,35	0,37	0,34	0,44	1,50	0,37	0,30
Bicycle priority	0,11	0,15	0,14	0,16	0,56	0,14	0,11
Heavy truck priority	0,21	0,13	0,14	0,16	0,64	0,16	0,13
Car priority							0,20
Sum	1,00	1,00	1,00	1,00	4,00	1,00	1,00

Table 23: Normalized matrix for subcriterion ‘Conflicts & priorities’ with the ‘Normal eigenvector’ (weight).

Appendix F - Screenshots online questionnaire

http://www.its-survey.eu


ITS survey Copenhagen

Welcome to this survey: Adaptive traffic management systems in Copenhagen.

Thank you for your time.

The survey

This survey is an important part of a research to the possibilities of adaptive traffic management systems in Copenhagen. Your input will be used to judge and compare the suitability of the several area's in Copenhagen.

The survey consist of 5 parts. In each part you will see an network/corridor (group of intersections) in Copenhagen. For each network you have to evaluate 11 different criteria. Each criteria is scored on a 10 point scale by your best judgement. If your view of the area is too limited, please select 'no answer'. It will take approximately 15 minutes to fulfill this survey.

A note on privacy
This survey is anonymous.
The record kept of your survey responses does not contain any identifying information about you. There is no way of matching identification tokens with survey responses in this survey.

There are 11 questions in this survey.

Load unfinished survey | Next | Exit and clear survey


In which department within the municipality of Copenhagen (København kommune) are you working?

Check any that apply

- ☐ Traffic Design
- ☐ Traffic Plan
- ☐ Cycling Secretariat
- ☐ Financial Department
- ☐ Other:

Description:
Above you see a big picture of the Nørreport area, the yellow shading indicated the network existing of 9 intersections (05.01 / 05.02 / 05.03 / 05.04 / 05.05 / 05.06 / 05.07 / 18.08).

scale	1	2,3,4	5-6	7,8,9	10
Network comlexity	very simple nework	↔	normal network	↔	very complex network
Network robustness	fragile network	↔	normal network	↔	very robust network
Expansion possiblities	none	↔	normal	↔	extreme many
Red light violation	no red violation	↔	normal percentage	↔	extreme high percentage
Unpredictable traffic patterns	100% predictable	↔	normal traffic patterns	↔	extreme unpredictable
Changing traffic conditions	never change	↔	normal changes	↔	extreme many changes

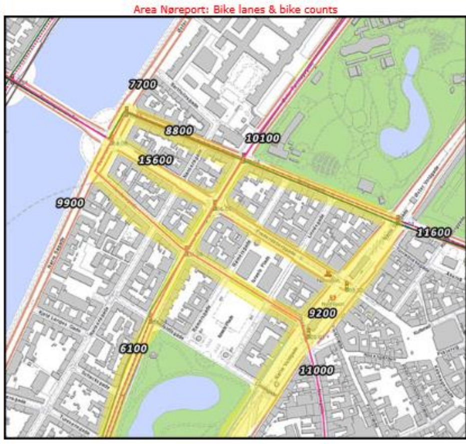
For a detailed explanation of the critera, move your mouse over the next criteria: Complexity, Robustness, Expansion possibilities, Red light violation, Unpredictable traffic patterns, Changing traffic conditions.

Judgments:
We would like to receive your best judgment on a scale from 0 - 10 of the several criteria shown above in the table. If your view/understanding of this area is too limited, please select 'no answer'.

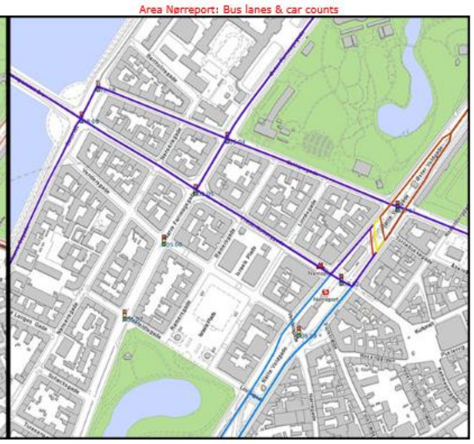
	1	2	3	4	5	6	7	8	9	10	No answer
Network Complexity	○	○	○	○	○	○	○	○	○	○	◉
Network robustness	○	○	○	○	○	○	○	○	○	○	◉
Expansion possibilities	○	○	○	○	○	○	○	○	○	○	◉
Red light violation	○	○	○	○	○	○	○	○	○	○	◉
Unpredictable traffic patterns	○	○	○	○	○	○	○	○	○	○	◉
Changing traffic conditions	○	○	○	○	○	○	○	○	○	○	◉

traffic patterns
Changing traffic conditions ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ◉

Area Nøreport: Bike lanes & bike counts



Area Nørreport: Bus lanes & car counts



Description:
In the area around Nørreport are many bicycle lanes seperated from the normal lanes. Aboven in the left picture you can see the average number of bikes (total of both directions) for several bike lanes (2008-20011). Most of the bike paths belong to the Plusnet, some are designated to the green bicyle network. There is also planned a super bicycle path in this area, which is shown by the green line going through Gothersgade.

The area is characterized by several major bus lines driving to or leaving from Nørreport station. The right picture above shows the several buslines. The most important bus lines are: 5A / 6A / 11A / 150S / 350S / 173E.

Description:
In the area around Nørreport are many bicycle lanes seperated from the normal lanes. Aboven in the left picture you can see the average number of bikes (total of both directions) for several bike lanes (2008-20011). Most of the bike paths belong to the Plusnet, some are designated to the green bicyle network. There is also planned a super bicycle path in this area, which is shown by the green line going through Gothersgade.

The area is characterized by several major bus lines driving to or leaving from Nørreport station. The right picture above shows the several buslines. The most important bus lines are: 5A / 6A / 11A / 150S / 350S / 173E.

scale	1	2,3,4	5-6	7,8,9	10
Conflicting modalities / traffic flows	no conflicts	↔	average nr. of conflicts	↔	extreme many conflicts
Bicycle priority	no priority	↔	average priority	↔	extreme high priority
Heavy traffic priority	no priority	↔	average priority	↔	extreme high priority
Public traffic priority	no priority	↔	average priority	↔	extreme high priority
Car priority	no priority	↔	average priority	↔	extreme high priority

For a detailed explanation of the critera, move your mouse over the next criteria: Conflicting modalities/traffic flows, bicycle priority, heavy vehicle priority, public transport priority, car priority.

Judgments:
We would like to receive your best judgment on a scale from 0 - 10 of the several criteria shown above in the table. If your view/understanding of this area is too limited, please select 'no answer'.

	1	2	3	4	5	6	7	8	9	10	No answer
Conflicting modalities/traffic flows	○	○	○	○	○	○	○	○	○	○	◉
Bicycle priority	○	○	○	○	○	○	○	○	○	○	◉
Heavy vehicle priority	○	○	○	○	○	○	○	○	○	○	◉
Public transport priority	○	○	○	○	○	○	○	○	○	○	◉
Car priority	○	○	○	○	○	○	○	○	○	○	◉

Resume later | ◂ Previous | Next ▸ | Exit and clear survey

Appendix G - Data set online questionnaire

	Norrport area											Jagtvej										
ID	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**
4	8	5	4	5	6	7	5	8	4	7	4	7	7	7	5	6	6	4	7	3	6	7
5							8	8	3	9	3	7	4	6	9	3	2	9	10	2	10	4
9	5	6	2	3	8	10	8	8	4	9	2	2	2	3	4	2	9	4	8	5	8	3
12	7	4	6	9	5	4	9	9	5	9	4	4	7	8	8	3	4	5	8	6	9	4
14	5	8	2	5	2	3	2	7	5	8	3	3	6	1	5	3	2	3	7	3		3
15	5	3	3	3	4	6	6	7	2	6	3	3	5	3	5	5	5	5	5	4	6	5
18	8	4	2	5	3	6	9	10	7	10	8	5	3	2	5	5	5	7	7	6	8	7
22	8	4	5	4	4	4	9	9	2	9	3	5	5	4	4	4	4	7	7	5	6	5
23							9	10		10								10	10		10	10
24	9	2	2		9	4	8	10	7	10	7	9	1	1		7	4	8	10	8	10	8
26	7	4	4	6	8	7	8	7	2	9	3	4	5	3	7	2	5	5	7	5	7	5
28	5	6	3	2	3	4	3	9	5	7	5	1	8	3	3	4		4	7	3	9	4
30	4	6	2	6	5	7	6	8	6	8	6	3	3	3	6	6	7	5	6	5	7	5
31	9	4	4	6	5	8	7	10	1	10	5	4	6	6	5	3	9	5	8	2	4	8
39	5	5	1		5	5	9	10	8	10	6	5	5	1		5	3	7	10	3	10	5
40	5	3	1		4	3	9	7	2	10	2	2	5	2		2	7	6	5	5	7	5
41																						
44																						
49	2	3	5	8	4	7	4	5	4	6	9	4	5	3	9	4	6	4	8	2	8	4
50							7	7	8	8	4				5	5	5	7	9	5	5	5
53	8	5	5	7	4	8		5	3	7	7	4	7	2	5	5	5	7	5	5	6	6
54																						
56	7	7	3	5	7	9	7	7	3	7	3	7	4	3	6	5	5	7	5	3	7	3
57	8	4	3	9	4	4	9	7	7	10	7	8	8	8	6	5	4	6	5	6	7	7
63	6	4	1	4	4	3	4	8	3	6	5	8	3	1	4	2	2	6	7	3	7	5
66	7	5	3	8	3	9	8	9	2	9	6	4	4	3	6	5	5	5	7	4	8	3

ID	Central station											Lyngbyvej										
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
4	7	6	2	6	5	6	7	7	4	8	5	7	7	4	8	5	6	7	7	6	5	7
5	10	4	3	7	3	2	8	10	3	10	4	9	5	7	7	4	3	9	10	8	10	8
9	6	7	8	4	5	5	8	8	5	9	4	7	7	8	5	5	9	7	8	8	9	6
12	6	6	7	6	3	3	3	7	5	8	4	8	6	7	8	4	3	4	7	6	9	7
14	6	4	1	5	4	4		8	2	10	2	4	5	6	5	4	2	3	6	8	10	8
15	7	6	6	5	5	5	7	6	5	7	5	5	7	8	5	4	5	7	4	6	7	7
18	8	3	2	5	7	7	9	9	7	10	7	7	6	4	5	3	7	7	8	7	9	8
22	9	7	8	6	5	5	9	8	3	10	3	5	8	8	5	4	6	3	9	7	9	9
23							10	10		10	10							10	10		10	10
24	8	4	3		3	7	6	7	10	9	9	8	8	6		4	6	8	8	8	9	8
26	7	4	5	7	4	5	8	7	4	8	4	6		6	5	3	5	4	7	7	7	8
28	3	6	2	7	8	7	4	8	7	9	3	2	9	2	3	9	5	3	2	3	9	8
30	8	3	2	6	7	7	8	5	7	9	6	6	7	7	4	4	8	7	4	6	7	8
31	8	4	7	5	8	8	7	7	2	10	4	6	5	6	5	4	8	5	5	7	8	9
39	8	5	2		5	5	7	10	2	10	5	6	7	6		3	3	6	10	8	10	8
40	6	4	4		8	8	9	4	4	9	4	8	4	6		4	7	10	8	8	10	7
41																						
44																						
49	7	1	4	7	8	10	5	7		8	6	3	6	1	4	6	3	3	6	4	10	4
50			9	7	7	7	6	3	6	7	6				6	4	5					
53	7	5	5	7	5	7	9	7	5	8	7	5	6	6	3	5	8	8	4	7	8	8
54																						
56	5	7	5	5	5	6	5	6	3	7	3	5	8	8	6	7	7	7	5	6	7	6
57	6	6		7	4	4	9	7	7	9	8	8	8	8	5	5	5	5	8	7	8	8
63	5	7	2	5	4	6	5	7	4	7	5	5	3	3	3	4	5	5	7	5	8	7
66	8	3	3	7	5	7	8	6	3	8	4	5	6	7	3	4	6	6	6	7	9	8

Network south Copenhagen

ID	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
4	6	7	4	5	6	6	5	6	7	6	7
5	7	5	6	3	2	2	7	5	10	10	10
9	6	7	8	5	2	9	3	8	9	9	8
12	8	6	7	8	3	2	4	6	7	7	8
14	3	6	4	6	2	2	2	6	10	7	10
15	4	7	7	5	3	5	2	3	7	8	8
18											
22	5		7	5	5	7	7	8	7	6	7
23							10	10		10	10
24	6	2	3		3	7	5	3	10	3	10
26	8	6	3	4	5	5	8	6	8	7	8
28	7	7	5	4	4	6	5	4	4	4	8
30	4	7	8	5	4	8	4	4	7	5	9
31	5	5	7	5	6	10	6	4	8	4	10
39	8	6	4		5	5	8	10	7	10	7
40	7	5	6		2	3	8	2	8	3	8
41											
44											
49	4	8	6	4	7	6	3	4	8	8	8
50							6	4	8	7	8
53	3	7	7	2	3	3	4	5	6	7	7
54											
56	5	8	7	6	6	6	7	4	6	7	6
57	7	6	6	6	4	4	7	5	6	7	8
63	6	3	3	3	2	3	6	6			
66	6	5	6	5	3	6	6	4			

Prioritizing areas for the implementation of an adaptive traffic management system within the municipality of Copenhagen

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ABSTRACT

In recent years, governments are facing the challenges of climate change. Traffic is responsible for several environmental problems in urban areas. Traffic congestion poses a challenge for all large and growing urban areas. Especially Carbon Dioxide has become an increasingly serious problem due to its negative impacts on the climate change. Because of this, the municipality of Copenhagen wants to become completely CO2 neutral by 2025. Within the area of mobility, budgets have been set for the coming years. A part of this budget is reserved for the implementation of ITS solutions in Copenhagen, which among other things will contribute to a CO2 reduction. One of the This study is focused on the implementation of adaptive traffic management systems within municipality of Copenhagen.

Keywords: Adaptive traffic management systems, Analytical Hierarchy Process, Pair-wise comparison, Quantitative dominance scores, Municipality of Copenhagen.

Introduction

Carbon Dioxide has become an increasingly serious problem due to its negative impacts on the climate change. Because of this, the municipality of Copenhagen wants to become completely CO2 neutral by 2025. At present, traffic is responsible for 21% of the city's overall CO2 emissions, but it is intended that this will be reduced to **11%** by 2025.

Alongside the limited budget within the area of mobility, the municipality has to deal with the 'old' fixed time traffic technologies in the city and the limited possibilities for expansion of the infrastructure. Because of that, the municipality aims to optimize the current traffic network. One of the solutions is to implement adaptive traffic management systems (ATMS) in several areas of the city. One attraction of ATMS is the potential to achieve a better performance off an existing traffic network infrastructure without having to build expensive extra lanes or change the physical geography of a city's street network.

But one of the most difficult challenges is to find out which areas are (most) suitable for implementing an adaptive traffic management system (ATMS). This level of suitability depends on several criteria with various importance's that characterize an area. Obtaining this knowledge is the first step in selecting areas for implementing these ATM-systems.

Research aim

The main objective of this research is to show a ranking of areas that are (most) suitable for implementing an adaptive traffic control systems within the municipality of Copenhagen.

In order to achieve this main objective, the following goals are formulated:

• Construct a list of most important criteria for implementing an ATMS, and set the weights/priorities of each criteria;

• Select and characterize the different (relevant) areas within the municipality of Copenhagen by means of the chosen criteria;

• Rank the alternatives by using the overall dominance scores.

Research approach

To gain data for this research project, a certain approach has to be adopted. First of all, it is important to select the required methods and techniques.

Methods and techniques

There are several scientifically research methods available. In this research an Multi-Criteria Evaluation (MCE) is used. The MCE is a qualitative research method, used for comparing several independent alternatives based on various criteria. The complexity is caused by the multiplicity of criteria that are important in the strategic choice: ranking the areas for implementing an ATMS. A multi-criteria evaluation approach is suitable when an intuitive approach is not appropriate, for example because the decision-maker(s) feel the decision is too large and complex to handle intuitively, because it involves multiple objectives, or multiple stakeholders.

In this study, AHP (Analytical Hierarchy process) has been applied to identify the best suitable area for an ATMS. AHP is a specific research method of the Multi-Criteria Decision Analysis (MCDA). The AHP method makes it possible to decompose the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analysed independently.

The composition of the entire set of criteria that play a role in the strategic choice between alternatives, were identified based on literature research and in-depth **interviews** with experts in the field of ATMS. To compare areas with the AHP method, it is important to know which criteria are more important. One of the major strengths of the AHP is the use of pair-wise comparisons. In this research the **pair-wise comparison** is applied to obtain the weights of the elements.

The next important step in a AHP is defining the alternatives (or choice-possibilities). The alternatives represent the 'different possibilities to solve the problem'. In this study, the alternatives are the different areas in Copenhagen and were selected in a group session with **expert panel II**. Expert panel II consist of several decision makers from different departments within the municipality of Copenhagen.

The criteria applied in a MCE serve as a tool to test the various decision alternatives from a particular point of view. After defining the areas, an online **questionnaire** is constructed to characterize the alternatives. The characterization of the areas is conducted by experts from 3 different departments of the municipality of Copenhagen. This characterization includes all criteria selected in the previous step.

The information obtained from the previous described steps will lead to the final step. The final step is to rank the chosen alternatives by using the characterization of the alternatives and the obtained weights. In this research the quantitative dominance overall scores will be used to rank the alternatives.

Results

Twelve criteria (or characteristics) were evaluated in this pair-wise comparison. Changing network conditions is considered as the most important characteristic for implementing an ATMS, while public transport priority (0,118) and conflicting modalities (0,0102) are considered as second and third most important characteristics. This is not surprising , because a network with a high degree of changing traffic conditions is difficult to manage with fixed time control. A network managed with fixed time control can work with several timing plans changed based of the time of the day. However when traffic conditions change frequently, the adaption of fixed time is limited. Partly because of these reasons, a high degree of 'changing traffic conditions' is considered by experts as the most important characteristic. One of the strengths of an ATMS is, that it can adapt to changing traffic conditions in real time. Table 1 shows the constructed list of most important criteria for implementing an ATMS.

Sub-criteria	Global weight
Changing traffic conditions	0,124
Public transport priority	0,118
Conflicting modalities	0,102
Network congestion	0,099
Network robustness	0,097
Unpredictable traffic patterns	0,095
Expansion possibilities	0,082
Car priority	0,079
Network complexity	0,067
Heavy traffic priority	0,050
Bicycle priority	0,044
Special lanes	0,022
Red light violation	0,020
Sum	1,00

Table 1: **Final weights of all sub criteria.**

Si	Alternative	Name	Ranking
0,045	A1	Central station	1
0,044	A3	Nørreport	2
-0,016	A4	Jagtvej	3
-0,028	A2	Lyngbyvej	4
-0,045	A5	South CPH	5

Table 2: Total scores Si and final ranking.

The second part of the research contained the characterization of the selected areas. Experts are required to evaluate the alternatives, as their judgments possess deeper knowledge about traffic management and they are familiar with the different areas in Copenhagen. For this online survey 50 invitations for participation are sent to experts of three departments of the municipality of Copenhagen (København kommune). These departments are: Traffic design, Traffic plan, and the Cycling department. The response rate of the 50 invited experts for the online survey was about 50 % (i.e. 26 completed questionnaires).

The result from both previous results are combined to calculate the final ranking. The quantitative dominance overall scores is used to rank the 5 area's. Table 2 shows the final ranking of the areas. Central station and Nørreport area are ranked as the most suitable areas for implementing an ATMS. Compared to the other areas evaluated in this research, these two areas are located in the centre of the city and contain all modes of travelling. These areas are both characterized by the many major and minor bus lines driving to or leaving to the Central station or Nørreport station. Together with the many cyclist and pedestrians this results in many conflicting situations. Considering the criteria it is not surprising that these two areas are ranked as number one and two.

Further research

For further research, it could be interesting if the various objectives for each area of the city will be determined. In some areas there is need for reducing the average waiting time for buses, in other areas the number of stops of cars should be reduced. There may be objectives concerning minimizing queue lengths, or prioritizing public transport, cyclers, trucks etc. To reach consensus between all involved actors and define the various objectives for each area is the basis for the implementation of ITS (e.g. ATMS).

The first ATMS is currently implemented in Valby. Valby is located south-western corner of The municipality of Copenhagen. An evaluation of the implementation of the real-time ATMS in the area of Valby should be performed. Disparities between the real operational improvements and the data from the simulation should be compared. Also the obstacles and difficulties during the implementation need to be defined. This evaluation will improve the implementation in other areas of the city in the nearby future.

Samenvatting

In de afgelopen jaren, zijn overheden geconfronteerd met de uitdagingen van de klimaatverandering. Het verkeer is verantwoordelijk voor verschillende milieuproblemen in stedelijke gebieden. Verkeerscongestie vormt een uitdaging voor alle grote en groeiende stedelijke gebieden. Vooral de uitstoot van Koolstofdioxide is een steeds ernstiger probleem vanwege de negatieve gevolgen op het klimaat. Mede hierdoor wil de gemeente Kopenhagen volledig CO2 -neutraal zijn in 2025 . Binnen de sector mobiliteit zijn budgets vastgesteld voor de komende jaren. Een deel van dit budget binnen mobiliteit is gereserveerd voor de toepassing van ITS-oplossingen in Kopenhagen. Deze toepassingen zullen ook bijdragen aan een CO2-reductie. Adaptieve verkeersmanagement systemen (AVMS) zijn een onderdeel van ITS-oplossingen. Dit onderzoek richt zich op de implementatie van Adaptieve verkeersmanagement systemen in Kopenhagen.

Introductie

De gemeente Kopenhagen wil volledig CO2 -neutraal worden in 2025 . Op dit moment is het verkeer verantwoordelijk voor 21 % van de totale CO2-uitstoot van de stad Kopenhagen , maar de bedoeling is dat dit zal worden gereduceerd tot 11 % in 2025 .

Naast het beperkte budget binnen de sector mobiliteit , heeft de gemeente Kopenhagen te maken met de 'oude' verkeersregelsystemen in de stad en de beperkte mogelijkheden van uitbreiding van de infrastructuur. Mede hierdoor, wil de gemeente het huidige verkeersnetwerk optimaliseren. Een van de oplossingen is om adaptieve verkeersmanagement systemen in verschillende gebieden van de stad te implementeren. Een sterk kenmerk van AVMS is het potentieel om een betere prestatie te realiseren binnen het bestaande verkeersnetwerk zonder extra dure rijstroken te bouwen andere infrastructurele veranderingen door te voeren.

Een van de moeilijkste uitdagingen is om uit te vinden welke gebieden (het meest) geschikt zijn voor de implementatie van een adaptief verkeersmanagementsysteem. Dit niveau van geschiktheid hangt af van verschillende criteria met verschillende prioriteiten die een gebied karakteriseren. Het verkrijgen van deze kennis is de eerste stap in het selecteren van gebieden voor de implementatie van AVMS.

Onderzoeksdoel

Het hoofddoel van dit onderzoek is om een rangschikking van gebieden te maken die (het meest) geschikt zijn voor de implementatie van een AVMS binnen de gemeente Kopenhagen.

Om dit hoofddoel te bereiken worden de volgende doelstellingen geformuleerd:

- Stel een lijst samen van de belangrijkste criteria voor de implementatie van een AVMS, en bepaal de gewichten/prioriteiten van elk criteria;

- Selecteer en karakteriseer de verschillende (relevante) gebieden binnen de gemeente Kopenhagen aan de hand van de gekozen criteria;

- Rankschik de alternatieven met behulp van de totale dominantie scores.

Onderzoeksmethoden en theoretisch kader

Er zijn verschillende wetenschappelijke onderzoeksmethoden beschikbaar. In dit onderzoek is gebruik gemaakt van een ‘Multi-Criteria Evaluation’ (MCE). De MCE is een kwalitatieve onderzoeksmethode, die wordt gebruikt voor het vergelijken van verschillende onafhankelijke alternatieven op basis van diverse criteria. De complexiteit wordt veroorzaakt door de veelheid van criteria die van invloed zijn bij het maken van een strategische keuze: de rangschikking van de gebieden voor de implementatie van een AVMS. Een Multi-criteria evaluatie aanpak is geschikt wanneer een intuïtieve benadering niet geschikt is , bijvoorbeeld omdat de beslissing bevoegde beoordeelt dat de beslissing te groot en complex is om intuïtief te behandelen; omdat het gaat om meerdere doelstellingen, of meerdere belanghebbenden.

In dit onderzoek, is de ‘Analytical Hierarchy Process’ (AHP) toegepast om de meest geschikte gebieden voor een AMVS te identificeren. AHP is een specifieke onderzoeksmethode die behoort tot de ‘Multi-Criteria Decision Analysis’ (MCDA) groep. Met de AHP methode is het mogelijk om het probleem te ontleden in een hiërarchie van sub-problemen, die elk onafhankelijk kunnen worden geanalyseerd.

De samenstelling van de gehele set van criteria die een rol spelen in de strategische keuze tussen alternatieven, werden geïdentificeerd op basis van literatuuronderzoek en diepte-interviews met experts op het gebied van AVMS. Om gebieden te vergelijken doormiddel van de AHP methode, is het belangrijk te weten welke criteria belangrijker zijn. Een van de sterke punten van de AHP methode is het gebruik van paarsgewijze vergelijkingen. In dit onderzoek is de paarsgewijze vergelijking toegepast om het gewicht van de criteria te verkrijgen.

De volgende belangrijke stap in een AHP is het definiëren van de alternatieven (of keuzemogelijkheden). De alternatieven vertegenwoordigen de verschillende mogelijkheden om het probleem op te lossen. In dit onderzoek zijn de alternatieven de verschillende gebieden in Kopenhagen, en deze werden geselecteerd in een groepssessie met experts. Deze experts zijn afkomstig van verschillende afdelingen binnen de gemeente Kopenhagen .

De criteria die toegepast worden in een MCE dienen als een instrument om de verschillende alternatieven vanuit een bepaald standpunt te toetsen. Na het definiëren van de gebieden, is een online vragenlijst geconstrueerd om de alternatieven te karakteriseren. De karakterisering van de gebieden wordt uitgevoerd door experts van 3 verschillende afdelingen binnen de gemeente Kopenhagen. Deze karakterisering bevat alle criteria die geselecteerd zijn in de vorige stap.

De verworven informatie uit de vorige stappen zal leiden tot de laatste stap in dit onderzoek. De laatste stap is om een rankschikking te construeren van de alternatieven met behulp van de karakterisering van de alternatieven en de bepaalde gewichten. In dit onderzoek worden de kwantitatieve dominantie scores gebruikt om alternatieven te rangschikken.

Resultaten

In het eerste gedeelte van het onderzoek werden twaalf criteria (of kenmerken) geëvalueerd door middel van de paarsgewijze vergelijking methode. Veranderende netwerk condities (0,124) werd beschouwd als het belangrijkste kenmerk voor de implementatie van een ATVS, terwijl openbaar vervoer prioriteit (0,118) en conflicterende modaliteiten (0,0102) werden beschouwd als tweede en derde belangrijkste kenmerken. Dit is niet verrassend, omdat een netwerk waarbij de condities veelvuldig veranderen moeilijk te beheren is met een ‘vaste’ verkeersregelinstallatie. Een netwerk beheerd door een ‘vaste’ verkeersregelaar kan werken met verschillende tijdsplannen gewijzigd op basis van het tijdstip van de dag . Echter wanneer de verkeerssituatie vaak veranderd, is de aanpassing van de verkeersregelaar beperkt. Mede omwille van deze redenen, wordt een hoge mate van 'veranderende verkeerssituaties' door experts beschouwd als het belangrijkste kenmerk. Een van de sterke punten van een ATVS is , dat het zich kan aanpassen aan veranderende verkeerssituaties in ‘real time’. Tabel 1 toont de geconstrueerde lijst van de belangrijkste criteria voor de implementatie van een AVMS.

Sub-criteria	Global weight
Changing traffic conditions	0,124
Public transport priority	0,118
Conflicting modalities	0,102
Network congestion	0,099
Network robustness	0,097
Unpredictable traffic patterns	0,095
Expansion possibilities	0,082
Car priority	0,079
Network complexity	0,067
Heavy traffic priority	0,050
Bicycle priority	0,044
Special lanes	0,022
Red light violation	0,020
Sum	1,00

Table 1: Final weights of all sub criteria.

Si	Alternative	Name	Ranking
0,045	A1	Central station	1
0,044	A3	Nørreport	2
-0,016	A4	Jagtvej	3
-0,028	A2	Lyngbyvej	4
-0,045	A5	South CPH	5

Table 2: Total scores Si and final ranking.

In tweede deel van het onderzoek, werden de geselecteerde gebieden gekarakteriseerd. Deskundigen zijn gevraagd om de alternatieven te evalueren, omdat zij veel kennis hebben over verkeersmanagement en ze vertrouwd zijn met de verschillende geselecteerde gebieden in Kopenhagen. Voor dit online onderzoek zijn 50 uitnodigingen verstuurd aan deskundigen van drie afdelingen binnen de gemeente Kopenhagen (København kommune). Deze afdelingen zijn: : 'Traffic design', 'Traffic plan', en de 'Cycling department'. De respons van de 50 uitgenodigde deskundigen voor de online enquête was ongeveer 50% (26 ingevulde vragenlijsten).

De resultaten van beide gedeeltes zijn gecombineerd om de kwantitatieve dominantie scores te berekenen. De kwantitatieve dominantie totaalscores wordt gebruikt voor het rangschikken van de 5 regio's. Tabel 2 toont de eindstand van de gebieden. 'Centraal station' en 'Nørreport' zijn gerangschikt als de meest geschikte gebieden voor de implementatie van een ATMS. In vergelijking met de andere geselecteerde gebieden in dit onderzoek, zijn deze twee gebieden gelegen in het centrum van de stad en bevat alle vormen van reizen. Deze gebieden worden beiden gekenmerkt door de vele grote en kleine buslijnen die het gebied doorkruisen. Samen met de vele fietsers en voetgangers in deze gebieden resulteert dit in vele conflicterende situaties. Gezien de criteria en de bijbehorende gewichten (zie tabel 1) is het niet verwonderlijk dat deze twee gebieden zijn gerangschikt als nummer een en twee.