The effects of bus priority on the delay and emissions of busses and the other vehicles

A Copenhagen case study

8/19/2015

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Summary

To keep up with the rapid and expanded urbanization solutions as traffic management and intelligent traffic solution is needed. Public transport can be essential to reduce traffic congestions, but it needs to be more competitive. One option to make the bus more attractive is bus priority, as it is expected to make the bus more predictable and reduce the travel times.

The city of Copenhagen wants to implement bus priority. Before implementing it throughout the city, Copenhagen wants to know what the effects will be. To determine the effects two options are used: testing the implementation on the street and doing a simulation study (= this research).

In 2014 a previous study about the effects of bus priority was conducted on the same network. However the previous study used a different traffic light configuration. This study will use the configurations as they will be implemented on the streets and thus will this study also show the effects that can be expected. Besides small changes to be capable to run the configuration, also small changes to make the network up to date were performed.

Vissim is used for the simulation of the 21 intersections in downtown Copenhagen. These 21 intersections are part of the 1a bus route, also lines 2a, 9a & 40 follow half of the testing network. Among the results of this network will be the average delay and emissions during peak hour (08.00-09.00) and off-peak hour (12.00-13.00). Both time periods will be run 10 times (5 times without bus priority to create a baseline and 5 times with bus priority).

Comparing the median runs with each other the following results were found: during peak hour the average delay of busses decreased by 3,00% against an increase of all vehicles by 1,63% (mainly caused due to the strong increase of the average per vehicle for bikes 8,57%). Off-peak hour showed an improvement of 5% for the average delay per vehicles of all vehicle classes, except the average delay time per vehicle of busses (+5,71% probably caused by outliers in the small number of HGVs). Results of emissions were only made on network level and showed a small decrease (around the 1%) of emissions for all classes but the HGVs (+2,5%).

The results found during this study are less than the improvement of 3-10% found during the previous study, but configuration and priority were completely different. Therefore, since only pre start and extension are allowed during the runs conducted during this study, the results found for the network are better than expected.

Looking at the delay on bus route scale: the results are different for every route, but in general show a positive effect of bus priority. The bus line (1a) shows better results than the lines which are only going through the bottom half of the testing network. The results of the intersections are also completely different for all the intersections: during peak hour on 50% of the intersections the bus benefits and during off-peak hour the bus benefits in 70% of the cases bus priority is implemented.

To determine what causes the different effects two analysis were performed: correlation and ANOVA. The only interesting correlation found is the relation between the average delay of all the vehicles and the average delay of the motorized vehicles. ANOVA showed a relation between the number of motorized vehicles and the effect of bus priority (bus priority has a better effect, on the average delay of busses, on intersections with less motorized vehicles).

Before Copenhagen can use the results from this study, comparing more runs with each other or running more runs so the mean can be used. But in general the results of this study are a good start for the recommendation of implementing bus priority (on certain intersections).

Preface

This study was conducted as part of my study: Civil Engineering at the University of Twente. To complete the bachelor research project of ten weeks has to be completed at an external organization. In my case Imtech Traffic & Infra had an assignment concerning bus priority in Copenhagen.

I started on the subject full of enthusiasm and at the end I have the same enthusiasm for the subject. Even a seven weeks delay of some parts important parts of the model couldn't discourage me. However the delay of those parts automatically resulted in a extension of my internship with the same seven weeks.

Before I started my internship I hoped to be able to process all the data and draw all kind of conclusion about the effects of bus priority on the Copenhagen network. Already in my first week I learned that getting the data and process is was far more work than previous expected / hoped. Unfortunately ten weeks was just enough time to create the tip of an iceberg and many things are left to be investigated.

Besides a working model, Imtech Traffic & Infra now has results on how the network / intersections perform (to present to Copenhagen or to compare to their own runs) and also a parameter causing the difference in effects was found.

These achievements wouldn't have been possible without the mental and constructional help of several people. So I would like to thank everybody who contributed in any way; the next people deserve special mentioning: My parents (for all their involvement), my daily supervisor Niels van den Bosch (for helping me with the research, whenever I needed it), my external supervisor Jaap Vreeswijk (for outlining the project and keeping me on track), Tom Thomas (for showing me how to investigate), Peter Bijl (for helping me with processing the emission data), Lars van Doremalen (for giving critical notes on my report) and of course all my colleagues (for the wonderful time at the office).

With kind regards,

Ynze Goinga

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Contents

1 Introduction

This first chapter shows the motivation for the research, the questions that need to be answered and the way it is investigated.

1.1 Research motivation

Rapid and expanded urbanization occurring around the world involves an increased number of trips in urban areas. An increasing demand for transport in urban areas has resulted in chronic congestion, with many adverse consequences such as delays and pollution. Traffic management and intelligent traffic solutions will play an important role in providing answers to those challenges.

The problem is that different priorities often need to be met in the intersections. The promotion of a smooth and eco-friendly mode of driving for car traffic is often a main policy. At the same time, (important) bus lines should be given priority and bicycle demand green waves for cyclist. Pedestrians ask for longer green when crossing the roads, and improvements to the driving behaviour of “Heavy Goods Vehicles” (HGV’s) can have a substantial contribution to the cities environment (Madsen & Bosch, 2013).

Focussing on the motorized transportation, the need for sustainable modes becomes more evident. The need for more plentiful and efficient public transport becomes essential to reduce traffic congestion which is mainly caused by private transportation. Public transport systems can move large numbers of people, thus collectively using scarce resources such as land and fuel more efficiently, resulting in lower overall environmental costs.

The most important benefit of public transportation is that it reduces the need and desire for private vehicle ownership to some extent and thus can massively reduce the amount of motorized travel. Successful public transport systems that compete with private modes, such as the car and the motorcycle, could retain customers from all social classes (not just the poor) and be used for a wide range of urban trips at all times of the day (not just for trips to work during peak hours). For this to be achieved there is a need for a well-planned public transport system which is affordable and is attractive to all groups of people (Bhandari, Advani, Parida, & Gangopadhyay, 2014).

For the end user, public transport has some less desirable characteristics. Travel times are often (but not always) longer than by private car. Waiting times at stops can be long, or maybe worse, can be unpredictable. For the public transport operator the variability and unpredictability of travel times leads to the need to deploy more vehicles than needed with a strict schedule adherence. Public transport priority at intersections can help not only to shorten travel times but also to make trips more predictable (Turksma & Vliet, 2014).

For a priority scheme to be successful, two conditions must be met (Turksma & Vliet, 2014): The priority works as intended, with the specified characteristics (travel time, stop reduction, regularity and/or punctuality) and the negative impact on other traffic must be minimal.

1.2 Research objective

The city of Copenhagen wants to implement bus priority. Before implementing bus priority throughout the city, Copenhagen wants to know what the effects will be. To determine the effects two options are used: testing the implementation of bus priority in real life on several intersections and doing a simulation study of the same network as the testing site.

Normally first a simulation study is conducted and then the results of that study will be used and tested in real life. In this case the simulation study and the testing in real life are done at the same time. The decision of Copenhagen to run both test at the same time has probably to do with wanting to present the result earlier. The faster both studies are completed, the faster comparing the two can start.

The aim of this study is to determine the effects of bus priority on the fuel consumption and delay of busses and other vehicles (given the Copenhagen configuration). Knowing these effects will help by decisions to implement bus priority on certain intersections of the testing network.

Besides determining the effects of bus priority, this study also aims to determine what causes the effects. If one knows what factors causes the effect of bus priority on certain intersections, it will be possible to predict whether other intersections will improve by implementing bus priority and to what extent.

1.3 Research questions

The main question addressed in this study is formulated as follow:

What is the effect of bus priority on the delay and fuel consumption of busses and the other vehicles?

To answer the main question several sub questions have been formulated. The first two sub questions address the research / model approach. The third and fourth sub questions are addressing the results of this study and the final question addresses the usefulness of the outcome of this study.

Sub questions:

- Is simulation the best practise for this study and, if so, what parameters should be used?
- What are the effects of bus priority on different levels (network, intersection, vehicle type, bus line, etc.)?
- How do intersection characteristics influence the performance of bus priority?
- Are the results of this study comparable to the results of previous study?
- What do the results mean for the practical implementation?

1.4 Research strategy

The first phase of this study is finding out what is known in the literature. The literature is used for a case study that will be conducted. The case study consists of setting the outline of the micro simulation, creating the model and using the model. The results of the model will be used to make recommendations towards Copenhagen and also identify what parameters causes the effects of bus priority.

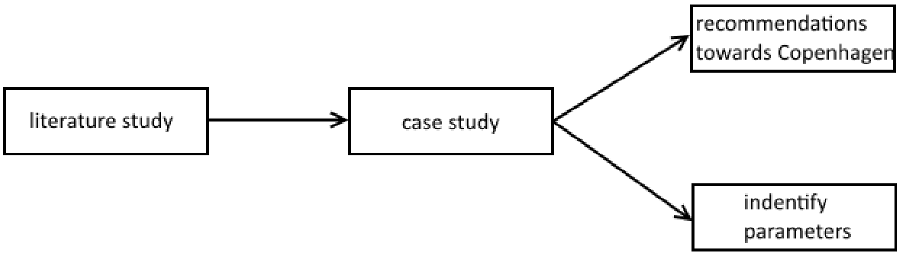

Figure 1: Research strategy

1.5 Reading instructions

The next chapter (2) will outline the three areas that are important to understand the case study: traffic lights, Cooperative Intelligent Traffic Systems and bus priority. The following chapter (3) tells why Copenhagen is chosen to for this case study and which intersections are in the network. Now that the outlines for the system are set, the model can be build. Which choices are made by designing the model and how the model runs is explained in chapter 4. The results are presented on different levels: the complete network (including the emissions), the bus routes and the intersections. These results inclusive the correlation and ANOVA analysis can be found in chapter 0. The report finishes with the conclusion and recommendation (chapter 6) and the bibliography (chapter 7).

2 Theoretical Framework

This chapter contains the theoretical framework for this study. The theoretical framework describes relevant subjects which form the foundation of this study. These are discussed in the following sub-sections: Traffic lights, Intelligent Transport Systems, Priority and Simulation. The paragraphs in this chapter all deal with one of the subjects, explaining what the subjects mean and which different option are possible within the subject. In Model characteristics (chapter 4) is explained how the different subjects are used in this research.

2.1 Traffic lights

A traffic intersection is defined by a point at which the sharing of right-of-way by two or more vehicles is required. In order to accomplish this sharing, intersection control is used. Contingent upon a number of warrants, as defined by the governing authority, a traffic signal may be used as an intersection control device (Shenoda, 2006). Computerized Urban Traffic Control (UTC) systems were introduced in the 1970's providing coordinated fixed time signal timings to control traffic flows in urban areas (Turksma & Vliet, 2014).

The traffic signal operates by allotting green time to the intersection approaches according to a chosen scheme or algorithm. Three methods of distributing green time to approaches are considered (Shenoda, 2006):

A) Fixed / Pre timed: The length of green and red during a cycle remains fixed for each approach for some period of time, whether that is an hour a "rush hour" period, a few days or indefinitely.
B) Actuated: The length of green and red is based on the vehicle arrival on a certain approach (there is however a minimum and maximum length of green time).
C) Adaptive: The traffic signal provides green time to each intersection approach based on anticipated arrivals for a cycle.

Pre timed traffic signal control is by far the most widely implemented method (also used in Copenhagen), and actuated control has also been widely implemented over the past few decades, particularly at isolated intersections. Adaptive traffic signal control is a relatively new method; research has only recently been increasing. Given the proper attention adaptive control has the potential to diminish the need for constant adjustment to enhance performance, which is the concern of pre timed control.

2.2 ITS

Intelligent Transport Systems (ITS) were initially developed to address traffic congestions. Later on application of ITS solutions has also proved to be very effective in reduction of emission and delay. The actuated and adaptive traffic light controllers are two examples of ITS, as they use local vehicle actuated control to coordinate the signal timing plans. The central computer in the semi adaptive control systems collects real-time traffic data and uses the information to calculate the signal timing for the next cycle (Turksma & Vliet, 2014).

ITS deployment can impact transportation system performance in six key goal areas, therefore the benefits of the ITS applications are needed to be measured. A wide variety of performance measures are used to assess ITS performance under each of these goal areas (Islam, 2014).

- Safety is measured through changes in crash rates or other alternative measures such as vehicle speeds, traffic conflicts, or traffic law violations.
- Mobility improvements are measured in travel time or delay savings, as well as travel time budget savings, and on-time performance.
- Efficiency findings document the capability of better managed transportation facilities to accommodate additional demand, typically represented through increases in capacity or level of service within existing road networks or transit systems.
- Productivity improvements are typically documented in cost savings to transportation providers, travellers, or shippers.
- Benefits in the area of energy and environment are typically documented through fuel savings and reduced pollutant emissions.
- Customer Satisfaction findings are measured usually through surveys, the perception of deployed ITS by the travelling public.

Turksma & Vliet (2014) state that the exact results of ITS mainly depend on the network, its demand and its baseline control. Not much improvement will be achieved in the oversaturated situation. In an oversaturated situation the other vehicles dictates the possibilities (I.E. speed or number of stops). Larger effects can be found when the application is implemented on a site with less advanced existing control systems (i.e. a poorer baseline).

2.3 Priority

Bus priority can be implemented in a variety of ways: passive, active and adaptive as discussed below (United States Department of Transportation, 2005):

- Passive priority is priority is given by creating a traffic light configuration which is ideal for the bus (Operational improvements to signal timing plans, such as retiming, reducing cycle lengths, or coordinating signals on a corridor, may improve traffic flow and reduce transit travel time as well).
- Active priority strategies provide priority treatment to a specific transit vehicle following detection and subsequent priority request activation. Various types of active priority strategies may be used if available within the traffic control environment.
    - Green extension / pre start
    - Inserting a special priority phase
    - Phase rotating
- Priority with adaptive signal control provides priority while simultaneously trying to optimize given traffic performance criteria. Adaptive Signal Control Systems continuously monitor traffic conditions and adjust control strategies.

During this study active priority will be used and then only the type green extension and pre start. The previous study conducted on this network used priority with adaptive signal control. In Appendix A: Providing priority a figure can be found about how priority is given.

2.4 Simulation

Testing different scenarios is often not possible in real life, because the expected results can't be measured on the streets. Reasons testing on the streets isn't possible include: the network size is too big to collect / handle all the data, also single results are too small to collect (results will only be visible when all results are totalled up). For those reasons simulation software was developed. Advantages of simulation software include (United States Department of Transportation, 2005):

- it allows users to test scenarios faster than in real life
- it is a cost effective way of testing and evaluating different scenarios
- it offers an insight into characteristics of traffic system operations that are important, allowing the user to make a more informed decision

To collect the data three different scales of modulation are available: macro, meso and micro (Alexiadis, Jeannotte, & Chandra, 2004):

Macroscopic simulation models: Macroscopic simulation models are based on the deterministic relationships of the flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. They do not, have the ability to analyse transportation improvements in as much detail as the microscopic models.

Mesoscopic simulation models: Mesoscopic simulation models combine the properties of both microscopic (discussed below) and macroscopic simulation models. As in microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. Their movement, however, follows the approach of the macroscopic models and is governed by the average speed on the travel link. Mesoscopic model travel simulation takes place on an aggregate level and does not consider dynamic speed/volume relationships.

Microscopic simulation models: Microscopic models simulate the movement of individual vehicles based on car-following and lane-changing theories. Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network over small time intervals (e.g., 1 second or a fraction of a second). Typically, upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type.

2.5 Reflection

Copenhagen is using pre timed signal control, which means that there are options for improvement of the system. Implementing bus priority with the pre timed signal control will lead to a semi-fixed timed signal control, because the intersection will react to the arrival of a bus. Since the other signal control systems are fitted to the number of arriving vehicles these systems will improve the results of the network.

The improvement of the network will be tested in delay savings, travel time and reduced pollutant emissions. The more vehicles there are in the network the harder it will be to fulfil request of the busses (no obstacles on its way). Copenhagen doesn't want to disrupt the other vehicles, so they decided to only implement a pre start and extension of the green phase. Since the other active priority strategies offer faster / more priority to busses, the effects of those strategies are stronger.

To collect the data needed from the model, it is necessary to have information about individual vehicles. Therefore the simulation model for this study will be microscopic.

3 Model environment

In the previous chapter the theory of three relevant subjects for this study is explained. This chapter focusses on why Copenhagen is selected for the case study. This starts with the introducing of a larger project to investigate the effects of C-ITS, then the specific Copenhagen case is explained. The explanation of the Copenhagen case is divided into an introduction of why Copenhagen is participating, the place of this study into Copenhagen's participating and what is investigated in this study.

3.1 Model study

3.1.1 Compass4D

Seven European cities (Bordeaux, Helmond, Copenhagen, Newcastle, Thessaloniki, Verona and Vigo) are participating in projects to make the road more efficient, safer and more comfortable. To reach these goals three services are deployed. These services are focussing on red light violation warning, road hazard warning and energy efficient intersections. Clustered under the name Compass4D, each city will test one or more of those services for at least one year on the street (Compass4D Consortium, 2015)

During the Compass4D project road operators, infrastructure providers, fleet operators and their drivers as well as other road users will cooperate to achieve the goals. Even after the testing phase is done they will continue working together.

All services will use Cooperative Intelligent Transport Systems (C-ITS). C-ITS allows vehicles to communicate with other vehicles and with the road infrastructure. C-ITS services also advise drivers how to act within specific situations, for example when there is a hazard on the road ahead or if a vehicle is going to violate the red traffic light (Compass4D, 2015).

Figure 2: Compass4D in Copenhagen (Compass4D Consortium, 2015)

The vehicles (in Copenhagen a total of 87 busses) will be equipped with a component that uses an antenna to send a signal to a road side unit (shown as RSU in Figure 2) that the vehicle is approaching. The message send by the vehicle can be handled at the site (which is the case in Copenhagen) or at a central location. Depending on the situation a reaction will be sent to the vehicle (in the case of a speed advice or a warning for a dangerous situation) or to the TLC (in the case of green priority). During this study only green priority is investigated (how the TLC can react is explained in chapter 4).

3.1.2 Copenhagen

In Copenhagen, the City Council has taken important steps towards their vision of being the first CO_2 neutral capital by 2025. To that end, the City Council came with the following solutions: increase the number of passengers with 20%, increasing transport by bike, introducing alternative fuels in 20 to 30% of light vehicles and in 30 to 40% of heavy vehicles, and using intelligent traffic management (Koenders & Vreeswijk, 2014).

During the Compass4D project an intelligent transport management system will be tested. On 21 intersections a total of 87 busses driving 4 different routes will be granted priority. These buses will also get a speed advice driving these routes, telling them to keep a certain speed which makes sure the bus will cross the intersection without stopping for a red light. Both systems will make the bus journey more reliable, comfortable, energy efficient and faster.

Figure 3 shows the map with the study area, the routes which are coloured cover the 21 intersections. As can be seen, only one bus line (1A) covers the complete route, the other 3 bus lines cover around half of the network that is equipped with bus priority. The map also shows that, on the part where only bus line 1a drives, part of the route is a one-way road.

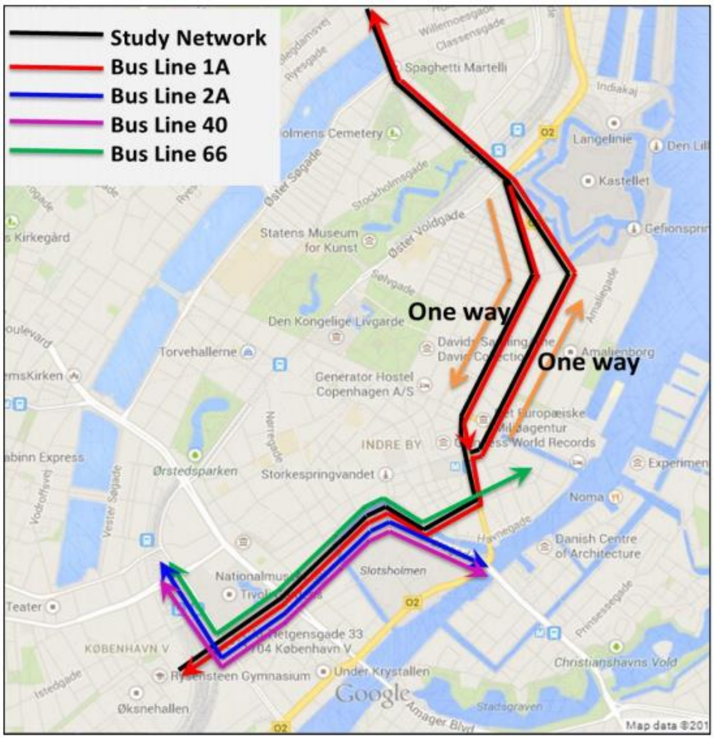

Figure 3: Overview study area with bus lines drawn into it (Islam, 2014)

3.2 Model selection

In the complete EU / Copenhagen project, the case study in this research is just a small part of the much larger project. To give an impression of the complete project Figure 4 was created. As can be seen Copenhagen works on the Compass4D project in cooperation with the EU. During this project Copenhagen is going to test the effect of bus priority both on the street as well as by simulation. The results of the simulation, and thus of this case study, will be used to improve the (test) situation on the street.

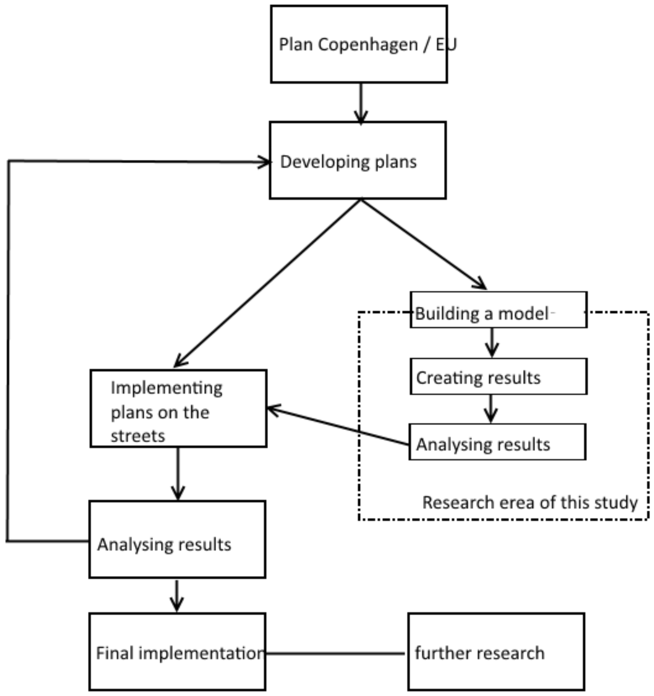

Figure 4: Place of the case study in the larger project

The boundary conditions of simulation are set in the developing plans, since that is outside off the research area; most of the conditions for the case study are already set. Another thing which can be seen in the figure is that only half of building a model is done during this case study. Including only half of building a model is done because: there was a model available in which the network geography had already been developed. (The next paragraph explains why Vissim is chosen for simulation and chapter 4 contains more information about building the model and creating results.)

3.3 Simulation software

Only a few simulation software packages are capable of simulating transit vehicles, so the options are limited; one of these packages is Vissim. Since Vissim is considered to be one of the better simulation software packages ((Lin, 2013) and (Tianzi, 2013)), and the company responsible to conduct the simulation study (Imtech Traffic & Infra) has a licence for this software, the model was built in Vissim (before this study was conducted). Given the availability of the already existing network in Vissim, this research is also done in Vissim (see Figure 5 below for the model).

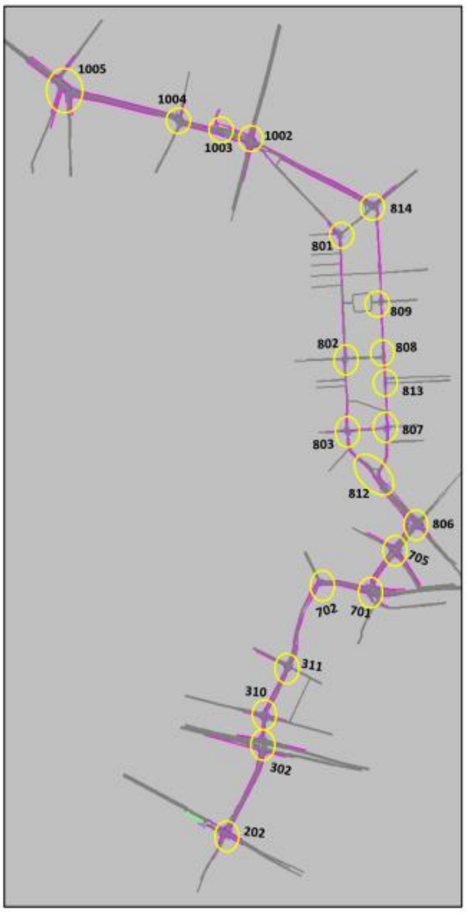

Figure 5: Overview of the simulated network (Islam, 2014)

4 Model characteristics

Now that both the theoretical and environmental mainframes have been explained it is time to create the model that creates the data. First the construction of the model will be explained in this chapter and then the way the model is put to use is explained.

4.1 Vissim preparations

In 2014 the student Faqhrul Islam of the technical University of Munich already researched, for his master thesis, the effects of bus priority on the same network of Copenhagen. The basis for the model used for this research project is the model that was used for the master thesis of Islam (2014). However the model used for this research has been altered in several ways. The two main reasons for altering the model used during Islam's research are:

- Different traffic light configuration
- Situations in the real network have changed

The different traffic light configuration is needed because Islam used ImFlow (a product of Imtech Traffic & Infra) during his modelling to configure the green intervals of a cycle. In this study the configurations which currently run on the streets will be used in the baseline runs (fixed time), for the priority runs the configuration developed to test priority in the real network will be used (semi-fixed time).

Combining bus priority with ImFlow, which uses adaptive signal control, is expected to have a stronger effect on the results of bus priority (since the TLC can faster grant priority on the direction of the bus). Therefore the results found during his study are probably more extreme. Islam found that bus priority contributes in a 10% decrease in delay for busses during peak period and 11% decrease of delay for busses during off-peak period. Also the emissions of the bus decreased with respectively 4% and 3% during peak and off-peak period (Islam, 2014).

In Appendix B the complete construction of the model in Vissim is described. Starting with explaining the connection between the modelled environment and the TLCs. Followed by explaining the conversion of the network to a Vissim model and finishing by the description of how the TLCs work.

There have been a couple of changes in the network since Islam did his research. The first change with a large impact is the new route of several bus lines. Especially bus line 66 which used to run through half of the study network, now it only crosses the study network twice. The second change with a lot of impact is the construction work which is performed on the study network. The construction work will last for five years and results in a change of routes in the network for all traffic between two intersections.

With the removal of the detectors, which were used for ImFlow, other modification to the model consisted of renaming signal heads and detectors to match them to the names in the signal control applications. The location of the detectors was also updated.

The model off course has some differences with the real world, but it tries to simulate it in the best way possible. Differences can for example be found in the input, routes followed, driving behaviour and road geography. Since it is impossible to resolve all flaws, the city of Copenhagen accepted the model as accurate.

In three cases there was only one version of the TLC, in all three cases only the current TLCs (not responding to priority requests) were ready. Therefore even in the scenarios with priority these TLCs don't give priority. How the data from these TLCs effects the overall data is different in every case. Sometimes it was possible to exclude them from the analysis; in other cases the (assumed) effect is discussed.

4.2 Running approach

4.2.1 Simulating

At the starting point of every road, bicycle – and pedestrian path an input link fills the network with vehicles. The moment of vehicle input is based on an algorithm in Vissim and it is different for every seed. Unfortunately this algorithm is a black box and therefore not possible to review; fore sure there will be differences with the real world. These differences will cause slightly different situations at the intersections, but that is inevitable.

The same small differences can be found in the behaviour of the vehicles in the network. The interaction between vehicles is more static or more fluent than what can be seen on the street. Causing that sometimes a vehicle will stop for another vehicle, where it would continue in the real world. In the case that stopping causes effects that don't resemble the real world measures were taken. Sometimes (due to the measures) a collision occurs, but in those cases the software just simulates one vehicle driving over the other after which both vehicles continue their way. Ignoring collisions in those cases resembles the real world the best way on intersection or network scale.

However other special manoeuvres or incidents that happen in the real world aren't happening in the simulation. It is simply not possible to simulate every possible action of a human being can make. Also the idea is to know what the situation will be in an average situation and not what happens in the case of a unique situation.

4.2.2 Four scenarios

To evaluate the effects of bus priority on a network, it is (at least) important to know how the network reacts during both peak hour and off-peak hour. For peak hour runs the timeslot 8.00 -9.00 is used and for off-peak the timeslot 12.00-13.00 is used. The advantage of using these timeslots is that the bus frequency in the network is the same for both timeslots. There is no need for bigger timeslots, since the input is the same during the complete run; bigger runs only take more time to run and also need to be converted to know the effects per hour.

Figure 6: The four scenarios

There are two differences between peak hour and off-peak hour: the vehicle input and the program the TLCs run. Since the data available to determine the vehicle input was limited and not available for off-peak period, the input for the off-peak hour was calculated as 0,65 x input peak hour (the 0,65 was advised by two experts by Imtech Traffic & Infra) . In Figure 7 the numbers of motorized vehicles per intersections during peak hour are shown (the number shows the number of vehicles coming from that direction).

Which program runs depends on the design of the TLC. Manually it is possible to change the program so that during peak and off-peak the same program runs, however the reaction of a particular program is part of the evaluation.

The difference between priority and no priority is the usage of different TLCs. During a no priority run the TLC won't react to an input from a detector. In case there is an input from a detector during a priority run, the TLC will determine how to handle the call for priority. The following paragraph will explain the way a TLC can react.

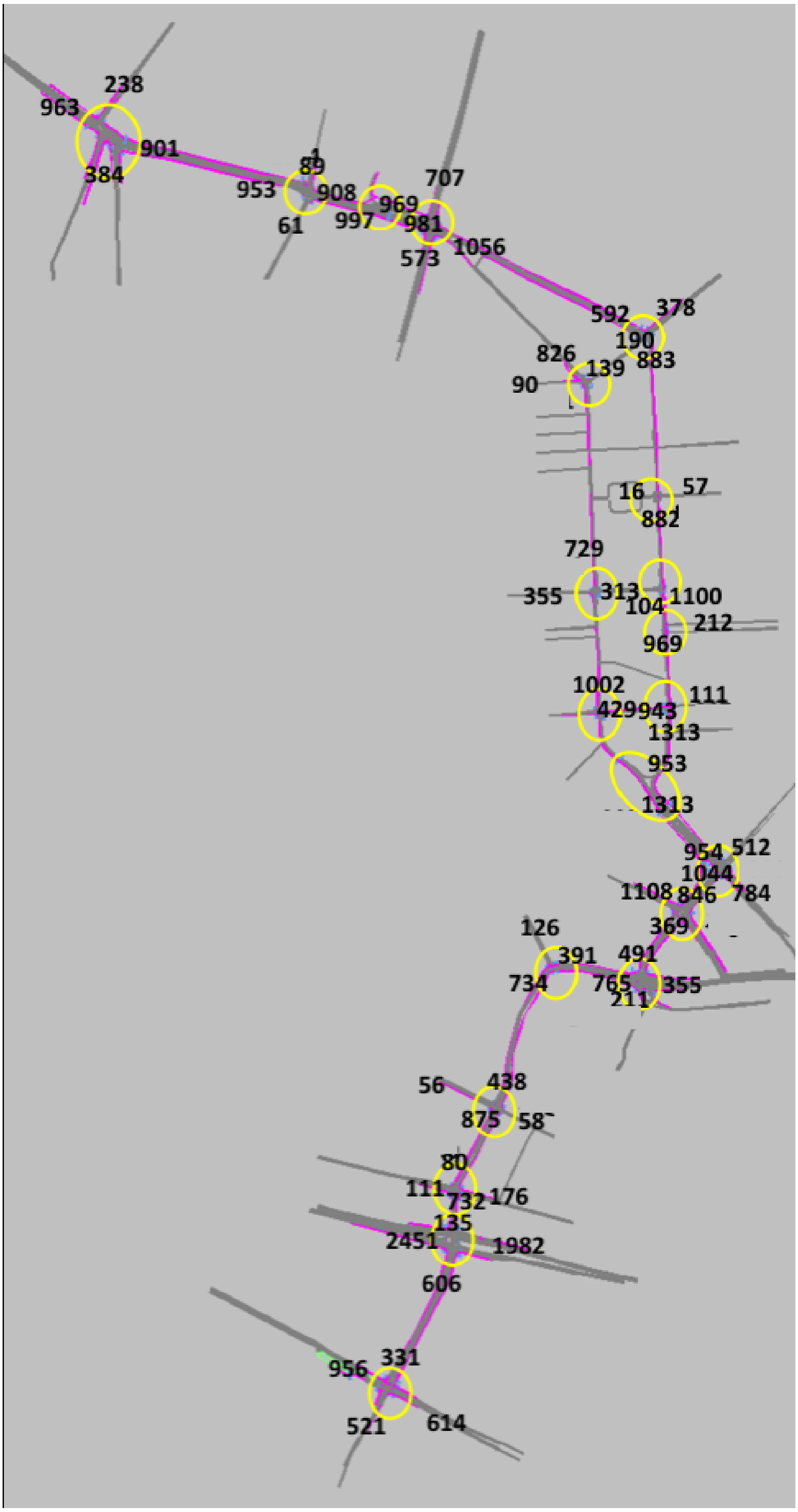

Figure 7: Number of motorized vehicle per intersection coming from different direction

4.2.3 Rules of priority

On network level the implementation of bus priority is the same. In the model all busses, which are detected, have the option for priority. Depending on the moment of detection three things can happen:

- Extension, the current green phase is extended until the bus passes the signal head or until the maximum extension is reached
- Prestart, the next green phase will start earlier (but no phase skipping!)
- Nothing, the bus arrives during a green phase and passes the signal head before the end of the phase or based on the configuration an extension and prestart is not allowed or possible.

Zooming in on intersection level, lots of differences can be noticed. The number of detection is different for every intersection; for example it is possible that all directions have detection, all directions don't have detection or just one (two/ three) direction has (have) priority.

Also the distance from an intersection that busses are detected is different for every intersection / detection. The distance is limited by other intersections and bus stops; the uncertainty of the time a bus has to wait at the other intersection or bus stop makes it useless to force an extension.

Besides the differences in placement of the detectors also the response of the TLC / the priority given is different for every intersection. The specific rules about the moment a request for priority is sent and how to respond have been developed in cooperation with Copenhagen. In these specific rules it is written whether an extension and / or prestart is allowed and under what conditions (for example the length of the extension). The table underneath shows the conditions for intersection 08.13 (which program runs depend on what time of the day it is).

Table 1: Conditions for granting an extension / pre start for intersection 08.13 (Imtech Traffic & Infra, 2014)

Second in cycle of incoming PT message	Action	Comment
No PT vehicle	Keep the normal Program	
Program 1: - Incoming message A < 46; - and no exit message A < 46 Program 2: - Incoming message A < 50; - and no exit message A < 50 Program 3: - Incoming message A < 40; - and no exit message A < 40 Program 4: - Incoming message A < 32; - and no exit message A < 32	Run Extension program A	PT vehicle incoming message arrives when it is still possible to extend green on A. As soon as the PT exit message is received, start with the B signal groups and/or keep running the normal program.
Program 1: - Incoming message A 46 ≤ second < 72; - and no exit message A < 66 Program 2: - Incoming message A 50 ≤ second < 72; - and no exit message A < 70 Program 3: - Incoming message A 40 ≤ second < 62; - and no exit message A < 60	Run Pre Start program A	Program has to switch as soon as possible to green for A.

4.3 Output files / nodes

To evaluate how the network behaves several files are produced. Underneath the different file types are named, in Appendix C: Output files / nodes is explained which output can be found in which file and how the output is created (as described in the Vissim manual (PTV Planung Transport Verkehr AG, 2012)). The different file types:

- Travel times
- Delay times
- Queue length and vehicle stops
- vehicle record
- Signal changes
- Node evaluation
- Network performance evaluation

4.4 Data sorting

4.4.1 Median run

All scenarios will be run five times, with different input seeds. Each run will last 4500 seconds and data is taken from second 901 to second 4500, the first 900 seconds are dedicated to fill up the network with vehicles. During simulation, the network will be checked at regular interval to ensure it is running well.

Two common ways of evaluating the output data are the mean and the median. The advantage of using the median is that the situation can really occur. Another advantage the median offers over the mean, where extreme values are prone to have much influence on the value of the (Armstrong & Collopy, 1992). The option to counter the effects extreme values have on the mean, are in the numbers: eventually even extreme values will level out. Unfortunately the time to do this research didn't allow it to do that many runs that extreme values would have levelled out.

So for this study the median value of the average delay time per vehicle for all vehicles is used for evaluating bus priority. Choosing this median value should help with bringing the number of other parameters with extreme values back, since other parameters influence this parameter (other average delays are used to calculate the all vehicle average delay).

Still the downside of using the median of one parameter is that other parameters / results can have extreme values, which don't occur in an average situation. By comparing two parameters based on the median of another parameter it is possible that two extreme values are compared, resulting in even more extreme values.

This possibility of creating extreme values might even be greater by picking the median of the average delay per vehicle of both the priority as well as from the no priority run, because this way to different seeds can be (/ are) used. The effect on intersection level might be completely different per seed, but on network level the results are more aligned (since by choosing the median the most extreme values are removed).

When the same seed for both the priority and no priority runs are compared, the possibility of comparing two data sets where one has extreme values is just also possible. The possibility that runs are corrupted by one or a more events that are affecting the complete network is reduced by choosing the median run. This study will therefore use the medians of both the priority and the no priority run instead of the runs with the same seed.

4.4.2 Display of results

The results of the median run (which is based on the average delay time per vehicle) will be evaluated on different levels. Evaluating only one level is not recommended since higher levels will level out the positive and negative effect on the lower levels. However the data displayed on the higher scale should be correct. The problem with evaluating the effects on the most detailed level is that by using the two median runs effects can be quite extreme.

The evaluation will start with displaying the results on network level. On the network level the results will show the effect of bus priority on the highest possible level. This is the only level that will show the impact of bus priority on emission.

There are other results that also will be displayed, besides showing results on network and intersection level. These results will be based on the travel time and delay of two bus routes: results of bus line 1a (runs through the complete simulation network) and results of bus lines 2a, 9a and 40 (runs through half of the network). The complete testing network is based on those two bus routes. On intersections the detection for bus priority is placed on the directions of those bus routes, sometimes other directions are also granted priority but in the majority of the cases only the directions followed by those lines (shown in Figure 8: Bus lines through the network).

Underneath Table 2 shows the different subject being discussed on the different levels.

Table 2: Subjects being discussed under results

Network level
Average delay time per vehicle [s]
Average number of stops per vehicle
Total travel time [h]
Emissions (CO_2)
Emissions (NO_x)
Bus lines
Travel time [s]
Delay [s]
Intersection
Average delay time per vehicle [s]

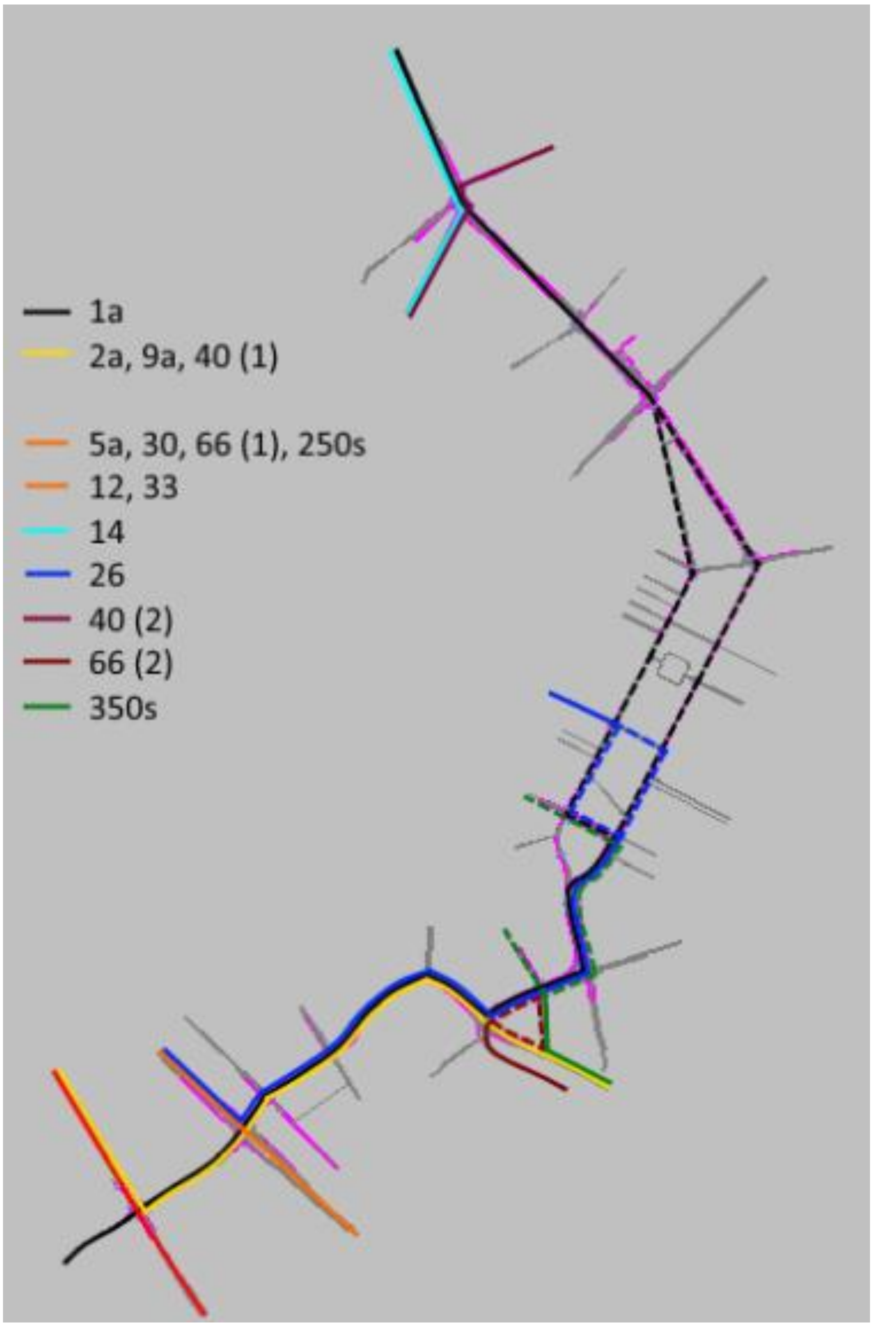

Figure 8: Bus lines through the network

5 Results

In this part the results from the runs are presented. First the network performance is shown, besides the delay and number of stops also the emissions will be in this chapter. The results of the network performance are followed by the results of different bus lines. Last, the results of the intersections are explored. The results will show the impact of bus priority on the average delay on different levels, also the effects on the emissions are mentioned. With the outcome of these results Copenhagen can help decide whether to implement bus priority and in which way. The two analyses which are conducted on the intersections can be found on the end of this chapter; these analyses try to identify what causes the effects.

5.1 Network performance

This first section will show the results of bus priority on network level. These results are gathered from the Network Performance Evaluation (NPE) file of the median runs of the four scenarios. The most important parameters are shown in this paragraph; other parameters are shown in Appendix D: Network performance. To give meaning to the effects the numbers of vehicles are presented below (Table 3)

Table 3: Number of vehicles (in the network and those that have left the network)

	Peak period		Off-peak period	
	Count	Percentage	Count	Percentage
All Vehicle	70293	100,0%	46371	100,0%
Bus	223	0,3%	223	0,5%
Car	13719	19,5%	9003	19,4%
HGV	767	1,1%	500	1,1%
Pedestrian	40319	57,4%	26434	57,0%
Bike	15266	21,7%	10212	22,0%

The number of pedestrians is extremely high (compared to the other means of travel). This has to do with the way of modelling. Almost every intersection has several crossings for pedestrians. Every crossing starts a few of meters before the intersection and stops a few meters behind the intersection. Therefor at every intersection new pedestrians are being put in the model (and therefore counted). With other means of transport vehicles go from one intersection to the next, instead of exiting the network and being put in at the next intersection (with a new number). The reason for simulating it this way, is that during every cycle at least one pedestrian will cross the street (which resembles the situation on the streets).

Besides the high number of pedestrians also the number of bikes is remarkable. The high number of bikes is corresponding with the actual situation on the streets (Copenhagen has lots of bikes). But this means that almost 80% of all the vehicles are non-motorized. The high percentage non-motorized vehicles have effects on the shown overall results. For example the effects on average delay per vehicle for all vehicles or the average number of stops for all vehicles is based on 80% non-motorized vehicles. Later if the effects of the high percentage non-motorized vehicles has an important influence on the outcome of other vehicles it will be mentioned.

Table 4: Part of the network performance results

Performance parameter	Vehicle class	peak period			off-peak period		
		no priority	priority	difference	no priority	priority	difference
		Value	Value	%	Value	Value	%
Average delay time per vehicle [s]	All Vehicle	48,7	49,5	1,63	38,9	37,1	-4,64
	Bus	173,8	168,6	-3,00	144,2	136,8	-5,18
	Car	95,4	93,7	-1,80	61,9	60,6	-2,12
	HGV	100,3	100,8	0,54	61,0	64,5	5,71
	Pedestrian	23,8	23,5	-1,28	25,1	23,2	-7,49
	Bike	68,4	74,3	8,57	51,1	48,4	-5,19
Average number of stops per vehicles	All Vehicle	1,70	1,74	2,71	1,36	1,30	-3,84
	Bus	3,96	3,74	-5,44	3,15	3,11	-1,14
	Car	2,76	2,76	-0,18	1,99	1,93	-3,02
	HGV	2,43	2,50	2,97	1,70	1,78	4,72
	Pedestrian	0,77	0,87	-0,39	0,76	0,75	-0,53
	Bike	3,13	3,34	6,71	2,31	2,11	-8,59
Total travel time [h]	Bus	18,9	18,7	-1,14	17,3	16,8	-2,73

5.1.1 Using the median run

The first thing that needs to be checked is whether using the median instead of the mean was justified. Therefore in Appendix E: Comparing the median with the mean, the results of the median are compared with the mean; the standard deviation of the mean difference is also provided.

For the peak period the results of the median and the mean mostly the same size and direction; only with the results of the HGVs and the vehicle count (in general) the results have a different direction. Taking all the results into account the average difference between the median and mean is 1,27% (leaving the biggest outliner out of it, the results improve to 0,96%). If the HGVs are left out of the results comparing the median and the mean the average difference even drops to 0,62%.

Besides the differences between the median and mean for the HGVs, also the bikes sometimes show some differences. For both vehicle types this can be explained by the point that they have the largest standard deviation of the mean differences. This means that the differences between the effects found during a priority run and a no priority run from one seed, are more scattered.

For most results a seed can be found that indicates the complete opposite of the results found by the median or mean, however this means subtracting the complete standard deviation from the mean (and even then the result in opposite direction is small (less than 0,5%)). However since those results are within the standard deviation, all the outcomes can be wrong.

The differences between the median and mean for the off-peak in general is really small (average difference is 0,10%). Also the standard deviation of the mean difference is a lot smaller. Therefore the standard deviation is often not capable of changing the direction of the results. The only vehicle for which above doesn't count is the HGV, which still has a significant standard deviation.

Since the difference between the median and mean isn't extreme, the results taken from the median run of the average delay of all vehicles will be used. One reservation needs to be made, the effect of using those runs will be stronger when zooming in more (and comparing results on that level).

5.1.2 During the peak period

The average delay time per vehicle for all vehicles increases slightly (+1,63%). This has to do with the strong increase of the average delay time per vehicle for bikes (+8,57%). Since the bus (-3,00%), car (-1,80%) and pedestrians (-1,28%) show some improvement of average delay time per vehicle during the scenario with bus priority.

A striking result is the difference in average delay time per vehicle for cars (-1,80%) and HGVs (+0,54%) . Since they drive on the same lanes and therefore have the same green cycle, one would expect them to have the same direction (either positive or negative) and the same size. The difference between the cars and HGVs can be explained by the number of HGVs. The total effects of HGVs react strongly to the effect of just one HGV, because of the small number of HGVs. The small number of HGVs results in the fact that just one HGV can easily cause the slight increase of the average delay time per vehicle for HGV. Also the results of the mean show a different result (that does correspond with the effect on cars).

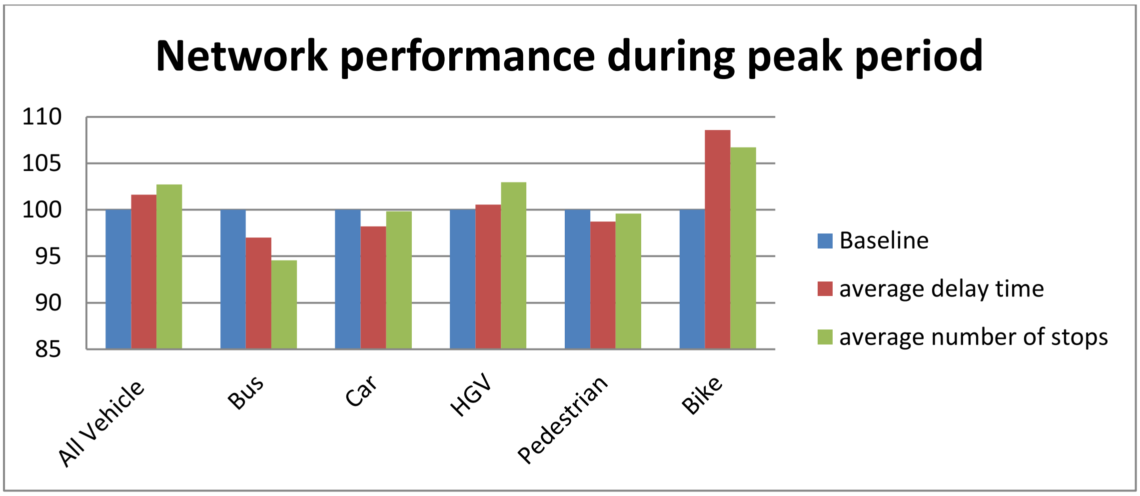

Figure 9: Network performance during peak period

Looking at Figure 9, one would assume that there is a relation between the average delay time per vehicle and the average number of stops per vehicle (in the network). And that is also what the correlation coefficient shows: for the peak period 0,89 , for the off-peak period 0,65 and in total 0,79. So especially during peak period they have an extreme strong relation, but also during off-peak period their relation is considered strong.

5.1.3 During the off-peak period

What immediately catches one's eye is the fact that during the off-peak period all the parameters show improved results for every vehicle class when bus priority is implemented, except for the HGV. Especially the average delay time per vehicle shows great improvement (around the 5% depending on what vehicle is looked at).

The small number of HGV may result in values for the effects that don't reflect the effect of bus priority on the HGVs. If the effect of the HGVs is influenced by just a couple of values, one could say that bus priority also has a positive effect on HGV. Which results in everybody benefiting from implementing bus priority on network level during off-peak.

When everybody benefits from bus priority the cycle isn't ideal; meaning that the intersection should run another cycle with restructured green times. So probably when zooming in different reactions (positive and negative) for different direction on bus priority can be expected. Otherwise the configuration run during bus priority should be implemented as the standard configuration.

An explanation for the fact that everybody benefits can be found in the fact that the stream of vehicles travelling in the same direction as the bus priority also are benefitting from the implementation. If the bus follows the main stream on the intersection, the number of other vehicles benefitting is larger than the number of vehicles suffering from the implementation. Further research is recommended to explain this effect.

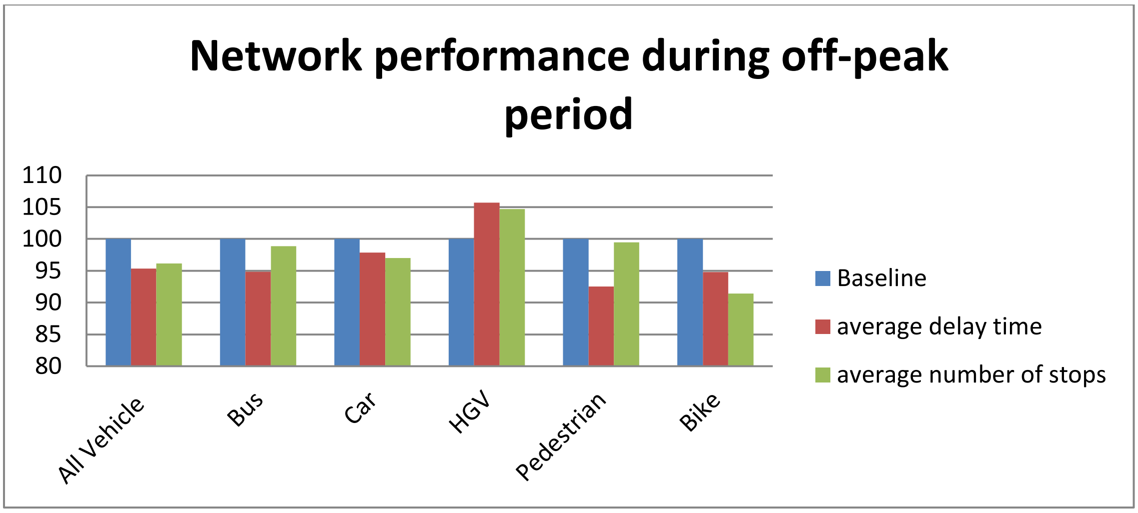

Figure 10: Network performance during off-peak period

5.1.4 Conclusion

The use of the median is justified when comparing the results of the median with the mean. However this is on network scale, so the effect of using the median on more zoomed level can be larger. The high number of non-motorized vehicles and the low number of HGVs might influence the results.

During peak hour the average delay of the bus decreases (-3%), where the average delay of all vehicle slightly increases (+1,6%). This effect is caused by the increase of delay for bikes. During off-peak hour on network level everybody benefits from bus priority with a decrease of around 5% on the average delay per vehicle type.

5.2 Emission report

The results which are presented in the emission reports below are created by performing several actions on the FZP files. The most important action is using Enviver to calculate the emissions per vehicle. Unfortunately it was not possible to create emission reports per intersection, so the results will only show the overall emission of different vehicles on network level. In this chapter only the emissions per driven kilometre are shown, in Appendix E: Comparing the median with the mean

peak period								
		median			mean			
Performance parameter	Vehicle class	no priority Value	priority Value	difference %	no priority Value	priority Value	difference %	standard deviation of difference
Average delay time per vehicle [s]	All Vehicle	48,7	49,5	1,63	48,68	48,92	0,50	1,11
	Bus	173,8	168,6	-3,00	170,12	165,51	-2,66	3,36
	Car	95,4	93,7	-1,80	96,35	94,72	-1,70	2,06
	HGV	100,3	100,8	0,54	97,91	95,40	-2,57	1,17
	Pedestrian	23,8	23,5	-1,28	23,83	23,67	-0,66	1,11
	Bike	68,4	74,3	8,57	67,14	70,45	5,02	3,52
Average number of stops per vehicles	All Vehicle	1,70	1,74	2,71	1,70	1,72	1,48	1,31
	Bus	3,96	3,74	-5,44	3,88	3,71	-4,24	3,88
	Car	2,76	2,76	-0,18	2,80	2,79	-0,33	1,45
	HGV	2,43	2,50	2,97	2,41	2,41	0,23	2,28
	Pedestrian	0,77	0,77	-0,39	0,77	0,77	-0,39	0,76
	Bike	3,13	3,34	6,71	3,08	3,22	4,51	2,98
Average stopped delay per vehicle [s]	All Vehicle	37,21	37,34	0,34	36,97	37,08	0,29	1,28
	Bus	79,32	74,84	-5,65	75,82	72,83	-3,85	4,93
	Car	59,11	57,27	-3,12	59,24	58,09	-1,92	2,85
	HGV	60,46	61,43	1,60	59,43	57,31	-3,60	2,12
	Pedestrian	22,65	22,35	-1,31	22,70	22,55	-0,67	1,14
	Bike	54,28	57,17	5,32	52,91	55,03	4,09	3,38
Total delay time [h]	All Vehicle	951,7	967,0	1,61	950,89	954,13	0,34	1,04
	Bus	10,8	10,4	-3,00	10,54	10,25	-2,66	3,36
	Car	364,0	356,5	-2,07	368,52	360,86	-2,09	1,93
	HGV	21,2	21,6	1,99	20,12	19,67	-2,22	1,60
	Pedestrian	266,4	262,6	-1,46	266,89	264,90	-0,74	1,00
	Bike	289,3	315,9	9,22	284,82	298,44	4,86	3,50
Number of Stops	All Vehicle	119280	122503	2,70	119311	120913	1,33	1,24
	Bus	882	834	-5,44	866	828	-4,24	3,87
	Car	37974	37802	-0,45	38535	38264	-0,71	1,40
	HGV	1848	1930	4,44	1782	1792	0,60	2,86
	Pedestrian	30975	30822	-0,49	31036	30893	-0,46	0,67
	Bike	47601	51115	7,38	47093	49136	4,35	2,91
Number of vehicles in the network	All Vehicle	2282	2304	0,96	2350	2274	-3,20	2,49
	Bus	16	14	-12,50	15	14	-7,54	6,36
	Car	651	617	-5,22	685	636	-7,04	2,94
	HGV	37	40	8,11	41	37	-9,60	10,38
	Pedestrian	489	496	1,43	500	476	-4,46	7,03
	Bike	1089	1137	4,41	1109	1111	0,14	2,48
Number of vehicles that have left the network	All Vehicle	68015	67984	-0,05	67972	67941	-0,05	0,07
	Bus	207	209	0,97	208	209	0,58	0,53
	Car	13086	13083	-0,02	13083	13078	-0,04	0,39
	HGV	724	732	1,10	698	705	0,96	0,67
	Pedestrian	39867	39786	-0,20	39823	39814	-0,02	0,08
	Bike	14131	14174	0,30	14160	14136	-0,17	0,20
Total stopped delay [h]	All Vehicle	726,6	728,9	0,32	722,22	723,15	0,14	1,19
	Bus	4,9	4,6	-5,64	4,70	4,51	-3,86	4,93
	Car	225,6	217,9	-3,39	226,55	221,34	-2,31	2,68
	HGV	12,8	13,2	3,08	12,22	11,82	-3,25	2,38
	Pedestrian	253,9	250,1	-1,49	254,30	252,38	-0,75	1,03
	Bike	229,5	243,1	5,95	224,46	233,10	3,93	3,36
Total travel time [h]	All Vehicle	2264,4	2275,9	0,51	2260,17	2261,32	0,05	0,42
	Bus	18,9	18,7	-1,14	18,73	18,44	-1,53	1,81
	Car	635,2	629,6	-0,90	641,13	633,25	-1,24	1,01
	HGV	34,5	34,8	0,65	32,67	32,30	-1,13	0,82
	Pedestrian	508,5	504,4	-0,79	508,87	506,76	-0,41	0,53
	Bike	1067,3	1088,5	1,99	1058,77	1070,57	1,12	0,85

off-peak period								
		median			mean			
Performance parameter	Vehicle class	no priority Value	priority Value	difference %	no priority Value	priority Value	difference %	standard deviation of difference
Average delay time per vehicle [s]	All Vehicle	38,9	37,1	-4,64	38,84	37,19	-4,26	0,33
	Bus	144,2	136,8	-5,18	144,04	136,80	-5,01	2,41
	Car	61,9	60,6	-2,12	61,28	60,50	-1,28	0,82
	HGV	61,0	64,5	5,71	60,10	61,58	2,60	5,43
	Pedestrian	25,1	23,2	-7,49	25,14	23,41	-6,85	1,02
	Bike	51,1	48,4	-5,19	51,27	48,96	-4,50	0,58
Average number of stops per vehicles	All Vehicle	1,36	1,30	-3,84	1,36	1,30	-4,00	0,43
	Bus	3,15	3,11	-1,14	3,23	3,02	-6,63	4,44
	Car	1,99	1,93	-3,02	1,98	1,92	-2,73	0,77
	HGV	1,70	1,78	4,72	1,69	1,72	2,03	6,86
	Pedestrian	0,76	0,75	-0,53	0,76	0,76	-0,37	0,58
	Bike	2,31	2,11	-8,59	2,32	2,13	-8,17	0,53
Average stopped delay per vehicle [s]	All Vehicle	30,87	29,43	-4,66	30,91	29,59	-4,25	0,45
	Bus	58,94	52,98	-10,12	58,33	53,62	-8,01	4,96
	Car	37,56	37,41	-0,42	37,37	37,37	0,01	1,10
	HGV	33,34	35,86	7,55	32,69	34,07	4,42	6,70
	Pedestrian	23,97	22,10	-7,79	24,03	22,31	-7,14	1,04
	Bike	42,22	40,39	-4,33	42,37	40,88	-3,51	0,82
Total delay time [h]	All Vehicle	499,6	478,3	-4,28	498,36	476,77	-4,33	0,20
	Bus	8,9	8,5	-5,18	8,92	8,47	-5,01	2,42
	Car	154,1	152,2	-1,17	152,41	150,48	-1,26	0,74
	HGV	8,4	9,0	7,40	8,24	8,44	2,62	5,87
	Pedestrian	184,4	170,1	-7,73	184,05	171,23	-6,95	1,05
	Bike	143,9	138,4	-3,81	144,75	138,15	-4,56	0,45
Number of Stops	All Vehicle	62713	60523	-3,49	62786	60231	-4,07	0,61
	Bus	702	694	-1,14	721	673	-6,63	4,44
	Car	17787	17411	-2,11	17685	17206	-2,71	0,74
	HGV	841	895	6,42	835	850	2,06	7,42
	Pedestrian	20019	19854	-0,82	20002	19897	-0,52	0,63
	Bike	23364	21669	-7,25	23544	21604	-8,23	1,04
Number of vehicles in the network	All Vehicle	1362	1395	2,42	1345	1318	-1,87	4,63
	Bus	12	11	-8,33	12	12	-5,18	13,50
	Car	316	326	3,16	319	312	-1,61	8,71
	HGV	22	10	-54,55	17	15	-7,45	31,79
	Pedestrian	359	358	-0,28	340	332	-1,54	10,42
	Bike	653	690	5,67	657	647	-1,33	4,99
Number of vehicles that have left the network	All Vehicle	44922	45062	0,31	44846	44838	-0,02	0,19
	Bus	211	212	0,47	211	211	0,39	0,92
	Car	8643	8720	0,89	8634	8642	0,09	0,48
	HGV	474	494	4,22	476	478	0,34	2,22
	Pedestrian	26109	26041	-0,26	26018	25996	-0,08	0,18
	Bike	9485	9595	1,16	9507	9511	0,04	0,71
Total stopped delay [h]	All Vehicle	396,9	379,8	-4,30	396,55	379,42	-4,32	0,31
	Bus	3,7	3,3	-10,13	3,61	3,32	-8,01	4,96
	Car	93,5	94,0	0,55	92,93	92,94	0,03	1,32
	HGV	4,6	5,0	9,30	4,48	4,67	4,44	7,06
	Pedestrian	176,2	162,1	-8,03	175,90	163,14	-7,25	1,08
	Bike	118,9	115,4	-2,95	119,62	115,35	-3,57	0,41
Total travel time [h]	All Vehicle	1361,8	1349,4	-0,91	1362,92	1341,17	-1,59	0,50
	Bus	17,3	16,8	-2,73	17,23	16,81	-2,46	1,31
	Car	333,0	332,9	-0,03	331,54	329,75	-0,54	0,55
	HGV	16,8	17,7	5,05	16,86	16,99	0,83	4,19
	Pedestrian	342,6	328,0	-4,28	341,76	328,81	-3,78	0,63
	Bike	652,1	654,0	0,30	655,52	648,80	-1,02	0,90

Appendix F: Emissions per vehicleare also the total emissions per vehicle for different scenarios shown.

Table 5: Emissions per driven kilometre during peak period

Peak period						
Class	No priority	Priority	difference	No priority	Priority	difference
	CO2 [g/km]	CO2 [g/km]	%	NOx [g/km]	NOx [g/km]	%
Car	337,87	336,07	-0,53	0,57	0,56	-0,67
HGV	1795,80	1849,60	3,00	14,98	15,46	3,24
Bus	1630,64	1611,49	-1,17	8,89	8,87	-1,29
Total	431,36	430,60	-0,18	1,40	1,41	0,30

Table 6: Emissions per driven kilometre during off-peak period

Off-peak period						
Class	No priority	Priority	difference	No priority	Priority	difference
	CO2 [g/km]	CO2 [g/km]	%	NOx [g/km]	NOx [g/km]	%
Car	303,02	299,45	-1,18	0,51	0,50	-1,17
HGV	1619,25	1656,91	2,33	13,41	13,74	2,52
Bus	1552,35	1534,15	-1,17	8,50	8,39	-1,34
Total	398,85	396,85	-0,50	1,31	1,32	0,75

The first thing that catches the eyes is the fact that the total effects are small. The effects of bus priority don't create a difference of more than one percent. During the off-peak period the difference on total NOx is even negative.

Another thing that stands out is the resemblance between the difference columns of the peak and the off-peak period. The only big difference between the two tables is in differences in totals of NOx; this has to do with the total production of NOx. In the case of CO2 around 70% of the total emissions are produced by cars. In the case of NOx only 35% is produced by cars and almost 50% is produced by HGVs.

Moreover the differences between the different vehicles, one can see that the car produces far less emissions per kilometre than the HGV and bus. Looking at the emission of CO2 the production for the bus and HGV (which are almost alike) is five times higher by cars. Comparing the emission of NOx production of the bus and the HGV with the car the results per kilometre are respectively 15 and 25 times as much.

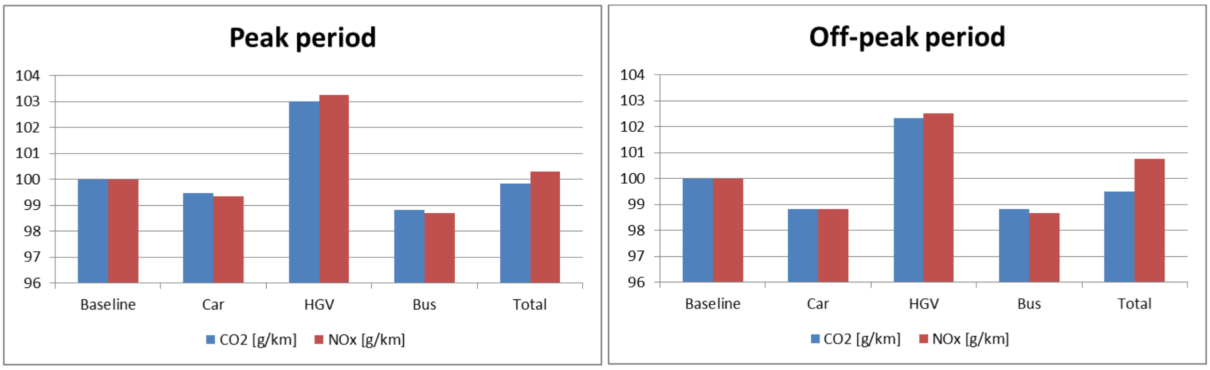

Figure 11: Differences in emissions during peak period (left) and off-peak period (right)

5.2.1 Comparing

Comparing the results of the network with the emission result, one can see that the effects of bus priority on average delay time and average number of stops is stronger and thus better than the effects on emission for the bus and the car. In the case HGV the results on emission are better than the results on the average delay an average number of stops. The decrease in travel time and the decrease in emissions are in a couple of cases almost exactly the same, in other cases they aren't exactly the same but there seems to be a relation.

5.2.2 Difference in emission with fewer vehicles

Because bus priority doesn't create a lot of effect on emissions, and Copenhagen is hoping that bus priority helps them to get closer to CO2 neutral, another table is created: a table comparing the emissions during peak and off peak period (see table underneath). The tables are showing that with a decrease of the number of vehicles with 35% a decrease in emissions of around 10% can be expected.

The effect on busses is lower during off-peak period; however the number of busses is the same during the peak period and off-peak period. So the effect on busses is not created by the smaller number of busses, but by the smaller number of overall vehicles.

Table 7: Emission per driven kilometre during no priority runs

No priority						
Class	Peak	Off-peak	difference	Peak	Off-peak	difference
	CO2 [g/km]	CO2 [g/km]	%	NOx [g/km]	NOx [g/km]	%
Car	337,87	303,02	-10,31	0,57	0,51	-11,09
HGV	1795,80	1619,25	-9,83	14,98	13,41	-10,48
Bus	1630,64	1552,35	-4,80	8,89	8,50	-4,36
Total	431,36	398,85	-7,54	1,40	1,31	-6,34

Table 8: Emission per driven kilometre during priority runs

Priority						
Class	Peak	Off-peak	difference	Peak	Off-peak	difference
	CO2 [g/km]	CO2 [g/km]	%	NOx [g/km]	NOx [g/km]	%
Car	336,07	299,45	-10,90	0,56	0,50	-11,52
HGV	1849,60	1656,91	-10,42	15,46	13,74	-11,13
Bus	1611,49	1534,15	-4,80	8,87	8,39	-5,37
Total	430,60	396,85	-7,84	1,41	1,32	-5,90

5.2.3 Conclusion

The positive effect that bus priority has on the emissions is less than one percent and the emission of NOx even rises slightly. So the effects bus priority has on delay are larger than the effects on emissions. The results of priority or no priority are almost the same for peak and off-peak, but if we compare both periods with each other (so a reduction of third of the vehicles) the reduction of emissions is almost 10%.

5.3 Bus lines

Two bus routes are used to check the impact of bus priority on the bus travel time and the delay. The first follows bus line 1a, the other follows bus lines 2a, 9a & 40. Bus line 1a is the most interesting, because it goes through the complete network. Bus lines 2a, 9a & 40 covers the bottom part of the network and contains lots of buses and for that reason also interesting. The results of the bus routes are displayed in Table 9.

The results of those two lines show the impact of bus priority on different lines better than the results found in the network performance. It also shows a more accurate result on bus lines than the results from the intersection, since it is one level higher. Comparing the different bus routes with each other gives another insight on how different parts of the network perform.

With the results Copenhagen can decide whether certain bus lines should be excluded from bus priority, because the results for that bus line aren't positive (enough). But before decisions like that can be made further research is needed to find out what the effects of excluding certain bus lines is. During this study the results just give a more reliable result of the effect of bus priority on the bus.

Table 9: Travel time and delay bus line 1a and bus lines 2a, 9a & 40

Travel time [s]		Peak period			Off-peak period		
busline		no priority	priority	difference	no priority	priority	difference
1a	S-N	1086,9	1104,2	1,59	900,3	897,2	-0,34
	N-S	980,1	930,1	-5,10	995,2	924,1	-7,14
	total	2067,0	2034,3	-1,58	1895,5	1821,3	-3,91
2a, 9a & 40	W-E	534,9	550,1	2,84	415,1	404,5	-2,55
	E-W	457,3	454,2	-0,68	443,1	428,9	-3,20
	total	992,20	1004,30	1,22	858,20	833,40	-2,89
Overall bus difference				-0,18			-3,40
Delay [s]		Peak period			Off-peak period		
busline		no priority	priority	difference	no priority	priority	difference
1a	S-N	641,9	654,0	1,88	449,0	444,5	-1,00
	N-S	520,4	461,7	-11,28	532,0	455,6	-14,36
	total	1162,3	1115,7	-4,01	981,0	900,1	-8,25
2a, 9a & 40	W-E	346,3	363,1	4,86	225,3	217,3	-3,55
	E-W	262,1	260,5	-0,61	251,7	235,1	-6,56
	total	608,39	623,63	2,50	476,96	452,45	-5,14
Overall bus difference				-0,75			-6,69

The N-S bound bus of line 1a shows every single time far better results than its opposite direction. In all cases the N-S direction improves from the implementation of bus priority, whereas the S-N direction has it results around the 1,5% (either positive or negative). One explanation is that the S-N direction comes across the three TLC without the priority configuration versus only one priority for the N-S direction. Moreover the effects of the three TLC without priority configuration are mentioned in the Intersection paragraph.

Taking all the results during peak period into account the implementation of bus priority shows a small improvement for the buses, but that has to do with the strong positive reaction of 1a N-S. For the results of the travel time 1a N-S compensates a strong negative effect of 2a, 9a & 40 W-E and for the results of delay it compensates for an even stronger negative effect of the same bus route (2a, 9a & 40 W-E)

During off-peak the results are far more in favour of bus priority. Except 1a S-N all the bus routes show an improvement of at least 3,5% (and even up to 14%). Also all the results show a positive reaction to bus priority.

The most remarkable thing that can be learned from the table is the fact that there is a different reaction of the upper half of the network and the bottom half of the network. Comparing S-N (1,59 & 1,88%) with W-E (2,84 & 4,86%) one can see that the results for peak hour is better for the upper half and for off-peak the bottom half reacts better (-0,34 & -1,00% Vs -2,55 & -3,55) . Comparing the N-S with the E-W with each other the effect of bus priority is stronger in the upper half in both the peak period as in the off-peak period. A more in-depth study in what causes these effects is recommended for further research.

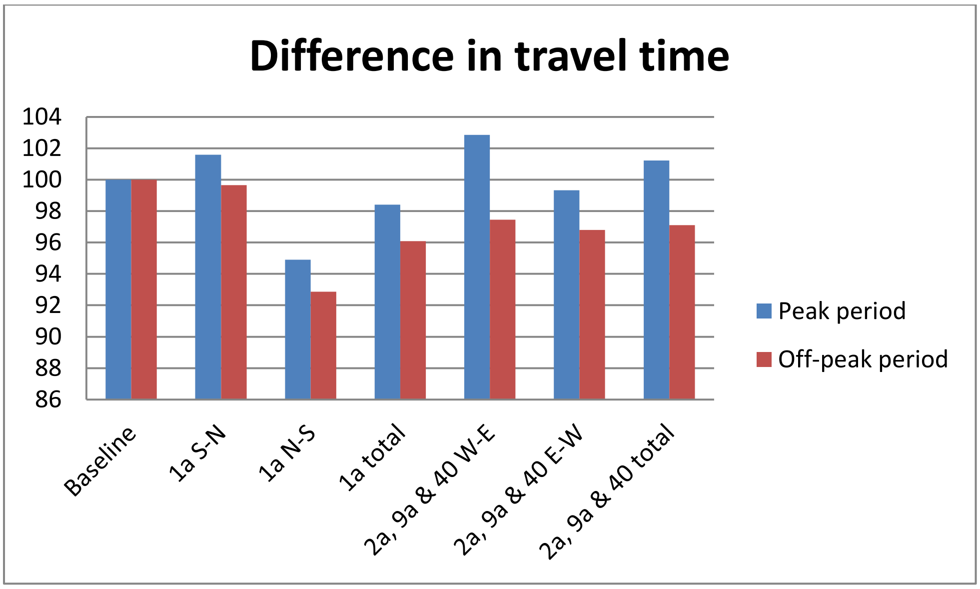

Figure 12: Difference in travel time for different bus lines compared to their own baseline

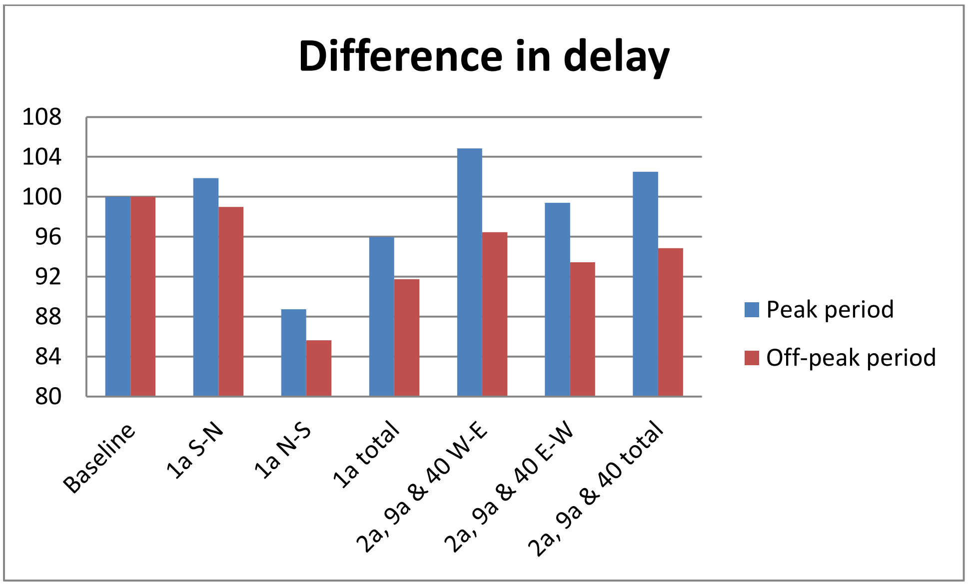

Figure 13: Difference in delay for different bus lines compared to their own baseline

5.3.1 Comparing

The results of all the busses in the complete network is -3,00% during peak period and -5,18% during off-peak period. When comparing those results with the results of the two most important bus lines, one can see that the differences are extensive. Only the results of bus lines 2a, 9a & 40 during of peak hour (-5,14%) is an almost spot on match with the network results during peak hour.

Comparing the results of the bus lines with the results of the bus's emissions the only match found is that in both cases bus priority has a positive effect. Besides that effect nor the travel time nor the delay shows any similarities. This effect can be caused by the fact that the emissions are based on all the bus lines and the results of the bus lines only take line 1a, 2a, 9a and 40 into account.

5.3.2 Conclusion

The results of those two lines show the impact of bus priority on different lines better and more accurate than the results found in the network performance. To realise reduction of average delay for busses the implementation of bus priority is a good idea, since the results during peak hour show an -3% delay and during off-peak hour an -5,2% delay.

The upper half of the network is performing better than the lower half, but what is causing the effects on the different routes needs further research.

5.4 Intersections

One of the most important tables of this study is presented below: the effects of bus priority on different intersection. Because the decision to implement bus priority is based on both the effect it has on the bus as well as on the effect it has on cars & HGVs, also those effects are shown. The results from intersections 807, 813 and 1002 are marked with an asterisk since they don't have a TLC with bus priority configuration, during evaluations these results are removed.

Table 10: Effects bus priority on intersections

Percentage difference between normal and with bus priority						
	peak				off peak	
Intersection number	Average of Delay (bus)	Average of Delay (car & HGV)		Intersection number	Average of Delay (bus)	Average of Delay (car & HGV)
both showing a positive effect						
1004	-54,27	-14,84		809	-80,52	-2,14
808	-40,68	-0,01		311	-13,78	-4,36
802	-38,71	-22,14		705	-6,68	-8,79
1005	-25,94	-15,86		806	-6,47	-6,18
302	-23,18	-0,79		310	-5,24	-3,90
801	-18,50	-0,08		202 _1	-5,05	-2,21
				812	-3,89	-4,15
				801	-1,01	-2,10
bus showing a positive effect, car & HGV showing a negative effect						
809	-73,75	7,72		802	-42,27	3,53
202_2	-8,48	1,03		1005	-18,38	21,03
310	-8,10	12,51		202_2	-18,02	1,20
812	-0,46	2,36		803	-9,68	9,59
				1002*	-4,14	22,93
				702	-3,73	4,31
car & HGV showing a postivive effect, bus showing a negative effect						
1002*	29,05	-1,45		302	11,98	-4,26
705	21,74	-2,64		807*	0,20	-18,52
806	0,92	-2,82		1004	407,93	-66,53
202 _1	23,35	-4,73				
807*	5,09	-14,62				
1003	1,51	-15,55				
814	15,84	-16,67				
both showing a negative effect						
701	2,21	39,68		701	4,42	15,45
702	4,67	18,87		808	7,21	16,27
311	10,96	0,44		1003	8,67	36,14
803	14,30	17,13		813*	20,03	120,21
813*	15,51	148,34		814	41,54	0,86

As can be seen in the figures below; bus priority results in a positive effect for the bus for 50% of the intersections during peak hour and for almost 70% of the intersections during off-peak hour. But only in the cases that both bus and car & HGV show a positive effect seem quite straight forward: implement bus priority. In the other cases decisions have to be made whether the effects on the bus justifies the negative effect on car & HGV. If the bus and car & HGV suffer from the implementation of bus priority, it seems logical not to implement bus priority on those intersections.

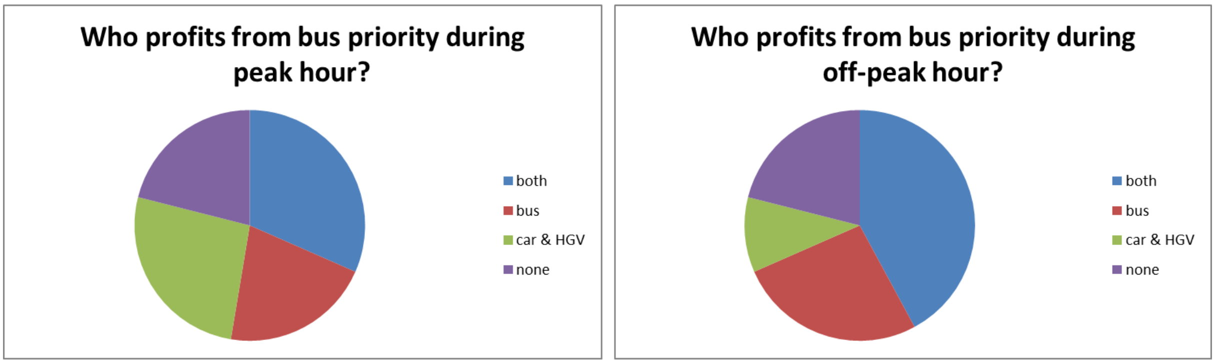

Figure 14: Pies showing the percentages of who is profiting from bus priority

5.4.1 Correlations

To determine what parameter causes the effects on intersection level several correlations have been calculated (the results can be found in Appendix G: Correlations)).The correlation is based on comparing two rows with parameters. The parameters are for every intersection the difference between the scenarios without bus priority and with bus priority. The parameters can create extreme values due to one of the two scenarios has an extreme value. These extreme values have a strong effect on the correlation, so it is better to remove these parameters all together.

After the removal of the results of intersection 701 during peak hour (extreme value in max delay) and the results of intersection 1004 during off peak (extreme value in average delay of bus). The following correlations were calculated:

- Average delay (of all vehicle, motorized, car & HGV, bus)
- Max of delay (bus)
- Number of vehicles
- Number of motorized vehicles
- Percentage motorized vehicles compared to all vehicles
- Number of lanes
- Percentage lanes used by a bus compared to the total number of lanes

The correlations with a score above the 0,5 are marked yellow in Appendix G: Correlations.

Unfortunately only a few correlations between the parameters are found. The reason for not finding that many correlations has to be one of the following: the correlation doesn't exist; the model isn't working correct or the use of the median run of the average delay of all vehicles doesn't create the right data to analyse.

Among the high correlations of the peak period the one between the average delay and the max of delay stands out. This can mean that there is a relation between the average delay and max of delay, or it could also mean that the max delay creates for a large portion the average delay.

Another correlation during the peak period that caches the eye is the relation between the average delay of all the vehicles and the average delay of the motorized vehicles. This means that all vehicles (motorized as well as bikes & pedestrians) are influenced by bus priority with the same factor.

Remarkable is that there is no correlation found between the average delay of the bus and the following parameters: the total amount of vehicles or for example the number of lanes. Before this research the expected outcomes were finding correlations between those subjects.

For starters it was expected that on intersections where the bus would profit the most from bus priority, the other vehicles would suffer the most. Since when the bus is granted priority, other vehicles have to stop. However the bus sometimes drives with the main stream and sometimes crosses the main stream, so the positive effects and the negative effects might level each other.

Also it was expected that the negative effect on other vehicles would be stronger on intersections with more vehicles. Since it would be harder to grant priority and if it was granted the effects would be stronger. Probably for the same reason as above the positive and negative effects level each other out.

The assumption about the number of lanes was that the more lanes the easier the bus would make it through the extension and therefor would benefit more on intersections with more lanes. But since the number of lanes doesn't say anything about the direction or the number of vehicles going in each direction, the assumption should have been more specified.

One of the recommendations will be to do more detailed research on what is causing the effects of bus priority. Since during this study both the network is too large to go in-depth and the main focus of this study was on finding out what the effects would be on the network and the intersection and then find the reasons for these outcomes.

5.4.2 ANOVA

Another way to determine what parameter causes the effect on intersection level is grouping values of a parameter that are alike and compare them to other another group of the same parameter. During this study the means of several parameters are compared with each other and later on an ANOVA is conducted to test whether the results only look different or that they are in fact different. The different parameters that are compared with each other all indicate the size of the intersection (total vehicle count, motorized vehicle count and number of lanes).

The same intersections as during the correlation research have been removed. So this means the three intersections without priority configuration, the results of intersection 701 during peak hour and the results of intersection 1004 during off peak. The values of the intersections in the different groups and also the calculations for the ANOVA can be found in Appendix H: ANOVA and the summary is shown below in Table 11.

Looking at the averages of the all vehicle count during off-peak one can see that intersections with less vehicle score better than intersections with many vehicles, since the average delay for the bus reduces the strongest (respectively for few vehicles -23,1% average vehicles -3,7% and many vehicles 4,7%). The same results are found for the count of motorized vehicles during off peak (-18,6%; 0,33%; 2,75%). The same trend can be seen during peak hour, with the intersection with fewer (motorized) vehicles performing better than those with more vehicles.

For the off-peak as well as the peak hour, the number of lanes the effect of the medium number of lanes (between the 5 and 10 lanes) has the best result in reducing the average delay for busses. During off-peak the intersections that are larger than 10 lanes score better (-5,3%) than the ones with less than 5 lanes (0,7%). During Peak hour those two are the other way around: more than 10 lanes scores 2,5% and smaller than 5 scores -16%.

The negative side of the means found for the groups is that the standard deviation is quite large for each group. So even inside one group the differences between two intersections can be huge, resulting in the fact that the overall result of the group can't automatically be copied to an intersection.

An ANOVA uses the mean and the compares the sum of squares between groups with the sum of squares within groups. In other words it compares the mean of one group with other groups taking the standard deviation into account. Depending on the total number of observations and the number of groups a critical value can be determined. If the value of the ANOVA is larger than the critical value, the groups are different from each other.

The results of the ANOVA show that, with a 95% certainty, there is no difference between the different groups with all vehicles. Since the larger intersections have a mean that indicates that the effects of bus priority works contra productive on reducing the delay of bus and the differences between the groups is not significant, so one can't conclude anything based on the total vehicle count.

However zooming in on only the number of motorized vehicle on an intersection the ANOVA shows that, with a 95% certainty, there is a difference between the groups. Taking another look at the means, one can conclude that the smaller intersections score have a better result in reducing the bus priority than the larger intersections.

The effect of the number of lanes is inconclusive, since during off peak hour there is a significant difference between the different groups but this difference is missing during peak hour. Looking at the means one can see contradicting results as well. During off peak hour the group with the smallest number of lanes shows a negative effect and the group with the largest intersection show slight improvement, but during peak hour this is just the other way around. In both periods the (positive) effect of bus priority is the strongest, but still not conclusive.

Table 11: Results of the ANOVA showing whether the average delay of busses is different per group

			Group 1	Group 2	Group 3	h_0
						$\mu_1=\mu_2=\mu_3$
Off-peak	count all vehicle		x <3000	3000 < x < 4000	4000 < x	keep
		mean	-23,08	-3,69	4,68	
		n	6	7	5	
		sd	33,1	7,8	23,3	
		F(2,15)	2,15			
		critical value	3,68			
Off-peak	count motorized		x <1000	1000 < x < 2000	2000 < x	reject
		mean	-18,63	0,33	2,75	
		n	8	8	2	
		sd	29	19,1	13	
		F(2,15)	7,62			
		critical value	3,68			
Off-peak	number of lanes		x <5	5 < x < 10	10 < x	reject
		mean	0,65	-13,99	-5,26	
		n	4	8	6	
		sd	34,5	28,3	9,9	
		F(2,15)	5,97			
		critical value	3,68			
Peak	count all vehicle		x <4000	4000 < x < 6000	6000 < x	keep
		mean	-25,30	-12,15	2,36	
		n	4	9	5	
		sd	33,1	25,5	24,8	
		F(2,15)	1,18			
		critical value	3,68			
Peak	count motorized		x <2000	2000 < x		reject
		mean	-15,68	-5,25		
		n	10	8		
		sd	27,8	27,3		
		F(1,16)	28,64			
		critical value	4,49			
Peak	number of lanes		x <5	5 < x < 10	10 < x	keep
		mean	-16,00	-18,71	2,49	
		n	4	8	6	
		sd	28,2	29,7	22	
		F(2,15)	1,13			
		critical value	3,68			

5.4.3 Comparing

Looking at the results from the complete network and the results of the separate intersections it seems almost impossible to tell if bus priority should be implemented on network scale. The result of any intersection is completely different to the results of every other. Also the results are different for the peak and the off-peak period. Effects on intersection level are much stronger than on network level. But what is experienced on network level (a positive effect of bus priority on the average bus delay) is also the overall conclusion of the intersections.

Including the information on intersection level another test can be made: what would be the result if one would exclude the three intersections that don't have a priority configuration. The results are presented in the table below.

Table 12: Difference in average delay for the complete network when the three intersection without priority configuration are removed

difference in average delay			
off peak		peak	
Car & HGVs	bus	Car & HGVs	bus
-0,64	-8,55	1,03	-7,91

Comparing those results with the network results, one can see that the effects for the bus have increased significant and for the car & HGV the results decreased a little. So it is expected that the results for the bus will improve, when also these three intersections will implement bus priority.

5.4.4 Conclusion

During peak hour 50% of the intersections show a positive effect on the average delay for busses; this percentage rises to 70% looking at off-peak. Only when both the busses as well as the other vehicles show a positive reaction to implementation, the advice is simple: implement bus priority.

Since the effects are so completely different for every intersection two analyses of what is causing the effects were conducted: the correlation and the ANOVA. The correlation of several parameters with the results showed only two relations worth mentioning: the first is between the average delay and the max delay, the second is between the average delay of all vehicles and the average delay of motorized vehicle.

Dividing the results into groups who share the same parameter showed more results. The average showed that intersections with less (motorized) vehicles created a stronger reduction in average delay for busses. The average didn't find such a connection for the number of lanes and the reduction in average delay for busses. But since the standard deviation was large for every group an ANOVA was conducted; showing that only the connection between the number of motorized vehicles and the average delay of busses was significant.

Since the reaction on bus priority is different for every intersection it is hard to tell what will be the outcome, but in general bus priority has an positive effect.

6 Conclusion and recommendations

6.1 Conclusion

The Copenhagen case study is ideal for this research; almost the complete simulation model was already built and later on the results can be tested on the streets as well. However the size of the study network could have been better, since it was extremely large. This resulted in the fact that it was hard to check whether the simulation was running correct and also processing the data was harder. Changing the network to a smaller size would take the same amount of time as working with this network, so for this research the complete network was used.

Since the applications on the streets have not been ready until recently it wasn't even possible to conduct the research on the street. It also would have been hard to measure the effects by any means but simulation for the effects per separate vehicle per intersection can be quite small. Also testing different scenarios would have been harder and would have taken a lot more time.

The scenarios run during this study are the most important periods during the day and represent the effects bus priority has the best. In a larger study it would have been possible to run another evening scenario with even fewer vehicles. Another necessary shortcoming of this study is using the median of one parameter to determine which dataset was being used, unfortunately due to time restrictions it wouldn't have been possible to run enough runs to level out the outliers. Having to choose between the median and the average of just five runs, the median should be chosen because it works with a situation that can occur on the streets.

The effects of bus priority on the average delay of a bus or the average delay of cars and HGVs is completely different for all intersections. During peak hour a little more than half of the intersections show a decrease of average delay for busses, in off-peak period that number even rises to 70% of the intersection showing a positive effect on the average delay for busses.

Looking at network level during peak hour, the simulations show a slight increase for the average delay for all vehicles (1,63%), which is (probably) cause by the extreme increase for bikes (8,57%). The average delay of the bus shows an improvement of 3,00%. Comparing those results to the values found for the main bus routes (improvement of 0,75%), the results can be explained by outliers who have a bigger impact on the measured results of bus routes.

The same difference can't be seen between the average delay of busses by looking at bus routes (-6,69%) and the complete network (-5,18%) during off-peak hour; so or the outliers don't occur or have less influence. Also the negative influence of bus priority on the other traffic is gone, resulting in an improvement of the average delay for all vehicles of -4,64% and for just the car -2,12%. Given the fact that everybody is benefitting of bus priority on network level during off-peak hour, one might question the current configuration.

To explain the differences between the different intersection two analyses were conducted: determining the correlation coefficient and the ANOVA. The correlation coefficient didn't show any relation between different parameters but the obvious. The ANOVA showed that there is no relation between the total vehicle count and the average delay, but there is a relation between the number of motorized vehicles and the average delay (presumably smaller intersection show a better result). The ANOVA was inconclusive whether the number of lanes has an influence.

The results of bus priority on emissions are for all four scenarios around the 1% reduction, exceptions are the impact on HGVs (probably caused by the small number of HGVs / outliers). To see whether the idea behind bus priority has a positive result on the emissions, the results between peak and off-peak period were compared: a reduction of 35% of the vehicles results in a reduction of 10% emissions.

The 1% reduction of emissions and the 3%-5% reduction in average delay are much smaller than the values found by the previous research of the effects of bus priority on this network (3% fuel and 10% delay reduction). However Islam (2014) used an adaptive signal control in combination with bus priority, which means that the bus is faster given priority. Comparing the results of this study with his outcomes, the results are even slightly better than expected.

Overall one can conclude that the effects of bus priority on the delay and fuel consumption of busses in general cause a reduction. For other vehicles the implementation of bus priority on network level also shows small reduction on delay and fuel. But the most important conclusion of this research is that the effects of bus priority are different for every intersection, so someone has to decide per intersection whether to implement bus priority or not.

6.2 Recommendation

First there are recommendations for Imtech Traffic & Infra / further research:

- Test whether other parameters influence the effects of bus priority (parameters such as place of bus stops and the distance to a previous intersection).
- Use a smaller model and go more in-depth to investigate what causes the results (things that need to be looked at are when busses arrive and how the TLC reacts to the priority request).
- Create more scenarios to see for example what happens if only a few bus lines are granted bus priority or what the influence is when several intersections are excluded from giving bus priority.
- Check whether intersections with less motorized vehicles in other cities show better results than intersections with more motorized vehicles.

The other recommendations are for Copenhagen:

- Compare other runs with each other to see whether the effects also occur during those runs, or run significant more runs of each scenario so the median can be used to evaluate the effects.
- Compare the results of the simulations with results seen on the street
- Decide on which intersections to implement bus priority (i.e. what negative effects are allowed to create positive effects).
- Continue exploring the option to reduce the number of vehicles, because a 35% reduction of vehicles causes a 10% decrease in emissions.

7 Bibliography

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8 Appendix A: Providing priority

In the cases of active and adaptive priority the system follows four steps to provide the priority, below the four steps are explained with the help of Figure 15. (United States Department of Transportation, 2005). In both cases the bus is detected and a message is send; the difference is the in the action that is initiated during step 2. Active priority chances the cycle that is being run and adaptive priority creates a cycle.

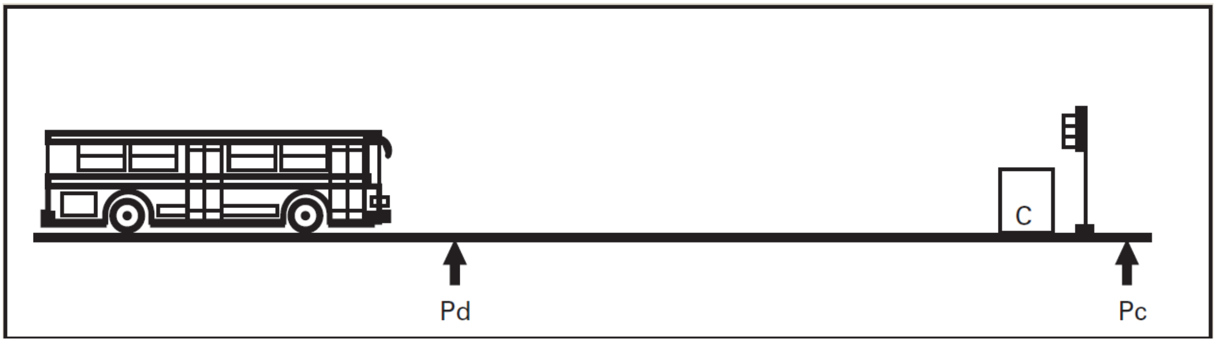


Figure 15: Figure to help explaining steps of bus priority

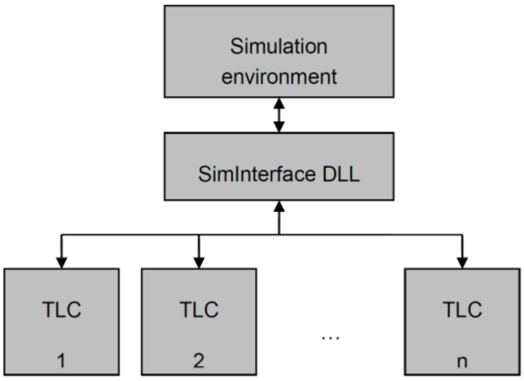
1. The bus approaching the intersection is detected at point Pd upstream of the intersection (various detection methods exist).
2. The Priority Request Generator unit is notified of the approaching bus and alerts the traffic control system that the vehicle would like to receive priority. The system processes the request and decides whether to grant priority based on defined conditions. The traffic controller C then initiates action to provide priority based on the defined priority control strategies (different strategies are listed above under active strategies).
3. When the bus passes through the intersection, clearance is detected by the bus detection system Pc and a communication is sent to the traffic controller that the bus has cleared the intersection.

On being notified that the bus has cleared the intersection, the controller C restores the normal signal timing through a predetermined logic.

9 Appendix B: Construction of the model

9.1.1 Model setup

Building the complete real network can just be done in as one part in Vissim. The model used during this study consists of two parts: one part is the simulation environment (in Vissim) with specifications to connect to external signal control and the other part is a DLL (Dynamic Link Library) with underneath the TLCs which takes care of the signal controls.



Figuur 16: Model setup (Vliet, 2007)

This setup allows for easy switching between different traffic light configurations, as it does not require updating the simulation environment. The reason for Imtech to create this SimInterface is that the TLC can connect to any brand of simulation environment. Since there are no downsides for using a model consisting of two parts instead of one part, I will be using a model consisting of two parts for my study.

9.1.2 Creating the simulation environment

The network was converted from an open street map to Vissim model by Imtech Traffic and Infra. All the intersections were modelled first and then added to the network. Necessary features like signal heads, detectors, routes, vehicles were added to complete the model.

Vissim Static Routing decision can be configured in two ways. First one is based on origin destination matrix (OD matrix). Routes were created from every vehicle input link to all the destination links over the network. The second method is adapted when sufficient data on OD matrix is not available. It also needs information concerning travel behaviour, time of day, etc. Vehicles checking in into an entry link are split according to the turning percentages of routes. This is done for all modes of traffic in every intersection. In Copenhagen network routes are created according to this second method. Input and output flows are verified and corrected to ensure consistency throughout the network.

The data for the vehicle input in for the model was generated in three different ways. Traffic data from detectors and manual counting was collected by the city of Copenhagen. For missing data, calibration was done based on the inflow-outflow and turning percentages. For buses the vehicle input is calculated from the time schedule obtained in the PT website of Copenhagen (Movia).

9.1.3 Traffic light configuration

The SimInterface connects the simulation environment with individual traffic light controllers. Imtech Traffic and Infra developed, in cooperation with Copenhagen, the optimal cycle for these Traffic Light

Controllers (TLCs). Most TLCs (in this network) have four different programs, for different times of the day and days of the week. In real-life the SimInterface connects the TLCs in the same way with the signal heads it now connects signal heads in the simulation environment with the TLCs.

The TLCs start at the same moment as the simulation. Depending on the rules in real life / the computer code a certain offset is used to align the TLCs with each other. However the different TLCs do not communicate with each other. The only connection they have is sending the output for the signal heads to Vissim and (in the case of priority) receiving a signal from a detector. The signal from the detector triggers (if the computer code dictates that) a reaction in the TLC.

10 Appendix C: Output files / nodes

To evaluate how the network behaves several files are produced. Underneath is explained which output can be found in which file and how the output is created (as described in the Vissim manual (PTV Planung Transport Verkehr AG, 2012)).

10.1.1 Travel times

During a simulation run Vissim can evaluate travel times if travel time measurement sections have been defined in the network. Each section consists of a start and a destination cross section. The travel time (including waiting or dwell times) is determined as the time required by a vehicle between crossing the first (start) and crossing the second (destination) cross section.

10.1.2 Delay times

Based on travel time sections Vissim can generate delay data. A delay measurement determines the mean time delay by comparing the travel time to the ideal travel time (no other vehicles, no signal control).

10.1.3 Queue length and vehicle stops

The queue length is measured from the location of the queue counter on the link or connector upstream to the final vehicle that is in queue condition. Thereafter the back of the queue is monitored until there is not a single vehicle left over on the approach that still merest the queue condition, though other vehicles between the initial start and the current end of the queue do no longer meet the queue condition (= a vehicle is in queue condition if its speed is less than the begin speed and has not exceeded the end speed yet).

Besides the average queue length, also the maximum queue length and number of vehicle stops within the queue are being logged. The output for queue length is in length and nog in number of cars.

10.1.4 Vehicle record

Vissim has the option to create a file containing any combination of vehicle parameters in a certain time resolution. During this study every second, for all vehicle types, the following parameters will be logged:

- Vehicle number
- Vehicle type number
- Vehicle type
- Speed
- Simulation time

Since the vehicle record creates a large file, it won’t be possible (for this study) to log more parameters.

10.1.5 Signal changes

Vissim provides a chronological list of all signal group (phase) changes of all selected signal controllers.

10.1.6 Node evaluation

Node evaluation is a way of collecting data for a user-defined area within a Vissim network. The evaluations are automatically collected using the node boundaries as the evaluation segment definitions. The node evaluation is designed especially for gathering intersection-specific data without the need to manually define all the data collection cross-sections.

The results of a node evaluation are grouped by turning movements. Each turning relation is named using the approximate compass directions (N / NE / E / SE / S / SW / W / NW) of its first and last link (at the node boundary) with "North" direction facing to the top of the Vissim network. If a compass with a user-defined North direction is active, any output direction data will refer to these settings. Example: "NE-S" is a movement entering from the North-East and leaving to the South.

The two link numbers can be written to the evaluation file as well to avoid ambiguity (two "parallel" turning relations with identical first and last links do look identical). All results are aggregated over a user-defined time period for time intervals with a user defined length.

The volume, average delay and standing time values as well as the number of stops are determined by a delay segment created automatically as a combination of new travel time measurements from all possible upstream starting points (with user-defined distance, but not extending across an upstream node boundary – unless there are more than four branches to side roads between the two nodes) to the node exit point of the respective turning relation. Also available is the number of passengers and the person delay by vehicle class.

The queue length values are collected by a queue counter crated automatically and placed at the first signal head or priority rule stop line on the link sequence of the turning relation. If there is no such cross section, the queue counter is placed at the node entry point. The node evaluation places a queue counter on every edge (movement) found inside the node. It is placed at the position of the signal head or priority rule stop line that is placed at the position of the signal head or priority rule stop line that is the closest one upstream to the node boundary on the respective edge.

Neither scheduled stops at PT stops nor stops in parking lots are counted as stops. Neither passenger transfer times nor dwell times at stop signs or time spent in parking lots is counted as delays (though time losses due to deceleration / acceleration before / behind PT stops do count for delay calculation).

10.1.7 Network performance evaluation

Network performance evaluation evaluates several parameters that are aggregated for the whole simulation run and the whole network.

11 Appendix D: Network performance

Performance parameter	Vehicle class	peak period			off-peak period		
		no priority	priority	difference	no priority	priority	difference
		Value	Value	%	Value	Value	%
Average delay time per vehicle [s]	All Vehicle	48,7	49,5	1,63	38,9	37,1	-4,64
	Bus	173,8	168,6	-3,00	144,2	136,8	-5,18
	Car	95,4	93,7	-1,80	61,9	60,6	-2,12
	HGV	100,3	100,8	0,54	61,0	64,5	5,71
	Pedestrian	23,8	23,5	-1,28	25,1	23,2	-7,49
	Bike	68,4	74,3	8,57	51,1	48,4	-5,19
Average number of stops per vehicles	All Vehicle	1,70	1,74	2,71	1,36	1,30	-3,84
	Bus	3,96	3,74	-5,44	3,15	3,11	-1,14
	Car	2,76	2,76	-0,18	1,99	1,93	-3,02
	HGV	2,43	2,50	2,97	1,70	1,78	4,72
	Pedestrian	0,77	0,77	-0,39	0,76	0,75	-0,53
	Bike	3,13	3,34	6,71	2,31	2,11	-8,59
Average stopped delay per vehicle [s]	All Vehicle	37,21	37,34	0,34	30,87	29,43	-4,66
	Bus	79,32	74,84	-5,65	58,94	52,98	-10,12
	Car	59,11	57,27	-3,12	37,56	37,41	-0,42
	HGV	60,46	61,43	1,60	33,34	35,86	7,55
	Pedestrian	22,65	22,35	-1,31	23,97	22,10	-7,79
	Bike	54,28	57,17	5,32	42,22	40,39	-4,33
Total delay time [h]	All Vehicle	951,7	967,0	1,61	499,6	478,3	-4,28
	Bus	10,8	10,4	-3,00	8,9	8,5	-5,18
	Car	364,0	356,5	-2,07	154,1	152,2	-1,17
	HGV	21,2	21,6	1,99	8,4	9,0	7,40
	Pedestrian	266,4	262,6	-1,46	184,4	170,1	-7,73
	Bike	289,3	315,9	9,22	143,9	138,4	-3,81
Number of Stops	All Vehicle	119280	122503	2,70	62713	60523	-3,49
	Bus	882	834	-5,44	702	694	-1,14
	Car	37974	37802	-0,45	17787	17411	-2,11
	HGV	1848	1930	4,44	841	895	6,42
	Pedestrian	30975	30822	-0,49	20019	19854	-0,82
	Bike	47601	51115	7,38	23364	21669	-7,25
Number of vehicles in the network	All Vehicle	2282	2304	0,96	1362	1395	2,42
	Bus	16	14	-12,50	12	11	-8,33
	Car	651	617	-5,22	316	326	3,16
	HGV	37	40	8,11	22	10	-54,55
	Pedestrian	489	496	1,43	359	358	-0,28
	Bike	1089	1137	4,41	653	690	5,67
Number of vehicles that have left the network	All Vehicle	68015	67984	-0,05	44922	45062	0,31
	Bus	207	209	0,97	211	212	0,47
	Car	13086	13083	-0,02	8643	8720	0,89
	HGV	724	732	1,10	474	494	4,22
	Pedestrian	39867	39786	-0,20	26109	26041	-0,26
	Bike	14131	14174	0,30	9485	9595	1,16
Total stopped delay [h]	All Vehicle	726,6	728,9	0,32	396,9	379,8	-4,30
	Bus	4,9	4,6	-5,64	3,7	3,3	-10,13
	Car	225,6	217,9	-3,39	93,5	94,0	0,55
	HGV	12,8	13,2	3,08	4,6	5,0	9,30
	Pedestrian	253,9	250,1	-1,49	176,2	162,1	-8,03
	Bike	229,5	243,1	5,95	118,9	115,4	-2,95
Total travel time [h]	All Vehicle	2264,4	2275,9	0,51	1361,8	1349,4	-0,91
	Bus	18,9	18,7	-1,14	17,3	16,8	-2,73
	Car	635,2	629,6	-0,90	333,0	332,9	-0,03
	HGV	34,5	34,8	0,65	16,8	17,7	5,05
	Pedestrian	508,5	504,4	-0,79	342,6	328,0	-4,28
	Bike	1067,3	1088,5	1,99	652,1	654,0	0,30

12 Appendix E: Comparing the median with the mean

peak period								
		median			mean			
Performance parameter	Vehicle class	no priority Value	priority Value	difference %	no priority Value	priority Value	difference %	standard deviation of difference
Average delay time per vehicle [s]	All Vehicle	48,7	49,5	1,63	48,68	48,92	0,50	1,11
	Bus	173,8	168,6	-3,00	170,12	165,51	-2,66	3,36
	Car	95,4	93,7	-1,80	96,35	94,72	-1,70	2,06
	HGV	100,3	100,8	0,54	97,91	95,40	-2,57	1,17
	Pedestrian	23,8	23,5	-1,28	23,83	23,67	-0,66	1,11
	Bike	68,4	74,3	8,57	67,14	70,45	5,02	3,52
Average number of stops per vehicles	All Vehicle	1,70	1,74	2,71	1,70	1,72	1,48	1,31
	Bus	3,96	3,74	-5,44	3,88	3,71	-4,24	3,88
	Car	2,76	2,76	-0,18	2,80	2,79	-0,33	1,45
	HGV	2,43	2,50	2,97	2,41	2,41	0,23	2,28
	Pedestrian	0,77	0,77	-0,39	0,77	0,77	-0,39	0,76
	Bike	3,13	3,34	6,71	3,08	3,22	4,51	2,98
Average stopped delay per vehicle [s]	All Vehicle	37,21	37,34	0,34	36,97	37,08	0,29	1,28
	Bus	79,32	74,84	-5,65	75,82	72,83	-3,85	4,93
	Car	59,11	57,27	-3,12	59,24	58,09	-1,92	2,85
	HGV	60,46	61,43	1,60	59,43	57,31	-3,60	2,12
	Pedestrian	22,65	22,35	-1,31	22,70	22,55	-0,67	1,14
	Bike	54,28	57,17	5,32	52,91	55,03	4,09	3,38
Total delay time [h]	All Vehicle	951,7	967,0	1,61	950,89	954,13	0,34	1,04
	Bus	10,8	10,4	-3,00	10,54	10,25	-2,66	3,36
	Car	364,0	356,5	-2,07	368,52	360,86	-2,09	1,93
	HGV	21,2	21,6	1,99	20,12	19,67	-2,22	1,60
	Pedestrian	266,4	262,6	-1,46	266,89	264,90	-0,74	1,00
	Bike	289,3	315,9	9,22	284,82	298,44	4,86	3,50
Number of Stops	All Vehicle	119280	122503	2,70	119311	120913	1,33	1,24
	Bus	882	834	-5,44	866	828	-4,24	3,87
	Car	37974	37802	-0,45	38535	38264	-0,71	1,40
	HGV	1848	1930	4,44	1782	1792	0,60	2,86
	Pedestrian	30975	30822	-0,49	31036	30893	-0,46	0,67
	Bike	47601	51115	7,38	47093	49136	4,35	2,91
Number of vehicles in the network	All Vehicle	2282	2304	0,96	2350	2274	-3,20	2,49
	Bus	16	14	-12,50	15	14	-7,54	6,36
	Car	651	617	-5,22	685	636	-7,04	2,94
	HGV	37	40	8,11	41	37	-9,60	10,38
	Pedestrian	489	496	1,43	500	476	-4,46	7,03
	Bike	1089	1137	4,41	1109	1111	0,14	2,48
Number of vehicles that have left the network	All Vehicle	68015	67984	-0,05	67972	67941	-0,05	0,07
	Bus	207	209	0,97	208	209	0,58	0,53
	Car	13086	13083	-0,02	13083	13078	-0,04	0,39
	HGV	724	732	1,10	698	705	0,96	0,67
	Pedestrian	39867	39786	-0,20	39823	39814	-0,02	0,08
	Bike	14131	14174	0,30	14160	14136	-0,17	0,20
Total stopped delay [h]	All Vehicle	726,6	728,9	0,32	722,22	723,15	0,14	1,19
	Bus	4,9	4,6	-5,64	4,70	4,51	-3,86	4,93
	Car	225,6	217,9	-3,39	226,55	221,34	-2,31	2,68
	HGV	12,8	13,2	3,08	12,22	11,82	-3,25	2,38
	Pedestrian	253,9	250,1	-1,49	254,30	252,38	-0,75	1,03
	Bike	229,5	243,1	5,95	224,46	233,10	3,93	3,36
Total travel time [h]	All Vehicle	2264,4	2275,9	0,51	2260,17	2261,32	0,05	0,42
	Bus	18,9	18,7	-1,14	18,73	18,44	-1,53	1,81
	Car	635,2	629,6	-0,90	641,13	633,25	-1,24	1,01
	HGV	34,5	34,8	0,65	32,67	32,30	-1,13	0,82
	Pedestrian	508,5	504,4	-0,79	508,87	506,76	-0,41	0,53
	Bike	1067,3	1088,5	1,99	1058,77	1070,57	1,12	0,85

off-peak period								
		median			mean			
Performance		no priority	priority	difference	no priority	priority	difference	standard deviation of
parameter	Vehicle class	Value	Value	%	Value	Value	%	difference
Average delay time per vehicle [s]	All Vehicle	38,9	37,1	-4,64	38,84	37,19	-4,26	0,33
	Bus	144,2	136,8	-5,18	144,04	136,80	-5,01	2,41
	Car	61,9	60,6	-2,12	61,28	60,50	-1,28	0,82
	HGV	61,0	64,5	5,71	60,10	61,58	2,60	5,43
	Pedestrian	25,1	23,2	-7,49	25,14	23,41	-6,85	1,02
	Bike	51,1	48,4	-5,19	51,27	48,96	-4,50	0,58
Average number of stops per vehicles	All Vehicle	1,36	1,30	-3,84	1,36	1,30	-4,00	0,43
	Bus	3,15	3,11	-1,14	3,23	3,02	-6,63	4,44
	Car	1,99	1,93	-3,02	1,98	1,92	-2,73	0,77
	HGV	1,70	1,78	4,72	1,69	1,72	2,03	6,86
	Pedestrian	0,76	0,75	-0,53	0,76	0,76	-0,37	0,58
	Bike	2,31	2,11	-8,59	2,32	2,13	-8,17	0,53
Average stopped delay per vehicle [s]	All Vehicle	30,87	29,43	-4,66	30,91	29,59	-4,25	0,45
	Bus	58,94	52,98	-10,12	58,33	53,62	-8,01	4,96
	Car	37,56	37,41	-0,42	37,37	37,37	0,01	1,10
	HGV	33,34	35,86	7,55	32,69	34,07	4,42	6,70
	Pedestrian	23,97	22,10	-7,79	24,03	22,31	-7,14	1,04
	Bike	42,22	40,39	-4,33	42,37	40,88	-3,51	0,82
Total delay time [h]	All Vehicle	499,6	478,3	-4,28	498,36	476,77	-4,33	0,20
	Bus	8,9	8,5	-5,18	8,92	8,47	-5,01	2,42
	Car	154,1	152,2	-1,17	152,41	150,48	-1,26	0,74
	HGV	8,4	9,0	7,40	8,24	8,44	2,62	5,87
	Pedestrian	184,4	170,1	-7,73	184,05	171,23	-6,95	1,05
	Bike	143,9	138,4	-3,81	144,75	138,15	-4,56	0,45
Number of Stops	All Vehicle	62713	60523	-3,49	62786	60231	-4,07	0,61
	Bus	702	694	-1,14	721	673	-6,63	4,44
	Car	17787	17411	-2,11	17685	17206	-2,71	0,74
	HGV	841	895	6,42	835	850	2,06	7,42
	Pedestrian	20019	19854	-0,82	20002	19897	-0,52	0,63
	Bike	23364	21669	-7,25	23544	21604	-8,23	1,04
Number of vehicles in the network	All Vehicle	1362	1395	2,42	1345	1318	-1,87	4,63
	Bus	12	11	-8,33	12	12	-5,18	13,50
	Car	316	326	3,16	319	312	-1,61	8,71
	HGV	22	10	-54,55	17	15	-7,45	31,79
	Pedestrian	359	358	-0,28	340	332	-1,54	10,42
	Bike	653	690	5,67	657	647	-1,33	4,99
Number of vehicles that have left the network	All Vehicle	44922	45062	0,31	44846	44838	-0,02	0,19
	Bus	211	212	0,47	211	211	0,39	0,92
	Car	8643	8720	0,89	8634	8642	0,09	0,48
	HGV	474	494	4,22	476	478	0,34	2,22
	Pedestrian	26109	26041	-0,26	26018	25996	-0,08	0,18
	Bike	9485	9595	1,16	9507	9511	0,04	0,71
Total stopped delay [h]	All Vehicle	396,9	379,8	-4,30	396,55	379,42	-4,32	0,31
	Bus	3,7	3,3	-10,13	3,61	3,32	-8,01	4,96
	Car	93,5	94,0	0,55	92,93	92,94	0,03	1,32
	HGV	4,6	5,0	9,30	4,48	4,67	4,44	7,06
	Pedestrian	176,2	162,1	-8,03	175,90	163,14	-7,25	1,08
	Bike	118,9	115,4	-2,95	119,62	115,35	-3,57	0,41
Total travel time [h]	All Vehicle	1361,8	1349,4	-0,91	1362,92	1341,17	-1,59	0,50
	Bus	17,3	16,8	-2,73	17,23	16,81	-2,46	1,31
	Car	333,0	332,9	-0,03	331,54	329,75	-0,54	0,55
	HGV	16,8	17,7	5,05	16,86	16,99	0,83	4,19
	Pedestrian	342,6	328,0	-4,28	341,76	328,81	-3,78	0,63
	Bike	652,1	654,0	0,30	655,52	648,80	-1,02	0,90

13 Appendix F: Emissions per vehicle

Peak period priority					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	14312,1	4809,9 73.1 %	336,07	8078,2 37.6 %	0,564
HGV	691,0	1278,1 19.4 %	1849,60	10685,7 49.7 %	15,46
Bus	307,1	494,8 7.5 %	1611,49	2722,0 12.7 %	8,865
Total	15310,1	6583,8	430,60	21486,0	1,407

Peak period no priority					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	14215,3	4802,9 73.2 %	337,87	8077,7 37.9 %	0,568
HGV	702,2	1261,0 19.2 %	1795,80	10517,9 49.3 %	14,98
Bus	303,4	494,7 7.5 %	1630,64	2724,4 12.8 %	8,981
Total	15220,9	6558,2	431,36	21320,0	1,403

Peak period difference					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	0,68	0,15	-0,53	0,01	-0,67
HGV	-1,59	1,35	3,00	1,60	3,24
Bus	1,22	0,03	-1,17	-0,09	-1,29
Total	0,59	0,39	-0,18	0,78	0,30

Off-peak period priority					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	9478,0	2838,2 69.8 %	299,45	4728,9 34.8 %	0,499
HGV	455,0	753,9 18.5 %	1656,91	6253,3 46.0 %	13,74
Bus	310,3	476,0 11.7 %	1534,15	2603,0 19.2 %	8,389
Total	10243,3	4068,1	396,85	13585,1	1,324

Off-peak period no priority					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	9389,7	2845,3 70.3 %	303,02	4739,6 35.7 %	0,505
HGV	443,8	718,6 17.8 %	1619,25	5949,3 44.6 %	13,41
Bus	310,1	481,3 11.9 %	1552,35	2636,4 19.8 %	8,503
Total	10143,6	4045,2	398,85	13325,4	1,314

Off-peak period difference					
Emission per vehicle class:					
Class	Distance	CO2	CO2	NOx	NOx
	[km]	[kg]	[g / km]	[g]	[g / km]
Car	0,94	-0,25	-1,18	-0,23	-1,17
HGV	2,52	4,91	2,33	5,11	2,52
Bus	0,06	-1,10	-1,17	-1,27	-1,34
Total	0,98	0,57	-0,50	1,95	0,75

14 Appendix G: Correlations

percentage change during peak period, average per bus lane											
	Average of Delay	Average of Delay			Max of Delay	Count	Count	% motorized/all	number of lanes	% bus lanes/lanes	% busstroken with prio
Row Labels	(all vehicles)	(motorized)	(car & HGV)	(bus)	(bus)	(all vehicles)	(motorized)				
1	-1,88	-2,45	-4,73	23,35	49,53	7172	2487	0,35	21	0,38	0,25
2	-1,41	0,17	1,03	-8,48	11,13	2357	1705	0,72	6	1,00	0,33
3	-0,80	-1,49	-0,79	-23,18	-44,41	10513	5133	0,49	17	0,59	0,10
4	1,37	11,47	12,51	-8,10	-40,86	5647	1092	0,19	7	0,29	0,50
5	2,28	0,90	0,44	10,96	-0,68	5399	1390	0,26	9	0,22	0,50
6	10,11	17,92	18,87	4,67	-2,88	5457	1219	0,22	13	0,62	0,63
8	-8,31	-2,21	-2,64	21,74	7,85	6336	2308	0,36	11	0,45	0,20
9	-0,76	-2,79	-2,82	0,92	-1,64	5803	3271	0,56	6	0,17	1,00
10	1,70	2,24	2,36	-0,46	2,72	3738	2261	0,60	4	0,75	1,00
13	1,97	17,05	17,13	14,30	-25,61	5275	1426	0,27	14	0,21	0,33
15	-5,71	-22,39	-22,14	-38,71	-3,17	4285	1403	0,33	3	0,67	1,00
16	7,73	-0,43	-0,01	-40,68	-34,89	4280	1204	0,28	3	0,33	1,00
17	-6,89	6,27	7,72	-73,75	-64,14	1832	941	0,51	7	0,29	0,50
18	-2,71	-16,59	-16,67	15,84	-1,84	6106	2009	0,33	3	0,33	1,00
19	5,48	-0,62	-0,08	-18,50	-21,21	3281	1056	0,32	8	0,25	1,00
21	35,13	-15,35	-15,55	1,51	24,86	4697	1949	0,41	7	0,29	1,00
22	-10,71	-14,91	-14,84	-54,27	-12,90	5623	2013	0,36	9	0,22	1,00
23	-4,74	-16,15	-15,86	-25,94	-30,64	9468	2474	0,26	20	0,40	0,63
correlation	1,00										
	0,08	1,00									
	0,09	1,00	1,00								
	-0,11	0,34	0,31	1,00							
	-0,26	0,38	0,36	0,80	1,00						
	0,02	-0,07	-0,09	0,17	-0,09	1,00					
	0,01	-0,24	-0,24	0,01	-0,16	0,78	1,00				
	-0,04	-0,24	-0,23	-0,21	-0,18	-0,18	0,44	1,00			
	-0,11	0,08	0,06	0,21	0,04	0,67	0,41	-0,21	1,00		
	-0,10	-0,11	-0,10	-0,01	-0,02	-0,08	0,18	0,50	-0,11	1,00	
	0,36	-0,23	-0,22	-0,20	-0,06	-0,28	-0,18	0,01	-0,55	-0,20	1,00

percentage change during off-peak period, average per bus lane

	Average of Delay	Average of Delay			Max of Delay	Count	Count	% motorized/all	number of lanes	% bus lanes/lanes	% busstroken with prio
Row Labels	(all vehicles)	(motorized)	(car & HGV)	(bus)	(bus)	(all vehicles)	(motorized)				
1	-3,65	-2,72	-2,21	-5,05	-3,95	4723	1648	0,35	21	0,38	0,25
2	-5,71	-3,92	1,20	-18,02	-35,04	1525	1111	0,73	6	1,00	0,33
3	-1,79	-3,80	-4,26	11,98	27,71	7140	3438	0,48	17	0,59	0,10
4	-1,69	-3,96	-3,90	-5,24	0,48	3753	765	0,20	7	0,29	0,50
5	-3,16	-5,10	-4,36	-13,78	-11,78	3563	977	0,27	9	0,22	0,50
6	-0,75	3,26	4,31	-3,73	10,16	3666	863	0,24	13	0,62	0,63
7	3,22	14,42	15,45	4,42	33,26	3701	1254	0,34	8	0,25	1,00
8	-3,83	-8,73	-8,79	-6,68	-4,79	4277	1607	0,38	11	0,45	0,20
9	-1,74	-6,20	-6,18	-6,47	-0,19	3871	2204	0,57	6	0,17	1,00
10	1,83	-3,91	-4,15	-3,89	-0,11	2496	1524	0,61	4	0,75	1,00
13	-5,17	8,50	9,59	-9,68	9,73	3477	981	0,28	14	0,21	0,33
15	5,04	1,67	3,53	-42,27	25,35	2857	960	0,34	3	0,67	1,00
16	11,82	16,02	16,27	7,21	0,00	2798	802	0,29	3	0,33	1,00
17	-9,99	-4,15	-2,14	-80,52	-72,22	1199	620	0,52	7	0,29	0,50
18	-33,50	1,09	0,86	41,54	-2,93	4046	1338	0,33	3	0,33	1,00
19	-1,99	-1,99	-2,10	-1,01	-4,04	2229	718	0,32	8	0,25	1,00
21	20,44	35,26	36,14	8,67	-16,18	3058	1274	0,42	7	0,29	1,00
23	0,51	18,68	21,03	-18,38	-28,66	6177	1623	0,26	20	0,40	0,63
correlation	1,00										
	0,55	1,00									
	0,55	0,99	1,00								
	-0,12	0,22	0,15	1,00							
	0,17	0,04	-0,01	0,55	1,00						
	-0,06	0,06	0,02	0,42	0,43	1,00					
	-0,03	-0,15	-0,18	0,34	0,33	0,75	1,00				
	-0,04	-0,27	-0,23	-0,20	-0,33	-0,32	0,34	1,00			
	0,04	0,12	0,12	-0,02	0,04	0,70	0,42	-0,26	1,00		
	0,10	-0,17	-0,17	-0,04	0,29	0,17	0,26	0,21	0,04	1,00	
	0,20	0,32	0,30	0,35	0,31	-0,22	0,16	0,31	-0,60	0,11	1,00

15 Appendix H: ANOVA

OFF-PEAK VEHICLE COUNT													
Group 1:	vehicle count <3000				Group 2:	3000 <vehicle count < 4000				Group 3:	4000 <vehicle count		
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2
1199	-80,52	-57,44	3299,34		3058	8,67	12,36	152,72		4046	41,54	36,86	1358,58
1525	-18,02	5,06	25,64		3477	-9,68	-5,99	35,87		4277	-6,68	-11,36	129,06
2229	-1,01	22,08	487,34		3563	-13,78	-10,10	101,97		4723	-5,05	-9,73	94,75
2496	-3,89	19,19	368,26		3666	-3,73	-0,04	0,00		6177	-18,38	-23,06	531,70
2798	7,21	30,30	917,88		3701	4,42	8,11	65,75		7140	11,98	7,29	53,20
2857	-42,27	-19,19	368,09		3753	-5,24	-1,56	2,43					
					3871	-6,47	-2,78	7,74					
sum	-138,51		5466,54		sum	-25,81		366,47		sum	23,41		2167,28
mean	-23,08				mean	-3,69				mean	4,68		
SSW	8000,29												
							Total Sum of Squares		10299,40				
	observations		x-mean	(x-mean)^2			Sum of Squares Within		8000,29				
	-80,52		-72,70	5284,76			Sum of Squares Between		2299,11				
	-18,02		-10,19	103,90									
	-1,01		6,82	46,50									
	-3,89		3,93	15,47									
	7,21		15,04	226,20			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)						
	-42,27		-34,44	1186,26				1149,555103					
	8,67		16,50	272,22									
	-9,68		-1,85	3,42									
	-13,78		-5,96	35,48			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)						
	-3,73		4,10	16,82				533,3526078					
	4,42		12,25	150,06									
	-5,24		2,58	6,68									
	-6,47		1,36	1,85			F=	1149,555103	/	533,3526078	=	2,155337926	
	41,54		49,37	2437,30									
	-6,68		1,15	1,32			F(2,15)	=	2,15		p<0,05		
	-5,05		2,78	7,71			critical value	=	3,68				
	-18,38		-10,55	111,27									
	11,98		19,80	392,20									
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**				
mean	-7,83												
			sum	10299,40	SST		**FAILED TO REJECT NULL HYPOTHESIS**						

OFF-PEAK MOTORIZED COUNT													
Group 1:	motorized count <1000				Group 2:	1000 <motorized count < 2000				Group 3:	2000 <motorized count		
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2
620	-80,52	-61,90	3831,17		1111	-18,02	-18,35	336,63		2204	-6,47	-9,22	85,05
718	-1,01	17,62	310,43		1254	4,42	4,10	16,77		3438	11,98	9,22	85,05
765	-5,24	13,38	179,13		1274	8,67	8,34	69,63					
802	7,21	25,84	667,70		1338	41,54	41,21	1698,64					
863	-3,73	14,90	222,03		1524	-3,89	-4,22	17,82					
960	-42,27	-23,64	558,95		1607	-6,68	-7,00	49,07					
977	-13,78	4,84	23,46		1623	-18,38	-18,70	349,80					
981	-9,68	8,95	80,13		1648	-5,05	-5,38	28,93					
sum	-149,02		5873,01		sum	2,61		2567,28		sum	5,51		170,10
mean	-18,63				mean	0,33				mean	2,75		
SSW	8610,38												
							Total Sum of Squares		17358,97				
	observations		x-mean	(x-mean)^2			Sum of Squares Within		8610,38				
	-80,52		-92,50	8556,31			Sum of Squares Between		8748,58				
	-18,02		-30,00	899,83									
	-1,01		-12,98	168,60									
	-3,89		-15,87	251,87									
	7,21		-4,76	22,70			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)						
	-42,27		-54,25	2942,64				4374,29141					
	8,67		-3,30	10,92									
	-9,68		-21,65	468,82									
	-13,78		-25,76	663,62			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)						
	-3,73		-15,70	246,59				574,0256644					
	4,42		-7,55	57,07									
	-5,24		-17,22	296,53									
	-6,47		-18,44	340,20			F=	4374,29141	/	574,0256644	=	7,620376024	
	41,54		29,56	874,09									
	-6,68		-18,65	347,98			$F(2,15)$	=	7,62		$p<0,05$		
	-5,05		-17,03	289,95			critical value	=	3,68				
	-18,38		-30,35	921,27									
	11,98		0,00	0,00									
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**				
mean	-7,83												
			sum	17358,97	SST		**REJECT NULL HYPOTHESIS**						

OFF-PEAK NUMBER OF LANES													
Group 1:	number of lanes <5				Group 2:	5 <number of lanes < 10				Group 3:	10 <number of lanes		
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2
3	7,21	6,56	43,10		6	-18,02	-4,03	16,21		11	-6,68	-1,42	2,02
3	-42,27	-42,92	1841,89		6	-6,47	7,53	56,65		13	-3,73	1,53	2,34
3	41,54	40,89	1672,31		7	-80,52	-66,53	4426,17		14	-9,68	-4,42	19,54
4	-3,89	-4,54	20,63		7	-5,24	8,75	76,58		17	11,98	17,23	296,93
					7	8,67	22,67	513,74		20	-18,38	-13,12	172,16
					8	-1,01	12,99	168,64		21	-5,05	0,20	0,04
					8	4,42	18,42	339,17					
					9	-13,78	0,21	0,04					
sum	2,59		3577,92		sum	-111,96		5597,20		sum	-31,53		493,03
mean	0,65				mean	-13,99				mean	-5,26		
SSW	9668,15												
							Total Sum of Squares		17358,97				
	observations		x-mean	(x-mean)^2			Sum of Squares Within		9668,15				
	-80,52		-92,50	8556,31			Sum of Squares Between		7690,82				
	-18,02		-30,00	899,83									
	-1,01		-12,98	168,60									
	-3,89		-15,87	251,87									
	7,21		-4,76	22,70			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)						
	-42,27		-54,25	2942,64				3845,410011					
	8,67		-3,30	10,92									
	-9,68		-21,65	468,82									
	-13,78		-25,76	663,62			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)						
	-3,73		-15,70	246,59				644,5431842					
	4,42		-7,55	57,07									
	-5,24		-17,22	296,53									
	-6,47		-18,44	340,20			F=	3845,410011	/	644,5431842	=	5,966101428	
	41,54		29,56	874,09									
	-6,68		-18,65	347,98			F(2,15)	=	5,97		p<0,05		
	-5,05		-17,03	289,95			critical value	=	3,68				
	-18,38		-30,35	921,27									
	11,98		0,00	0,00									
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**				
mean	-7,83												
			sum	17358,97	SST		**REJECT NULL HYPOTHESIS**						

PEAK VEHICLE COUNT													
Group 1:	vehicle count <4000				Group 2:	4000 <vehicle count < 6000				Group 3:	6000 <vehicle count		
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2
1832	-73,75	-48,45	2347,73		4280	-40,68	-28,52	813,48		6106	15,84	13,48	181,61
2357	-8,48	16,82	282,83		4285	-38,71	-26,56	705,25		6336	21,74	19,38	375,63
3281	-18,50	6,80	46,22		4697	1,51	13,67	186,79		7172	23,35	20,99	440,69
3738	-0,46	24,84	616,91		5275	14,30	26,45	699,84		9468	-25,94	-28,31	801,23
					5399	10,96	23,11	534,20		10513	-23,18	-25,54	652,50
					5457	4,67	16,82	282,96					
					5623	-54,27	-42,11	1773,56					
					5647	-8,10	4,06	16,48					
					5803	0,92	13,08	170,99					
sum	-101,21		3293,68		sum	-109,39		5183,55		sum	11,81		2451,66
mean	-25,30				mean	-12,15				mean	2,36		
SSW	10928,89												
							Total Sum of Squares		12651,62				
	observations		x-mean	(x-mean)^2			Sum of Squares Within		10928,89				
	-73,75		-62,71	3932,63			Sum of Squares Between		1722,73				
	-8,48		2,56	6,55									
	-18,50		-7,46	55,64									
	-0,46		10,58	111,94									
	-40,68		-29,63	878,08			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)						
	-38,71		-27,67	765,49				861,3638434					
	1,51		12,56	157,65									
	14,30		25,34	642,30									
	10,96		22,00	484,08			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)						
	4,67		15,71	246,82				728,5925303					
	-54,27		-43,22	1868,37									
	-8,10		2,95	8,70									
	0,92		11,97	143,17			F=	861,3638434	/	728,5925303	=	1,182229858	
	15,84		26,88	722,63									
	21,74		32,79	1074,97			F(2,15)	=	1,18		p<0,05		
	23,35		34,40	1183,23			critical value	=	3,68				
	-25,94		-14,90	222,02									
	-23,18		-12,14	147,34									
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**				
mean	-11,04												
			sum	12651,62	SST		**FAILED TO REJECT NULL HYPOTHESIS**						

PEAK MOTORIZED COUNT												
Group 1:	motorized count <2000				Group 2:	2000 <motorized count						
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2				
941	-73,75	-58,08	3372,80		2009	15,84	21,09	444,71				
1056	-18,50	-2,82	7,98		2013	-54,27	-49,02	2402,79				
1092	-8,10	7,58	57,51		2261	-0,46	4,79	22,91				
1204	-40,68	-25,00	624,88		2308	21,74	26,99	728,63				
1219	4,67	20,35	413,93		2474	-25,94	-20,69	428,24				
1390	10,96	26,64	709,51		2487	23,35	28,60	818,22				
1403	-38,71	-23,03	530,50		3271	0,92	6,17	38,09				
1426	14,30	29,98	898,71		5133	-23,18	-17,93	321,56				
1705	-8,48	7,20	51,77									
1949	1,51	17,19	295,53									
sum	-156,79		6963,11		sum	-42,00		5205,16				
mean	-15,68				mean	-5,25						
SSW	12168,27											
							Total Sum of Squares		33949,75			
	observations		x-mean	(x-mean)^2			Sum of Squares Within		12168,27			
	-73,75		-97,11	9430,11			Sum of Squares Between		21781,48			
	-8,48		-31,84	1013,65								
	-18,50		-41,86	1752,02								
	-0,46		-23,82	567,28								
	-40,68		-64,03	4099,91			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)					
	-38,71		-62,07	3852,14				21781,47909				
	1,51		-21,84	477,08								
	14,30		-9,05	81,98								
	10,96		-12,40	153,67			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)					
	4,67		-18,69	349,23				760,5168665				
	-54,27		-77,62	6025,29								
	-8,10		-31,45	989,05								
	0,92		-22,43	503,23			F=	21781,47909	/	760,5168665	=	28,64036295
	15,84		-7,52	56,50								
	21,74		-1,61	2,60			F(1,16)	=	28,64		p<0,05	
	23,35		0,00	0,00			critical value	=	4,49			
	-25,94		-49,30	2430,35								
	-23,18		-46,54	2165,66								
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**			
mean	-11,04											
			sum	33949,75	SST		**REJECT NULL HYPOTHESIS**					

PEAK NUMBER OF LANES													
Group 1:	number of lanes <5				Group 2:	5 <number of lanes < 10				Group 3:	10 <number of lanes		
	value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2			value	x-mean	(x-mean)^2
3	-40,68	-24,67	608,76		6	-8,48	10,23	104,66		11	21,74	19,25	370,69
3	-38,71	-22,71	515,66		6	0,92	19,64	385,56		13	4,67	2,18	4,74
3	15,84	31,84	1013,86		7	-73,75	-55,04	3029,44		14	14,30	11,81	139,48
4	-0,46	15,54	241,49		7	-8,10	10,62	112,77		17	-23,18	-25,67	659,04
					7	1,51	20,23	409,10		20	-25,94	-28,43	808,48
					8	-18,50	0,21	0,04		21	23,35	20,86	435,34
					8	10,96	29,67	880,43					
					9	-54,27	-35,55	1264,11					
sum	-64,01		2379,76		sum	-149,71		6186,12		sum	14,94		2417,78
mean	-16,00				mean	-18,71				mean	2,49		
SSW	10983,67												
							Total Sum of Squares		12651,62				
	observations		x-mean	(x-mean)^2			Sum of Squares Within		10983,67				
	-73,75		-62,71	3932,63			Sum of Squares Between		1667,95				
	-8,48		2,56	6,55									
	-18,50		-7,46	55,64									
	-0,46		10,58	111,94									
	-40,68		-29,63	878,08			Sum of Squares Between Groups/ degrees of freemdom (df=groups -1)						
	-38,71		-27,67	765,49				833,9751819					
	1,51		12,56	157,65									
	14,30		25,34	642,30									
	10,96		22,00	484,08			Sum of Squares Within Groups/ degrees of freedom (df=observations-groups)						
	4,67		15,71	246,82				732,2443519					
	-54,27		-43,22	1868,37									
	-8,10		2,95	8,70									
	0,92		11,97	143,17			F=	833,9751819	/	732,2443519	=	1,138930167	
	15,84		26,88	722,63									
	21,74		32,79	1074,97			F(2,15)	=	1,14		p<0,05		
	23,35		34,40	1183,23			critical value	=	3,68				
	-25,94		-14,90	222,02									
	-23,18		-12,14	147,34									
							h_0	**=**	**$\mu_1=\mu_2=\mu_3$**				
mean	-11,04												
			sum	12651,62	SST		**FAILED TO REJECT NULL HYPOTHESIS**						