Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Evaluation and Modelling of Bus Priority at Signalized Intersections

Master's thesis in Civil and Environmental Engineering
Supervisor: Arvid Aakre

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Abstract

According to the Norwegian Public Roads Administration (NPRA), one of four main purposes of signalized intersections is to prioritize public transport. Prioritizing public transport can increase the attractiveness of this travel mode, making it more competitive to other travel modes like private vehicles. Making public transport more attractive is also a contribution to the plan of zero growth in trips by private vehicles. There are several possibilities on how to prioritize public transport at signalized intersections. One of these is called active priority signalling (APS), which is related to signal planning. However, prioritizing public transport at signalized intersections may not only be a good option. It is not clear how the traffic conditions will change when a priority scheme is implemented. Therefore, the objectives for this thesis are to look at the impact the priority is having on the rest of the intersection, if the priority implemented is beneficial for the public transport, and if there are any alternative ways to making it even more efficient.

To study these objectives, a before and after study (BAS) of two signalized intersections in the municipality of Bergen was conducted, before some alternative solutions were being modelled in the traffic simulation software Aimsun Next. The BAS was done as a field study. For performance measures, delay, number of stops, and queue lengths were the focus when looking at the efficiency of the intersections.

From the field study, the results showed that the bus priority did not improve the delay, but rather increased it for most buses and vehicles. The queue lengths and the number of stops were also not showing any clear signs of improvements. There were a few places where the bus priority helped, and where the rest of the traffic could utilize on this benefit. However, as the duration of the bus priority in some places lasted for longer periods, it would mostly cause damage to other movements by increasing their red times. Also, where the arterial road was receiving a lot of priority due to a high number of buses, the disbenefits for the non-arterial roads became even greater. On the other hand, the model simulations showed that increasing the green time for the movements where there was a high traffic volume would make it easier for the buses as the approach could clear before they arrived to trigger the priority, thus making the duration of the priority lower. It would also be beneficial to give some movements on the same approach that are conflicting with each other green time at the same phase, preventing blocking of each other, which would delay both buses and all other vehicles.

Furthermore, due to the Covid-19 pandemic and limited resources, the collected field data, and the representativeness of this can be discussed. Therefore, to get a clearer view better conclude the efficiency of the priority and its effects on the intersections, larger data samples would be desirable.

Sammendrag

Ifølge Statens Vegvesen er et av fire hovedmål med signalregulerte kryss å prioritere kollektivtransport. Prioritering av kollektivtransport kan bidra til å øke attraktiviteten for dette reisemiddelet, og da gjøre det mer kompetitivt til andre reisemåter som private kjøretøy. Dette kan også bidra til å støtte opp under nullvekstmålet. For prioritering av kollektivtransport i signalregulerte lyskryss finnes det flere muligheter. En av disse er aktiv signalprioritering, som går på signalreguleringsteknikk. Men, det å prioritere kollektivtransport i signalregulerte kryss er ikke nødvendigvis bare en god løsning. Det er ikke helt klart hvordan trafikkforholdene vil endre seg når et kryss får et prioriteringssystem installert. Derfor har denne oppgaven satt som mål å se på hva slags påvirkning prioritering har for resten av krysset, om prioriteringen er fordelaktig for kollektivtransporten, og om det er noen alternative tiltak for å legge til rette for at den skal fungere enda bedre enn det den gjør.

For å svare på disse spørsmålene ble det gjort en før/etter-analyse av to lyskryss i Bergen kommune, før noen alternative forbedringer ble modellert ved hjelp av trafikksimuleringsprogrammet Aimsun Next. Forsinkelse, kølengder og antall stopp per kjøretøy dannet grunnlaget for å bedømme prestasjonen av kryssene.

Fra feltarbeidet kom det frem at prioriteten av kollektivtransporten ikke reduserte forsinkelsen, men heller økte denne for de fleste busser og kjøretøy. Resultatene angående kølengder og antall stopp per kjøretøy viste heller ingen klare tegn til forbedring. Noen steder kunne det virke som at prioriteten fungerte for bussene og at resten av trafikken kunne utnytte dette. Likevel så det ut til at ettersom lengden på prioriteten i mange tilfeller varte såpass lenge at den ville hovedsakelig skape mest ulemper for andre konflikterende bevegelser ved å gi disse for lang rødtid. I tillegg ble det observert at der hvor en hovedtrafikkåre opplevde en stor mengde prioritet ville ulempene på sidevegene øke enda mer. Derimot viste modelleringsresultatene at å øke grønntid for de bevegelsene hvor det er høyt trafikkvolum ville kunne gjøre det enklere for busser i og med at dette kunne bidra til å rydde ankomsten for biler før bussene aktiverer prioriteten. Dette medførte at lengden på prioriteten kunne bli redusert. I tillegg ville det være lønnsomt å gi flere bevegelser på samme ankomst som kan konfliktere med hverandre grønt lys i samme fase, noe som ville forhindre at en bevegelse hindrer en annen i å kunne ta seg frem på ankomsten, i tillegg til å redusere forsinkelsen for både busser og alle andre kjøretøy.

Videre er det viktig å ta med seg at på grunn av den pågående Covid-19 pandemien og lite tilgjengelig ressurser er det blitt hentet ut en begrenset andel data fra feltstudiene, og det kan diskuteres om dataene som er skaffet er representative for områdene. Derfor, for å få et klarere bilde og kunne være i stand til å få en bedre konklusjon om hvorvidt prioriteten er effektiv eller ikke, burde det blitt samlet inn mer data.

Preface

This thesis presents my work on the topic of bus priority and how this affects the traffic conditions at signalized intersections. The thesis is the last step before I finish my master's degree in civil engineering at the Norwegian University of Science and Technology (NTNU). The work related to this thesis has been undertaken in the period January to June 2021.

When deciding the topic for the thesis, Vestland Fylkeskommune played a great role in choosing the main topic, and locations for the work. The objectives for the thesis were decided on the background of the co-operation with them. Once I knew what to work with, and what research was to be done, it has been an interesting journey, however, with some challenging parts on the way. Though, I feel that I have been able to answer the objectives that were set for the thesis. This is greatly due to good guidance and several informative conversations with my supervisor at NTNU, Arvid Aakre. Also, being able to communicate with Trond Atle Karlsen at Vestland Fylkeskommune who has great knowledge about the areas that were studied, was a very positive factor for being able to answer the objectives.

As well as the abovementioned, I also want to thank Hege Løtveit at Vestland Fylkeskommune for giving me the possibility to work on this topic, Rune Sørensen at Swarco for helping me with controlling the traffic signals so I could carry out the field study in the best possible way, and Tone Borge at Skyss for providing data used in the results.

I hope the reading of this thesis will be interesting.

Lars R. Olsen

Lars Refsdal Olsen

Trondheim, 11th of June 2021

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List of abbreviations

The abbreviations below are used in the thesis. The list also shows the first page where the abbreviation is used.

Abbreviation	Description	Page
AADT	Average annual daily traffic	18
APS	Active priority signalling	2
BAS	Before and after study	2
CNOB	Cumulative number of buses	17
FCFS	First come first served	17
HV	Heavy vehicles	35
LV	Light vehicles	35
NPRA	Norwegian Public Roads Administration	1
OD	Origin/destination	82
PT	Public transport	62
SWAL	Special width approach lane	11
TSP	Transit signal priority	9
TTFF	Travel time under free flow	39
Veh/h	Vehicles per hour	15
Veh.h/h	Vehicle hours per hour	54

List of symbols

The following symbols are used in the thesis:

Symbol	Description	Unit
λ	Ratio of green time per cycle	$-$
C	Cycle time	s
c	Observed count	veh
D	Total delay	$veh * h/h$
d	Average delay	s/veh
d_1	Average delay due to uniform arrivals	s/veh
d_2	Average delay due to random arrivals	s/veh
d_3	Average delay due to an initial queue at the start of the analysis time-period	s/veh
d_{bus}	Average bus delay	s/veh
f_p	Supplemental adjustment factor for when a platoon arrives during green	$-$
f_{pf}	Progression adjustment factor	$-$
g	Green time duration	s
H	Complete stops for a period	$stops/h$
h	Number of stops per vehicle	$stops$
I	Upstream filtering adjustment factor	$-$
K	Delay adjustment factor	$-$
l	Length of test section	m
m	Modelled count	veh
$\overline{m}$	Average modelled count	veh
N	Average number of vehicles in queue	veh
N_m	Maximum back of queue length	veh
N_O	Variable for overflow queue	veh
n	Number of test intervals	$-$
PVG	Percentage of vehicles arriving at green	$-$
Q	Movement capacity of a road section	veh/h
q	Arrival flow	veh/h
q_{tot}	Total number of vehicles from one approach	veh/h
r	Effective red time	s

s	Saturation flow	veh/h
T	Total duration of analysis period	s
TT_{bus}	Travel time for bus	s
$TTFF_{bus}$	Travel time under free flow conditions for bus	s
u	Ratio of green time per cycle	$-$
Veh_A	Average vehicles in test interval	veh
Veh_E	Expected number of vehicles in test interval	veh
Veh_{tot}	Total vehicles in test interval	veh
v	Speed limit/travel speed in test section	m/s
y	Ratio of arrival flow to saturation	$-$
X	Vehicle to capacity ratio	$-$
X_i	Number of vehicles counted in test interval	veh
x	Degree of saturation	$-$
x_p	Practical degree of saturation	$-$

1 Introduction

1.1 Introduction to topic

According to the Norwegian Public Roads Administration (NPRA), there are four main purposes of having signalized intersection, e.g., traffic signals at intersections: 1) improve traffic safety, 2) increase the feeling of safeness close to schools and other institutions, 3) improve the traffic management and reducing the delay, and 4) prioritize public transport or other relevant transport modes (Statens Vegvesen & Vegdirektoratet, 2012). Traffic signals can, at signalized intersections, separate conflicting movements, e.g., left angle turns and pedestrian movements, thus decreasing the severity of accidents, as well as the number of accidents (Ranjitkar, 2020b). Signalized intersections may also lead to a decrease in speed due to more stops and waiting time than for a road section or intersection without traffic signals. During peak hours, a well-organised traffic signal plan can increase the traffic capacity, as well as reducing the delay, both overall and for minor roads. A minor road may struggle to access or cross a major road with a larger traffic volume. Therefore, having traffic signals, giving them time and opportunity to enter the intersection could reduce their delay time. Signalized intersections are also the places in urban networks where travellers are experiencing the most delay, both private vehicles, as well as public transport vehicles (Alhajyaseen et al., 2017; Yu et al., 2018). Therefore, one suggestion to reduce the delay for public transport is to prioritize these at signalized intersections. This can be done by looking only at isolated signalized intersections, or over a larger and more complex network, due to the easiness of co-operating several traffic signals over larger distances or in bigger networks.

Giving priority to public transport can also support the goal from The Norwegian Government to have zero growth in trips taken by private vehicles. Instead of having a growth in private vehicles, the goal is to have the growth in trips move to other travel modes like public transport, biking, or by foot (Miljødirektoratet, n.d.). Now, public transport is only catering for 12% of today's trips in Norway. Meanwhile, the percentage of drivers and car passengers combined are over 60% (Ryeng, 2020c). To be able to move towards this target, one way is to make the other travel modes more attractive. Some of the factors that can affect the attractiveness of these other travel modes are travel time, waiting time, comfort, and reliability (Ryeng, 2020b). Several of these factors are important for the attractiveness of public transport. Where private vehicles usually do not have to stop between the start and the finish point, a bus needs to stop at numerous bus stops, thus increasing the travel time for the passengers. Longer stops can also increase the waiting time for people waiting for the buses at bus stops, and longer waiting times than usual can reduce the reliability for these trips. Therefore, prioritizing buses at signalized intersections can contribute to decreasing the delay and waiting time, and at the same time increase the reliability and attractiveness of this travel mode.

There are several ways to prioritize public transport at signalized intersections. Two commons ways are to use either passive or active priority signalling (APS). A passive priority system is using a fixed priority scheme, whereas the APS adapts to the traffic conditions and the bus demand via detectors or other signals (Ryeng, 2020a). The latter is becoming more and more common to use and the benefits of the implementation are various. Also, by having a bus priority scheme, there can be the possibility for disbenefits for other travellers that are using the same space as the buses, e.g., other vehicles or cyclists. Therefore, when implementing this, one also needs to consider the effects this has on the other travel modes.

1.2 Objectives

The thesis will focus on what impact prioritizing public transport has on the performance of a signalized intersection. In this situation, there will be looked at an APS scheme at two isolated signalized intersections. To be able to give an answer to the topic, the following research questions, or objectives are made:

- How will the traffic conditions change when implementing public transport priority at a signalized intersection?
- Are the measures that are being implemented at the signalized intersection beneficial for the performance of the signalized intersection?
- Are there any alternative ways of prioritizing the public transport that will be more efficient for the overall performance of the signalized intersection?

To answer these objectives, there will be two case studies of two signalized intersections that are situated in the municipality of Bergen. These two signalized intersections have already implemented an APS system to prioritise public transport and will be interesting to study for the thesis. For the two signalized intersections, there will be undertaken a before and after study (BAS) to determine the performance of the intersections. The BAS will compare the intersections without the priority system (the no priority scenario) and with the implemented priority system (the priority scenario). Data for this BAS will be collected from a field study using recordings from the two sites for both situations and with equations and calculation models described later in the thesis, the performance of the intersections can be described. Based on these results, it is possible to get an understanding of how beneficial the new system is for the intersections. The data collection will also be necessary to answer the third objectives, which will be done by using traffic modelling software. For the thesis, Aimsun Next will be used. The software can try out new strategies and implementations to try to improve the performances of the intersections even further.

1.3 Limitations

The thesis is focusing on looking at the influence of the APS on the rest of the system, how the buses and other vehicles are affected. Therefore, as the focus is the traffic signal planning, considering the third objective, there will not be focused too much on larger physical changes to the intersection, but rather changes related to the traffic signals. This is also due to the limited space availability at one of the intersections, and that the second intersection has recently undergone a major design upgrade, which is described in chapter 3.3.

Also, due to the limited amount of time to work on this project, there will only be undertaken one field study for each condition at each intersection. Ideally, more data would have been better. However, the limited time and large amount of work limit this to one data collection per condition.

Furthermore, when looking at the performances of the intersection, the focus will be on the vehicles travelling through the intersection, i.e., cars, buses, and trucks. This means that the results regarding pedestrians and cyclists will not be included. However, as they affect the situation, they will be included in the thesis, but the results will focus on the vehicles. Regarding buses, the performance related to them will not include passenger numbers. The goal is to look at how the priority works, and since the priority should work for all operating buses, the passenger numbers are not being looked at.

1.4 Structure of thesis

The rest of the thesis is set up as follows: chapter 2 introduces traffic signal planning with the relevant measures of performance before a literature review related to the objectives. Chapter 3 describes the field study areas in the municipality of Bergen. This includes their geometric design, phase plans, and bus routes. In chapter 4, the method used in the thesis is presented. Chapter 5 describes in detail the data collection process for the field study, which includes what will be done and its relevance for the thesis. Furthermore, chapter 6 presents the results from the field studies, including a discussion of the results. Chapter 7 explains a step-by-step way to make the models for Aimsun Next, which is used for the last part of the thesis, as well as presenting the alternative solutions to improve the intersections with how to model the improvements into the models in Aimsun Next. After this, chapter 8 presents the results from these improvements. Then, chapter 9 includes a discussion on the results for both the modelling results, but also for the first part. A conclusion is presented in chapter 10 before a note on further work is added in chapter 11.

This thesis is a continuation of a preliminary project undertaken before the start of this thesis. The preliminary project's goal was to prepare the author for this thesis by preparing a time schedule, the method for the study, and conducting a literature study on the topic. The literature study in this preliminary project has been the foundation of chapter 2 in this thesis. Therefore, parts of this literature study are being re-used in this thesis. The same also applies to parts of chapter 3. The preliminary project is being submitted as a digital appendix. Also, in the thesis, several pictures are used as figures. Where these are not credited, these are taken by the author of this thesis.

At the end of the thesis, several attachments are included to show some of the important results and input data for the part of the thesis regarding the modelling in Aimsun Next. All the calculations and the rest of the results that are not shown in this thesis are submitted as appendices. This includes an appendix document, as well as some digital appendices including worksheets and the Aimsun Next models.

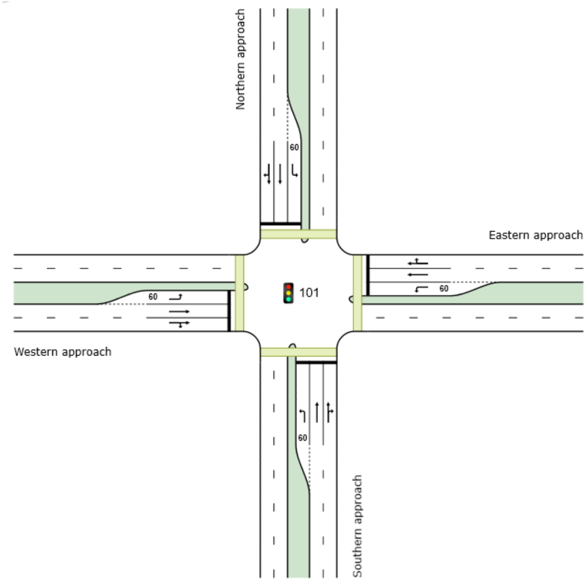
2 Literature

2.1 Design of signalized intersections

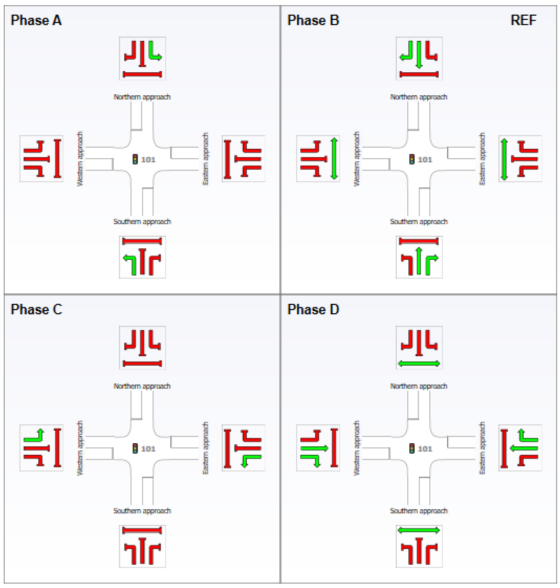
When there is a high traffic volume, and there are several conflicting movements, signalized intersections can often be used (Statens Vegvesen & Vegdirektoratet, 2012). Compared to other types of intersections like roundabouts, installing a signalized intersection is a cheap and efficient way to improve the performance of the intersection, and requires little or no additional land area to be installed (Ranjitkar, 2020b).

2.1.1 Movements, phases, and cycles

When designing a signalized intersection, the possible routes you can take from one approach to an exit, are called movements. These movements are allocated to different phases. The phases tell where each movement is given right of way (by having green light) at the intersection. When one phase ends, the movements allocated to that phase will no longer have right of way. In the next phase, other movements will have right of way. This change in phases is called a phase change (Akçelik, 1981). The time during a phase change, i.e., after one phase is over and before the next phase starts, is called the intergreen time. The intergreen time consists usually of yellow and/or all red lights. When all phases and the intergreen times between them have been completed, one cycle has finished. Figure 2.1 a) shows an example of an x-intersection, while Figure 2.1 b) shows a phase diagram with different movements and phases. Here, the green arrows indicate the movements that are receiving a green signal.



a) Design of a signalized intersection



b) Example of a phase diagram and movements

Figure 2.1: Example of signalized intersection design

2.1.2 Types of signal operations

At signalized intersections, three main signal operations are being used the most. These are pre-timed operation (also called pre-fixed), semi actuated operation, and fully actuated operation (Ranjitkar, 2020b). For a pre-timed operation, phase timings and cycle lengths are constant and follow a pre-determined plan designed for that specific intersection. However, the lengths of the phases and cycles can vary throughout the day depending on traffic conditions. For example, some movements can experience more demand at certain times during the day. Therefore, it is common to have at least a pre-timed operation for morning peak, afternoon peak, and for off-peak.

Where there is a minor road that connects to a major road with a high traffic load, the vehicles on the minor road may experience problems entering or crossing the major road. Therefore, a signalized intersection with this scenario can have a semi actuated operation. For this operation, vehicle detectors are being placed on the minor roads at the intersection. When there is a vehicle arriving at the intersection from the minor road, the detector gives a call to trigger a green light for the minor road so that the vehicle can enter the intersection. The waiting time after the detector gives the call may vary depending on the green time settings for the major road (Ranjitkar, 2020b). A push-button for pedestrians for crossing the road can also work as a detector.

A fully actuated operation is where all approaches at the signalized intersection are equipped with detectors. The detectors coordinate to determine the green times for each phase and the resulting cycle length. As the demand can vary rapidly, the cycle length can vary from cycle to cycle, as well as green times for the different phases. In cities or networks where fully actuated signal operations are close to each other, these may coordinate with each other creating a bigger traffic signal system (Ranjitkar, 2020b).

2.1.3 Saturation and capacity

One important aspect of signalized intersection theory is the saturation flow. This is the highest number of vehicles that can get through the intersection when there is a green light. At the beginning of the green light, vehicles must accelerate from zero, meaning fewer vehicles will pass through the intersection at the beginning of the phase. As vehicles have accelerated to the desired speed, the saturation will also increase. Likewise, at the end of the phase when vehicles need to slow down, the saturation flow will decrease. The saturation flow is being used when determining the capacity of a movement in the signalized intersection. The capacity is calculated using the equation below, where the saturation flow is represented as s, g denotes the length of the green time for the movement, and C denotes the length of a cycle (Akçelik, 1981, p. 6).

$$Q = s * \left(\frac{g}{C}\right) \qquad \text{Eq. 1}$$

Furthermore, the ratio of green time per cycle can also be described by using another parameter, u. This is shown below:

$$u = \frac{g}{C} \qquad \text{Eq. 2}$$

Sometimes the arrival flow is not equal to the saturation flow, for example right after the signal turns green and at the end of the green time. The ratio of arrival flow to saturation, y, can therefore be expressed as follows:

$$y = \frac{q}{s} \qquad \text{Eq. 3}$$

To determine how many arrivals are present compared to the capacity of the movement, the degree of saturation, x, can be obtained from the equations above. The degree of saturation is therefore defined to be the ratio of arrival flow to capacity (Akçelik, 1981, p. 6).

$$x = \frac{q}{Q} = \frac{q * C}{s * g} = \frac{y}{u} \qquad \text{Eq. 4}$$

If the degree of saturation is greater than one, meaning that the arrival flow for the movement is greater than the capacity, the movement is over-saturated. This will result in delays, more stops, and long queues at the intersection. These negatives will even start to arise as the degree of saturation approaches 1. Therefore, when the delay starts to increase, the number of stops increases and the queues are getting longer, one has passed a practical degree of saturation, which is represented as x_p (Akçelik, 1981, pp. 6-7).

2.1.4 Measures of performance

Delay

One measure of performance for a signalized intersection is the delay. The delay is the difference between the actual travel time for a vehicle, cyclist, or person (in this thesis, the focus will mainly be on vehicles), and the duration of the travel time at free flow. Free flow can be expressed as the travel time where no queue or waiting time is present (Akçelik, 1981, p. 23; Dion et al., 2004). The delay a vehicle is experiencing at a signalized intersection can be divided into three categories; deceleration delay, stopped delay, and acceleration delay. These three types of delays give the total delay for a vehicle, represented by the illustration in Figure 2.2.

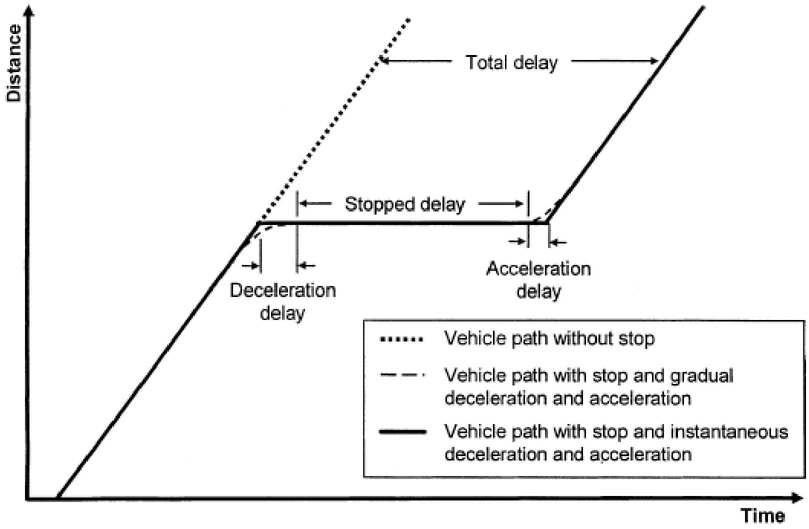


Figure 2.2: Types of delay for a vehicle (Dion et al., 2004)

Delay can be presented in several ways, like the average delay per vehicle and total delay. There are several ways of calculating the average vehicle delay. Webster (1958, p. 4) presented a way of calculating the average delay per vehicle that is shown in the equation below.

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0{,}65\left(\frac{C}{q^2}\right)^{\frac{1}{3}} x^{2+5\lambda} \quad \text{Eq. 5}$$

In this equation, d is the average delay per vehicle, c denotes the cycle time, λ shows the ratio of green time per cycle, q denotes the flow, s denotes the saturation flow, while x represents the degree of saturation. The first term in the equation is used when the arrival at the intersection is uniform, while the second term is used to consider more random arrival flows, and when there is a bottleneck forming at the intersection. The third term can be used to give a more detailed representation of the delay. However, in most types of flows, the two first terms are sufficient to calculate the average delay per vehicle (Webster, 1958, pp. 4-5). Several other models for calculating the delay has been proposed, including Adams Delay Formula (Adams, 1937) and Akçelik (1981, p. 25). The method presented by Akçelik is presented in the equation below.

$$D = \frac{qC(1-u)^2}{2(1-y)} + N_O * x \quad \text{Eq. 6}$$

Here, the total delay is represented by D, qC is the average number of arrivals per cycle, u represents the green time ratio, y shows the ratio of arrival flow to saturation, and N_O is used when there is an overflow queue, i.e., the number of vehicles left in the queue after the green time is over. From this equation, the average delay is the total delay divided by the flow of vehicles and is shown in the equation below (Akçelik, 1981, p. 25).

$$d = \frac{D}{q} \quad \text{Eq. 7}$$

Furthermore, in 1988, a newer model for determining the delay was presented by Akçelik (1988), followed by another model by Burrow (1989), which is considered a universal model for calculation of delay (Cheng et al., 2016). There are several variations of this formula depending on the type of delay and publications. One variation is presented in Eq. 8 and it consists of an average delay due to uniform arrivals (d_1), a progression adjustment factor (f_{PF}), an average delay due to random arrivals (d_2), and an average delay due to an initial queue at the start of the analysis time-period (d_3) (Dion et al., 2004; Ranjitkar, 2020a). The first three components are presented in Eq. 9 – Eq. 11.

$$d = d_1 * f_{PF} + d_2 + d_3 \qquad \text{Eq. 8}$$

$$d_1 = 0{,}5C * \frac{\left(1 - \frac{g}{C}\right)^2}{(1 - \frac{g}{C} * min[X, 1.0]} \qquad \text{Eq. 9}$$

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{KIX}{qT}}\right] \qquad \text{Eq. 10}$$

$$f_{PF} = \frac{(1 - PVG)f_p}{1 - \frac{g}{C}} \qquad \text{Eq. 11}$$

Here, c, g and s are as in Eq. 1. X represents the vehicle to capacity ratio, T is the total duration of the analysis period, K is a delay adjustment factor that depends on the signal controller mode. An upstream filtering adjustment factor is represented with I, q is as in Eq. 3, PVG is the percentage of vehicles arriving at green, and f_P is a supplemental adjustment factor for when a platoon arrives during green.

For undertaking calculations of the delay from real-life scenarios, e.g., looking at the traffic at a road section or an intersection, there are several ways to measure an estimation for this. When Al-Deek et al. (2014) studied the impacts of a transit signal priority (TSP) system in Orlando, Florida, they measured the delay by riding a bus through the area of interest. The same was done by Consoli et al. (2015). Similarly, Bråtveit (2016) drove through the studied section numerous times, acquiring both the travel time under free flow conditions and the travel time with a lot of traffic, thus getting the delay. Siddiqui (2015) looked at queue lengths at intersections over several intervals and combined with the number of vehicles arriving, it was possible to calculate the delay on the different approaches. Queue lengths were also used to calculate the delay by Skulbru (2015). For this method, the total delay was calculated by studying the queue lengths over a time interval, and from the total delay, the average delay could be obtained. Magfirona et al. (2015) calculated the delay by studying a section on the different approaches at a signalized intersection. Here, the vehicles were studied in 15 seconds intervals and the delay was obtained by looking at the number of vehicles waiting and stopping in the queue.

Stops

Another measure of performance for a signalized intersection is the number of stops for a vehicle. The number of times a vehicle is stopping is called the stop rate. The number of stops per vehicle is denoted by h, and the formula for how to calculate the stop rate is shown in Eq. 12 (Akçelik, 1981, p. 25).

$$h = 0.9\left(\frac{1-u}{1-y}+\frac{N_O}{qC}\right) \quad \text{Eq. 12}$$

In this equation, the notations are the same as for Eq. 6, while 0.9 represents a reduction factor that considers partial stops. Eq. 12 can only be used for fixed-time operated signalized intersections, and not for semi or fully actuated operated signalized intersections. From Eq. 12, the complete stops for a period can be calculated by multiplying the stop rate with the flow rate q, which is shown in Eq. 13 (Akçelik, 1981, pp. 25-26).

$$H = q * h \quad \text{Eq. 13}$$

Queue length

A third way to measure a signalized intersection's performance is to look at the length of the queue at the start of the green period for a lane or a movement. At the start of a green period, the average number of vehicles in the queue, N, is presented in the equation below.

$$N = qr * N_O \quad \text{Eq. 14}$$

Here, q and N_O are the same as for Eq. 6, while r denotes the effective red time, which is the time during the cycle where the signal is not green $(C - g)$. The maximum back of queue length, N_m, which is described as the farthest away from the intersection the queue is located, in vehicles, is obtained by the equation below (Akçelik, 1981, p. 26).

$$N_m = \frac{qr}{1-y} + N_O \quad \text{Eq. 15}$$

In this equation, q, r, and N_O are as in Eq. 6, while y is the ratio of arrival flow to saturation.

Other measures of performance

There are other measures one can use to determine the performance of a signalized intersection. Some of these are delays, stops, and queues for pedestrians, and fuel consumption (Akçelik, 1981, pp. 26-27). Pedestrian performances can be of interest when studying the part of a signalized intersection that relates to pedestrians, especially the delay these are experiencing when crossing the road. Fuel consumption can be derived from the results of delay and stops. However, these are not interesting for the study in this thesis.

2.1.5 Ways of reducing delay

Of the measures of performance that are explained in the chapter above, the delay is perhaps the most important factor (Dion et al., 2004). Therefore, there have been proposed several ways to reduce delays for vehicles, both light and heavy, at signalized intersections.

One proposed method of reducing delay is to aim at increasing the capacity at signalized intersections by having approach lanes divide into smaller lanes, thus cater for more light vehicles at the same time (Zhao et al., 2016). This technique, called SWAL (Special width approach lane), works by changing one lane into two lanes that can fit two light vehicles in the width. This way, heavily congested signalized intersections can increase their capacity. Furthermore, when a heavy vehicle (e.g., truck, bus etc) is approaching the intersection, it can use both lanes, like the original state. However, this technique may have some flaws as one of the two lanes can become under-utilised (not using its full capacity) if a heavy vehicle is blocking the lane for other vehicles. If the lanes are fully utilised, the system can help to increase the capacity, thus having more vehicles pass through the intersection in a shorter period, and therefore reduce the delay at the intersection. Figure 2.3 shows an illustration of the system, showing both initial condition, good conditions, and bad conditions regarding lane utilisation.

Another technique that has been looked at is to change the lane assignments for the approaches at signalized intersections (Alhajyaseen et al., 2017). By using dynamic lane assignment, the different movements for the approach will get different lanes to operate in depending on the traffic demand. This way, lanes that are originally not in use, or not experiencing high demand at one time, can be used to cater for other movements instead, or both several movements simultaneously. This technique was in this scenario looked at for an isolated signalized intersection. The results showed that it had some potential difficulties that could arise, including communication between the system and the road users. When a lane is assigned another movement, this assignment also needs to be communicated to the road users to not cause confusion or dangerous situations.

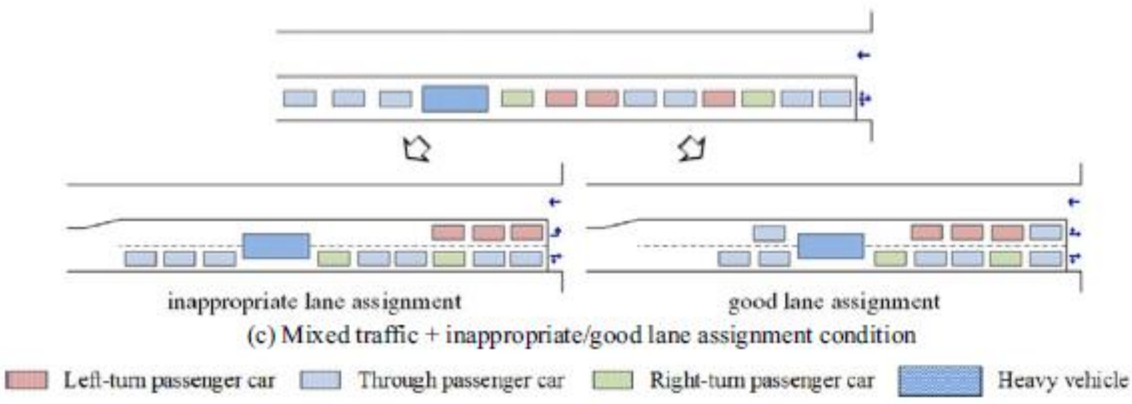


Figure 2.3: Illustration of SWAL (Zhao et al., 2016)

Other ways of trying to reduce the delay at signalized intersections have also been proposed. Yao et al. (2017) looked at different ways to optimize the signal timings and to reduce delay on different signal phase plans, green times and lengths of lanes, especially short-left lanes by using different combinations of signal phases, movements and other lane assignments. Wu et al. (2018) looked at the delay for vehicles at the back of the queue at a signalized intersection and proposed several models to calculate and optimize the performance of the intersection based on these models.

2.2 Public transport priority at signalized intersections

McLeod and Hounsell (2003) have proposed five different levels of priority strategies at signalized intersections for buses. Strategy P0 gives no priority to buses, meaning the buses must use the same facilities as all other vehicles without any benefits. Level P1 gives an extension of the green time if required. However, this only applies during the green time. Thus, after the green time is over, there will be no recall of green time for an arriving bus. Level P2 gives priority to buses that are behind their planned schedule. Hence, buses that are on schedule will not receive any priority. Level P3 is a combination of P1 and P2. This involves giving priority to late buses, while other buses can get an extension of the green time. Level P4 is the opposite of P0. At P4, all buses always receive priority. These different levels will affect other travel modes in different ways. From the work done by McLeod and Hounsell (2003), the priority strategies that focuses on prioritizing late buses gets the best scores for effectiveness for the whole network. Giving full priority to buses can be a good measure to make public transport more attractive as a travel mode for road users. However, the negative impacts this will have on other traffic will be very significant and is not recommended as an effective strategy for the efficiency of the entire network.

2.2.1 Why have priority of public transport

There are several reasons why to prioritize public transport. Public transport plays an important of people's everyday life, whether it is for commuting, leisure, or other types of activities that require travelling. The effectiveness of public transport will therefore contribute to improving the travel times for travellers that are using this mode (Norheim, 2007). As well improving the travel times when prioritizing public transport, doing this can also promote other goals. Norheim (2007) presents four goals that can be achieved when prioritizing public transport. These are 1) access to mobility for everyone, especially those with no other options for transport available, 2) provide the best supply to the travellers, this includes fares, travel time, comfort, and availability, 3) improve the effectiveness of the urban transport and reduce the need for private vehicles, and 4) public transport is considered a more environmentally friendly way of travelling, therefore, this can help reduce emissions. All these goals can contribute to achieving the target of zero growth in private vehicle use in the future in the cities (Miljødirektoratet, n.d.). The first goal will contribute to working towards a universal design, where everyone, no matter conditions, ethnicity, gender, income etc. can use the services. The second and the third goal will make the system able to challenge other more attractive transport modes, such as private vehicles. In several areas, public transport is not considered as effective as private vehicles. Therefore, it is a need to improve public transport and make it more competitive in the future (dell'Olio et al., 2011). Meanwhile, the fourth goal will try to reduce emissions, which will make it a more sustainable travel mode.

2.2.2 Types of public transport priority

There are different types of ways to give priority to public transport in an urban network. Slinn et al. (2005) mention four common measures to give priority to public transport, which include having bus lanes and busways, traffic and parking management measures, improvements for bus stops, and traffic signal control. Bus lanes and busways are common in several cities. These lanes will separate the bus from other traffic, thus allowing them to pass an eventual queue. Traffic and management measures can include having movements at intersections that only public transport vehicles can use. It can also include parking restrictions for other vehicles to improve the accessibility and safety of the public transport system. Improvements for bus stops can include having designated zones like bus hubs where several buses can enter and exit at the same time without interruption from other vehicles. Other measures can include better information at bus stops, including timetable information. Bus priority at traffic signals includes giving priority by different ways of operating the traffic signal system.

2.2.3 Traffic signal priorities

NPRA describes some different traffic signal installations that can be used to give priority to buses at signalized intersections. Passive and active priority signalling and real-time priority are three different strategies that aim to prioritize public transport at signalized intersections. (Statens Vegvesen & Vegdirektoratet, 2007; Wei et al., 2012).

Passive priority signalling

In systems where there is a passive priority for public transport, the benefits, or types of priority, is already implemented in the system. Hence, this system does not cater for various demands but follows an initial setting. One way of using passive priority is to extend the green time for phases which include buses (Statens Vegvesen & Vegdirektoratet, 2007). In this case, the extension of the green time will be constant and will not change if there is, for example, an absence of buses.

Active priority signalling

Where passive priority follows an initial setting, active priority is changing the level of priority according to the demand. This means that when there are no buses at or near the intersection, there are

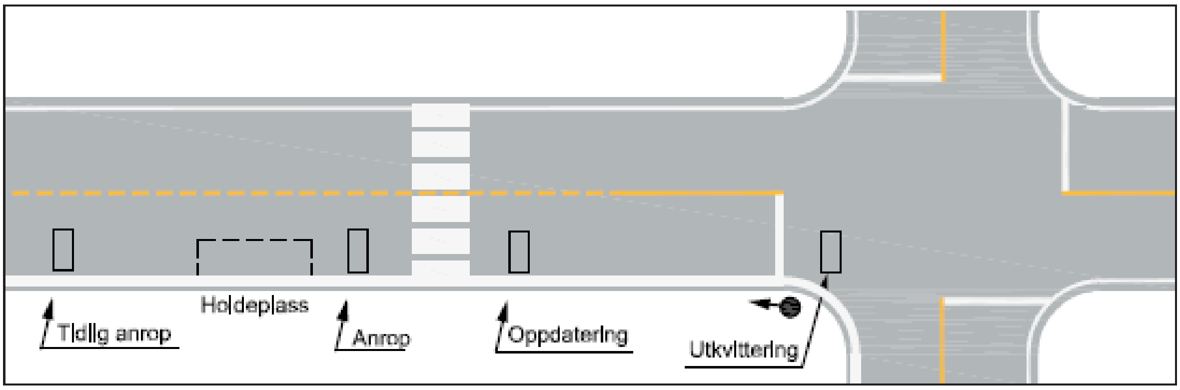


Figure 2.4: Ways of detecting a bus upstream of an intersection (Statens Vegvesen & Vegdirektoratet, 2007)

no benefits for phases buses are using. When buses are present at the intersection, the system will try to minimise the delay for the buses. To be able to determine when buses are approaching an intersection, different types of detection methods can be used. For instance, if the buses are using bus lanes, detectors for this lane can be used, meanwhile, if the buses are using shared lanes, other forms of communications like radio detection or inductive communication can be used. The purpose of the detection is to determine how far from the intersection the buses are. Hence, when to initiate the priority strategy to let the buses pass through the intersection with minimised delay (Statens Vegvesen & Vegdirektoratet, 2007). Figure 2.4 shows different places upstream of an intersection where detection tools can be used. This includes an early call to tell that the bus is approaching the intersection, a call when the priority strategy can start, an update to inform if there are any obstacles or unexpected situations that will delay the bus, and detection for when the bus has entered the intersection so that the priority can end.

The APS can consist of either one or several functions. For example, a green time can be extended if a bus arrives late during a phase. This way, the bus will be able to enter the intersection before the next phase starts. Another way is to shorten the other phases. If a bus arrives at a red signal, the green time for the other phases can be reduced so that the waiting time for the bus is reduced. Another strategy when a bus is arriving at a red signal is to switch the order of the phases to make the phase for the bus appear earlier, thus reducing the waiting time for the bus. If the bus is arriving right after the green time for their phase ends, they can ask for a signal recall. This means that instead of starting with the next phase, the traffic signal changes back to the phase that involves the bus (Statens Vegvesen & Vegdirektoratet, 2007).

Real-time priority

Strategies for real-time priority can include optimization of delay. This can be, for example, delay for passengers, vehicle delay, or a combination of several types of delay. The real-time priority strategy uses data from observations in real-time to be able to do this optimization. By using this method, one can optimize the control over an intersection or an entire network. However, this method is not used as much as the two former strategies (Mirchandani et al., 2001).

2.2.4 When to give priority to public transport

Giving too much priority to public transport will affect the other transport modes in a negative way that will result in more disbenefits than the benefits of having all the priority (McLeod & Hounsell, 2003). Therefore, it is important to know when to have priority, and when to not have priority of public transport at signalized intersections. Efimenko et al. (2018) developed an algorithm to determine for what conditions it would be useful to give priority to public transport systems at signalized intersections. Hence, also when not to give priority. The simulations they did with the algorithm was on an x-intersection with flows varying from 50 veh/h to 600 veh/h, and passenger load on buses from 0 to 110. From the simulations, the use of public transport priority would be efficient if the number of bus passengers exceeded 80, the frequency on buses were less than five minutes, the flow in the same direction as the buses was in the range 50 veh/h to 600 veh/h, and the competing direction had a flow in the range 300 veh/h to 600 veh/h. From this, they conducted that, if the load on the public transport vehicle is low, or the frequency of the public transport vehicles is low, or the flow rates were outside the ranges, the priority could result in a very small benefit or even loss in time gain.

2.2.5 Performance of signalized intersections with public transport priority

Kyoungho and Rakha (2006) conducted a study in northern Virginia to investigate how a transit signal priority system would affect the different travel modes at a corridor consisting of several signalized intersection by focusing on green extension. They found that the priority system would not lead to a huge impact on the intersection in general. This was because the corridor, where most of the buses were operating, had much more green time than the side roads, which meant that the green extension seldom came into use. However, an increase in traffic on the corridor would lead to less efficiency for the intersection but an increase of traffic at the side roads would not do this. Also, by having more transit vehicles, the benefits for transit vehicles would increase even more, but cause more detriments for the rest of the traffic.

Tu et al. (2012) compared different types of bus priority strategies at signalized intersections. These strategies included bus signal priority as green extension or early green, and bus pre-emption scenarios, which involved having private phases for buses that only became active when buses were present. This study showed that by increasing the priority, the travel time for buses would decrease, but also increase for non-buses.

Liu et al. (2018) did a study on a signalized intersection in China where they compared an active priority strategy with an optimized fixed time control strategy to evaluate the effectiveness of bus priority. The results they found showed that the active priority strategy proved to be more effective regarding the delay and average travel time, not only for buses but also for all vehicles at the intersection. The system was therefore beneficent not for only the buses but, by having this strategy, the entire intersection. However, they did not cater for an increase in the traffic volume, which could lead to a different result, something that Xu et al. (2010) looked at. In their study, the active priority strategy would lead to an increased delay during off-peak when the traffic volume increased.

2.2.6 Problems that can arise with public transport priority

How public transport priority affects cross streets and other modes

As mentioned by McLeod and Hounsell (2003), too much priority can result in a negative result for other modes. This problem was discussed by Skabardonis and Christofa (2011). They looked at how a bus priority at one road segment in a signalized intersection would affect the delay for the traffic at cross streets and the level of service at the intersection. Different formulas for calculating the possibility of bus priority were introduced, and the responding delay caused from these. They showed that the bus priority would have less negative impact if the cycle times were long, as this would reduce the chance of having long queues on the cross streets. Also, the higher green time on the cross streets to the cycle time, the less the negative impacts would be.

Another study that was focusing on this problem was done in a master's thesis by Høsser (2017). This thesis discussed how one could give priority to both public transport, cyclists, and pedestrians at intersections. The model that was used was not based on a specific site, but instead was trying to look at the impacts of public transport priority. Both SIDRA INTERSECTION and Aimsun were used to determine the causes of the prioritizing of public transport, here buses. It showed that the bus priority did not affect the other vehicles in a big way. Also, as they were given priority, little or no delay for cyclists or pedestrians were found.

Shaaban and Ghanim (2018) also looked at the consequences for existing traffic when implementing priority for public transport. They looked at the potential impact on the existing traffic conditions by implementing a transit signal priority route on an urban arterial road in Doha, Qatar. The road section used was a network that consisted of four intersections with three bus routes operating in the network. They used an algorithm to implement the TSP. Meanwhile, for the modelling, they were using VISSIM. The results showed that there would be a significant reduction in delay for buses, while the changes for other travel modes would be close to minimal-to-none.

Several vehicles asking for priority or entering the intersection at the same time

Another problem that can arise when having a public transport priority system is when several modes/vehicles are asking for priority at the same time. A study on this topic was done by He et al. (2014). They looked at how a situation where vehicles from several approaches asked for priority at a signalized intersection at the same time. To evaluate and to be able to find a solution to this problem, they created a model to create a system that could cater for coinciding priority requests from several approaches. Their model showed that for an actuated signal control plan, using a numerical case study, they would reduce the delay by 24.9% for buses, 14% for pedestrians, meanwhile, the passenger car delays would stay mostly unchanged. The model they created could be used for several travel modes like buses, cars, pedestrians, but also emergency vehicles, cyclists, and trains at railway crossings.

Lian et al. (2019) conducted a study on different APS systems for different arrival rates of buses. They looked at the FCFS (first come first served) strategy and the CNOB (cumulative number of buses) strategy. By simulating an intersection in China, they found that as the proportion of bus priority requests got higher, the average delay for the intersection decreased. When there were several buses at an intersection with a bus stop downstream, a higher number of buses led to queues downstream at the bus stops, which could contribute to reducing the effectiveness at the intersection. This phenomenon was presented by Lin et al. (2014) and was furthermore studied by Gao et al. (2020), where they only allowed two buses from each movement in the same platoon. Their simulations to implement this restriction showed that the bunching of buses downstream would disappear and create a more reliable and efficient bus service.

3 Existing conditions of study areas

3.1 Introduction to Bergen and the study areas

Bergen is the second largest municipality in Norway with a population of almost 260,000 and is the largest city in Western Norway (Statistics Norway, 2020). The city lies in the county of Vestland, where it serves as the county capital. Being located on the west coast of Norway, Bergen has a larger distance to other big cities than for instance, around the Oslo region (Eastern Norway). However, there are several smaller populated areas around Bergen, e.g., Straume in the west in the municipality of Øygarden, and Knarvik in the municipality of Alver to the north along European Road 39 (E39). E39 is one of the major arterials running through Bergen with an AADT of over 50,000 at some places (Statens Vegvesen, n.d.). Flesland Airport, which serves as the city's main airport, lies southwest of the city. It is the second largest airport in Norway and serves over six million passengers annually, with a capacity of seven and a half million passengers (Avinor, n.d.).

Skyss is the provider of the public transport system in Bergen (Skyss, 2020). The public transport system consists of buses, light rail, boats, and ferries (Skyss, 2021), with the light rail system being just over ten years old, going from the city centre to the airport, and having between 18 and 19 million travellers annually (Bybanen, 2020).

Figure 3.1: Location of intersections for case study (Finn, n.d.)

Figure 3.1 shows, with red circles, the two intersections which are located south-east of the city centre, which is to the upper left in the figure. The two intersections are approximately one kilometre away from each other, and both are located along county road 585[1], which goes from Sandviken north of the city centre, and eastwards from the city towards Haukeland and Paradis further south, where it ends.

3.2 Intersection 1

The first intersection is located where Nattlandsveien[2] meets Hagerups vei. It is a t-intersection. A satellite photo of the intersection is shown in Figure 3.2. Nattlandsveien, which runs from north to south through the intersection is a crowded road with high volumes of traffic. North of the intersection, the AADT is found to be 13,900 vehicles. Of these, the percentage of heavy vehicles is 6%. For the southern approach, the AADT is 10,900, 8% of these being heavy vehicles. For Hagerups vei, which is the western approach, the AADT is 5,000, with a 5% share of heavy vehicles (Statens Vegvesen, n.d.). The data on AADT and the percentage of heavy vehicles is presented in Table 3.1.

Figure 3.2: Satellite photo of intersection 1 (Kartverket, n.d.)

[1] At different sections of county road 585, it has different street names.
[2] This road is a part of county road 585

Table 3.1: Traffic volume for the approaches at intersection 1

Approach	AADT	Heavy vehicle percentage
Southern approach	10,900 vehicles per day	8%
Northern approach	13,900 vehicles per day	6%
Western approach	5,000 vehicles per day	5%

3.2.1 Design

There are two lanes on the northern approach, one southbound, towards the intersection, and one northbound, away from the intersection. A view of the northern approach towards the intersection is shown in Figure 3.3 a). Both sides of the road have cycle lanes and footpaths. However, at the intersection, the cycle lanes on both sides disappear. The northbound cycle lane starts approximately 45 metres downstream of the intersection, which is shown in Figure 3.3 b). At about 80 metres away from the intersection on the northern approach, there is a bus stop that interrupts the cycle lane for approximately 40 metres before the bus stop ends. Figure 3.3 c) shows that the southbound cycle lane shares the road with a bus stop up to 100 metres before the intersections. From there, it goes 40 metres before it fades away, making room for a short right turning lane at the intersection. At the intersection, the two directions are separated by a refuge which is approximately 16 metres long. At this approach, there is a zebra crossing at the intersection for pedestrians which is signalized. The zebra crossing and the refuge is shown in Figure 3.3 d).

On the southern approach, there are three lanes, one exiting the intersection, and two approaching the intersection. The approach consists of one left turning lane, and one through lane. Just over 100 metres before the intersections, these two lanes merge into one lane. There is a refuge that is dividing the two directions of traffic which is approximately 75 metres long. Both sides of the road have footpaths. A bit further south along the road, there are bus stops located on both sides of the road. There are no pedestrian crossings at the intersection on the southern approach. Figure 3.4 a) and b) shows the intersection and the southern approach.

There is one lane in each direction on the western approach. Both sides of the approach are equipped with cycle lanes. However, the cycle lane adjacent to the approaching lane is fading away and makes room for an additional lane at the intersection. This lane is a right turning lane, while the already existing lane works as a left turning lane. The cycle lanes on both sides continue to the next intersection and even farther away from the intersection to the west. The cycle lane that is adjacent to the lane exiting the intersection is combined with a bus bay as there is a bus stop just 50 metres away from the intersection. This bus stop can be seen on the left in Figure 3.5 a). At the intersection, there is a small refuge to

a) Intersection 1 seen from the northern approach

b) The cycle lane on the northbound lane on the northern approach starts after the intersection

c) The cycle lane and the bus stop shares the same space on the northern approach

d) Refuge dividing the two directions at the northern approach

Figure 3.3: Pictures of the northern approach at intersection 1

a) Intersection 1 seen from the southern approach

b) The southern approach as seen from intersection 1

Figure 3.4: Pictures of the southern approach at intersection 1

separate the vehicles entering and exciting the intersection. A signalized zebra crossing is located at the intersection at the western approach. The refuge and the zebra crossing can be seen in Figure 3.5 b).

3.2.2 Surrounding elements and bus routes

The areas around the intersections mostly consist of residential areas, with apartment buildings being the most frequent residential option. To the west of the intersection, there is a school and a kindergarten just a few hundred meters away. There are also a few grocery stores and some restaurants located west of the intersection as well. South of the intersection, there are some restaurants, grocery stores and other

a) Intersection 1 and the western approach

b) Refuge and zebra crossing for the western approach at intersection 1

Figure 3.5: Pictures of the western approach at intersection 1

service functions as a gas station along the road. To the north of the intersection, there are a few parks and recreational areas.

Several bus routes are going through the intersection. Table 3.2 shows the names of the bus stops which are closest to the intersection on each approach and the bus routes that are stopping at these bus stops (Skyss, n.d.).

Table 3.2: Bus stops and bus routes for intersection 1

Approach	**Name of bus stop**	**Bus routes**
Southern approach	Landåstorget (southbound)	2, 21, 60, 80
	Landåstorget (northbound)	2, 21, 60, 80
Northern approach	Hagerups vei (northbound)	2, 3, 21, 25, 60, 80, 101, 530, 604, 740, 934
	Hagerups vei (southbound)	2, 3, 21, 25, 60, 80, 101, 530, 604, 740, 934
Western approach	Birkeveien (westbound)	3, 25, 604, 934
	Birkeveien (eastbound)[3]	3, 25, 604, 934

3.2.3 Signal phasing

The signal phasing for intersection 1 is as shown in Figure 3.6. The signal plan consists of three signal phases, phase A, B, and C, respectively. Phase A, which is the first phase in the signal cycle gives way for the movements along Nattlandsveien, i.e., the through movements on the southern and northern approach. The phase also gives green light for the pedestrian crossing on the western approach. Phase B gives a green signal for the right turns on the northern and western approach, as well as the left turn on the western approach. The right turn on the western approach is an overlapping movement, i.e., the

[3] This bus stop is located downstream of another intersection, which means that bus route 101 does not stop here, but rather goes to the south along Birkeveien to another bus stop called Adolph Bergs vei.

movement is in more than one phase. It also appears in phase C alongside the left turn on the southern approach, and the pedestrian crossing on the northern approach. For this signal phasing plan, there are no opposing movements that appear in the same phase.

For the signal phase plan, some conditions can trigger some alterations to the phase allocations of the movements. For instance, if the pedestrian signal on the western approach is not being called upon, the right turn on the northern approach will receive a green signal in phase A which will overlap into phase B. Furthermore, if the pedestrian crossing on the northern approach is not being called upon, this will trigger a green signal for the through movement on the southern approach in phase C, thus overlapping into phase A in the next cycle. If none of the movements in a phase is called upon[4], this phase will be skipped, meaning no green time for this phase.

3.2.4 Bus priority

The function of the bus priority at intersection 1 is to set the green time for the movements that are being prioritized to a guaranteed time so that the buses can pass through the intersection before the end of the green time. This is being done by extending the minimum green time by two seconds. This is the case for all the approaches. What the priority is not doing is to shorten the green time for other phases and movements. The priority only extends the green time in the corresponding phase. The priority for all approaches are triggered via detectors, i.e., when the buses are passing the detectors, the priority is being triggered. The detectors for each approach are situated a distance before the intersection, approximately 150 meters away on the southern approach, 60 meters on the northern approach, and 125 meters on the western approach. As the buses enter the intersection, they pass another detector which ends the priority (T. A. Karlsen, personal communication, December 7th, 2020).

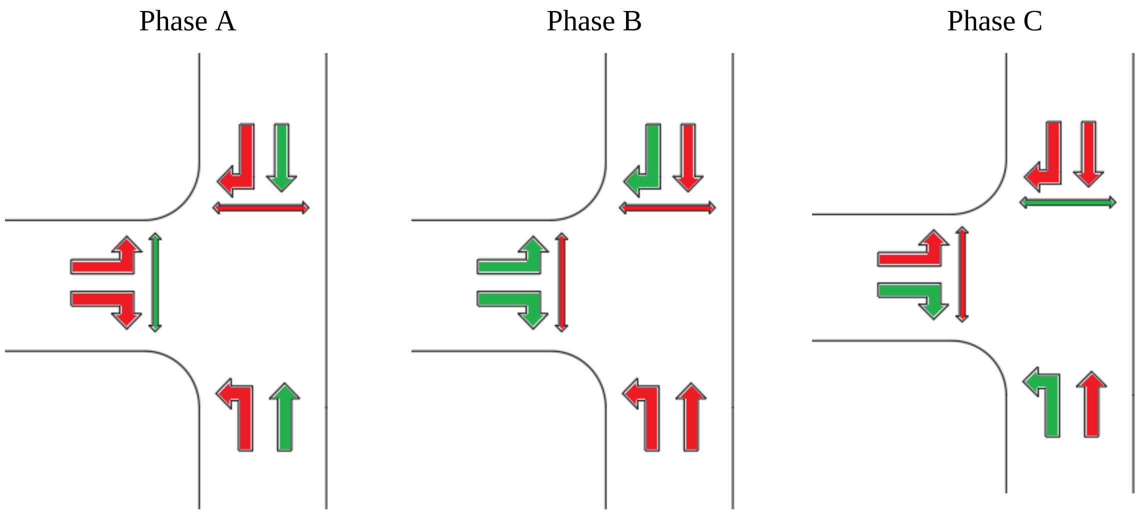


Figure 3.6: Signal phasing for intersection 2

[4] A movement that is only located in this phase.

3.3 Intersection 2

The second intersection is located further north along county road 585[5], right next to the Haukeland University Hospital. The intersection is located where Haukelandsveien meets Ibsens gate from the west and another part of Haukelandsveien to the east. Haukelandsveien also runs through the intersection to the north. Figure 3.7 shows a photo of the intersection taken from the south-east. On the southern approach, the AADT is 13,500, where 6% of these are heavy vehicles. The northern approach has an AADT of 11,900, 7% heavy vehicles. Meanwhile, the western approach has an AADT of 7,600. Of these, 6% are heavy vehicles (Statens Vegvesen, n.d.). All the values on AADT and heavy vehicle percentage are shown in Table 3.3.

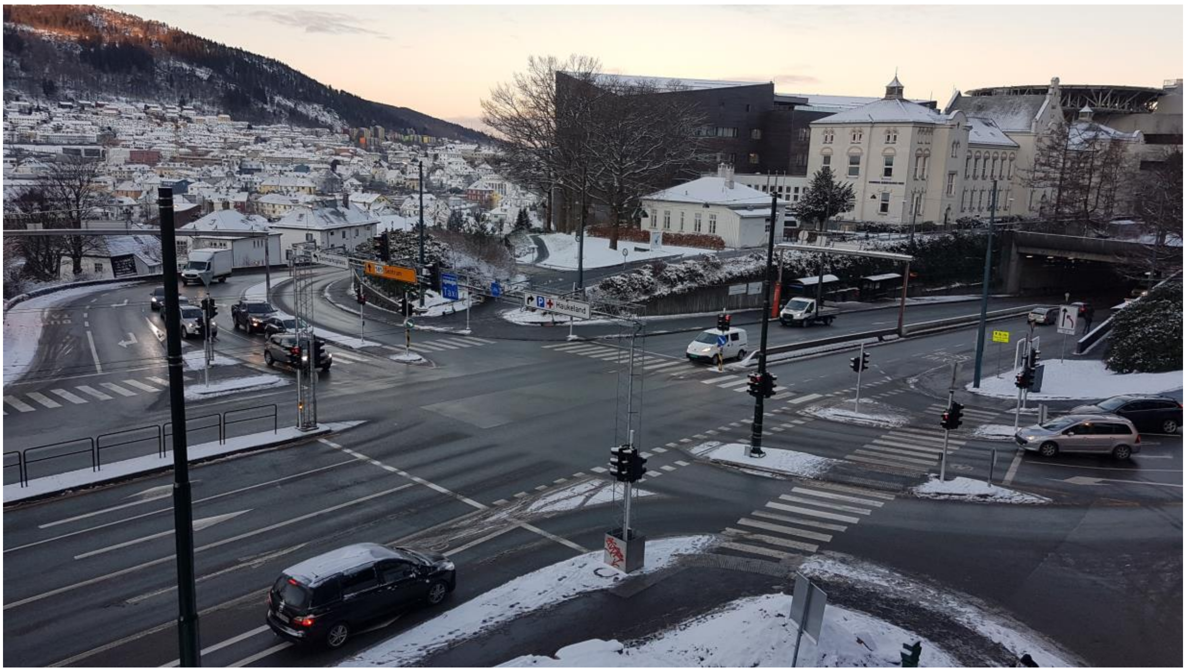


Figure 3.7: Photo of intersection 2 seen from the south-east

Table 3.3: Traffic volume for the approaches at intersection 2

Approach	AADT	Heavy vehicle percentage
Southern approach	13,500 vehicles per day	6%
Eastern approach	Not measured	Not measured
Northern approach	11,900 vehicles per day	7%
Western approach	7,600 vehicles per day	6%

3.3.1 Design

On the southern approach, four lanes are entering the intersection while two lanes are exciting the intersection. Of the four lanes arriving at the intersection, there is one right turning lane, two through

[5] At some point between the two intersections, county road 585 changes name from Nattlandsveien to Haukelandsveien.

a) The approaching lanes on the southern approach are being divided by a pedestrian crossing

b) Lanes on the southern approach

Figure 3.8: Pictures of the southern approach at intersection 2

lanes, where one is dedicated to buses and taxis, and one left turning lane. The right turning lane is a short lane. Before the intersection, two lanes are arriving on this approach. These two lanes are being separated by a pedestrian crossing which consists of two zebra crossings and an island in the middle. After this pedestrian crossing, the right lane is divided into the two rightmost lanes, and the left lane is divided into the two leftmost lanes. The pedestrian crossing is shown in Figure 3.8 a). Between the short right turning lane and the bus and taxi lane, there is a cycle path that goes through the intersection. Of the two exiting lanes, the right lane is only present for approximately 40 metres as it functions as a bus stop, before merging with the other lane downstream of the intersection. After the merging, a cycle lane is also appearing at this side of the road. To separate the two traffic directions, there is a refuge starting at the intersection which runs approximately 60 metres south. There are no pedestrian crossings at the intersection on this approach apart from the crossing just south of the intersection. Figure 3.8 b) shows the lanes at the intersection.

The eastern approach works as an access road to Haukeland University Hospital, as well as providing access to some other facilities close by. The road consists of two lanes, one in each direction, which is shown in Figure 3.9 a). However, at the intersection, this lane divides into three lanes where one is a slip lane turning right, one is a through lane, and the last is a left turning lane. The slip lane is separated from the two other lanes by a small refuge. The lane exiting the intersection is separated from the two leftmost lanes entering the intersection with another refuge. Only the lane entering the intersection has a footpath adjacent to the road. For the opposing direction, there is a rock wall followed by a rock-cut next to the road. There is a signalized zebra crossing for pedestrians at the intersection at this approach that is divided into three parts by the refuges. This is shown in Figure 3.9 b).

a) The road leading from Haukeland University Hospital to the intersection

b) The pedestrian crossing is divided into three parts on the eastern approach

Figure 3.9: Pictures of the eastern approach at intersection 2

The northern approach goes into a tunnel 75 metres north of the intersection. This tunnel is 353 meters long and goes underneath parts of the Haukeland University Hospital (Statens Vegvesen, n.d.). The tunnel can be seen in Figure 3.10 a). There is one lane exiting the intersection towards the tunnel, and one lane which functions as a bus bay. The bus bay starts at the intersection and merges with the other lane just in front of the tunnel. For the lanes arriving at the intersection, there is one short left turning lane that starts right after the tunnel. The middle lane is a through lane, while the right lane is a right turning lane except for public transport vehicles like buses and taxis. This lane also has a bus stop that stretches from the tunnel and almost to the intersection. Figure 3.10 b) shows the lanes in both directions while Figure 3.10 c) shows the lane assignments for the approaching lanes. The footpath adjacent to the approaching lanes stops at the start of the tunnel. For the footpath adjacent to the exiting lanes, the footpath continues into a separate tunnel that follows the other tunnel and ends up on the northern side of Haukeland University Hospital, which can be seen in Figure 3.10 d). The footpath adjacent to the approaching lanes stops at the tunnel. At the intersection, there is a signalized zebra crossing for pedestrians that crosses this approach and connects with one of the refuges on the eastern approach. There is also a refuge on this approach, separating the travelling directions that go from the intersection to the tunnel.

On the western approach, there are two lanes, one in each direction. However, when the approaching lane arrives at the intersection, it splits up into four different lanes. Of those four, one of them is a left turning lane, one is a through lane, and two of them are right-turning lanes, whereas both are short lanes. The short lane closest to the side of the road is a lane dedicated to buses and taxis. The two right-turning short lanes are separated from the two other lanes by a refuge at the intersection. Meanwhile, there is a refuge going 55 metres along the approach separating the two travel directions. There is only one side of the road which has a footpath adjacent to the road, which is the side leading away from the intersection. 150 metres away from the intersection, there is a zebra crossing right before a bus stop on the same side of the road as the footpath. After the zebra crossing, there are footpaths on both sides of the road. At the intersection, there is a signalized zebra crossing at this approach. The zebra crossing is divided into three parts separated by two refuges. The right side of the zebra crossing, as seen from the

a) There is a tunnel 75 metres north of the intersection

b) The intersection seen from the northern approach

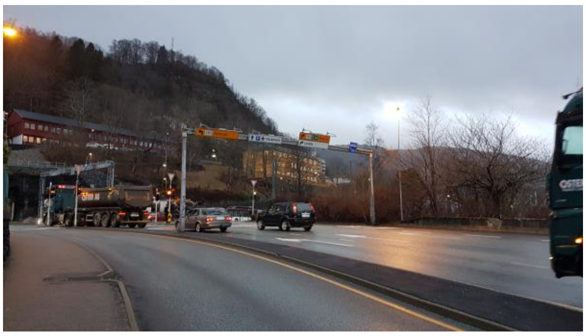
c) Lane assignment for the approaching lanes on the northern approach

d) The other side of the tunnel on the northern approach

Figure 3.10: Pictures of the northern approach at intersection 2

a) A bit further away from the intersection on the western approach, there is a zebra crossing

b) When the refuge starts, the approaching lane splits into four lanes



c) Lane assignment for the approaching lanes on the western approach

d) The pedestrian crossing is divided into three parts on the western approach

Figure 3.11: Pictures of the western approach at intersection 2

approach towards the intersection, leads to the bus stop on the southern approach, and to a foot path that goes from the zebra crossing 150 metres away from the intersection to the pedestrian crossing south of the southern approach. Figure 3.11 a) to d) shows the different features of the western approach.

3.3.2 Surrounding elements and bus routes

This intersection lies right next to the Haukeland University Hospital. This means that a lot of the traffic in and around the hospital is using this intersection. County Road 585 (at this intersection also known as Haukelandsveien) works as an arterial road in the eastern part of Bergen, connecting several urban areas both to the north and to the south of the intersection. The western approach, Ibsens gate also attracts a lot of traffic coming from the city centre and possibly other traffic from European Road 39. The intersection is also close to the Western Norway University of Applied Sciences and Brann Stadion, home of the football club SK Brann. As well as these facilities, the area surrounding the intersection also consists of a lot of residential housing, single units and terrace houses being most common. South of the intersection, there are some recreational areas as well as some service facilities and restaurants. To the north of the intersection, there is a cemetery after the tunnel under the hospital, as well as a grocery store and a pharmacy.

After the tunnel, at the time of the field study, there is some construction work going on which can affect the traffic flow in some way. In some places, the road becomes narrow which can slow down the speed, creating queues and delays which can create a ripple effect through the tunnel and into the intersection. Figure 3.12 shows some of the construction work on this side of the tunnel.

Figure 3.12: Construction work on the northern side of the tunnel north of intersection 2

Several bus routes use both the southern, northern, and western approaches at this intersection. Information over which bus routes are using each bus stop close to or at the intersection is shown in Table 3.4 (Skyss, n.d.).

Table 3.4: Bus stops and bus routes close to intersection 2

Approach	Name of bus stop	Bus routes
Southern approach	Haukelandsveien (southbound)	20, 25, 403
	Fridalen (southbound)	2, 3, 12, 21, 25, 60, 80, 530, 604, 740, 934
	Fridalen (northbound)	2, 3, 12, 21, 25, 60, 80, 530, 604, 740, 934
Northern approach	Haukeland sjukehus sør (northbound)	2, 3, 12, 20, 21, 25, 27, 28, 60, 80, 403, 604
	Haukeland sjukehus sør (southbound)	2, 3, 12, 20, 21, 25, 27, 28, 60, 80, 403, 604
Western approach	Haukeland sjukehus (westbound)	27, 28, 530, 740, 934

3.3.3 Signal phasing

The signal phases for intersection 2 is presented in Figure 3.13. This intersection has four signal phases to cater for all the movements. There are in total 18 movements, where 12 of these are vehicle movements, and six are pedestrian movements. The pedestrian crossings on the eastern and western approaches are separated into three and two separate crossings respectively, thus making the number of pedestrian movements six. The southern approach does not have any pedestrian movements as there is no crossing at the intersection on this approach.

Phase A caters for the through traffic at the southern and northern approach, as well as the right turn on the southern and northern approach. It also gives a green signal for the two northernmost pedestrian crossings on the eastern approach, which are not interfering with the right turn movement on the south approach. The western pedestrian crossing also receives a green signal in phase A. However, here the pedestrian crossing interferes with the right turn movement from the northern approach.

In phase B, all the vehicle movements on the eastern approach receive a green signal. The southernmost pedestrian crossing on this approach also gets a green signal during this phase, as well as the northern pedestrian crossing. The right turn on the eastern approach does not interfere with the pedestrian movement on the northern approach as it does not cross this zebra crossing, which is described in chapter 3.3.1.

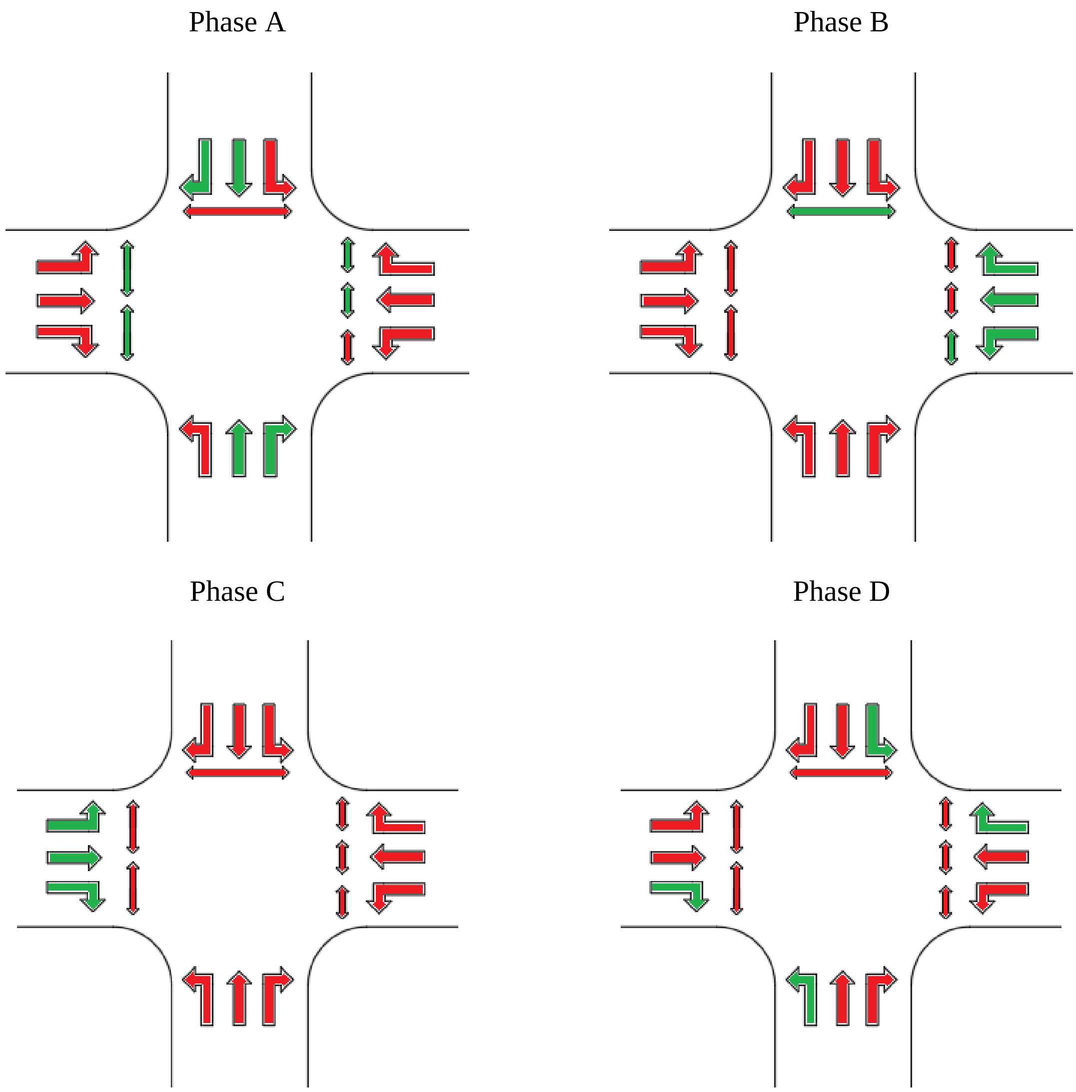


Figure 3.13: Signal phasing for intersection 2

For the third phase, all the vehicle movements on the western approach receive a green signal. For this phase, there are no pedestrian movements that receive a green signal. In phase D, the right turns on the eastern and western approach, as well as the left turns on the southern and northern approach receives a green signal. This phase also has no pedestrian movements.

If there are no calls, the phases B, C, and D can be skipped. Also, if the pedestrian movement on the northern approach is being called upon, this will increase the time for phase B. However, if the demand on the left turn in this phase is low, the movements in phase C that are not interfering with the rest of the movements in phase B, i.e., the through and right turn movement, will receive a green signal before the left turn on the western approach[6]. For phase D, if some movements are not being called upon, some movements in phase A can be called upon instead. For instance, if there are no left-turning vehicles from

[6] This depends if the southernmost pedestrian crossing on the eastern approach is called upon. Also, this crossing is shorter than the pedestrian crossing on the northern approach, thus requiring a lower green time.

the northern approach, the right turn on the southern approach can receive an early green light. The same goes for the through movement on the southern approach if no vehicles are turning right from the eastern approach as well.

3.3.4 Bus priority

For intersection 2, there are several different types of priorities for public transport. The buses that are travelling to and from the southern and northern approach are experiencing a moderate priority, i.e., when the buses trigger the priority, the green time will be extended so that the buses will be able to pass through the intersection in time. From the southern approach, this will be done through a detector located approximately 150 metres away from the intersection. For the northern approach, the bus stop located in front of the intersection will make most of the buses stop to load and unload passengers. The priority for this approach is therefore being triggered when the bus doors are closing.

The buses arriving on the western approach will also be detected approximately 150 metres away from the intersection. When the priority is triggered, the conflicting movements at the intersection will only be given minimum green time, while the prioritized movement will receive a green extension to get through the intersection (T. A. Karlsen, personal communication, December 21st, 2020).

4 Method

4.1 Before and after study

To answer the first two objectives presented in chapter 1.2, there will be undertaken a BAS. The BAS will look at how the priority works by comparing it to a situation where the priority is not present, i.e., the priority is turned off. The study will be done by a field study where data will be collected from the sites and studied afterwards to obtain the relevant results to answer the objectives. This will be done through so-called quantitative methods, i.e., methods that are operating with obtained data from field studies. Chapter 5 presents in detail all the data that will be collected in the field study for the BAS including how the data will be collected, and its relevance for the objectives. Some of the things that will be collected are the performance measures that are described in chapter 2.1.4, which are delay, number of stops and queue lengths. The procedure on how to collect these are explained in detail. Also, as well as these performance measures, data regarding traffic count, the share of traffic load, and green times are being collected to acquire both sufficient data to answer the first two objectives, but also to use for the third objective, which is looked at by using traffic software models.

4.2 Aimsun Next modelling

For the last objective in chapter 1.2, the traffic simulation software Aimsun Next will be used. Based on the results obtained from the BAS, it will be presented some suggestions for improvements to make the intersection perform better. To see if the suggested improvements work, this software is being used to recreate a scenario as close to a real-life scenario as possible. Chapter 7 describes this part of the thesis in detail. This includes the creating of the Aimsun Next models, calibration of the models, the suggested improvements, and how these are modelled. Furthermore, these improvements are then compared to what is found in the BAS to see whether these improvements are useful.

5 Data collection

One major part of the work to answer the objectives presented in chapter 1.2 is to collect data that will be used to both 1) answer the two first objectives, and 2) get data that will be used in the modelling part which is essential to answer the third objective, that is to be able to come up with something that will make the intersections even more effective. This chapter presents the different parts of data that will be collected during the field studies and from external sources.

5.1 Field observations

5.1.1 Site inspection

The first part of the data collection is to get to know the site and being able to plan the upcoming parts of the data collection. This is being done through a site inspection. The goal of the site inspection is to get an understanding of how the intersections work, and what kind of factors are influencing them. By doing this, the element of surprise when doing the data collection presented later in chapter 5 will be removed. Doing the data collection is an important task and being as prepared as possible is essential to get the best data possible.

As well as getting to know the site, the site inspection is also necessary to figure out how to do the data collection. This includes the locations on the cameras that will be used to record the site during the collection. The recordings are necessary as it is impossible to see the whole site and collecting the necessary data at the same time with a limited number of people doing the data collection. The recordings are therefore there to study afterwards. They can also be helpful to discover unexpected events that occur during the recordings. When deciding for the locations of the cameras, it is important to use locations that can get a good view over the approaches, movements, or other factors they will have to record, and at the same time not be too difficult to get access to, e.g., to place the cameras at a signpost above the road may be the best position, but impossible to get access to in case something happens while recording without disturbing the traffic. The final locations for the camera positions are described in chapter 5.3.

The third part which is important with the site inspection is to prepare for when to undertake the data collection. At the intersections, there may be parts during the day where the traffic conditions are not relevant, or interesting to study. This can be times where the traffic is very low so that the saturation on the approaches are very low, thus decreasing the delay (Akçelik, 1981, p. 25). There may also be times during the day where the traffic conditions are over-saturated. This situation will make the data very extreme as the performance measures presented in chapter 2.1.4 will be very high, and more complicated to determine. Therefore, the time of the day is necessary to determine during the site inspection. As well as the time of the day, the day of the week is important. It is desired to get a situation that is “as close as possible" to normal conditions. Normal conditions would be where there are as few as possible factors affecting the intersections negatively, and where the traffic conditions are the closest to what they would be the entire year. Therefore, finding a day of the week where this is possible to achieve, and two weeks where the situations are similar, is essential.

5.1.2 Conditions on site

A thing that is also worth mentioning when observing the areas for the study, is to look at how the conditions are on the site. This can be either regarding weather, temperatures, and seasons, but also if there is something unexpected happening on the site. The field recordings will be done during the winter, which means that the possibility of snow and cold temperatures are significant. During the winter, the hours of daylight are also lower than during the summer. This means that there may be difficulties recording as sight can become a problem for the cameras. Even though most intersections are illuminated, there may be shadowy parts around the intersections.

The second part that is also worth noticing when looking at the conditions on the site is the presence of any unexpected happenings. The intersection has recently had some construction work where the design of the intersection has been improved, for example, by adding an extra vehicle lane on the southern approach and changing the design of the pedestrian crossing just south of the intersection. At the time of the recordings, the upgrading of the intersection is finished. However, there may be some other work going on, at either intersection, which needs to be accounted for.

5.2 Traffic count

5.2.1 Goal with counting

The goal with counting the traffic at the intersections is to both 1) be able to answer the first two objectives in chapter 1.2, and 2) collect data to use for the models which will be used to answer the third objective. The traffic count will get an overview of the traffic load and show what approaches and movements experience the highest and lowest traffic loads. It will also separate the load of types of vehicles, i.e., it can be convenient to see where the heavy vehicles are travelling, and where they are not travelling. It will also show the routes cyclists are choosing. The traffic load also affects the performance measures, thus making it important for this section as well.

5.2.2 Traffic load

The traffic load at the intersections will be used to get an overview of the number of vehicles that are using the intersections. The traffic load can be used to determine whether the intersections experience a high load, thus having a higher saturation, or if there are few troubles regarding capacity and that they are performing well. An intersection that is experiencing a high traffic load, thus increasing the saturation, can furthermore get a higher delay compared to intersections where the traffic loads are lower. However, some intersections are designed to have a higher capacity than others, making them more capable of handling higher traffic loads. Therefore, getting an understanding of the traffic loads at the intersections is important when concluding how high the saturation is compared to the saturation rate the intersection can service.

The traffic loads at the intersections will be acquired by counting the flows at each approach and movement by using the recordings from the field studies. The traffic loads will then be presented in chapter 6.

5.2.3 Share of traffic modes

As well as getting an overview of the traffic load, it is necessary to look at the share of the different traffic modes at the different approaches and movements. As the thesis is focusing on the evaluation of bus priority, especially looking at buses will be an important part, and to get a view over the share of buses is therefore essential. It is also worth looking at the share of other heavy vehicles. This includes trucks, trailers, and other motorised vehicles that are longer and bigger than smaller vehicles, which can be passenger cars and vans. A reason for why the share of vehicles is interesting, apart from looking at the buses for the priority, is that different types of vehicles have different vehicle characteristics. This includes lengths, weight, and turning radius (Statens Vegvesen & Vegdirektoratet, 2019). Of these characteristics, the length of the vehicle is of great interest as a longer vehicle is using more space, which will lead to less vehicle in and around the intersections. This will especially be relevant for the delay calculations as the presence of longer vehicles will make room for fewer vehicles in the delay model sections, which are described in chapter 5.5. Heavy vehicles also have different characteristics when it comes to speed and acceleration. As heavier vehicles may use more time accelerating, they may slow down the traffic, which can increase the number of stops for them and other vehicles, as well as increasing the queue lengths. This is described in chapter 5.6.

The share of traffic modes will be done the same way as the traffic load in chapter 5.2.2. When the traffic load is being counted, the traffic loads will be split into different modes. For this thesis, there are three different motorised categories used for the mode share. These are light vehicles (LV), buses, and heavy vehicles (HV) that are not buses[7].

[7] This category will be referred to as heavy vehicles.

5.2.4 Measures of performance

The traffic count will be used to calculate the different performances measures, i.e., delay, number of stops and queue lengths on the different approaches. The traffic count will give the traffic flow for the approaches, which is a part of the later calculations. These three performance measures are also affected by other factors like signal timing, intersection capacity, and topography[8]. However, more traffic and less green time on one approach will most likely lead to higher (more negative) values on the performance measures, especially measures like queue length and total vehicle delay. These and the rest of the performance measures are described in detail in chapter 5.5 and 5.6

5.3 Camera setup

The camera setup is an important part of the data collection. As the recordings from the field studies will be necessary for analysing the performance of the intersections, getting the best camera setup will be essential to obtain the best data. This includes choosing the best positions to observe all relevant factors that will affect the intersections. However, as the most ideal positions may not be available, the goal is to find the most practical positions with the best views.

5.3.1 Intersection 1

Figure 5.1 shows the camera locations at intersection 1. To observe the approaches at the intersection, two cameras are necessary. These are shown in the figure with a red and a purple circle. The sightlines of the two cameras are shown as the lines from each camera in the figure. One of the cameras covers the northern approach, while the other observes both the western and southern approach. Both cameras have been mounted to a railing that sits on a small, elevated walkway above the road. This can be seen in Figure 5.2. Having the cameras at a higher elevation than the road makes it easier to observe the traffic further upstream on the approaches, which is essential for calculating delay and looking at queue lengths.

5.3.2 Intersection 2

For the second intersections, three cameras are necessary for being able to observe all the approaches and a sufficient distance upstream on the approaches. As for intersection 1, the three cameras are all placed at a higher elevation than the roads and the intersection with two being very close to each other on top of a staircase, while the last being placed along a minor road that leads to the eastern approach, where it can observe far upstream on the south approach. One of the cameras on top of the staircase covers the intersection and the eastern, northern, and western approaches, while the other covers another part of the southern approach, which is not being observed by any of the two other cameras. The position

[8] The driving characteristics of vehicles can differ if there is a downhill, uphill, or flat approach/exit.

of the cameras and their sightlines are shown in Figure 5.3, while Figure 5.4 a) and b) shows the mounting of the cameras. One of the cameras on top of the staircase, which is marked with purple in Figure 5.3 is mounted to a railing, while the other camera next to it is standing on a tripod. The third camera, which is marked in green in Figure 5.3, is mounted to a railing along the mentioned minor road.

Figure 5.1: Position of cameras with sightlines at intersection 1 (Kartverket, n.d.)

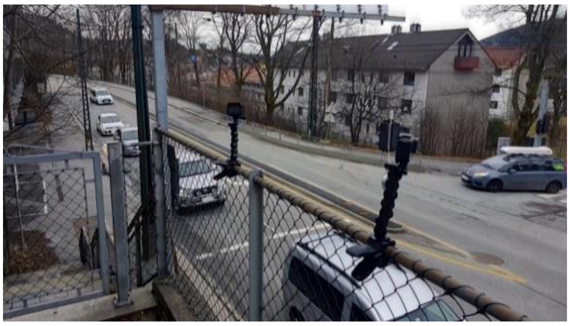


Figure 5.2: Mounting of cameras at intersection 1

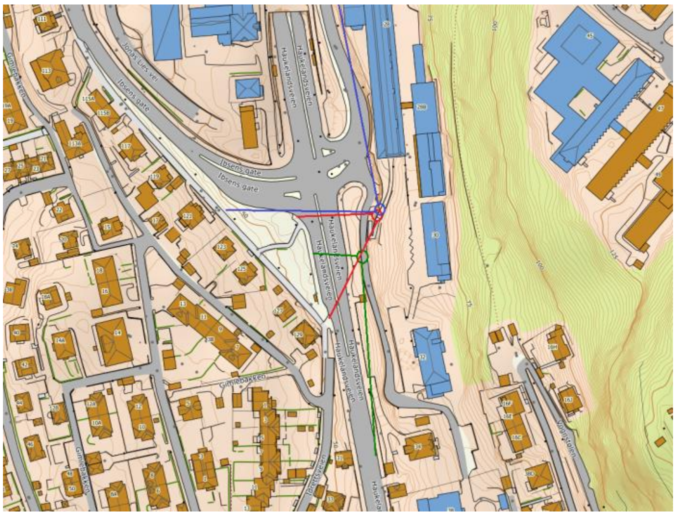
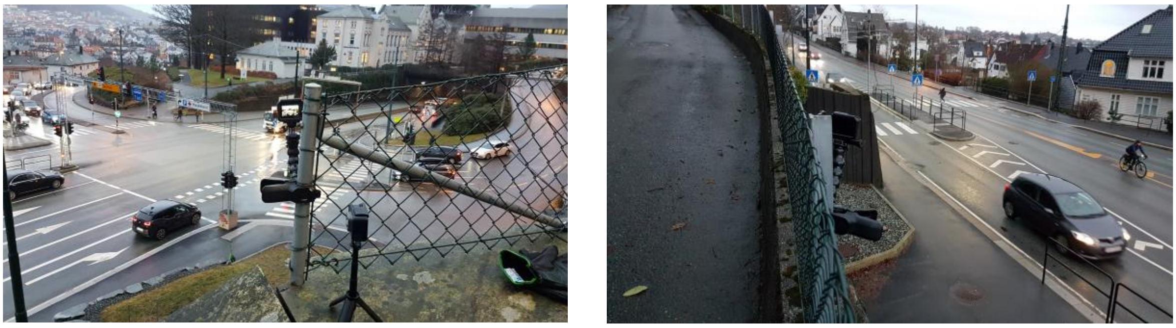


Figure 5.3: Position of cameras with sightlines at intersection 2 (Kartverket, n.d.)



a) Mounting of the northernmost cameras at intersection 2 b) Mounting of the southernmost camera at intersection 2

Figure 5.4: Mounting of cameras at intersection 2

5.4 Signal data

5.4.1 Variable green times

During the field recordings, to be able to understand the intersections, the green times for each phase are collected. The green times are explained in chapter 2.1.1 as the time in which a signal phase has a green signal. These green times can be an indicator to which movements experience the most traffic load and which movements are prioritized the most, i.e., a phase that contains a movement that experiences a high traffic load may trigger a longer green time than a phase with less traffic load on the movements.

Looking at the green times for the no priority scenario compared to the priority scenario is also interesting as it can give an indicator of how the priority scheme affects the priority for the different phases when it comes to green extension and the shortening to minimum green time.

To obtain the green times from the recordings, a random ten consecutive cycles will be used. The green times for each phase in these ten cycles will be noted and the average will be presented. As some phases will be skipped if there are no calls either by vehicles or pedestrians, some recorded cycles may have a green time for these phases of zero, which will affect the average value. However, a phase being skipped may also be an indicator of a low traffic load on the corresponding movements compared to other movements in other phases.

5.5 Delay calculations

5.5.1 Description of delay model

To be able to determine the delay for each approach at the intersections, a similar approach to the one used by Magfirona et al. (2015) is being used, but with a few differences. The method compares the average travel time with the expected travel time for the vehicles at a part of the approach. The part of the approach that will be looked at is called the test section. To determine the average travel time for the test section, it is necessary to observe all queue in the test section, which will be counted every fifteenth second. Every period of fifteen seconds will be called a test interval. To determine the average vehicles in the test intervals, Veh_A, Eq. 16 is being used, where the number of test intervals is the number of times the queue is being counted. Letting n be the number of test intervals, and X_i be the number of vehicles counted in test interval i, where $1 \leq i \leq n$, then, one can write the formula as below:

$$Veh_A = \frac{1}{n}\sum_i X_i = \frac{Veh_{tot}}{n} \qquad \text{Eq. 16}$$

To determine the expected travel time at the intersection, the travel time during the free flow condition and the total vehicle flow needs to be determined. The travel time during free flow is shown as the relationship between the length of the section used, l, and the speed limit/travel speed in the section, v. The travel time during free flow, $TTFF$, is shown in Eq. 17.

$$TTFF = \frac{l}{v} \qquad \text{Eq. 17}$$

The expected number of vehicles, Veh_E, in the test section is computed by taking the product of the travel time under free flow and the total vehicle flow, which is the total number of vehicles passing through the intersection, denoted as q_{tot}.

$$Veh_E = TTFF * q_{tot} \qquad \text{Eq. 18}$$

The average delay for each vehicle, d, is shown as the difference between the average number of vehicles in the test section and the expected number of vehicles in the test section, divided by the total vehicle flow. This is shown in Eq. 19.

$$d = \frac{Veh_A - Veh_E}{q_{tot}} \qquad \text{Eq. 19}$$

From Eq. 7 presented in chapter 2.1.4 and Eq. 19, one gets that the total delay for the approach is given by $D = Veh_A - Veh_B$.

5.5.2 Test sections

Intersection 1

The southern approach has a bend that starts approximately 70 metres south of the intersection. After this bend, it will be difficult to record the queue on the approach. Therefore, the test section for this approach will end in this bend, making the length of the test section 75 metres. This includes a small part of the bend. An illustration of the text section is shown in Figure 5.5, while Figure 5.6 shows the test section from the position of the camera.

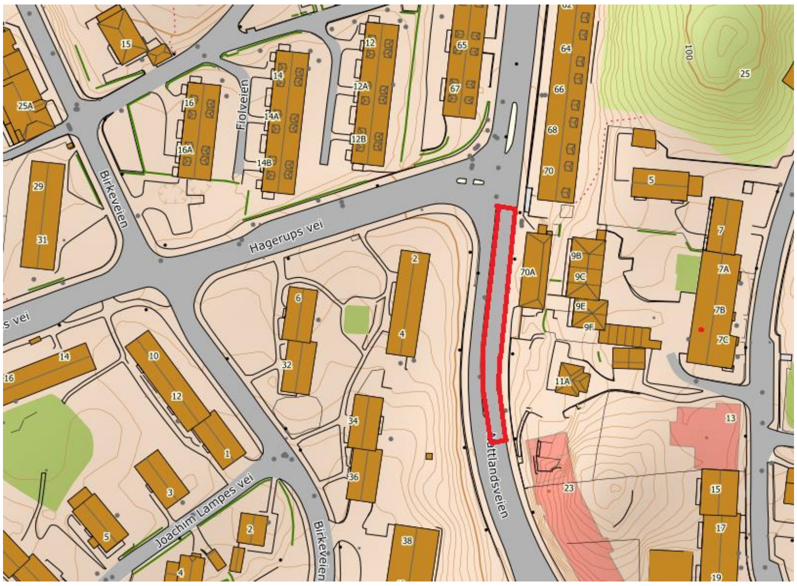


Figure 5.5: Location of test section on the southern approach at intersection 1 (Kartverket, n.d.)

Figure 5.6: Test section on the southern approach at intersection seen from the position of the camera

The test section on the northern approach goes from the intersection up to the bus stop on the approaching lane. This distance is approximately 100 metres. The sight from the position of the camera is longer than 100 metres. However, to get a better delay estimate, starting the test section after the bus stop will be more convenient. The test is illustrated in Figure 5.7 and seen from the position of the camera in Figure 5.8.

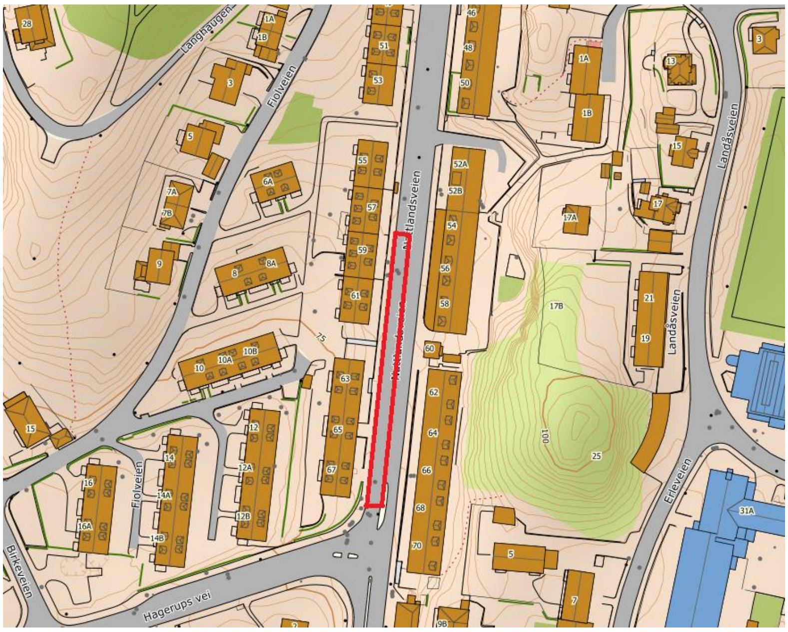


Figure 5.7: Location of test section on the northern approach at intersection 1 (Kartverket, n.d.)

Figure 5.8: Test section on the northern approach at intersection 1 seen from the position of the camera

The test section on the western approach is illustrated in Figure 5.9. It goes from the intersection to the intersection where Hagerups vei meets Birkeveien, which is the intersection closest to intersection 1 to the west. The test section stops at this intersection so it will only focus on the traffic leading to the intersection. The length of the test section is approximately 100 metres. The test section seen from the camera position is shown in Figure 5.10.

A summary of all test sections at intersection 1 with information on where the section stops is presented in Table 5.1.

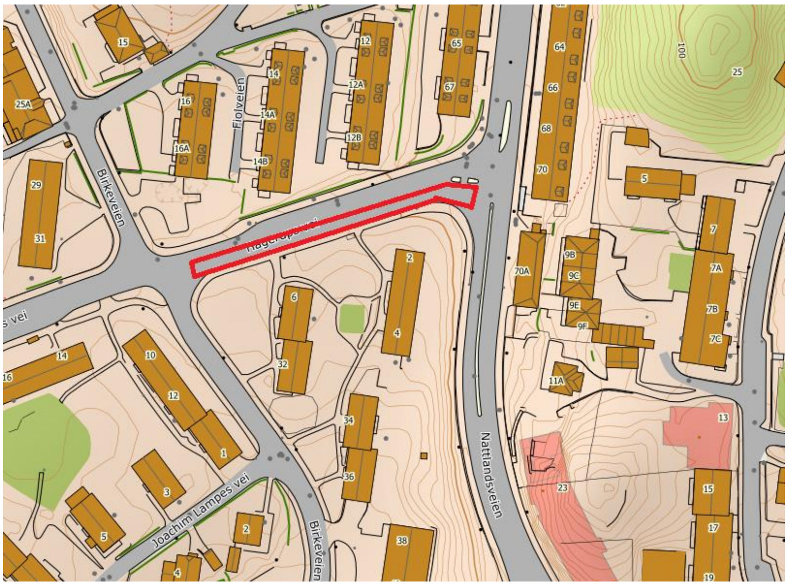


Figure 5.9: Location of test section on the western approach at intersection 1 (Kartverket, n.d.)

Figure 5.10: Test section on the western approach at intersection 1 seen from the position of the camera

Table 5.1: Summary of test sections at intersection 1

Approach	**Length of test section**	**To where**
Southern approach	75 metres	From the intersection to just after the beginning of the bend
Northern approach	100 metres	From the intersection to the bus stop along the approaching lane
Western approach	100 metres	From the intersection to the intersection between Hagerups vei and Birkeveien

Intersection 2

The test section on the southern approach is shown in Figure 5.11. The test section stretches from the intersection south approximately 100 metres. The test section will also cover the pedestrian crossing on this approach which is described in chapter 3.3.1. South of the pedestrian crossing, it goes to where the approaching lanes are being divided on each side of the pedestrian crossing, which is approximately 15 metres south of the pedestrian crossing. The test section also stops where there is an access road to a house right next to Haukelandsveien. The access road to the house can be seen in the bottom right corner of the figure. To cover this section with the cameras, several cameras must be used. The views of the test section from these cameras can be seen in Figure 5.12, Figure 5.13, Figure 5.15, where the first figure shows the southernmost part of the test section, the second figure covers the middle part of the test section, and the last figure covers the part that is closest to the intersection.

Figure 5.11: Location of test section on the southern approach at intersection 2 (Kartverket, n.d.)

Figure 5.12: Middle part of the test section on the southern approach at intersection 2 seen from the position of the camera

Figure 5.13: Southern part of the test section on the southern approach at intersection 2 seen from the position of the camera

The test section used for the eastern approach is shown in Figure 5.14. It stretches from the intersection up to a right turning curve seen from the south, which is approximately as far north as to where the tunnel on the northern approach starts when travelling north from the intersection. The distance of the test section is approximately 90 metres from the stop line for the left turning and through lanes. The test section can be seen from the position of the camera in Figure 5.15.

Figure 5.14: Location of test section on the eastern approach at intersection 2 (Kartverket, n.d.)

Figure 5.15: Test section on the eastern and northern approach at intersection 2 seen from the position of the camera

The test section on the northern approach goes from the intersection to the beginning of the tunnel, which is, as mentioned in chapter 3.3, 75 metres. As there would be challenges to record inside the tunnel, the test section is set to only go to the beginning of the tunnel. The bus stop on this approach is located within the test section, which can create some difficulties when it comes to the calculations of the delay. This is discussed in chapter 5.5.3. An illustration of the test section is shown in Figure 5.16, while the test section seen from the camera position is shown in Figure 5.15.

Figure 5.16: Location of test section on the northern approach at intersection 2 (Kartverket, n.d.)

A large part of the western approach is blocked from the position of the camera due to the topography and vegetation to the north of the approach. Therefore, the test section on the western approach stretches to where the camera is no longer able to see the approach, which is just after the end of the refuge in the middle of the approach. This is shown in Figure 5.17, while the test section seen from the camera position is shown in Figure 5.18. The length of the test section is approximately 65 metres from the stop line of the left turning and through lanes, and approximately 72 metres from the stop line of the two right-turning lanes. The length of the test section is therefore set to 68 metres, which is the average[9] between the two lengths.

A summary of all test section related to intersection 2 is presented in Table 5.2.

Figure 5.17: Location of test section on the western approach at intersection 2 (Kartverket, n.d.)

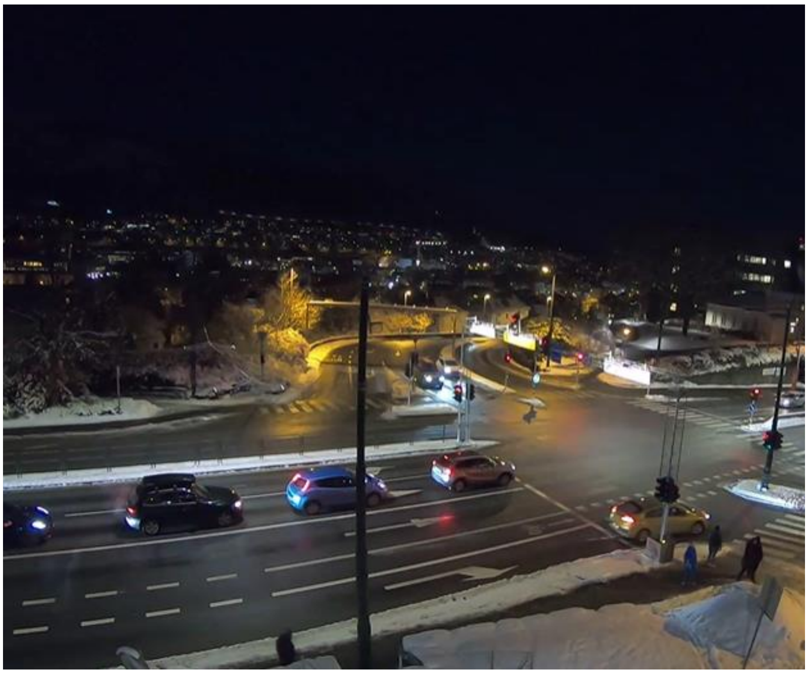


Figure 5.18: Test section on the western approach at intersection 2 seen from the position of the camera

[9] Average is 68.5 metres. However, the left turning and through lanes experience higher traffic load, so the length of the test section is rounded down to 68 metres.

Table 5.2: Summary of test sections at intersection 2

Approach	**Length of test section**	**To where**
Southern approach	100 metres	From the intersection to where the approaching lanes start to divide before the pedestrian crossing further south on the approach
Eastern approach	90 metres	From the intersection to the right bending curve located as far north as the start of the tunnel on the northern approach
Northern approach	75 metres	From the intersection to the beginning of the tunnel
Western approach	68 metres	From the intersection to right after the end of the refuge dividing the two travel directions on the approach

5.5.3 Uncertainties with calculations

As this delay calculation method is based on data from field studies, there may be several uncertainties that can affect the calculations or the final delay estimate one obtains with the calculations. Firstly, the TTFF obtained by Eq. 17 is based on either the speed limit at the site or the speed the vehicles are travelling at. This difference can be relevant if the travelling speed shows a significant difference from the speed limit. A way to obtain an estimate of the speed parameter in this equation is to take the average travel time in the section for each vehicle that travels under free flow conditions. Though, by using this method, one can get situations where there are people that are driving at speeds that are either very high or very low. The first can occur if the driver expects the light to change from green to red while he is in the section and does not want to stop and wait for another cycle. Therefore, increasing the speed to make sure he passes the stop line at the intersection will increase the speed desired to use in the equation. The latter, where one drives slowly, can be a result of nervousness, e.g., first time driving on the site, or that there are some factors on the side of the road that can disturb the driver. However, taking an average of vehicles travelled at free flow still can be considered a convenient way if the number of vehicles included increases. By having a larger number of vehicles included, the percentage of these anomalies may be under-represented, as most vehicles will be driving “normally”. The free flow travel time one ends up having in the model will furthermore affect the value of the expected number of vehicles in the test section, presented in Eq. 18. A higher free flow travel time will make the expected number of vehicles value in the test section higher, thus reducing the delay and vice versa.

The length of the test section used in the calculations can also affect the results. The length of the test section is also a part of Eq. 17, but it also affects the space available for vehicles. Some of the approaches in both intersection 1 and intersection 2 consists of one lane further away from the intersection, and several lanes at the intersection. An example of this is the western approach at intersection 2, where the traffic moves at one lane before it divides into four different lanes at the intersection based on the different movements the vehicles can go. If one movement at the intersection experiences high demand, the queue at this movement may therefore exceed the movement lane at the intersection and extend into the one lane that all movements are sharing further upstream of the intersection. In a situation like this, this queue may block the accessibility for vehicles that are going in another direction, thus making the other lanes under-utilised. This can especially happen if the movement experiencing high demand usually has a low demand, so the usual green time is low for this movement, or if it has an opposing movement, i.e., another movement it must give way to before itself gets the right of way. If the queue goes outside the test section, the delay estimate from the model can become less than the actual delay as the model will not be able to account for the waiting time the vehicles are undertaking while standing in the queue outside the test section. If this does not happen often during the field observations, the results may not have a big impact on the total delay for the approach, but if it happens more frequently, the test section should be extended. However, extending the test section will make be difficult due to lack of sight. Some approaches may be blocked due to vegetation, constructions, and topography, which can be difficult to cater for with limited resources.

It is also worth noticing that the delay model looks at the delay for an approach, not separate movements at the approach. Looking at the delay for each movement would have been possible. However, this requires a lot of resources, and the fact that the different movements share the same lane as described in the previous paragraph, the different movements affect one another too much. Therefore, the focus of the delay estimations is to look at each approach. The model described in chapter 5.5.1 takes the total flow at the approach, so by looking at the entire approach, one can get a sense of which of the approaches are having problems regarding the delay. Therefore, by knowing which approaches that are experiencing high delay, it can be easier and more understandable to figure out where to implement alternative improvements. Even though several of the movements on an approach does not necessarily have a green signal in the same phase group, focusing on the entire approach instead of each movement will be a feasible strategy.

Another thing that can cause problems with the delay estimations is an abnormal event happening at the intersection. For instance, a vehicle collision or some form of accident can lead to an extensive increase of queues, thus waiting times and an increase of delay. Some collisions can be non-severe, and the traffic may return to normal very soon. However, for more serious or more complex collisions, the intersection, or parts of the intersection cannot be possible to use for an extended period. In that way, the parts of the intersections that are closed may not be able to cater for the demand and will therefore be over-saturated, which will lead to an increase of the delay (Akçelik, 1981, p. 25). Another event that is in some way similar to a collision is the presence of emergency vehicles. Although these vehicles only stop or slow the traffic for a short time, these will disrupt the traffic. As both intersections are close to the Haukeland University Hospital, intersection 2 being right next to it, the presence of emergency vehicles like ambulances is not unlikely. The disruption an emergency vehicle causes to the traffic can lead to several vehicles not being able to travel through the intersection during their phase, which leads to a larger queue upstream of the intersection. This can furthermore lead to the same problem as described in the second paragraph of this chapter. The presence of cyclists in the road can also lead to a disruption in the traffic, causing it to go slower than normal. A few of the approaches have several cyclists using the road section as there is no alternative way. Even though some cyclists tend to move at a speed close to the speed of the traffic, some factors like topography or wind can reduce the speed so that there will be a queue behind the cyclists. In the delay calculation, cyclists are not included as the focus is on the vehicles, being both light and heavy vehicles, and buses. However, the cyclists still have an impact on the delay at the different approaches they operate at.

On the northern approach at intersection 2, the bus stop is placed in the test section. This can make the delay for the buses a bit more complicated to calculate as it can be difficult to see when they are ready to drive from the bus stop, and when they are loading and unloading passengers during the dwell time. As they will stop and start inside the test section, the time they will use inside the test section will be very different from the TTFF if they could drive through the test section without having to stop at a bus stop. However, as the bus stop is placed where it is on that approach, it will be more reasonable to have the bus stops included in the test section than to start the test section after the bus stop. This would have given a test section that would have been very small and not suitable for these delay calculations.

5.6 Other measures of performance

5.6.1 Bus delay

To see how the buses are experiencing the priority, there will be done calculations on the delay for the buses separately as well as for all vehicles at the intersections. The bus delay calculations will be undertaken by looking at the time the buses are spending in the test sections described in the delay calculations in chapter 5.5, i.e., the travel time. The delay will be calculated as the difference between travel time and the TTFF, which is presented in the equation below.

$$d_{bus} = TT_{bus} - TTFF_{bus} \qquad \text{Eq. 20}$$

Furthermore, the average delay for buses at an approach is obtained by taking the average of all the bus delays calculated with Eq. 20.

5.6.2 Number of stops

To find the number of stops, there will be an analysis of each approach where the number of vehicles that will have to stop during a cycle will be counted. A vehicle will be included if the wheels are standing still (full stop), and not if it only must slow down the speed. The number of vehicles stopping will be compared to the total number of vehicles that are passing through the intersection, giving an average percentage of vehicles stopped during the cycle. For each approach, this will be done over ten cycles.

5.6.3 Queue length

The queue lengths for each approach will be analysed in the same way and at the same time as the number of stops. During each cycle, the longest queue length will be collected. This will also be done over ten cycles, thus also getting an average maximum queue length.

5.7 External data

Skyss, which is the provider of the public transport system in Bergen, can look at journey times, passenger numbers and other data from trips. Therefore, as well as looking at the performance measures during the field study, their data can be used to verify some of the results. Especially regards to the bus delay, which is an important part of the objectives for the thesis. The data Skyss is providing regarding bus delay looks at the time travelled between two bus stops, i.e., the time starts when the bus leaves a bus stop and stops when departing the next bus stop, thus including a dwelling time at the last bus stop. This is not like the bus delay calculation used in this thesis, which is by looking at the time used in the test sections on the approaches. The data from Skyss also operates with an expected travel time, which is including expected waiting times at the intersection(s) it goes through. This is also different to this thesis's delay calculation, where the delay is calculated from the travel time and a situation where there is no other traffic affecting the bus, free flow condition. However, the provided data can be of use to get an indication of the travel time. The bus delay will also be presented along with the field study results.

6 Results from field studies

6.1 Site conditions

6.1.1 Time of field study

All the recordings during the field study were undertaken during February 2021. For intersection 1, the recordings without priority were undertaken on Tuesday the 2nd of February, while the recordings with priority were done on the 23rd of February. Both situations were recorded during the afternoon peak hours, i.e., from 3:30 pm to 4:30 pm. For the first situation, i.e., when there was no priority, the priority scheme was turned off from 2:00 pm to 5:00 pm.

The recordings from the second intersection were undertaken on the 3rd of February, and on the 24th of February. Both situations were done during, and at the end of the morning peak, i.e., from 7:35 am to 8:35 am. During the no priority situation, the priority was turned off from 6:00 am to 9:30 am.

Ideally, the recordings should have been closer to each other. However, due to the local outbreaks of Covid-19, followed by stricter restrictions, the second recordings had to be postponed a couple of weeks.

6.1.2 Weather conditions

As all recordings were undertaken during February, during the Norwegian winter, the weather conditions could in some ways affect the recordings. Also, considering the climate in Bergen, the weather and the temperature can change rapidly from week to week. During the first two recordings, i.e., the recordings without the priority turned on, the sites contained snow, some ice, and low temperatures. In the days before the recordings, there had been some snowy weather, but no precipitation during the recordings. During the recording at intersection 1, the temperature was minus two degrees Celsius, and minus eight degrees Celsius at intersection 2. Due to Norway's northern location, the amount of sunlight per day is fairly reduced during the winter, making the intersections dark at the end of the afternoon recordings, and not light until the end of the morning recordings, respectively.

For the second part of the recordings, which included the sites with the priority turned on, the weather had changed a lot from the previous recordings. At the first intersection, the temperature was eight degrees Celsius during the recording, with no snow, or precipitation. For the second intersection, there had been some rainfall during the night before the recordings but clear at the time of the recordings. This intersection also had a temperature of eight degrees Celsius during the recording, with no snow present.

6.2 Intersection 1 without priority

6.2.1 Traffic volume

The traffic count from intersection 1 during the no priority scenario is shown in Table 6.1. The traffic count includes the turning flows for each vehicle type at all approaches, which is shown in Table 6.2, including the pedestrian count. From the count, one can observe that most of the traffic arrives on the northern approach, where the flow is larger than the southern and western flows combined. These numbers are understandable considering that this approach leads towards the city and that the traffic during the afternoon peak goes from the city and to the suburbs. When looking at the bus flows, no buses are travelling from the western to the southern approach or vice versa, but all buses travel on the northern approach. Therefore, it is not surprising that this approach experiences the highest flow of buses. However, one noteworthy thing is the low percentage of heavy vehicles. Both buses and the rest of the heavy vehicles represents less than 4% of the total flow at the intersection.

Table 6.1: Traffic count for intersection 1 without priority

Approach	LV	Bus	HV	Bike	Total
South	334	16	2	2	354
North	756	23	4	19	802
West	312	10	1	4	327
Total	1402	49	7	25	1483

Table 6.2: Traffic count for separate approaches at intersection 1 without priority

a) Traffic count southern approach

Movement	LV	Bus	HV	Bike	Total
Left turn	88	0	0	0	88
Through	246	16	2	2	266
Total	334	16	2	2	354

b) Traffic count northern approach

Movement	LV	Bus	HV	Bike	Total
Through	472	14	2	17	505
Right turn	284	9	2	2	297
Total	756	23	4	19	802

c) Traffic count western approach

Approach	LV	Bus	HV	Bike	Total
Left turn	189	10	1	2	202
Right turn	123	0	0	2	125
Total	312	10	1	4	327

d) Pedestrian count

Approach	Pedestrians
Southern approach	0
Northern approach	34
Western approach	31

6.2.2 Signal phases

The average phase times for the three different phases are presented in Figure 6.1. From the figure, it can be observed that it is the first phase that receives the highest amount of green time during the cycles. As this phase caters for the through movements on the southern and northern approach, it is not surprising that this is the case. The two following phases receive somewhat similar green times, which are very low. This can be explained by the fact that the phases were in some cycles not called upon[10]. Hence, the average green time would be reduced. Phase A on the other hand was not skipped once but was in several cycles experiencing green times way higher than the average green time presented in the figure.

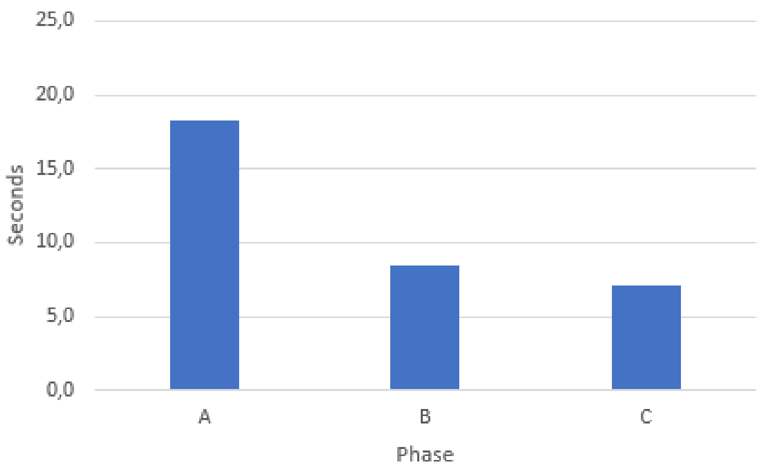


Figure 6.1: Average green time for the different phases at intersection 1 without priority

[10] Phase B was in one cycle not called upon, while phase C was skipped twice.

6.2.3 Vehicle delay

The results from the delay calculations are presented in Table 6.3. From the results, one can observe that the southern approach experience a very small delay per vehicle, less than ten seconds, while the two other approaches have an average vehicle delay between 15 and 20 seconds, the western approach being the approach with the highest delay. However, even though the western approach has a higher average delay than the northern approach, due to the higher traffic flow on the northern approach, the total delay calculated on this approach is a lot higher than for the western approach, which is presented in Table 6.3.

Table 6.3: Delay for approaches at intersection 1 without priority

Approach	Average delay (s/veh)	Total delay (veh.h/h)
Nattlandsveien S	8.36	0.82
Nattlandsveien N	17.13	3.74
Hagerups vei	18.02	1.62

6.2.4 Bus delay

Based on the bus delay results shown in Table 6.4, the buses experience less delay on all approaches compared to the overall average vehicle delay presented in Table 6.3. Especially the southern approach experiences a bus delay that is half of the average vehicle delay. The other two approaches also show lower results in delay with several seconds. It can also be observed that the bus delay presented from Skyss varies from the observed bus delay from the field study. Especially the southern and northern approach have larger differences from the observed delay. This can be a result of longer dwelling times or a presence of pedestrians at any pedestrian crossing that may cause the buses to slow down and wait.

Table 6.4: Average delay for buses at intersection 1 without priority

Approach	Average delay (s/veh)	Delay Skyss (s/veh)
Nattlandsveien S	3.62	14.2
Nattlandsveien N	13.00	3.9
Hagerups vei	15.13	21.3

6.2.5 Number of stops and queue lengths

From Table 6.5, when it comes to the number of vehicles stopped, most vehicles are stopping on the northern approach. However, the western approach is the approach that is experiencing the highest percentage of stopped vehicles, where four out of five vehicles need to stop. This corresponds with the fact that this approach also experiences the highest delay per vehicle, but the northern approach has the highest total delay, like with the number of vehicles stopping. The northern approach also experiences the longest queue lengths with the maximum queue averaging almost five vehicles, with seven vehicles as the maximum queue. The southern approach shows a low average maximum queue length having several cycles with a maximum queue of only one vehicle.

Table 6.5: Stops and queue lengths for intersection 1 without priority

Approach	Arriving vehicles	Stopping vehicles	%vehicles stopped	Max queue length
Nattlandsveien S	4.9	2.5	51.0%	2.1
Nattlandsveien N	10.4	5.4	51.9%	4.8
Hagerups vei	4.6	3.8	82.6%	4.0

6.3 Intersection 1 with priority

6.3.1 Traffic volume

The traffic count from the scenario with bus priority for intersection 1, which is shown in Table 6.6, with the separate movements shown in Table 6.7, shows that there is not a large change in the traffic flow, either for the entire intersection or the separate approaches. However, some approaches experience a slight increase in the traffic, e.g., both approaches on the northern approach contribute to increasing the number of vehicles from 783 in the no priority scenario, to 814 in the priority scenario. Even though this increase is only 4%, it can still make the saturation higher at certain times during the count, thus creating longer queues and higher delays. Furthermore, another noticeable observation from this count is the large increase of cyclists. The number of cyclists increases from 25 to 70, whereas most of these also arrive on the northern approach. The northern approach also has an increase in the number of pedestrians, which can lead to this movement blocking the through movement on the south approach.

Table 6.6: Traffic count for intersection 1 with priority

Approach	LV	Bus	HV	Bike	Total
South	329	15	1	6	351
North	781	28	5	56	870
West	327	11	0	8	346
Total	1437	54	6	70	1567

Table 6.7: Traffic count for separate approaches at intersection 1 with priority

a) Traffic count southern approach

Movement	LV	Bus	HV	Bike	Total
Left turn	84	0	0	6	90
Through	245	15	1	0	261
Total	329	15	1	6	351

b) Traffic count northern approach

Movement	**LV**	**Bus**	**HV**	**Bike**	**Total**
Through	482	16	3	51	552
Right turn	299	12	2	5	318
Total	781	28	5	56	870

c) Traffic count western approach

Approach	**LV**	**Bus**	**HV**	**Bike**	**Total**
Left turn	205	11	0	2	218
Right turn	122	0	0	6	128
Total	327	11	0	8	346

d) Pedestrian count

Approach	**Pedestrians**
Southern approach	0
Northern approach	49
Western approach	32

6.3.2 Signal phases

For the priority scenario, all the phases are experiencing an increase in green times compared to the no priority scenario. As the priority only increase green times for movements and do not reduce any green times, it is understandable that the average green times are being increased if there are buses present, which there are in both phase A and phase B. For phase C, the increase in green time can be explained by the increase in pedestrians on the northern pedestrian crossing. The number of left-turning vehicles

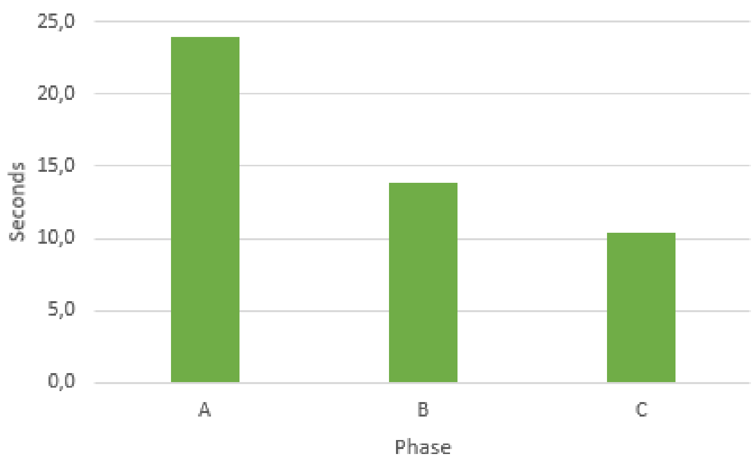


Figure 6.2: Average green time for the different phases at intersection 1 with priority

on the southern approach and the right turn on the western approach is close to the same for both scenarios. Hence, the increase of pedestrians can have led to this movement being triggered more often in this scenario, thus extending the green time for the phase.

6.3.3 Vehicle delay

The average delay and total delay from the priority scenario is shown in Table 6.8. In this scenario, all approaches experience an increase in delay compared to the no priority scenario, with the northern approach being the approach with the highest increase, both relative and numerical. However, even though there is an increase in delay for all approaches, the increase is not large for any of the approaches. But, on the other hand, the bus priority is causing an increase in delay for all approaches, thus no approach is gaining on the priority scheme.

Table 6.8: Delay for approaches at intersection 1 with priority

Approach	**Average delay (s/veh)**	**Total delay (veh.h/h)**
Nattlandsveien S	10.49	1.00
Nattlandsveien N	22.17	5.03
Hagerups vei	21.80	2.04

6.3.4 Bus delay

The bus delay is presented in Table 6.9. As with the vehicle delay, the buses also get an increase in delay. Especially the northern and the western approaches are experiencing a large numerical increase in delay for buses. Even though the relative increase of the delays on the southern and the northern approach is the same, the increase on the southern approach, which is from four seconds to six seconds, can be explained by some slower moving buses, i.e., the bus drivers were driving a bit faster in the no priority scenario. Although, there may be something else causing this increase too. However, for the northern approach, an increase from 12 to 19 seconds can be a result of something else than the driver characteristics. It can be a result of the increase in the traffic flow on the approach, and the increase of cyclists, which can slow down the speed on the approach. It can also be explained by the fact that the buses are arriving at a time where there is a lot of traffic or just more than in the no priority scenario. This can also contribute to the increasing delay, for instance, if the bus is further back in the queue, the shock waves that are being created from when the cars are moving are taking longer to reach the buses, making the waiting time in the queue longer.

Table 6.9: Average delay for buses at intersection 1 with priority

Approach	Average delay (s/veh)	Delay Skyss (s/veh)
Nattlandsveien S	7.00	18.2
Nattlandsveien N	19.67	13.2
Hagerups vei	25.43	30.6

Furthermore, the reason for the increase in delay on the western approach, which is the highest increase, can also be a result of unlucky arrivals for the buses. It can also come from the increase in buses, especially on the northern approach, even though this increase is not large. The increase in buses on the northern approach could have increased made the priority for this approach as significant that the priority on the western approach would not function to its purpose. When looking at the delay obtained from Skyss, all approaches are also experiencing an increase in delay from the no priority scenario. The northern approach is experiencing the highest increase, with the western approach also having a large increase.

6.3.5 Number of stops and queue lengths

As with the delay, the percentage of vehicles stopping for the southern and northern approach is increasing when implementing the bus priority. Even though the increases are not very large, there is still an increase. The same goes for the average maximum queue length. Here, the northern approach is experiencing some queue lengths of ten vehicles. The western approach, on the other hand, is experiencing a decrease in both the percentage of vehicles stopped and the maximum queue length. This can be a result of the buses allowing more vehicles to pass through the intersection, thus taking advantage of the bus priority. It can also be that the vehicles are arriving perfectly before their green time. Yet, there is still a decrease, which is beneficial, nonetheless. All information for the different approaches related to the number of stops and queue lengths is shown in Table 6.10.

Table 6.10: Stops and queue lengths for intersection 1 with priority

Approach	Arriving vehicles	Stopping vehicles	%vehicles stopped	Max queue length
Nattlandsveien S	5.9	3.4	57.6%	3.1
Nattlandsveien N	11.2	7.0	62.5%	6.0
Hagerups vei	4.4	2.7	61.4%	2.8

6.4 Intersection 2 without priority

6.4.1 Traffic volume

Table 6.11 shows that for the traffic count from intersection 2 in the no priority scenario, the southern approach is experiencing the highest flow of vehicles arriving at the intersection, almost double the flow of the second highest approach which is the western approach. As this count was undertaken during the morning peak, this observation is not a surprise as many of these vehicles can be commuters going to work, either at the Haukeland University Hospital or in the city centre. Table 6.12 a) shows that the flow on the southern approach mostly goes through the intersection heading, but several vehicles are turning both left and right as well. For the western approach, which is the approach with the second highest flow, the traffic is divided in a way where the access to the hospital (through movement) is experiencing the highest flow, with the left and right turn only having a closer to equal vehicle distribution with 18 vehicles difference. This is shown in Table 6.12 d).

Most buses operating at this intersection is travelling between the southern and northern leg, with some buses travelling to and from the western approach as well. The eastern approach does not have any buses. Also, some of the legs experience a high load of pedestrians, especially the eastern approach, where there were recorded 268 pedestrians crossing. The northern and western leg also have some pedestrians, however, a smaller number than for the eastern approach. The share of pedestrians is shown in Table 6.12 e). There are also several cyclists present at this intersection, most of them arriving on the southern approach.

Table 6.11: Traffic count for intersection 2 without priority

Approach	**LV**	**Bus**	**HV**	**Bike**	**Total**
South	694	39	9	45	787
East	162	0	8	0	170
North	234	42	14	2	292
West	359	12	11	3	385
Total	1449	93	42	50	1634

Table 6.12: Traffic count for separate approaches at intersection 2 without priority

a) Traffic count southern approach

Approach	**LV**	**Bus**	**HV**	**Bike**	**Total**
Left turn	227	2	1	3	233
Through	327	37	8	24	396
Right turn	140	0	0	18	158
Total	694	39	9	45	787

b) Traffic count eastern approach

Approach	LV	Bus	HV	Bike	Total
Left turn	71	0	3	0	74
Through	60	0	4	0	64
Right turn	31	0	1	0	32
Total	162	0	8	0	170

c) Traffic count northern approach

Approach	LV	Bus	HV	Bike	Total
Left turn	60	0	1	1	62
Through	133	40	5	1	179
Right turn	41	2	8	0	51
Total	234	42	14	2	292

d) Traffic count western approach

Approach	LV	Bus	HV	Bike	Total
Left turn	105	5	9	0	119
Through	161	0	1	3	165
Right turn	93	7	1	0	101
Total	359	12	11	3	385

e) Pedestrian count

Approach	Pedestrians
Southern approach	0
Eastern approach	234
Northern approach	167
Western approach	87

6.4.2 Signal phases

The average green times for the phases at intersection 2 is presented in Figure 6.3. From the figure, one can observe that the second phase, which consists of the movements from the eastern approach and the northern pedestrian crossing, is receiving the longest green times. This can be explained by the presence of the pedestrians crossing on the northern approach. The vehicle movements are not requiring that much green time with the volume that is observed from the recordings. However, the crossing time for the pedestrians are requiring a longer green time, thus extending the green time for the phase when these

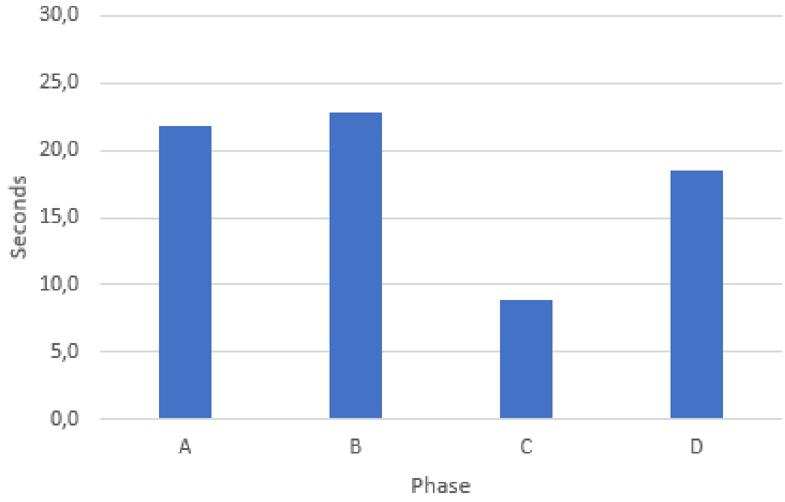


Figure 6.3: Average green time for the different phases at intersection 2 without priority

are present. This is the case in eight out of ten phases where the green times were collected. When the pedestrians were not present, the green times for the phase were lower.

The phase with the second highest green times was phase A. In many cases, the left movement on the northern approach and the right turn on the eastern approach was not present, thus giving both the through and right turning movement on the southern approach green in phase D. The time these movements gained are not included in the figure above, but is rather a part of phase D. This may cause a lower green time needed as some of the traffic on this approach will be cleared during phase D.

Phase C is the phase that receives the lowest green times. As with the two movements in phase A that receives green during phase D, the through and right turn movement in phase C can receive green during phase B, which reduces the need for green time in phase C. The green time in phase C will therefore mostly be to clear the traffic on the left-turning movement, as the other movements have, in most times, cleared their queues.

6.4.3 Vehicle delay

Table 6.13 shows the average vehicle delay and total delay for the different approaches during the no priority scenario. From this, it can be observed that the western approach is experiencing the highest average delay per vehicle. However, as the southern approach has a larger vehicle flow, the total delay on this approach is higher than for the western approach. Even though the eastern approach has a large average delay, the low traffic flow yields a low total delay.

Table 6.13: Delay for approaches at intersection 2 without priority

Approach	Average delay (s/veh)	Total delay (veh.h/h)
Haukelandsveien S	40.58	8.40
Haukelandsveien E	52.47	2.48
Haukelandsveien N	34.58	2,78
Ibsens gate	60.58	6.43

6.4.4 Bus delay

The average bus delay is for the no priority scenario is presented in Table 6.14. As with the average vehicle delay, the western approach is experiencing the highest delay. However, the average bus delay is lower than the average vehicle delay for all approaches, i.e., the buses are experiencing less delay than the rest of the vehicles. Also, the approach with the highest traffic flow, which is the southern approach, is experiencing the lowest average bus delay. This can be due to their high green time, and that they have a separate public transport (PT) lane for the through movement. For the delay by Skyss, the southern and western approaches are showing the highest delays. For the northern approach, the delay is close to zero. This can mean that the buses are using almost the same time as expected for the section between the two bus stops, thus waiting the same time at the intersection as expected.

Table 6.14: Average delay for buses at intersection 2 without priority

Approach	Average delay (s/veh)	Delay Skyss (s/veh)
Haukelandsveien S	21.2	31.3
Haukelandsveien N	30.1	2.1
Ibsens gate	76.8	116.0

6.4.5 Number of stops and queue lengths

For the no priority scenario, all approaches at intersection 2 are experiencing a high percentage of vehicle stops. This is shown in Table 6.15. The northern approach, which is the approach with the lowest average vehicle delay, is also the approach with the lowest percentage of vehicles stopped, with 5% fewer stops than the southern approach. On the eastern and western approach, approximately nine out of ten vehicles need to stop, making these two the approaches with the highest percentage of stopping vehicles. This may not seem surprising, especially the western approach, as this approach receives the lowest green times. As for the queue lengths, the southern approach is experiencing the highest queue lengths. This can be justified with the high traffic volume on this approach, which is more than twice the volume of the approach with the second highest volume, the western approach. The southern approach also has several lanes, so it can cater for many vehicles in the queue. In most cycles, the approach is cleared during the green time. As for the western approach, which is experiencing the highest average maximum queue length, the approach can clear the queue in only a few cycles. Thus, some vehicles need to wait for another cycle before they can clear the intersection. Even though the maximum queue length on this approach is lower than the one for the southern approach, the approach is not able to cater for as many vehicles as the southern approach.

Table 6.15: Stops and queue lengths for intersection 2 without priority

Approach	Arriving vehicles	Stopping vehicles	%vehicles stopped	Max queue length
South	18.0	15.2	84.4%	16.2
East	6.6	5.9	89.4%	5.8
North	6.8	5.4	79.4%	5.3
West	9.4	8.7	92.6%	10.0

6.5 Intersection 2 with priority

6.5.1 Traffic volume

For the priority scenario for intersection 2, the overall traffic volume was recorded to be the same as for with no priority. However, the flow on some of the approaches have changed, i.e., some approaches are experiencing a lower flow, while some approaches experience a higher flow. Furthermore, the southern approach is still experiencing the highest flow, which is approximately twice as high as the western approach, which is the approach with the second highest flow. The flow for every vehicle type for every approach is shown in Table 6.16, with the movement distribution in Table 6.17 a) to d). As for the no priority scenario, most buses are travelling between the north and south approach, with a few buses also coming from the western approach, where they are both going to the north and the south. A difference between the two scenarios is that for the priority scenario, the number of cyclists has increased a lot. In the no priority scenario, 50 cyclists were recorded, while the priority scenario included over 130, whereas most of them still arrived on the southern approach, as in the previous scenario. However, both the northern and western approach is experiencing an increase in cyclists too. For the pedestrians, the situation is like the no priority scenario, both related to the total number of pedestrians, and the distribution on the different legs. This is shown in Table 6.17 e).

Table 6.16: Traffic count for intersection 2 with priority

Approach	LV	Bus	HV	Bike	Total
South	690	35	7	121	853
East	167	0	7	0	174
North	247	47	20	10	324
West	341	12	10	5	368
Total	1445	94	44	136	1719

Table 6.17: Traffic count for separate approaches at intersection 2 with priority

a) Traffic count southern approach

Approach	LV	Bus	HV	Bike	Total
Left turn	235	1	1	10	247
Through	299	34	6	71	410
Right turn	156	0	0	40	196
Total	690	35	7	121	853

b) Traffic count eastern approach

Approach	LV	Bus	HV	Bike	Total
Left turn	67	0	2	0	69
Through	72	0	2	0	74
Right turn	28	0	3	0	31
Total	167	0	7	0	174

c) Traffic count northern approach

Approach	LV	Bus	HV	Bike	Total
Left turn	57	0	4	1	62
Through	155	42	8	7	212
Right turn	35	5	8	2	50
Total	247	47	20	10	324

d) Traffic count western approach

Approach	LV	Bus	HV	Bike	Total
Left turn	95	7	8	0	110
Through	167	0	1	5	173
Right turn	79	5	1	0	85
Total	341	12	10	5	368

e) Pedestrian count

Approach	Pedestrians
Southern approach	0
Eastern approach	234
Northern approach	167
Western approach	87

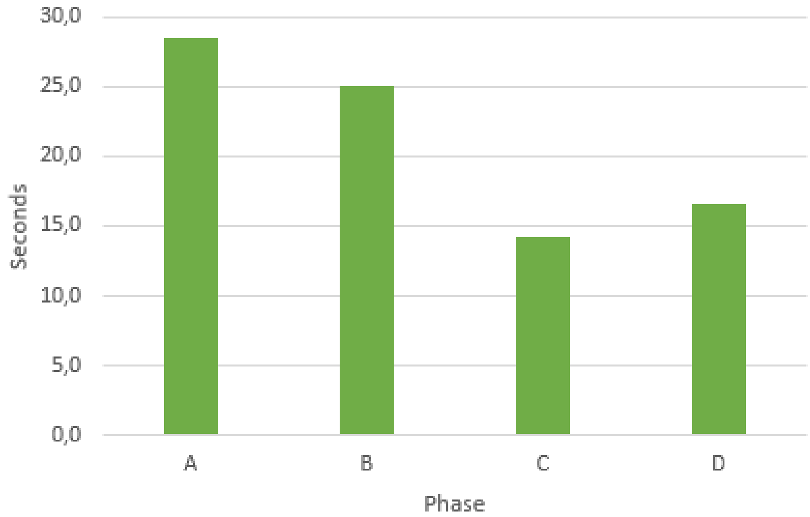


Figure 6.4: Average green time for the different phases at intersection 2 with priority

6.5.2 Signal phases

The green times for the intersection with priority is shown in Figure 6.4. In the priority scenario, phase A is now experiencing more green time than phase B, where it was the opposite in the no priority scenario. This can be explained by the implementation of green extension for the through movements on the southern and northern approach as one of the priority strategies. The priority scheme of reducing the green time to the guaranteed green time when a bus is present on the western approach is in some cases working. However, as more buses are travelling between the southern and northern approach, this priority looks to be triggered more often than the guaranteed green time scheme. However, when there were buses present on the western approach, the green time for the left turn movement was extended, which can be observed by the increase in green time for phase C.

As with the no priority scenario, phase B is still experiencing very high green times, which is the result of the pedestrian movement on the northern approach. during the ten cycles analysed, the pedestrian crossing was used in all cycles, making the green time for this phase the same for all ten cycles.

6.5.3 Vehicle delay

Table 6.18 shows the average vehicle delay and total delay for the different approaches with the priority scheme. For this scenario, all the approaches are experiencing an increase in the average vehicle delay. The eastern and northern approaches are only experiencing a small increase. However, the southern and western approaches have recorded a large increase in delay, with the southern approach increasing by over 55% and the western approach over 40%. As these two approaches are the ones with the highest flows, the total delay is also increasing a lot on these approaches, while the increase for the eastern and northern approaches are not as large.

Table 6.18: Delay for approaches at intersection 2 with priority

Approach	Average delay (s/veh)	Total delay (veh.h/h)
Haukelandsveien S	64.06	13.03
Haukelandsveien E	53.87	2.68
Haukelandsveien N	36.61	3.21
Ibsens gate	85.92	8.66

6.5.4 Bus delay

The average bus delay for each approach is shown in Table 6.19. As with the vehicle delay, the delay for buses has also increased on the southern and western approach. For both approaches, this increase has been very large. For instance, on the western approach, the buses are now experiencing on average several minutes of delay. The increase in delay can be a result of unlucky arrival times when it comes to green times and initial queue. However, this large increase is nonetheless an interesting observation. The northern approach, on the other hand, is experiencing a decrease in the bus delay with the priority scheme. The delay from Skyss is showing a much larger value for both the southern and western approaches. This can indicate that there may be some queue stretching further back than the test sections that were used to calculate the delay, which is reasonable as there were large queues during the recording. However, the northern approach is still showing a low bus delay. This can imply that this approach has been operating close to normal conditions, in contrast to the two other approaches.

Table 6.19: Average delay for buses at intersection 2 with priority

Approach	Average delay (s/veh)	Delay Skyss (s/veh)
Haukelandsveien S	43.1	119.9
Haukelandsveien N	21.6	3.7
Ibsens gate	168.3	204.7

6.5.5 Number of stops and queue lengths

Table 6.20 shows the percentage of vehicles stopping and the average maximum queue length for intersection with priority. After the implementation of the priority, one can observe that the percentage of vehicles stopped is decreasing from the no priority scenario on all approaches except for the southern approach, where it is approximately the same. The western approach is showing the largest decrease. This can come from the vehicles taking advantage of the extended green time the buses on this approach receive, which can be observed by the increase in green times. However, as for the maximum queues, all approaches are experiencing an increase in the average maximum queue. The southern and the western approach is experiencing the highest increases in maximum queue lengths, both over 40%. As

Table 6.20: Stops and queue lengths for intersection 2 with priority

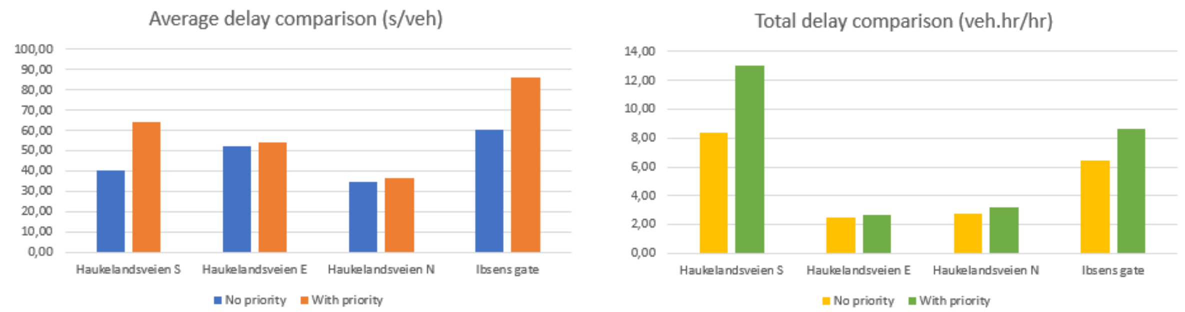
Approach	Arriving vehicles	Stopping vehicles	%vehicles stopped	Max queue length
South	22.6	19.1	84.5%	23.7
East	6.4	5.6	87.5%	6.1
North	8.3	6.3	75.9%	6.2
West	13.3	11.2	84.2%	14.2

the green times of other phases are increasing, there is more time for the queue to build up on the other approaches that are having red signals.

6.6 Discussion on results from field study

6.6.1 Delay

When looking at both the intersections after doing the field study, it can be observed that the average delay for vehicles is increasing on all approaches at both intersections. Some approaches are showing only a small increase, but some others are showing a large increase. The larger increases are mostly occurring at intersection 2, with the southern and western approach being the two most critical, which is shown in Figure 6.5. The two other approaches at intersection 2, the eastern and southern approach, are only showing small increases. Still, these are increases and not reductions. The eastern approach does not have any buses on its approach. Therefore, an increase in delay can be understandable when prioritizing the other approaches without giving benefits to this approach. The northern approach is receiving some priority, as with the southern approach by having a green extension for the buses. This has seemed to be helping the buses as the bus delay have been reduced by almost nine seconds on this approach. When the buses have not been present, there seems to be not too many disbenefits for this approach as, even though there is a slight increase in average vehicle delay, this increase is not very large, only increasing by approximately two seconds.



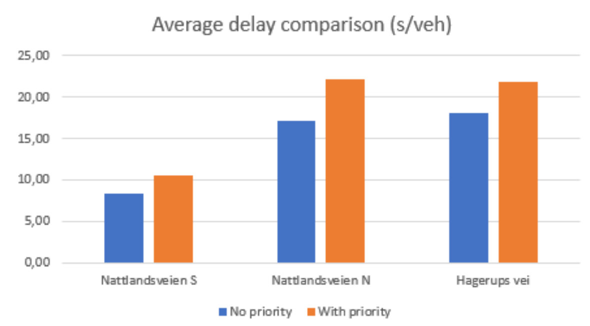
a) Average delay

b) Total delay

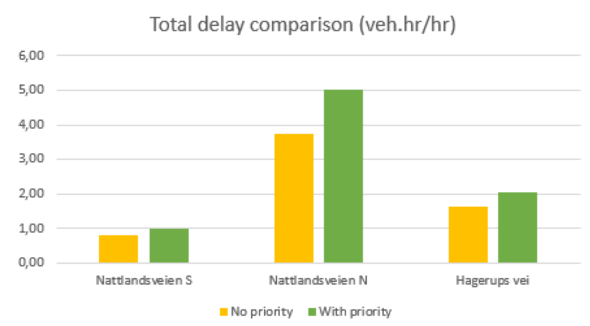
Figure 6.5: Delay comparison for intersection 2

The southern approach did only have an average vehicle delay a bit higher than the northern approach when the bus priority was not included. However, when the bus priority was implemented, the delay increased by over 50%, and the bus delay more than doubled from 21 to 43 seconds. This increase is mostly caused by the mid part of the recordings, where the delay at several ten-minute intervals exceeded one minute, one interval even over two minutes. During this period, the downstream on the northern approach was experiencing queues extending into the intersection. This occurrence also happened during the no priority scenario, but not for the same duration as during the priority scenario. This could have been the result of the construction work going on at the northern side of the tunnel on this exit. This downstream queue did prevent some vehicles on the southern approach to drive even during their green phase, thus increasing the delay when they should have cleared the intersection. Looking at this approach before and after this occurrence, the average vehicle delay was closer to the level of the situation without priority.

The western approach may also have been affected by this downstream queue during the priority phase. The left turn on this approach did on some occasions have to stop entering the intersection as the queue on the northern exit was stretching out into the road, and not clearing before the green time for the left turn was done. However, this approach is also experiencing a very low green time, both with and without the priority. On top of this, with the approach having only one lane dividing into four lanes very close to the intersection, the probability of queues building upstream along this one lane is high with the traffic volume counted for this approach. As mentioned, the left-turn on this approach is sometimes conflicting with the downstream queue on the northern exit, thus making vehicles having to wait on the approach for longer than usual. This can create longer queues on this approach that extends into the one approaching lane further upstream, which furthermore will block the other lanes for the through and right-turn movements. On top of this, as the through and right turn movements get a green signal before the left-turn movement, if these movements are blocked, their green time may become redundant. If there are vehicles in the through and right turning lanes, them getting green before the left turn can be okay to clear the lanes for the vehicles arriving further upstream. However, being able to clear all the queue at once could be a more prominent solution.



a) Average delay



b) Total delay

Figure 6.6: Delay comparison for intersection 1

As for intersection 1, even though the increase with the bus priority is not as high as for intersection 2, all approaches are experiencing an increase, thus showing worse results. However, being a small three-legged intersection in an urban area as this intersection, with not much space available and the recorded traffic volume, one can argue that the results related to delay is still not very high. Being able to decrease the delay when the delay is already very low can be a difficult job. But even though the delays are very low, the total delay for the northern approach is a lot higher than the total delay for the other two approaches. With the priority, during the hour of the recordings, the approach spent over five hours more time than it would have done under free flow conditions, and 3.74 hours for the scenario without the priority. As these numbers are a lot higher than for the other approaches, these numbers can be a target to decrease to optimize the intersection.

Looking at the overall effectiveness of the bus priority system, the priority does not seem to benefit the rest of the system properly but rather increases the disbenefits of the other vehicles. As mentioned by McLeod and Hounsell (2003), giving priority to buses may harm the rest of the system, which can be observed in both of these intersections. What is also interesting about this priority system is that the delay for only the buses itself are not improving, but rather gets worse for all approaches except the northern approach at intersection 2. The reason for the increase in bus delay at the intersection can also be a result of the buses arriving either exactly during their green phase without the priority, or just too late for the situation with priority, so they have had to wait during the other movements. When looking at the bus delays for intersection 1, which is presented in Figure 6.7, especially the southern approach shows a very low delay for the no priority scenario. For this approach, most of the buses did not need to stop or merely had to slow down in front of the stop line, without needing to stop. In the no priority scenario, a couple more buses had to stop and wait for a few seconds, thus quickly increasing the average delay, yet only to seven seconds.

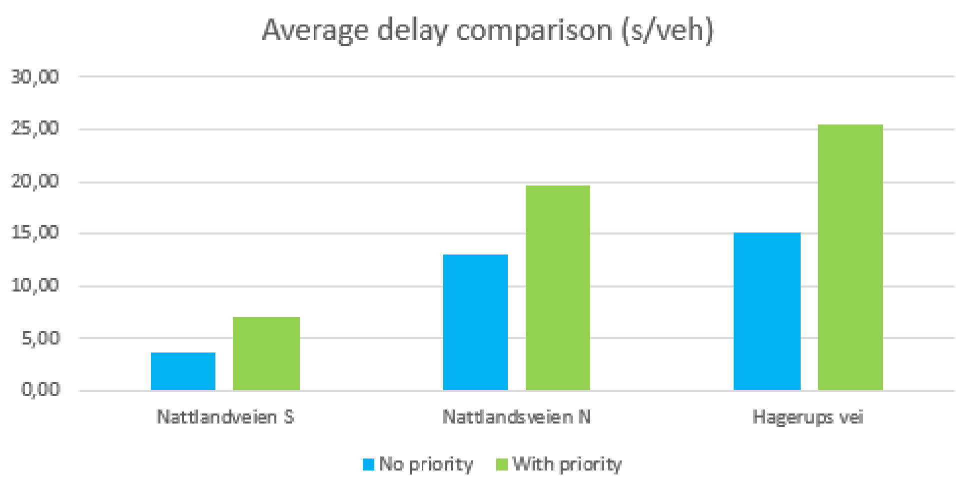


Figure 6.7: Average bus delay comparison for intersection 1

For the northern approach, not many buses were able to drive through the intersection without stopping or slowing down, both with and without the priority. During the no priority scenario, some buses only had to reduce the speed, thus experiencing a delay between two to eight seconds. For the priority scenario, the number of buses that could do this was lower. This can be a reason for the increase of vehicles on this approach during the priority scenario compared to the no priority scenario. There was counted approximately 30 vehicles more in the no priority scenario. Here, the flow was also more evenly spread out during the hour of the recording, i.e., less deviation in the flow. This could mean that the buses are experiencing other vehicles around themselves more often, thus having to adapt to their behaviour. The shock waves created from the other vehicles in front may also impact the buses further back, increasing the delay. Another important factor with the northern approach is the width of the lanes. Close to the intersection, the two lanes are not very wide, not wide enough for buses to pass smaller vehicles. Therefore, if one of the movements on this approach have a green signal, while the other has a red signal, some vehicles may make the path inaccessible for the buses, making them wait until the vehicles in front have entered the intersection.

As with the northern approach, most buses had to stop or slow down on the western approach before entering the intersection. The waiting times for these buses were even longer during the priority scenario. This can be a reason for the extended green time caused by the presence of buses on the southern and northern approach, or the increase of vehicles on these approaches, making their green times last longer. There is also a small increase in vehicles on this approach. However, this is a very small increase, so the traffic volume on the other approaches may affect the bus delay more than the volume on the same approach as the buses on the western approach.

The trend that is observed from the field studies also looks to be the same as the delay data provided from Skyss. The delay comparison from these data is presented in Figure 6.8. All the approaches are showing an increase in delay, with the western approach being the approach with the highest delay. As this delay method is using the difference between real travel time and expected travel time and not free flow travel time, an approach like the northern approach is experiencing a smaller delay than the southern approach. On the route the buses on the southern approach are using, there may be that there are factors like pedestrian crossings affecting the travel time, making the buses having to slow down or stop more often than expected. There may also be an increase in dwelling time at the last bus stop on the section of the Skyss delay calculation. A longer dwelling time than usual will lead to more time spent, thus an increase in delay. For the northern approach, it seems that the real travel time is very close to the expected travel time for the no priority scenario, due to the low delay. However, for the priority scenario, there is also an increase in delay for this approach. As mentioned above, this can be a result of the increase in traffic, in combination with vehicles being blocked by other vehicles on the narrow approaching lanes. For the western approach, the delay is very similar to the delay from the field studies,

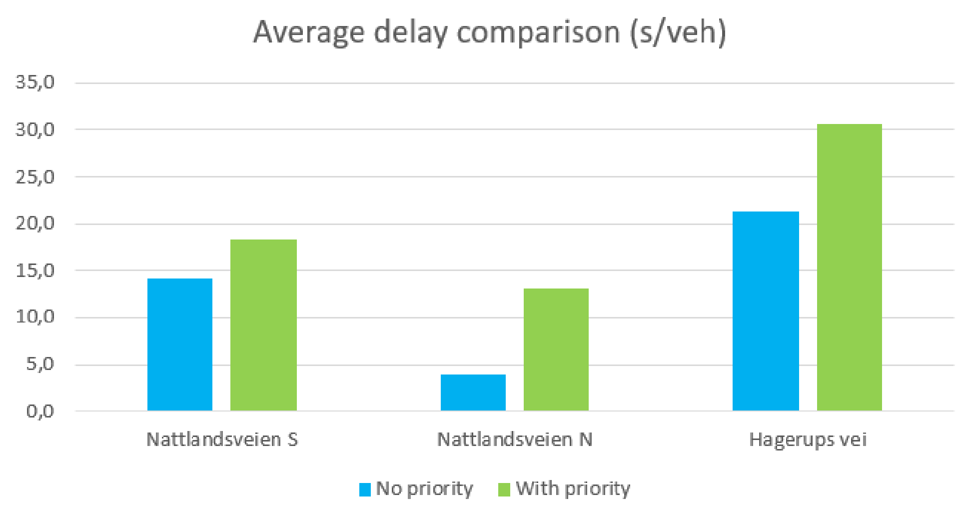


Figure 6.8: Average bus delay comparison for intersection 1 with data from Skyss

only here with a small increase for both scenarios. This can come from an unexpected waiting time in an intersection before the approach lane, e.g., giving way for other vehicles or pedestrians, or an increase in dwelling time at the bus stop.

As mentioned above, the northern approach at intersection 2 is the only approach that experiences a decrease in average bus delay. For this approach, several buses were able to only experience a small delay, i.e., from one to ten seconds, during the priority scenario, whilst for the no priority scenario, several buses had to wait for a long time, some over a minute before entering the intersection. For this approach, the bus priority was being triggered when the bus door closed while being at the bus stop at the approach. As some buses were able to enter the intersection in a short time after exiting the bus stop, the extended green time for the phase seemed to prove useful for this approach. For the buses that had to wait a long time, these may have triggered the priority just too late, or at the end of the phase. Therefore, as this priority does not shorten the green time on the other phases, the buses on this approach

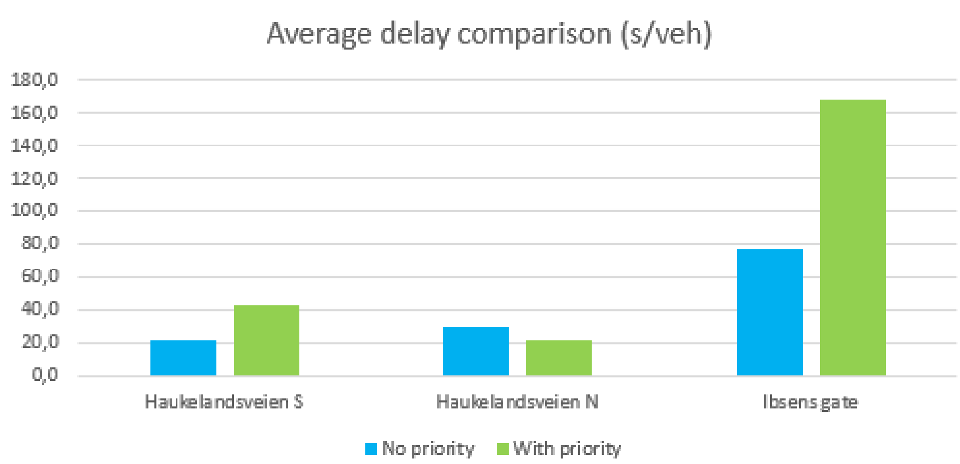


Figure 6.9: Average bus delay comparison for intersection 2

had to wait for a whole cycle, which could be extended if the other approaches were having higher traffic volumes than usual.

One would also think that the same benefits the northern approach received would also be applicable for the southern approach as these have green signal in the same phase and have the same priority system, the green time extension. This seems to be the case for parts of the count. However, as mentioned, due to the downstream queue on the northern approach, some buses were not able to cross the stop line and enter the intersection as the bus stop on the northern approach was already full and could not be cleared in time, thus making the buses on the southern approach wait longer than planned. This can be observed by some buses experiencing a delay between one and a half and two and a half minutes, even though the green time was extended to cater for them. If some of these were excluded from the average delay calculations, the bus delay would be reduced significantly. However, this downstream queue also occurred during the no priority scenario, but this time not causing too extreme results as for the priority scenario.

The downstream queue on the northern approach seems to also affect the buses on the western approach. As well as the vehicles being affected by this, also causing distractions to the other movements on this approach due to the late separation of the lanes, the buses also seems to be heavily affected by the blockage on the northern approach. Where light vehicles can be a bit more flexible with manoeuvring and access small gaps, a small disruption in the flow or a couple of vehicles more than expected may block the buses totally, making it impossible for them to enter the intersection, and therefore having to wait up to several cycles to enter the intersection. Furthermore, the priority for this approach was to shorten the green time for the phases and extend the green time for this movement. On several occasions, the green time was extended so that the buses were able to advance in the queue. However, on some bus arrivals, this green extension was not triggered, making the bus operate under no priority conditions, meaning a very short green time. Even though the green time during the other phases was still shortened, the buses still experienced a lot higher delays than if the green time would have been extended every time.

For the Skyss delay, which is presented in Figure 6.10, the trend is also close to the field study results for this intersection. However, here the results are a bit more extreme. For instance, both the southern and western approach is experiencing an increase in delay in the priority scenario which is way higher than the results from the field study, while as for the northern approach, the delay is very close to zero for both scenarios. The large increase in delay for the two approaches can indicate that there might have been queues or a lot of traffic stretching further away from the intersection than what has been included in the delay calculations during the field study. If the buses are experiencing queues and extended waiting times outside the test sections used for the delay calculations, this would not be included in the

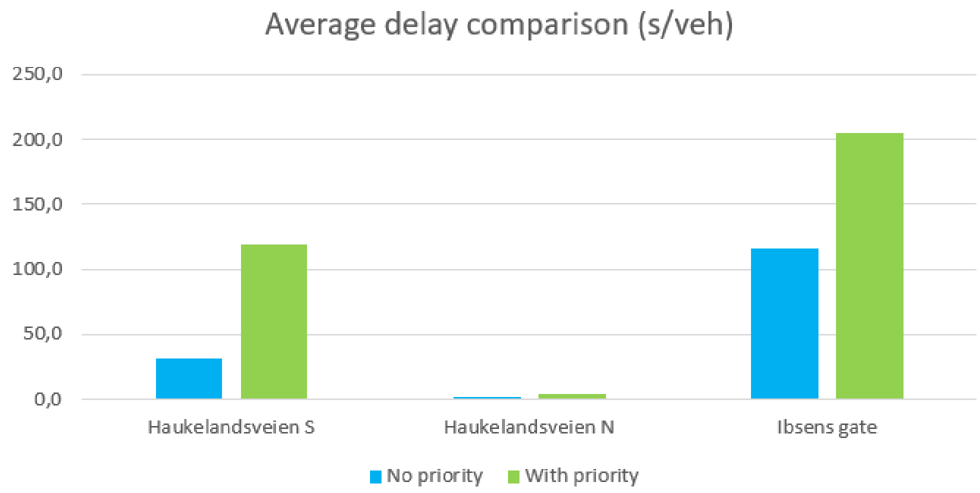


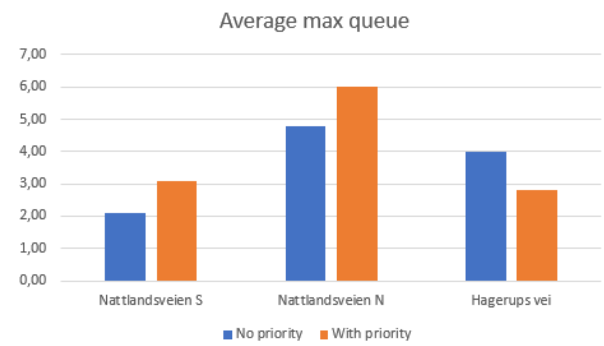
Figure 6.10: Average bus delay comparison for intersection 2 with data from Skyss

field study results, though be in the data from Skyss. This can also raise the question of whether the average vehicle delay and the total delay should be higher than what it is calculated to be with the method used. An increase in delay, both average and total, with the priority scheme implemented, can furthermore argue that the bus priority is not working as good as it is hoped to be. On the other hand, the downstream queue on the northern approach, as well as the construction work on the northern side of the tunnel need to be considered when answering that question. It could therefore be of interest to study the area both when the construction work is finished, but also outside of peak hours, where the traffic may not be that big, thus maybe avoiding these downstream queuing problems.

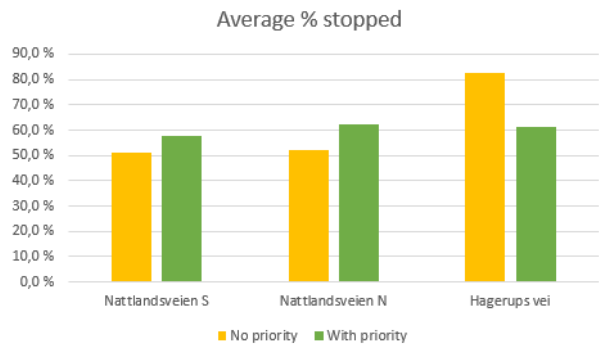
6.6.2 Stops and queues

Looking at the percentage of stopping vehicles at intersection 1, one can observe that with the priority activated, more vehicles are stopping on the southern and northern approach than without the priority, whilst for the western approach there is a decrease in the percentage of stopping vehicles. This can be seen in Figure 6.11. As mentioned in chapter 6.3.5, the scenario with the priority had an increase in traffic on the northern approach which could lead to more vehicles being packed, thus having a lower vehicle percentage being able to pass through the intersection during the green time. This is reflected in the average maximum queue length, also presented in Figure 6.11.

The average maximum queue also increases for the northern approach. These results can be a result of the extended green time the western approach is experiencing with its bus priority, as well as the traffic increase. The same can be the case for the southern approach, where the results are like the northern approach for both maximum queue and percentage of vehicles stopped.



a) Average maximum queue



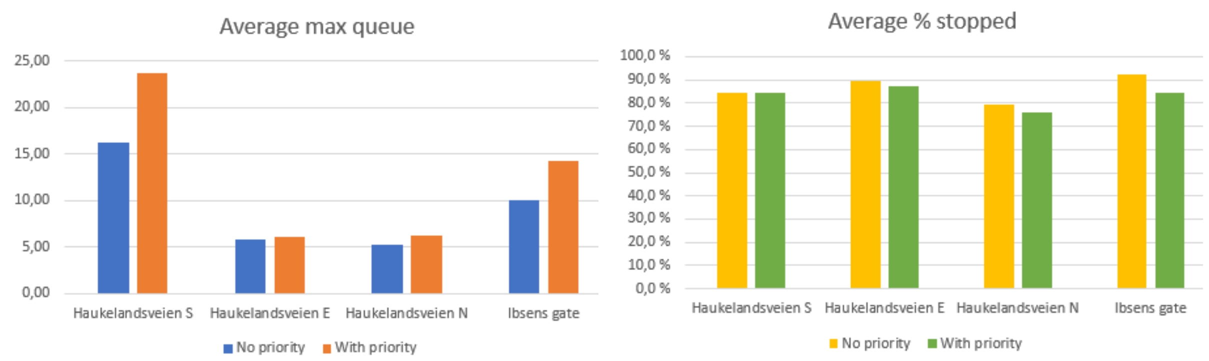
b) Average percentage stopped

Figure 6.11: Queues and stops comparison at intersection 1

The decrease in both queue length and stopped vehicles on the western approach can be a result of the priority making the vehicles able to utilise the green extension for the buses. However, one would think that as the southern and northern approaches also receives priority as a green extension, the waiting time for the western approach would be longer, thus increasing the probability for vehicles needing to stop and create longer queues. However, during the recordings, there were no increase in stopped vehicles, nor queue lengths. This can be a coincidence of vehicles arriving in time to not having to stop more often during the no priority scenario than during the priority scenario. On the other hand, this approach could also benefit with extended green time not only for buses arriving on this approach but also for right-turning buses on the northern approach, as these have both green signal in phase B. Therefore, the priority would have been triggered more than only the eleven times a bus arrived on this approach.

Looking at intersection 2, all approaches are increasing their queues. However, the eastern and northern approach only increase a small percentage, 5.2% and 17.0%, respectively. The increase on the eastern approach is not unlikely since it does not have any bus priorities benefitting it, and an increase in green time on other approaches will therefore lead to more waiting time. However, as the western approach priority triggers a green time reduction, this further shortens the waiting time for the eastern approach, thus equalizing the increase in waiting time due to the extended green times for the other phases. Furthermore, the eastern approach is experiencing a decrease in the percentage of vehicles stopping with the priority. The reduction is not very large, but it is a reduction. This can be a result of the increase in green times for the movements. In the priority scenario, the pedestrian crossing on the northern approach was more often triggered than without the priority, extending the green time for the through and right turn movement.

The other approach that has a small increase in the maximum queue is the northern approach. This approach also shows a reduction in vehicles stopping. The increase in the queue can be a result of the increase in green times for both phase B and phase C. B due to the pedestrian crossing, and C for the bus priority on the western approach. During the green time, i.e., during phase A, the bus priority gives



a) Average maximum queue

b) Average percentage stopped

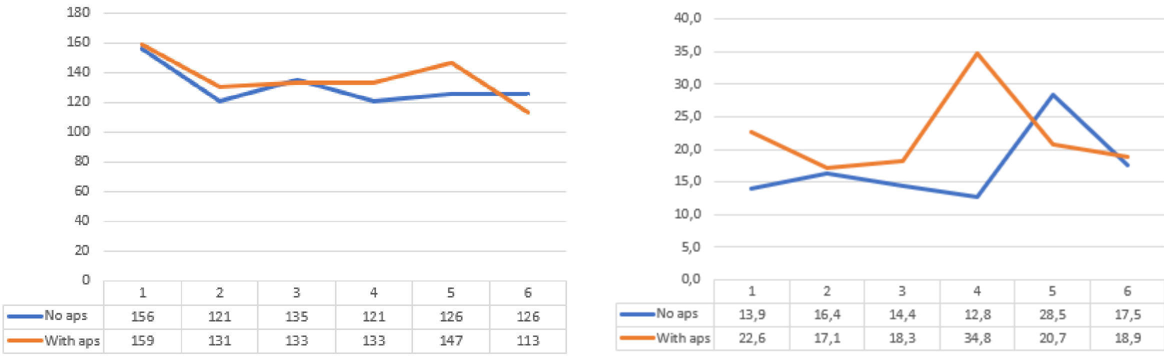
Figure 6.12: Queues and stops comparison at intersection 2

this approach an extension in green time, which gives the vehicles arriving during the phase free access to enter the intersection without stopping. This approach is also not experiencing as much traffic as some of the other approaches, and with three lanes, the approach can clear most of the vehicles during the green time, especially the through and right moving vehicles. The traffic volume not being so high may also be a reason for just the small increase in the maximum queue. It may also explain why the average maximum queue on this approach also is very low.

The two approaches with the highest delays, both for buses and for all vehicles, the southern and western approach, are also experiencing the highest increase in the maximum queue with 46.3% and 42%, respectively. The maximum queue for both approaches can be caused by the blockage from the downstream queue on the northern exit. For the southern approach, not all vehicles were able to clear the approach section, thus there was in several cases already an initial queue. The western approach was also not able to clear the section during its green time. On the other hand, the western approach is the approach at the intersection that is showing the largest decrease of vehicles stopping. This can be explained by the extended green time from the bus priority. Once the green time is being extended and the vehicles can enter the intersection, this will also clear the path for the through and right-turning vehicles making them not having to stop but have time to get through the intersection during the green time.

6.6.3 Traffic conditions

As mentioned in chapter 6.6.1 and 6.6.2, the increase in traffic may have impacted some increase in the delay, the number of stops, and queue lengths. Intersection 1 is the intersection where there is an increase in the number of vehicles from the no priority scenario to the priority scenario. Intersection 2 has approximately the same number of vehicles in both situations. The increase of traffic will create situations where the saturation is higher, especially if many vehicles are arriving during a short period. The northern approach is the approach that is experiencing the highest increase in traffic volume. Figure 6.13 a) shows the flows for each ten-minute interval during the recordings. The traffic volume shows,



a) Traffic flow b) Average delay

Figure 6.13: Data comparison for northern approach at intersection 1

at most times, a higher value for the priority scenario, denoted with aps. However, for the interval with the highest deviation, i.e., the fifth interval, the delay is higher for the no priority scenario, which can be observed in Figure 6.13 b). This can be explained by the traffic being able to finally clear after a period with more queueing, which have led to the large deviation in delay in the fourth interval, where the priority scenario experienced a delay almost three times as high as the no priority scenario. Therefore, when all the vehicles experiencing this delay cleared, this may have led to a large flow during the next interval, thus creating a larger deviation in traffic flow.

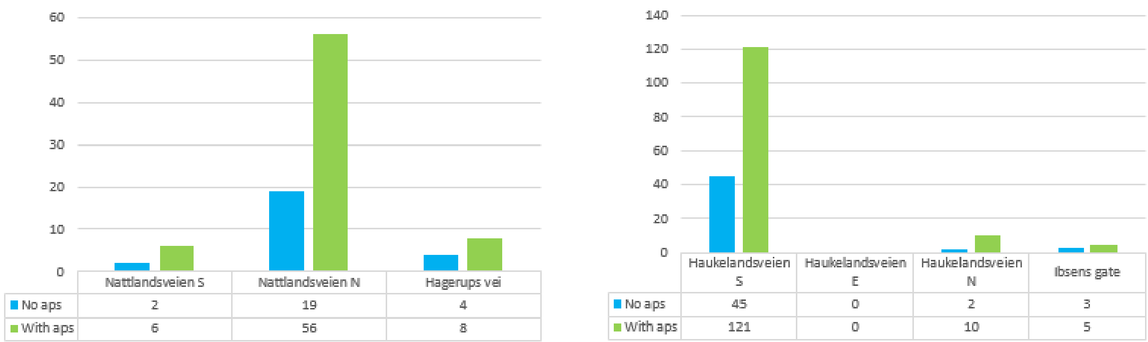
Another approach that is experiencing a large increase in delay is the southern approach at intersection 2. However, this approach is having a reduction in traffic volume in the priority scenario compared to the no priority scenario. It is already mentioned the impacts from the downstream queue on the northern approach. The effects this happening had on the southern approach can be seen in Figure 6.14 b), where it is heavily impacting the southern approach over three intervals in the priority scenario, and only during one in the no priority scenario. Once this downstream queue was cleared, the flow increased significantly in the priority scenario, also decreasing the delay a lot. Nevertheless, if one were to look at the delay on the approach without including the intervals where the downstream queue affects the delay, the no priority scenario would still show better results. Therefore, one can argue that despite this downstream queue, it does not look like the bus priority is helping the overall traffic on the southern approach.

a) Traffic flow b) Average delay

Figure 6.14: Data comparison for southern approach at intersection 2

Choosing to do the observations during the peak hours, in the morning for intersection 2, and in the afternoon for intersection 1, also means that different situations with large traffic volumes can occur. Also, as the peak hours are the times during the day where the intersections are usually experiencing the highest degree of saturation, it is not unlikely that there are high values on the various performance measures. Once the degree of saturation is increasing, the delay can also increase rapidly, which is the case for intersection 2. If the observations were being done outside peak hours, it would be reasonable to assume the delay would be lower, both the average and the total delay as the approaches would be able to clear all the queue, and the fact that the traffic volume would be lower. The latter would give a lower total delay. Nevertheless, during peak hour, the buses are usually having a higher frequency, thus arriving more often. Therefore, it is easier to study the buses during peak hours. If also the approaches can cater for a larger volume of vehicles, the total delay can be reduced a lot during the peak hours. The peak hours are therefore interesting to study as the benefits of improving the traffic conditions at this time of the day is greater than for a non-peak period.

Another factor that can have had a role to play in the negative results for the priority scenario is the increase of cyclists during the priority scenario. Figure 6.15 shows the comparison of the number of cyclists at both intersections. Some approaches at both intersections experience large increases in the number of cyclists. The northern approach at intersection 1 and the southern approach at intersection 2 are having the most cyclists, but some other approaches are also experiencing a large relative increase. Even though some of the approaches are equipped with bike lanes, the places where the cyclists are interfering with the rest of the traffic, the speed of the vehicles can be reduced as the cyclists may not travel at the same speed. For instance, a cyclist in front of a queue may reduce the speed of the vehicles behind, making the travel speed lower than during free flow conditions, thus increasing the delay. On the other hand, even though some approaches have a high relative increase, for instance, the northern approach at intersection 2, the approaches should be able to cater for that small number of cyclists during one hour without increasing the delay and queues too much. The approaches that do have bike lanes should especially be able to cater for the counted numbers of cyclists.



a) Intersection 1 b) Intersection 2

Figure 6.15: Cyclists comparison for intersection 1 and 2

6.6.4 Weather conditions

Due to the outbreaks of Covid-19 between the two observations, the priority scenario had to be postponed for two weeks, meaning the two observations got a larger gap between each other than what was ideal. To get the best results possible, ideally, the two scenarios would have had, as well as the traffic conditions, also the same weather conditions. Even though all recordings were undertaken in February 2021, the weather in a city like Bergen can change rapidly from week to week. During the no priority scenario, both recordings were influenced by cold temperatures and snowy weather. The cold temperatures and snow on the ground could lead to fewer cyclists, people driving more careful and taking more precautions compared to travelling on dryer roads and during warmer days. For the priority scenario, the cold temperatures were replaced by warmer temperatures, above the freezing level. There was no snow at either intersection. The conditions for the second observations were therefore more inviting for faster driving and the presence of cyclists and pedestrians. The change in the weather conditions can therefore explain the increase of cyclists presented in Figure 6.15. As explained above, the increase of cyclists may have affected the performance measures results. However, when these were not present and the vehicles could drive under normal conditions, one would assume that these conditions allowed for more aggressive driving, e.g., faster speed and a smaller gap between vehicles. This looked not to be the case, considering the negative results from the priority scenario.

7 Modelling improvements in Aimsun Next

7.1 Introduction to Aimsun

To answer the third objective presented in chapter 1.2, which is to look at alternative solutions to make the system better than the existing conditions, one can use different types of traffic simulation software. These are useful to look at potential/alternative situations and changes in a model instead of using a lot of extra resources to implement in a real-life scenario before knowing the benefits or disbenefits. By making a simulation using simulation software, one can create a close to real-life scenario based on observations and calibration parameters. The simulation will therefore be able to tell whether a suggestion of improvement is worth pursuing or if it has a less positive effect.

One common traffic simulation software is Aimsun Next. This is a traffic simulation tool created by Aimsun which is used to develop and model transportation networks of all sizes. This includes different types of intersections, road users, vehicles, and trip purposes (Aimsun, n.d.-a). The software is well known worldwide and is being used to model traffic in a large number of big cities (Aimsun, n.d.-b).

Some of the most used applications of Aimsun Next are to model TSP, impact analyses of infrastructure constructions or improvement, toll and road pricing, traffic safety analysis, traffic signal control plans, and much more (Aimsun, n.d.-a).

Due to the range of opportunities of Aimsun Next, this software will be used to answer the third objective in chapter 1.2. To answer the objective, a model of each intersection will be made. This includes inserting all the relevant input gathered from the field study and other sources. After the model is built, it needs to be calibrated to verify that it is good to use, i.e., it is as close to representing a real-life scenario as possible. Once this is done, alternative solutions to improve the efficiency of the intersections can be done. The rest of this chapter presents the steps for creating the model and how the output results can be shown, as well as the steps for calibrating the model before the improvements are implemented at the end of the chapter.

7.2 Build up

7.2.1 Road geometry

When creating a signalized intersection in Aimsun Next, the intersection is being created by having several sections connected via nodes. The sections represent the different approaches to the intersection and can be set with a random number of lanes and purposes. The lanes can be set as full-length lanes or short lanes. When having a two-way road, there need to be two sections going in opposite directions. An example of a two-way road in Aimsun is shown in Figure 7.1.

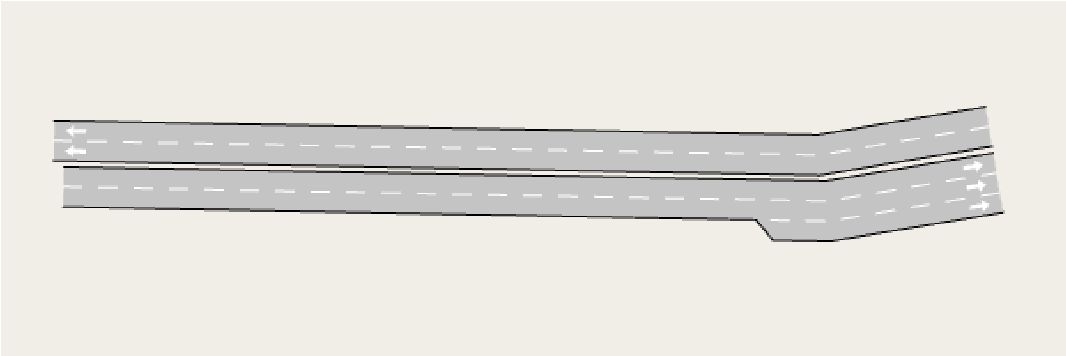


Figure 7.1: Example of a two-way road section in Aimsun

The road sections and lane in the sections can be set as having different purposes. For instance, there can be public transport lanes, bike lanes or tram lines. A road section can also be set to have different speed limits, road shoulders, capacity, and other parameters that are relevant for the section.

To connect several sections into an intersection, the node tool is being used. This allows connecting the sections by different movements. When defining the movements at a node, these can also be assigned to a signal group which will be used when implementing a signal control system. For the intersection, which has been created with the node tool, pedestrian crossings can be added with the pedestrian crossing tool. Figure 7.2 shows intersection 1 where the sections have been put together at the intersection, including pedestrian crossing on the northern and western approach.

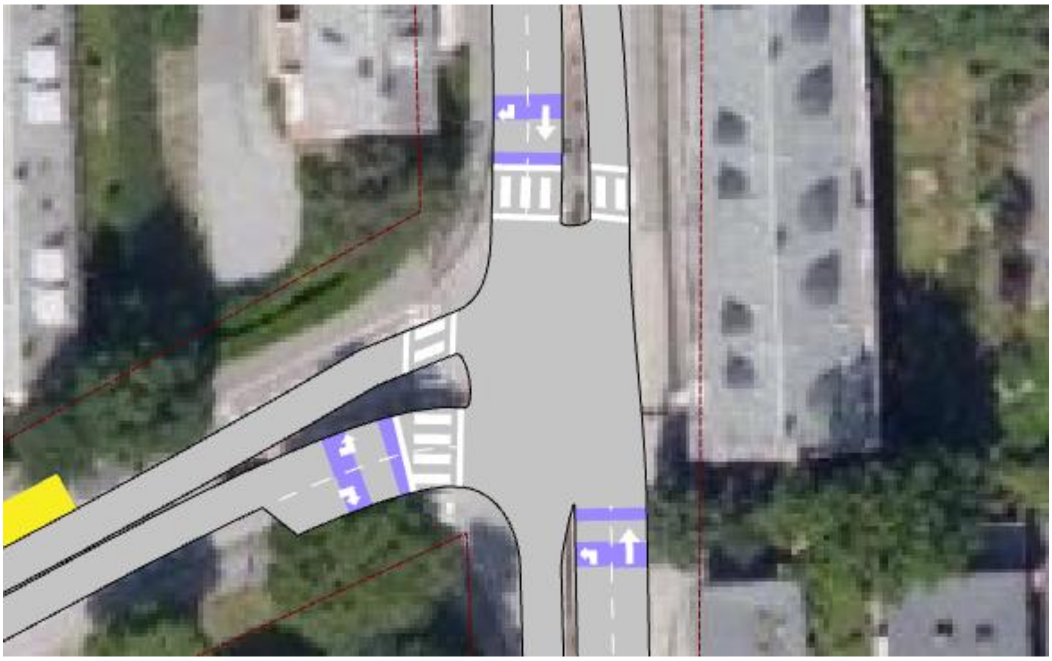


Figure 7.2: Intersection 1 in Aimsun with pedestrian crossings

7.2.2 *Pedestrian modelling*

To model the pedestrians that are present at the intersection and the areas around, the Aimsun Pedestrian tools are being used. This involves creating a pedestrian area in which the pedestrian can move freely

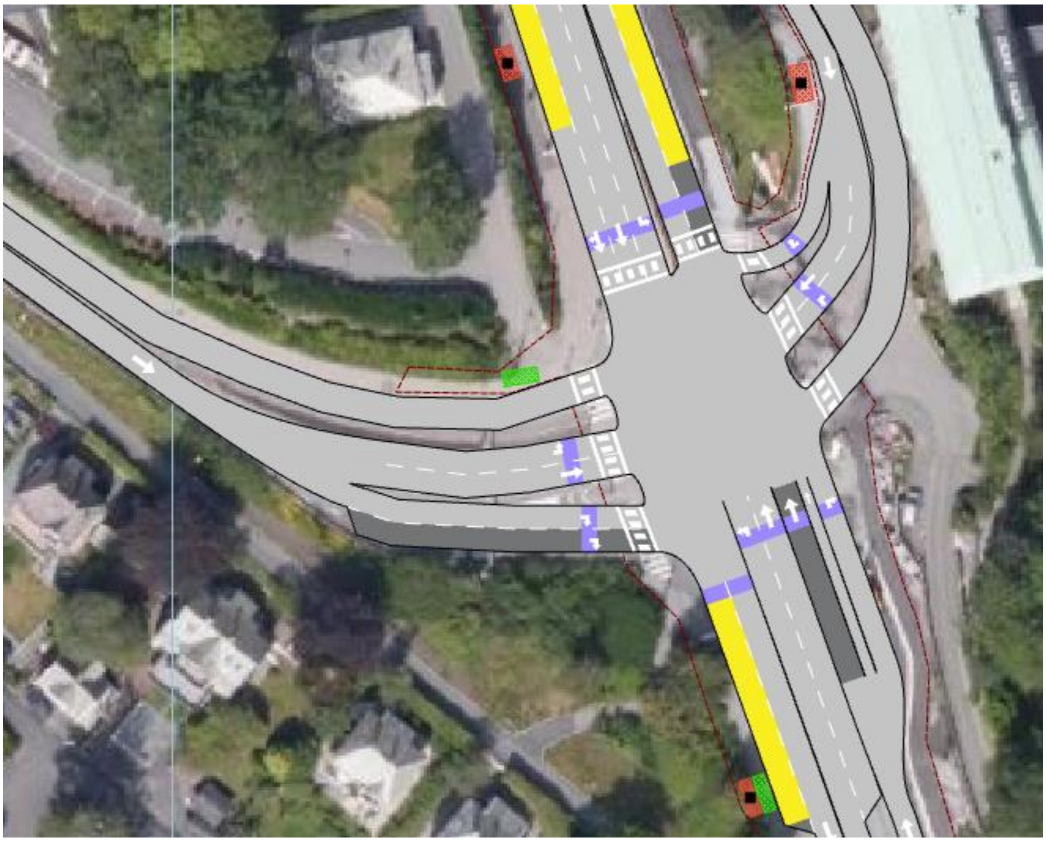


Figure 7.3: Illustration of a pedestrian area at intersection 2 with pedestrian entrances and exits in Aimsun

from their starting point to their end point. These starting points and end points are called “pedestrian entrances” and “pedestrian exits”, respectively. Figure 7.3 shows intersection 2 with the pedestrian area as a red dotted line surrounding the roads and the intersection. The pedestrian entrances are represented by green boxes and pedestrian exits by red boxes.

7.2.3 Traffic control plan

When implementing traffic signals to an intersection, a control plan and a master control plan needs to be made. After creating the control plan, the intersection can be given the different signal timings and settings, as required by using the signal groups for the movements, explained in chapter 7.2.1. If the traffic signals are actuated, which both traffic signals in this thesis are, the “actuated” setting must be chosen. Other types are fixed, external, uncontrolled, and unspecified. Furthermore, the signal phases and their parameters must be set. For implementing bus priority, the priority tab is activated and the public transport routes that will be implemented is being added and allocated to their phases. Detectors on the approaches and/or exits will be used to determine when priorities start and end.

After creating a control plan for the intersection, this control plan is then put in a master control plan, which is being used for simulating at a later stage. The master control plan can also be used to cater for several control plans at several intersections.

7.2.4 Simulation

After all the inputs are made and the model is ready for simulation, a dynamic scenario is added. For a dynamic scenario, it is possible to add traffic states, master control plans, and public transport plans. The time of the day and duration of the simulation is also chosen. When a dynamic scenario is made, one can choose to have either a microscopic simulation, macroscopic simulation, meso/micro hybrid simulator, or macro/meso hybrid simulator as the network loading, and either a stochastic route choice or a dynamic user equilibrium as the assignment approach. In this project, a microscopic network loading with a stochastic route choice is being used.

7.3 Input parameters

When creating the models of the intersections, both intersections are being run with two simulations each. The first simulation is without the bus priority, and the second is with the priority. The input parameters will therefore be a bit different in some places for these two situations. The input parameters that will be explained below are collected from both the field studies, as well as from other collected data.

7.3.1 Flow

The traffic demand that will be used for the simulations is put into the model by using origin/destination (OD) matrices. The reason for using OD matrices instead of traffic states to represent the traffic demand is the opportunity to include pedestrians in the models. The OD matrices are therefore used to explain the starting point and end point for each vehicle and cyclist. The origins and destinations are represented by centroids placed at the end of each approach. The centroids are then being connected to the sections to and from the intersection. The names of the centroids for intersection 1 and intersection 2 are presented in Table 7.1. The OD matrices are made up of the traffic counts that have been done during the field studies and that is presented in chapter 6. However, in the OD matrices for the buses, only the buses that are not part of the public transport system presented in chapter 7.3.2 is included. The buses

Table 7.1: Description of centroids at intersection 1 and intersection 2

Intersection	**Centroid**	**Description**
Intersection 1	South approach	At the end of the southern sections
	North approach	At the end of the northern sections
	West approach	At the end of the western sections
Intersection 2	South approach	At the end of the southern sections
	East approach	At the end of the eastern sections
	North approach	At the end of the northern sections
	West approach	At the end of the western sections

in the public transport system will be included in the simulations. Therefore, if these were to be included in the OD matrices, the number of buses would be too high.

Due to the different vehicle types, there will be made OD matrices specifically for each vehicle type. In the simulations, there will be five different vehicle types. These are light vehicles[11], trucks[12], bicycles, buses, and pedestrians[13]. Attachment A shows the OD matrices for each vehicle type.

The pedestrians are not using the centroids presented in Table 7.1. These must use the pedestrian entrances and pedestrian exits as described in chapter 7.2.2. The pedestrian entrances and exits for intersection 1 and intersection 2 are presented in Table 7.2.

To cater for vehicles using different routes to get from their origin centroid to their destination centroid, some OD routes have been implemented at intersection 2. The purpose of these OD routes are to direct the different vehicle types to the parts of the sections where they are supposed to be, e.g., a bus should try to be in the public transport lane and not use other lanes instead. There is also an OD route for cyclists to keep the bicycles in the cycle lane on the southern approach at the intersection. There are also two OD routes for cyclists travelling south from the western and northern approaches. These routes are for making the cyclists use the bike lane south of the bus stop on the southern exit. Table 7.3 shows the OD routes used at intersection 2. For intersection 1, no OD routes have been implemented.

Table 7.2: Location of pedestrian entrances and exits at intersection 1 and intersection 2

Intersection	Pedestrian entrance/exit		Location
Intersection 1	Pedestrian entrance	South W	On the western side of the southern approach
		North E	On the eastern side of the northern approach
		West N	On the northern side of the western approach
	Pedestrian exit	South E	On the eastern side of the southern approach
		North W	On the western side of the northern approach
		West S	On the southern side of the western approach

[11] Motorbikes and scooters are included as light vehicles in the simulation.
[12] Heavy vehicles that are not buses are represented as trucks.
[13] Pedestrians counts as a vehicle type in Aimsun.

Intersection 2	Pedestrian entrance	South W	On the western side of the southern approach
		South E	On the eastern side of the southern approach
		North E	On the eastern side of the northern approach
		West N	On the northern side of the western approach
	Pedestrian exit	South W	On the western side of the southern approach
		South E	On the eastern side of the southern approach
		East N	On the northern side of the eastern approach[14]
		North W	On the western side of the northern approach

Table 7.3: OD routes for intersection 2

OD route	**From/to**	**Description**
OD Route bike south north	Southern to northern approach	Making the cyclists use the bike lane at the intersection on the southern approach
OD Route bike north south	Northern to southern approach	Making the cyclists use the bike lane after the bus stop on the southern exit
OD Route bike west south	Western to southern approach	Making the cyclists use the bike lane after the bus stop on the southern exit
OD Route bus south north	Southern to northern approach	Making the buses use the public transport lane at the intersection on the southern approach
OD Route car north south	Northern to southern approach	Making the cars not use the bike lane after the bus stop on the southern exit

[14] As this approach turns to the north, the pedestrian exit on the northern side will be on the western side.

7.3.2 Public transport system

To implement the public transport system into the models, the bus stops located on the different sections have been added. Bus stops that are located outside the section and/or the intersection are not included in the models. An overview of the bus stops included in the models is presented in Table 7.4.

Table 7.4: Overview of bus stops included in the models

Intersection	Bus stop	Type of bus stop
Intersection 1	Hagerups vei northbound	Bus bay
	Hagerups vei southbound	Bus bay
	Birkeveien westbound	Bus bay
Intersection 2	Haukelandsveien southbound	Normal[15]
	Haukeland sykehus sør northbound	Normal
	Haukeland sykehus sør southbound	Normal

After the bus stops have been added, the public transport routes are assigned to their public transport line. For intersection 1, the bus routes that are added are the ones in Table 3.2 that operate at the time of the recordings, while for intersection 2, the bus routes are the ones in Table 3.4 that are operating during the recordings. For the bus routes that are operating at both intersections, the timetable for each route is added to the public transport line. All public transport lines together make up the public transport plan. Information about all public transport lines, their frequency and start time is presented in attachment B.

7.3.3 Signal timings

Actuation

Both intersection 1 and 2 are actuated and will therefore be modelled with the actuated signalized intersection type. As some movements within the same phase are having different green times at both intersections, several rings for the timing settings are added. These rings can adjust for different green times for movements in the same phases, as well as extending some green times into more than one phase. The timing phases for intersection 1 are shown in Figure 7.4, while for intersection 2, the signal phases are shown in Figure 7.5. The phase numbers are explained in Table 7.5 and Table 7.6 for intersection 1 and 2, respectively. The movements that are in phase D in Figure 3.6 have been put in the first barrier to accommodate for the through movement from the southern approach to start before the through movement from the northern approach.

[15] In Aimsun Next, a normal bus stop is an in-line sidewalk stop.

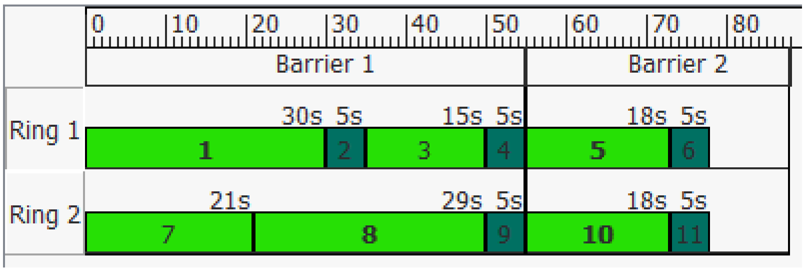


Figure 7.4: Signal timings for intersection 1 in Aimsun Next

Table 7.5: Phases for intersection 1 in Aimsun Next

Phase	**Movement(s)**
1	Through from south
	Through from north
2, 4, 6, 9, 11	Interphases
3	Left turn from west
	Right turn from west
5	Left turn from south
	Right turn from west
	Pedestrian crossing north
7	Pedestrian crossing west
8	Right turn from north
10	Left turn from south
	Right turn from west

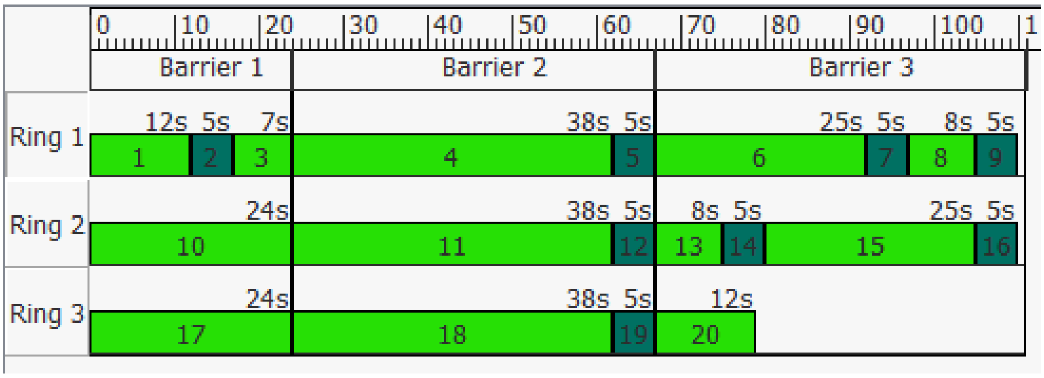


Figure 7.5: Signal timings for intersection 2 in Aimsun Next

Table 7.6: Phases for intersection 2 in Aimsun Next

Phase	Movement(s)
1	Right turn from east
	Left turn from north
2, 5, 7, 9, 12, 14, 16, 19	Interphases
3	Through from south
	Two northernmost pedestrian crossings east
4	Through from south
	Two northernmost pedestrian crossings east
	Pedestrian crossing west
6	Through from east
	Southernmost pedestrian crossing east
	Pedestrian crossing north
8	Left turn from west
10	Left turn from south
11	Through and right turn from north
13	Left turn from east
15	Through from west
	Right turn from west
17	Right turn from west
18	Right turn from south
20	Right turn from east

For each of the phases in Table 7.5 and Table 7.6, individual green times and passage times are used. For the different green times, Aimsun Next operates with a minimum green and a max-out, which is a maximum green time for the phase. The passage time shows the maximum gap between the detector actuations, i.e., the maximum headway between vehicles for it to continue to be green. All the minimum green times, maximum green times, and passage times for all phases in intersection 1 and 2 are shown in attachment C. To detect the traffic and for the actuation to work, detectors on each approach are being used. The detectors for each phase and movement are also presented in attachment C.

Priority

For the priority scenarios, the priority function for the signalized intersections is used. A screenshot from Aimsun Next of the priority settings is shown in Figure 7.6. The priority settings function by adding the public transport lines with their corresponding phases to the type of priority. Furthermore,

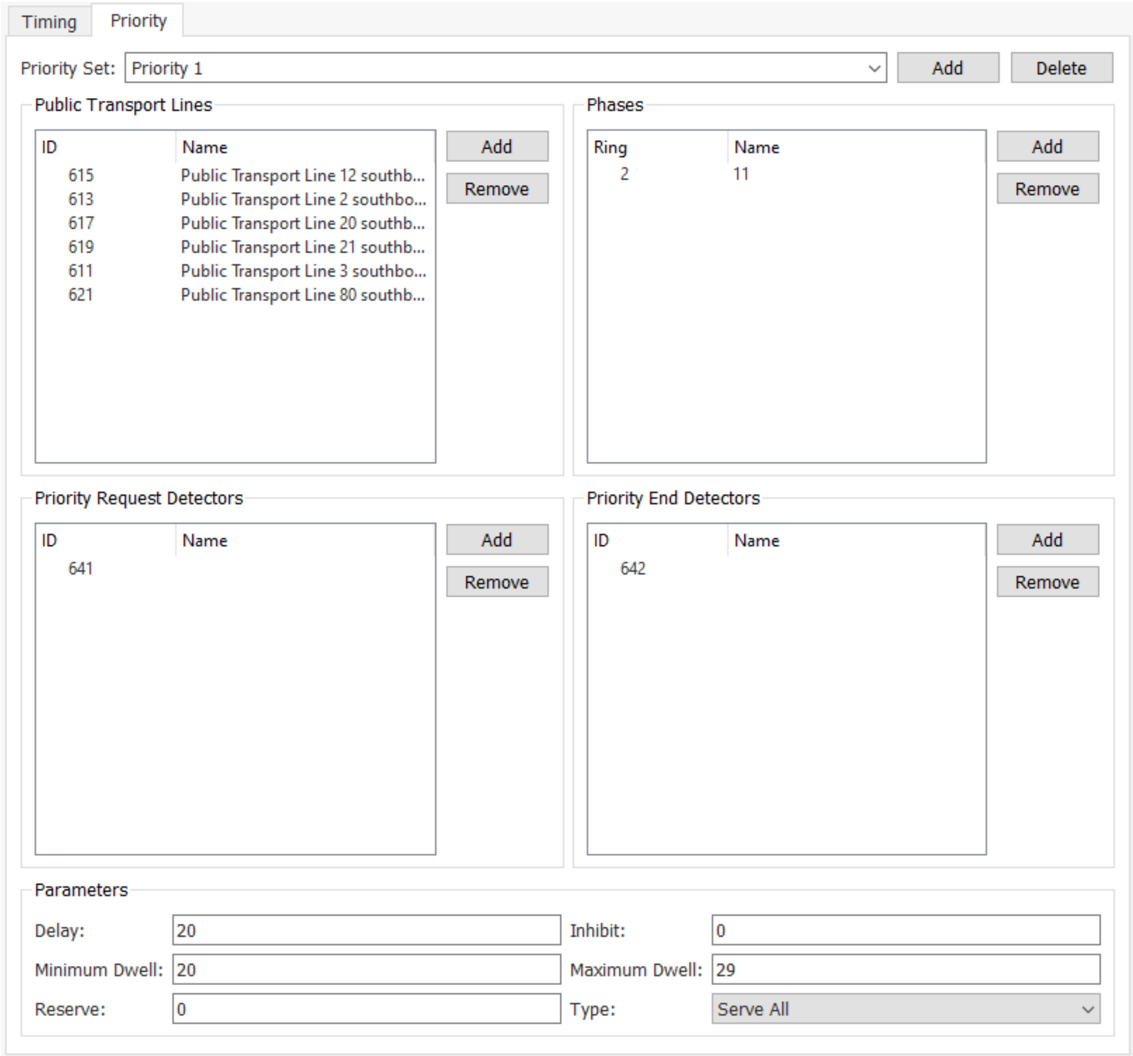


Figure 7.6: Priority function in Aimsun Next

detectors are used to detect the buses and to trigger and end the priority. To adjust the priority settings, there are a few parameters that can be adjusted. These are: delay, inhibit, minimum dwell, maximum dwell, reserve, and type. Details on the different priorities for intersection 1 and 2 are shown in attachment D.

7.4 Output results

When the simulations are run in Aimsun Next, the outputs of interest are related to the performance measures from chapter 2.1.4. As well as these performance measures, the traffic count for each approach is observed as it gives an indicator for if the models are returning the right number of vehicles as they were from the input. For intersection 1, the outputs can be found by looking at the time series for the approach sections. For intersection 2 on the other hand, some of the approaches have been divided into several sections. For instance, the western approach is divided into three sections connected by a node as shown in Figure 7.7. This is to cater for the road geometry at the intersection. In these cases, the

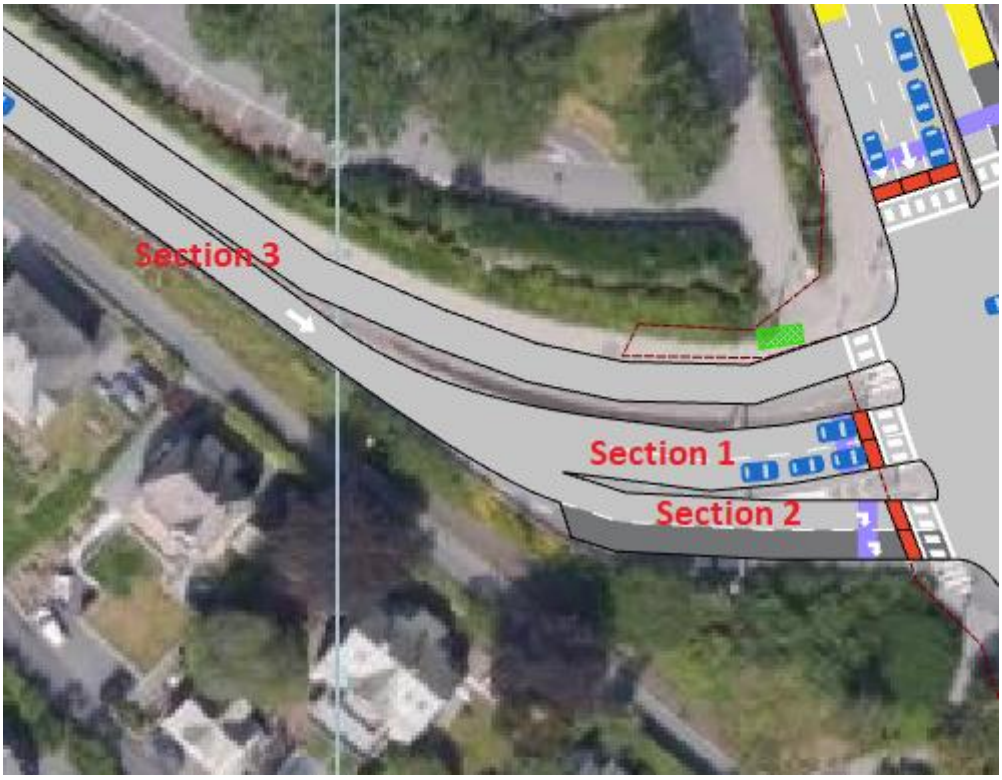


Figure 7.7: Sections on the western approach at intersection 2 in Aimsun Next

performance measures will be displayed as a weighted average from the sections that are necessary to include.

The outputs can be displayed in a table format, as well as by using graphs. In the simulation, it can also be shown by using dynamic labels, which gives the real-time value, where the table and graph format gives the output during time intervals. Table 7.7 shows an example of the average delay on the northern approach for every ten minutes for cars, buses, and trucks. Where a value is absent, no vehicle has been detected, e.g., for some time intervals, no trucks have been detected.

The same types of output presentations can be obtained for the number of stops per vehicle, which can be used to get the total number of stops. The same goes for queue lengths, both average and maximum.

Table 7.7: Example of delay output from intersection 2 in Aimsun Next

	Delay Time - Replication 496 - Car (sec)	Delay Time - Replication 496 - Bus (sec)	Delay Time - Replication 496 - Truck (sec
03.02.2021 07.45	38,41 (25,36)	45,31 (33,97)	8,66 (9,69)
03.02.2021 07.55	28,39 (25,97)	42,19 (34,51)	53,10 (27,50)
03.02.2021 08.05	35,30 (25,79)	37,34 (32,69)	
03.02.2021 08.15	40,63 (26,26)	13,00 (22,96)	66,43 (12,39)
03.02.2021 08.25	25,84 (21,05)	42,69 (33,90)	36,67 (7,17)
03.02.2021 08.35	40,80 (27,66)	13,58 (10,14)	
Aggregated	35,97	32,98	41,22
Mean	34,90	32,35	41,22

7.5 Calibration

7.5.1 Calibration approach

As explained in chapter 7.1, the model can be used to answer the third objective in the thesis once it is calibrated and validated. The goal with the calibration is to get the output results of the models as close to the observed (from the field study) results as possible, i.e., the error between the models and the field studies should be as low as possible. There are several ways of calibrating the models. To calibrate the models in this thesis, it will be looked at average vehicle delay, queue lengths, and the number of stops, i.e., the performance measures calculated in the field study. The calibration goal will therefore be to achieve results from the models as close to the obtained results from the field study.

As there are different traffic volumes and differences in performance results at the intersections, there will be different demand that needs to be met to achieve a desirable calibration of the models, i.e., there will be allowed a larger deviation in the performance measures for intersection 2 than for intersection 1. The demand for each performance measure for each intersection is presented in Table 7.8.

Table 7.8: Calibration demands

Intersection	**Calibration measure**	**Maximum error**
Intersection 1	Average vehicle delay	5 seconds
	Maximum queue length	3 vehicles
	Number of stops	30.0%
Intersection 2	Average vehicle delay	15 seconds
	Maximum queue length	10 vehicles
	Number of stops	30.0%

7.5.2 Calibration parameters

In Aimsun Next, many parameters can be used to calibrate the models. Røys (2015, p. 57) mentions several parameters that can be categorized into three main parameters: global parameters, local parameters, and vehicle parameters. The global parameters are connected to the settings when running a simulation. These include a warmup period, reaction times, and maximum give way times. The local parameters consist of the parameters that can be set in the section and node properties, i.e., those who are specific for these intersections and sections. These include, among others, speed limits, safety margins, visibility, and gradient of the section. The last category of parameters is the one concerning the vehicles. This category consists of both vehicle characteristics and driver characteristics. These parameters can include the length of vehicles and their maximum desired speed, as well as maximum acceleration and retardation. For the drivers, their acceptance to follow the set speed limit is an option, as well as several sensitivity parameters. A summary of the above-mentioned parameters is presented in Table 7.9.

Table 7.9: Calibration parameters

Global parameters	Local parameters	Vehicle parameters
Warmup period	Speed limit	Vehicle length
Reaction times	Safety margins	Maximum desired speed
Maximum give way times	Visibility	Acceleration
	Gradient	Speed limit acceptance
	Acceleration factors	Sensitivity parameters
	Additional reaction times	

7.5.3 Calibrated models

Attachment F shows the meetings of the demands set for calibration of the models in Aimsun Next presented in 7.5.1. Furthermore, the parameters used to calibrate the models for intersections 1 and 2 are presented in attachment E. The attachment shows the relevant parameters and their new values for the calibrated models. With the models being calibrated, it is possible to implement the suggested improvements used to answer the third objective for the thesis.

7.6 Intersection improvements

To answer the third objective presented in chapter 1.2, several suggestions to improve the systems is being presented. As mentioned earlier in chapter 7, the models created in Aimsun Next will be used to test these suggestions and see if these can improve the existing systems. Some of the suggestions can be a direct change to the bus priority, while some are changes that can be made adjacent to using the bus priority. Table 7.10 shows the proposed suggestions for the intersections. The suggestions are labelled with the intersection number and an alphabetical code. The rest of this chapter describes the different improvements suggested for intersection 1 and 2.

Table 7.10: Suggested improvements for intersection 1 and 2

Intersection	Name	Suggested solution
Intersection 1	1A	Extend minimum time in phase A
	1B	Give green for northern right turn and pedestrians in phase A
Intersection 2	2A	Greater minimum and maximum time for phase C
	2B	Changing order of phases B and C

7.7 Intersection 1

7.7.1 Improvement 1A

The first suggestion to improve intersection 1 is to focus on the approach that is experiencing the most extreme negative values, i.e., the northern approach. The total delay on this approach is in both situations a lot higher than the other two approaches. Therefore, by giving more benefits to this approach, the goal is to reduce the total delay for this approach and the total delay for the entire intersection. One way of doing this is to extend the minimum time for phase A, where the through movement is having green time. Extending the minimum green time will make it possible for the arriving vehicles on this approach to have a larger headway. If the headway is too large and the minimum green time is passed, the phase will terminate. However, by extending the minimum green time, it will increase the chances of a vehicle arriving with a larger headway, thus having more vehicles entering the intersection and less delay. The suggested extension of minimum green time is presented in Table 7.11. The priority will remain the same, i.e., increasing the minimum green time by two seconds when the bus is detected arriving at the intersection. The table is therefore presenting a suggested minimum green time both with and without priority.

Giving more benefits to phase A means that there will be disbenefits to the other phases, thus disbenefits to the movements that are not in this phase. If the minimum green time in phase A is often used as the green time in the cycle, i.e., the green time does not last longer than the minimum green time, the probability of the other movements having to wait longer in this suggested situation is being increased. This increase will most likely lead to an increase in the delay, stops, and queue lengths for the other movements. However, to reduce the total delay for the intersection, it is desirable to try to reduce the delay on the approach with the highest total delay. Therefore, an increase in the delay and stops for the other approaches can be justified if the total delay is being reduced.

To extend the minimum time for phase A, the control plan for the intersection is being edited. The movement which will be edited is phase 1 presented in Table 7.5 and shown with the other phases in Figure 7.4. To extend the minimum when the priority is not triggered, the actuated tab connected to this phase is being modified. Here, the minimum green is changed from ten seconds to 16 seconds. The change is presented in Figure 7.8. As the maximum green time will not be changed, nor any other parameters, the rest remain unchanged from the existing scenario.

Table 7.11: Suggested minimum green time for phase A at intersection 1

Phase	Minimum green time without aps	Minimum green time with aps	Suggested minimum green time without aps	Suggested minimum green time with aps
A	10 seconds	12 seconds	16 seconds	18 seconds

To extend the green time when the priority is triggered, the parameters that need to be adjusted lies in the priority tab in the control plan. For the priority which relates to this phase, denoted Priority 0 in Aimsun Next, the parameter "minimum dwell" represents the minimum green time. This value is therefore changed from 12 seconds, as in the existing scenario, to 18 seconds, which is the proposed suggestion. The change is presented in Figure 7.9, which shows the priority tab and Priority 0. With these changes, the scenario can be run with a new master plan for the suggested improvement.

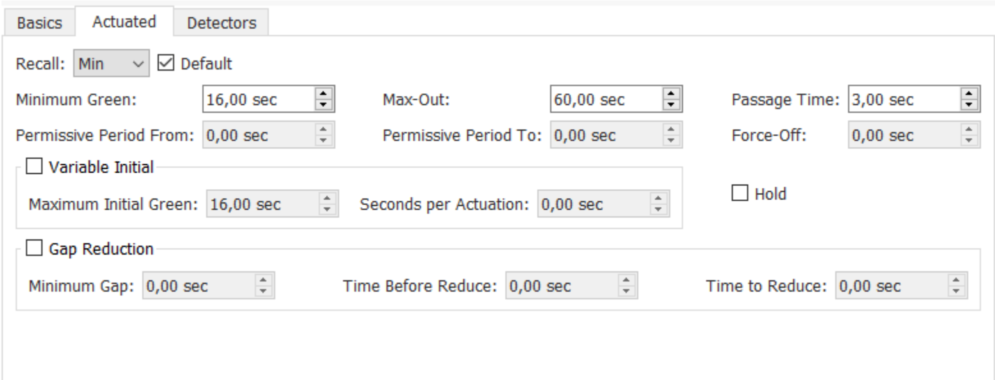


Figure 7.8: Actuation tab with adjustments for improvement 1A

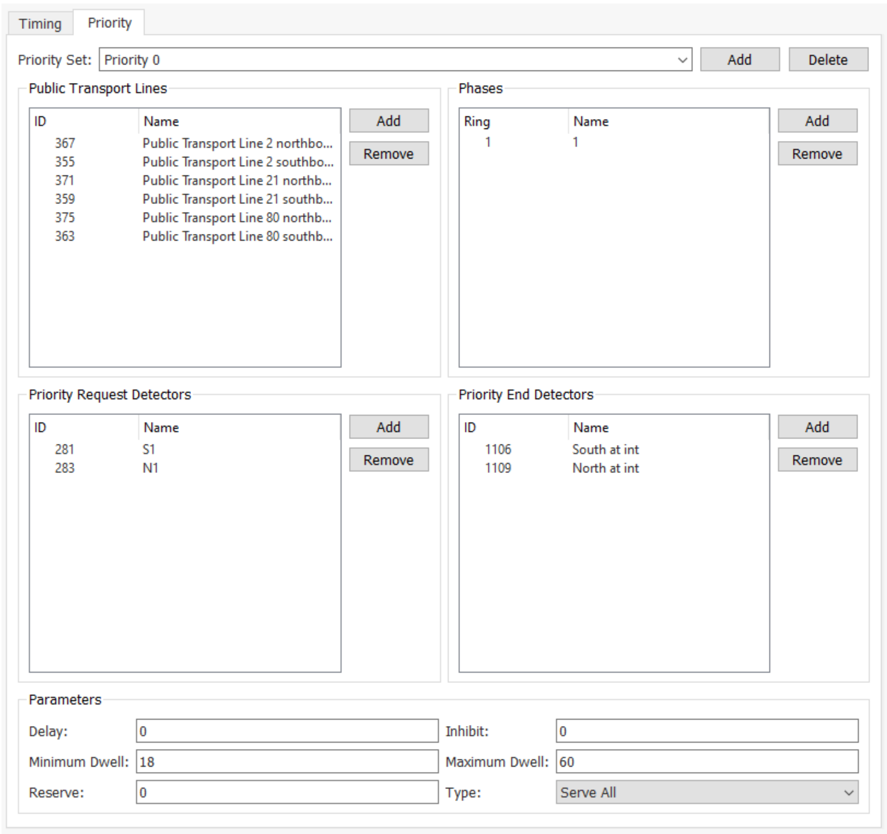


Figure 7.9: Priority tab with adjustments for improvement 1A

7.7.2 Improvement 1B

Another suggestion, which also aims to reduce the delay and other negative results on the northern approach is to give the right turn movement on the northern approach green signal in phase A. Under normal circumstances, this movement does not receive a green signal before phase B but will be given a green signal in phase A if no pedestrians are crossing the western approach. With this suggestion, this movement will receive a green signal in phase A independently whether there are any pedestrians or not on the western approach. However, if there are any pedestrians present, the vehicles will have to give way to the pedestrians, so that they can cross the road. Nevertheless, it will still allow the approach to clear faster as the vehicles can drive as soon as the pedestrians have cleared the path. The proposed changes to phase A can be seen in the phase plan shown in Figure 7.10.

In the present situation, the vehicles on the right turn movement on the northern approach will still receive a green signal if there are no pedestrians. But, if someone is triggering the pedestrian crossing, the movement needs to wait until phase B, eventually until the clearance time for the pedestrian crossing is up. With this suggestion, these two movements receive green signal at the same time, thus allowing the vehicles to take gaps if there is enough space to do so. On the other hand, making the vehicles interfere with the pedestrians in this way may arise questions related to traffic safety as these are conflicting movements. In today's situation, there are no conflicting movements in any phases. However, a right turn movement and a pedestrian crossing receiving green at the same time is not uncommon. This happens in phase A at intersection 2. In this situation, the visibility is good, and the speed of the vehicles is low. Therefore, it can be argued that the safety risk of this suggestion will be acceptable.

Improvement 1B follows the same method as improvement 1A, where the change is being done in the traffic control. However, here the change is being done in the basics tab. In the basics tab, one can

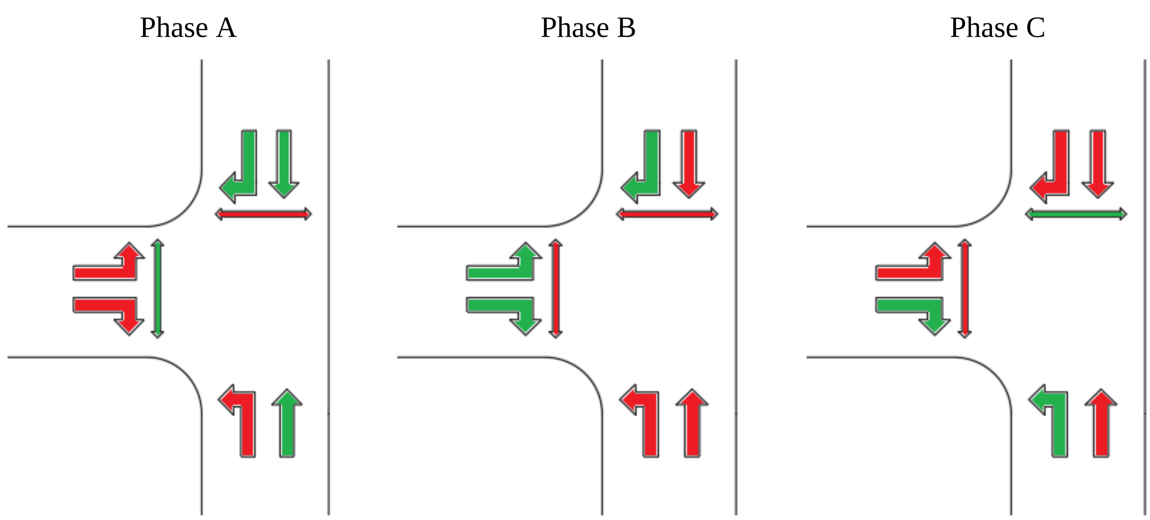


Figure 7.10: Suggested change for phase A at intersection 1

choose which movements are receiving a green light in each phase, as well as some other choices, for instance flashing, yellow time and whether it is an interphase. For improvement 1B, phase 1, which originally consists of the through movements on the southern and northern approaches, will be set to also include the right turn on the northern approach. Figure 7.11 shows the basics tab for phase 1, with the included right turn from the north, denoted Signal N RT. Also, to make the pedestrian crossing on the western approach safer, a clearance distance for vehicles is set to four meters. This means that a vehicle encountering pedestrians on this crossing will keep a four meters safety margin between them and the pedestrians. This change is done in the settings for the pedestrian crossing itself.

As with suggestion A, the improvement is being run in a separate scenario with its own master control plan.

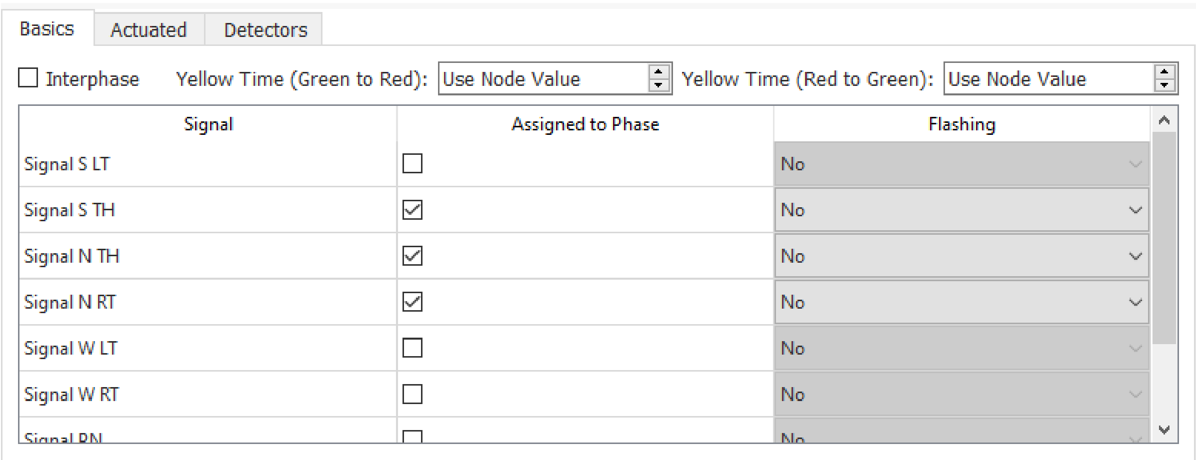


Figure 7.11: Basics tab with adjustments for improvement 1B

7.8 Intersection 2

7.8.1 Improvement 2A

For intersection 2, as discussed in chapter 6.6, the left turn on the western approach is experiencing a lot of traffic, combined with a low green time. Often, large queues are appearing on this approach due to the low number of vehicles that can enter the intersection during the green time. This does not only increase the delay and queue length for this movement but does also hinder the other movements on this approach. As a way of increasing the number of vehicles that can enter the intersection during this movement's green time, a suggestion is to increase the minimum and maximum green time for the approach when the bus priority is not triggered. Now, the approach is having a minimum green time of five seconds, which during the recordings only were enough to clear three to five vehicles. The maximum time was also five seconds, meaning the phase would only last for five seconds regardless of the number of vehicles in the queue. When the priority is being triggered, the maximum green time is extended to 50 seconds, which is to make sure the bus can enter the intersection in case of a long queue in front of the bus. By increasing the minimum and maximum green time when the priority is not

Table 7.12: Suggested green time for phase C at intersection 2

Phase	Minimum green time without aps	Maximum green time without aps	Suggested minimum green time with and without aps	Suggested maximum green time without aps
C	5	5	9	15

triggered, the goal is to clear more vehicles from the approach than it can do now. As mentioned, during the morning peak, there can be periods of long queues on this approach, and with the low green time, this queue is not able to be cleared. It can be cleared if a bus triggers the priority, and the green time is extended. However, when this does not happen, the queue has been observed to struggle to clear, thus heavily increasing the delay on this approach, not only to the left-turn movement but also for the other movements as these are not able to get past the left-turning queue. A suggested new green time for the movement is shown in Table 7.12. The table shows the existing minimum and maximum green time without priority, the suggested minimum green time for with and without the priority, and the suggested maximum green time without priority. The maximum green time with priority will not be altered but stay at 50 seconds.

An increase of the green time for this approach will make the waiting time for the other approaches longer, thus increasing the delay for these. However, when looking at the delay this approach is experiencing, both the average and the total delay, the approach is causing a lot of delay at the intersection. Therefore, a potential increase in delay for the approaches can be worth obtaining if this suggestion reduces the delay for this approach significantly.

The implementation of improvement 2A into the model in Aimsun Next is done the same way as for improvement 1A. After creating a new traffic control plan to cater for this improvement, the change is being done to signal phase 8, presented in Table 7.6. In the actuation tab, the minimum green and max-out parameters are set to the new time presented in Table 7.12. No other changes are being made for the signal phase, or for the rest of the intersection to implement this improvement. The new actuation parameters for this signal phase is shown in Figure 7.12.

After the changes are being made, a new master control plan is created to include this newly edited traffic control plan, before running the simulation.

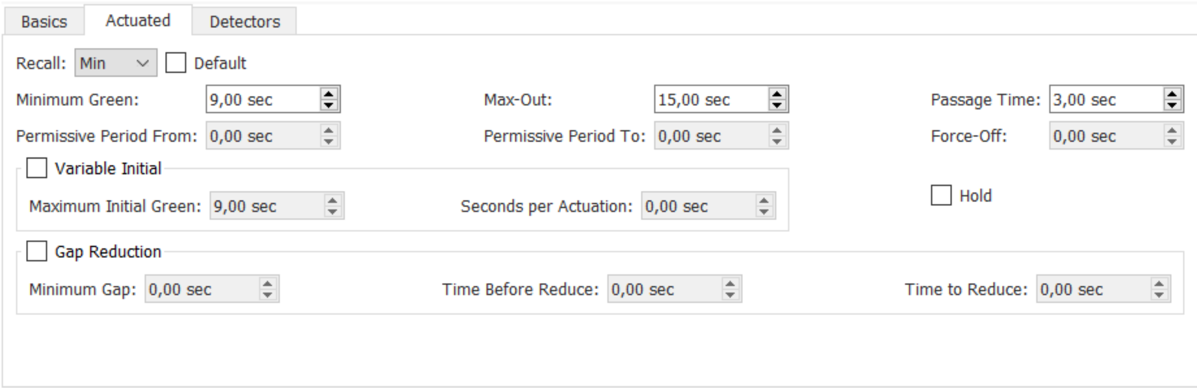


Figure 7.12: Actuation tab with adjustments for improvement 2A

7.8.2 Improvement 2B

Another way of handling the queue that is appearing on the western approach, especially considering the left turn, is to change the phase order of phases B and C. The queue appearing for the left turn on this approach is at times causing a blockage for the rest of the movements. Combined with the fact that the through and right turn movements can receive an earlier green because of low demand on the opposing movements in phase B, the green time for these two movements can be unnecessarily high as there at times are no vehicles able to arrive on these. Therefore, if phase B and phase C is changing order, all three movements on this approach may receive green at the same time, meaning all queue can be catered for during the green time. Figure 7.13 shows how the signal plan for intersection 2 will look with the proposed suggestion. The goal with this suggestion is to be able to cater for more vehicles on this approach, reducing the delay and other negative performance results this approach is experiencing. This involves both the performances of buses, but also all other types of vehicles. As presented in chapter 6, this approach had some of the most negative performance results. Therefore, it is desirable to reduce these negatives. Also, since during the low green time for the left-turn movement, not many vehicles were able to enter the intersection during the green time. Therefore, the minimum and maximum green time for the left-turn movement is set to be the same as for improvement 2A. The through movement is also getting the same minimum and maximum green times as the left movement. For the right turn movement, the maximum green time is also set to the same time as the two other movements. This makes the green times for all the three movements both start at the same time but also end at the same time if the maximum green time is triggered.

The changing of the phases B and C will probably also bring up some negatives for some of the other approaches. If all the movements on the western approach will receive the same amount of green time, and phase C (as presented in Figure 7.13) only starts when all the movements in phase B are done, phase C will have a large green time considering the pedestrian crossing on the northern approach. For this pedestrian crossing, the need for a long green time is necessary for the pedestrians to cross in time, and

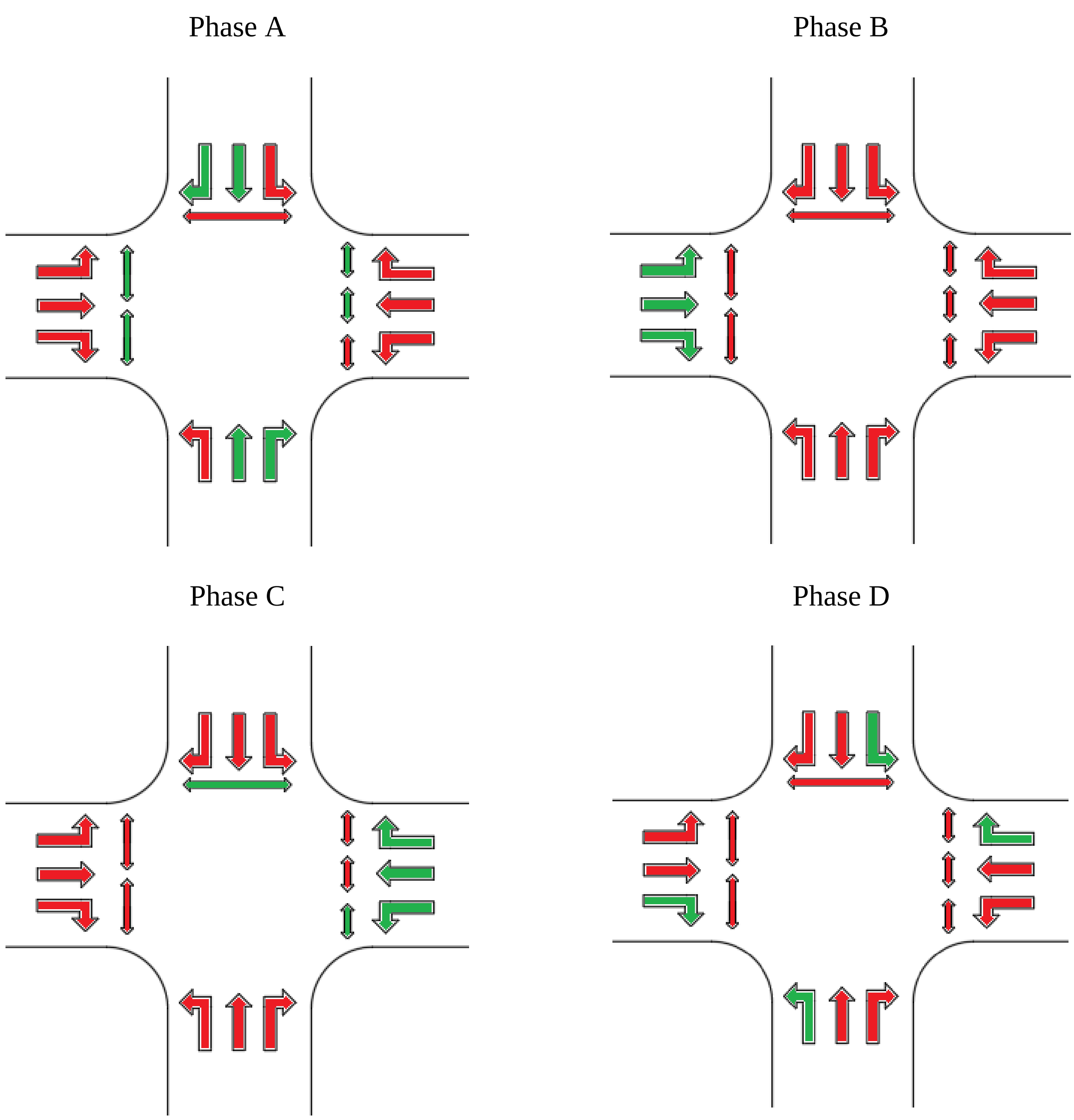


Figure 7.13: Suggested new signal phasing for intersection 2

safely. If this leads to a longer duration for phase B and C combined, the waiting time for the vehicles in phases A and D will be longer than originally. This can lead to more negative results for the movements in these phases. However, as the goal with this suggestion is to reduce the negative performances for the western approach, an increase for the other movements can be necessary. Although, as there will probably only be a few more seconds waiting time than in the original scenarios, the disbenefits for the movements in phases A and D may not necessarily be that big.

To change the order of the phases B and C, a new traffic control plan is created, as with the abovementioned improvements. When the two phases are being rearranged, several steps need to be done to make the signal system operate the right way. This includes doing some of the steps recently described regarding creating an actuated signal system, as well as adding priority. The new signal timings created for this improvement is shown in Figure 7.14, with the movements for each phase described in Table 7.13.

Afterwards, the minimum and maximum green time for the movements on the western approach is set to the mentioned values. For the priority on the western approach, the phase the priority is operating for is being changed to phase six, which consists of the left turn on the western approach. This is shown in Figure 7.15. Afterwards, a master control plan is created for the traffic control plan created, before running the simulation.

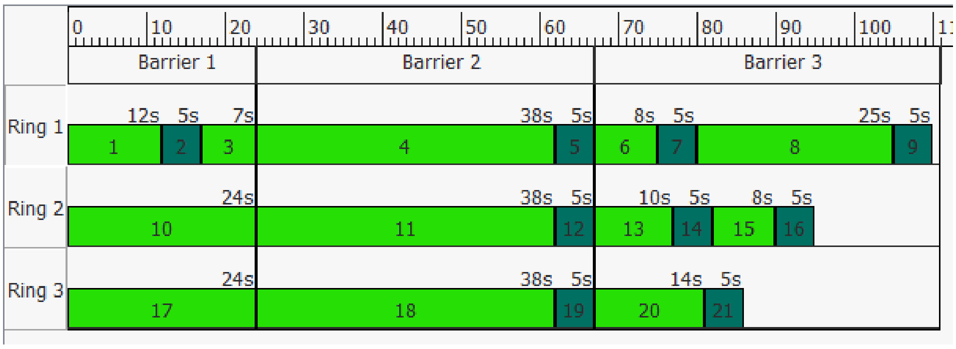


Figure 7.14: Signal timings for improvement 2B in Aimsun Next

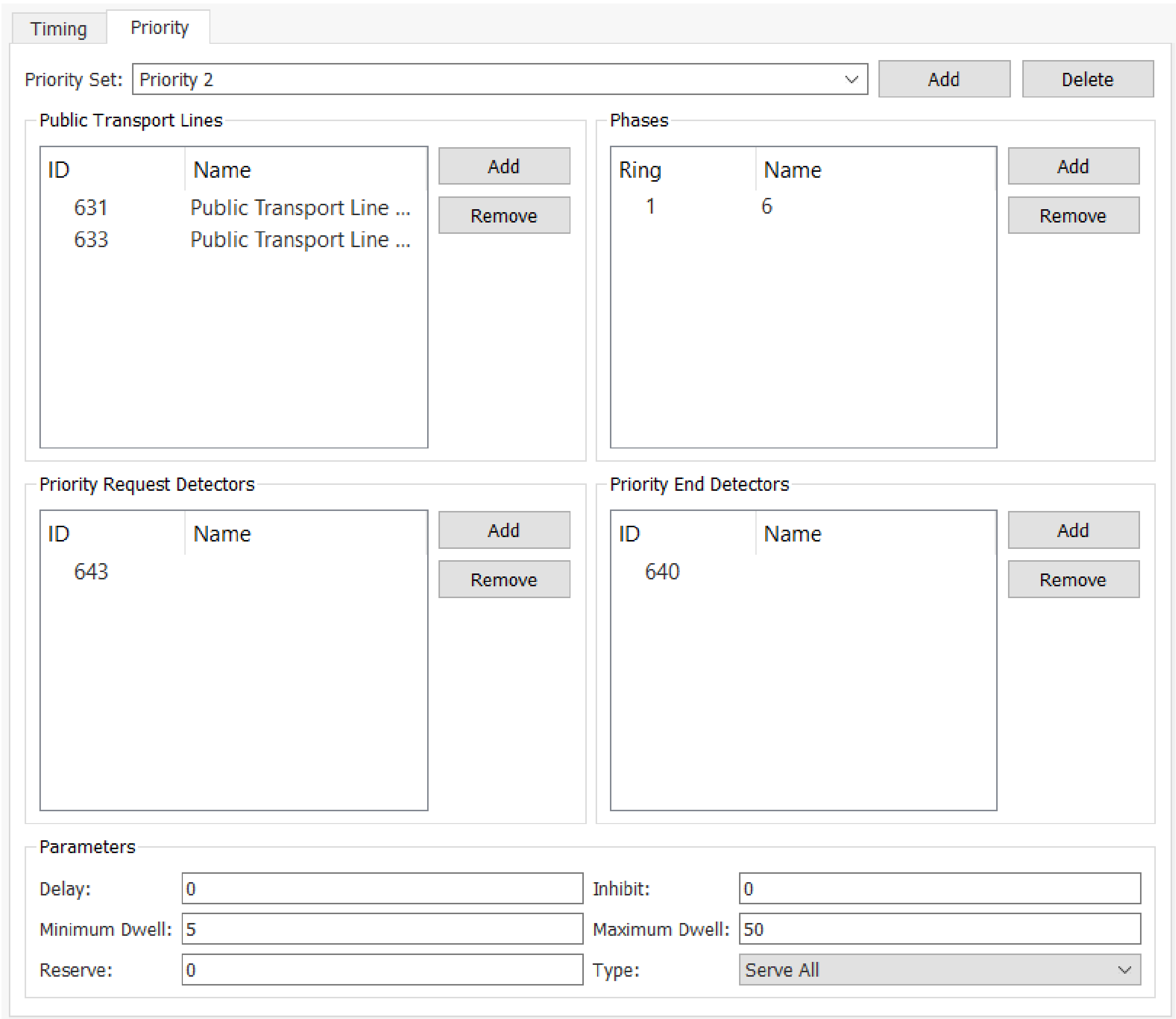


Figure 7.15: Priority adjustment for improvement 2B

Table 7.13: Phases for improvement 2B in Aimsun Next

Phase	**Movement(s)**
1	Right turn from east
	Left turn from north
2, 5, 7, 9, 12, 14, 16, 19, 21	Interphases
3	Through from south
	Two northernmost pedestrian crossings east
4	Through from south
	Two northernmost pedestrian crossings east
	Pedestrian crossing west
6	Left turn from west
8	Through and right turn from east
	Southernmost pedestrian crossing east
	Pedestrian crossing north
10	Left turn from the south
11	Through and right turn from north
13	Through from west
15	Left turn from east
17	Right turn from west
18	Right turn from south
20	Right turn from west

8 Modelling results

8.1 Improvement 1A

8.1.1 Delay

The results related to delay for improvement 1A is presented in Table 8.1 and Table 8.2. It can be observed that with this improvement, the northern and western approaches will receive higher delays than the southern approach, as they did in the priority scenario. The southern approach is experiencing very low delay, both average and total delay. The northern and western approaches are both having similar results related to the average vehicle delay. However, due to the large difference in traffic volume, the total delay on the northern approach is significantly higher than on the western approach.

Table 8.1: Vehicle delay for improvement 1A

Approach	**Average delay (s/veh)**	**Total delay (veh.h/h)**
Nattlandsveien S	8.26	0.83
Nattlandsveien N	21.20	5.16
Hagerups vei	21.25	2.09

Looking at the average bus delay, the southern approach is experiencing a very low delay, almost none. As for the other approaches, the buses are experiencing a slightly lower delay than the average delay. The northern approach is experiencing a difference with a couple of seconds, and the western approach with only a few milliseconds.

Table 8.2: Bus delay for improvement 1A

Approach	**Average delay (s/veh)**
Nattlandsveien S	2.28
Nattlandsveien N	19.90
Hagerups vei	21.18

8.1.2 Queues and stops

The maximum queue and number of stops are presented in Table 8.3. For the number of stops and maximum queue lengths, the northern approach is experiencing the highest results. The maximum queue on this approach is more than twice as large as the maximum queue on the western approach, and three times as large as the one on the southern approach. Considering the abovementioned large difference in traffic volume, this is not unreasonable as the queue might increase fast once this approach is not receiving any green signal. The low delay presented in Table 8.1 for the southern approach may also correlate with the low maximum queue and the low amount of the number of stops. For the southern approach, less than half the vehicles need to stop at the intersection but instead can drive through the intersection unaffected. For the other two approaches, the number of stops is way higher, with three out of four having to stop on the western approach and 84% on the northern approach.

Table 8.3: Maximum queue and number of stops for improvement 1A

Approach	Maximum queue	Number of stops
Nattlandsveien S	3.4	39%
Nattlandsveien N	10.8	84%
Hagerups vei	5.2	74%

8.2 Improvement 1B

8.2.1 Delay

Looking at the delay for the second improvement, which is presented in Table 8.4 and Table 8.5, the southern approach is still experiencing a delay that is way lower than the other two approaches. However, for this improvement, the northern and western approach are both receiving a decrease in delay compared to improvement A. The average delay for the northern approach is decreasing by three seconds, leading to a decrease in the total delay to almost one vehicle hour. The western approach is also having a decrease in total delay, however not as large as the northern approach. For this approach, the reduction is 0.22 vehicle hours. The delay on the southern approach remains somewhat the same, both for the average and total delay.

Table 8.4: Vehicle delay for improvement 1B

Approach	Average delay (s/veh)	Total delay (veh.h/h)
Nattlandsveien S	8.32	0.81
Nattlandsveien N	17.99	4.21
Hagerups vei	19.31	1.87

Table 8.5: Bus delay for improvement 1B

Approach	Average delay (s/veh)
Nattlandsveien S	4.48
Nattlandsveien N	18.10
Hagerups vei	23.82

For the bus delay, where the delay for the southern approach was almost non-existent in improvement A, it is a bit higher for improvement 1B, yet still very low. For the northern approach, the bus delay is a bit lower for this improvement, but for the western approach, there is a slight increase in the delay for buses.

8.2.2 Queues and stops

Table 8.6: Maximum queue and number of stops for improvement 1B

Approach	Maximum queue	Number of stops
Nattlandsveien S	4.2	41%
Nattlandsveien N	12	72%
Hagerups vei	5.2	73%

Where the delay results were the same or increasing for improvement 1B, the maximum queue for the approaches is showing the opposite results. From Table 8.6, one can observe that the maximum queue is increasing for both the southern and northern approaches, whilst remaining the same for the western approach. However, the increases are not very large, both with approximately one vehicle difference. As for the number of stops, the northern approach is the only approach that is showing a noticeable difference with a 12% reduction, whereas the two other approaches give somewhat similar results for both improvements.

8.3 Improvement 2A

8.3.1 Delay

Table 8.7 shows the average and total vehicle delay for improvement 2B. From the table, one can observe that the southern approach, which is having the largest traffic volume, is having the highest average delay, therefore also the highest total delay for the approaches. The southern approach is having a total delay over twice as large as the approach with the second highest total delay, which is the western approach. The western approach is the approach that has been focused on trying to decrease the negative performance results. Compared to the priority scenario, the delay for the approach has been decreased by over 25 seconds. However, this may be at the expense of the other approaches, where some are experiencing an increase in average delay.

Table 8.7: Vehicle delay for improvement 2A

Approach	Average delay (s/veh)	Total delay (veh.h/h)
Haukelandsveien S	67.09	14.18
Haukelandsveien E	46.23	2.25
Haukelandsveien N	39.78	3.45
Ibsens gate	59.63	6.10

Furthermore, when looking at the bus delay for the improvement, the western approach still experiences a high delay, even with an increase in green time for when the buses are not present, and with the priority. However, even though the bus delay is high, there is still a reduction from the priority scenario, where the buses were experiencing on average several minutes of delay. Also, the western approach is not the only approach decreasing the delay. The southern approach is also having a decrease in bus delay. Meanwhile, the northern is experiencing an increase in delay.

Table 8.8: Bus delay for improvement 2A

Approach	Average delay (s/veh)
Haukelandsveien S	29.31
Haukelandsveien N	34.77
Ibsens gate	70.03

8.3.2 Queues and stops

As the southern approach is the one having the highest traffic volume, it is not surprising that this approach is experiencing the highest maximum queue length. This queue length is very similar to the maximum queue length in the no priority scenario, which it is for most of the approaches apart from the northern approach. Here, the maximum queue is decreasing from the priority scenario by almost half, from eight vehicles to between four and five vehicles. Apart from this, the improvement does not seem to affect the maximum queue lengths by much.

For the number of stops, most approaches have an increase in the number of stops, with the northern approach almost with the highest value. On this approach, on average almost all vehicles need to stop once. The eastern approach is the only approach showing a decrease in the number of stops. However, this is only a small decrease. For the western approach, the improvement does not seem to affect the number of stops as the percentage of vehicles stopping is almost exactly as in the priority scenario, with only a small increase. All results regarding maximum queues and the number of stops for improvement 2A is shown in Table 8.9.

Table 8.9: Maximum queue and number of stops for improvement 2A

Approach	Maximum queue	Number of stops
Haukelandsveien S	28.8	94.76%
Haukelandsveien E	12.2	84.13%
Haukelandsveien N	4.2	98.0%
Ibsens gate	19.8	84.47%

8.4 Improvement 2B

8.4.1 Delay

As for the second improvement option for intersection 2, none of the approaches are gaining on the implementation of the shift in phase order and extended green times for the western approach compared to the first improvement option. The western approach is the approach that is receiving the highest average delay, with the southern approach having 12 seconds less in average delay. On the other hand, compared to the priority scenario, the western approach experiences a small decrease in average delay, which is approximately six seconds. However, this is the largest decrease from the priority scenario results. The eastern approach is also experiencing a decrease, though smaller than the western approach. The other two approaches are getting an increase in delay. The average delay and total delay for all approaches can be seen in Table 8.10.

Table 8.10: Vehicle delay for improvement 2B

Approach	**Average delay (s/veh)**	**Total delay (veh.h/h)**
Haukelandsveien S	67.14	14.38
Haukelandsveien E	52.37	2.77
Haukelandsveien N	40.02	3.51
Ibsens gate	79.59	6.79

Regarding the bus delay, which is presented in Table 8.11, both the southern and western approach are getting a delay that is lower than the delay in the priority scenario. The northern approach is also here experiencing an increase in the bus delay. Compared to improvement 2A, only the southern approach is getting a lower delay.

Table 8.11: Bus delay for improvement 2B

Approach	**Average delay (s/veh)**
Haukelandsveien S	26.40
Haukelandsveien N	36.18
Ibsens gate	77.40

8.4.2 Queues and stops

The results regarding the maximum queue and number of stops per vehicle are shown in Table 8.12. For this improvement suggestion, all approaches except the northern approach are getting an increase in maximum queue length from both the priority scenario and improvement 2A. However, the increase is in most cases not very large. The eastern approach is the approach that is experiencing the largest increase from the priority scenario to improvement 2B with four vehicles. The northern approach, on the other hand, is experiencing a reduction in maximum queue length, both compared to the priority scenario and improvement 2A.

For the number of stops per vehicle, this improvement is experiencing the worst results here as well. The southern approach shows similar results to the other improvement, but still higher than the priority scenario. Meanwhile, the eastern approach is also showing similar results to both the priority scenario and improvement 2A. However, when looking at the northern and western approaches, one can observe that both approaches are having a result of over 100%. This means that, on average, several vehicles needs to stop more than once, i.e., even though some vehicles can just drive through the entire section without stopping, several others will have to stop up to numerous times.

Table 8.12: Maximum queue and number of stops for improvement 2B

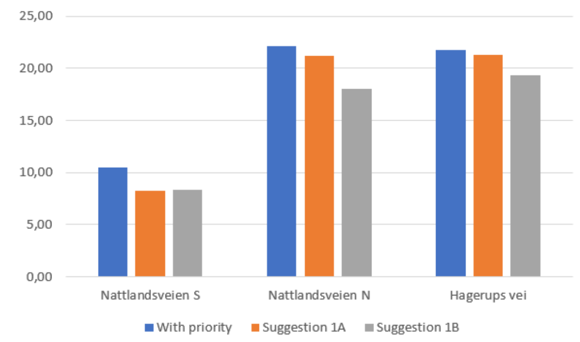
Approach	**Maximum queue**	**Number of stops**
Haukelandsveien S	30	94.42%
Haukelandsveien E	14.4	86.36%
Haukelandsveien N	4	101.00%
Ibsens gate	21	106.06%

9 Discussion

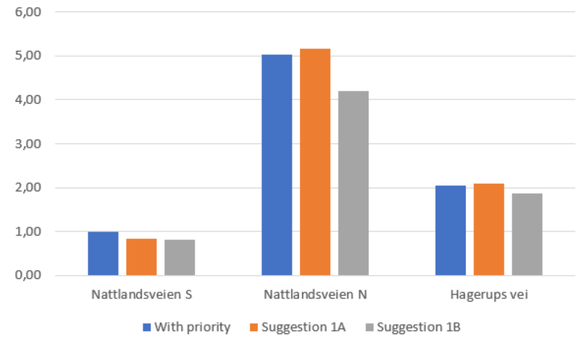
9.1 Intersection 1

Looking at the two improvements simulated for intersection 1, one can observe that both improvements are achieving a lower average vehicle delay for all approaches compared to the priority scenario. However, for both improvements, the reduction in average vehicle delay is not very high for neither of the approaches. As there are not the same number of vehicles arriving on each approach during the simulations, the total delay for improvement 1A is higher than the total delay for the priority scenario. In this case, the improvement 1A have recorded a higher number of vehicles on the northern approach, thus getting a larger total delay. This can be seen in Figure 9.1 a) and b). This shows the small difference one gets from the implementation of the improvement 1A, little to no difference in the average and total delay. Improvement 1B on the other hand shows a bit bigger decrease with a little over one hour difference in total delay. Looking at Figure 9.1 d) and e), which shows the maximum queue and number of stops, one can observe that several approaches are experiencing worse results with the improvements included. The southern approach is the one approach that scores better with the improvements than in the priority scenario.

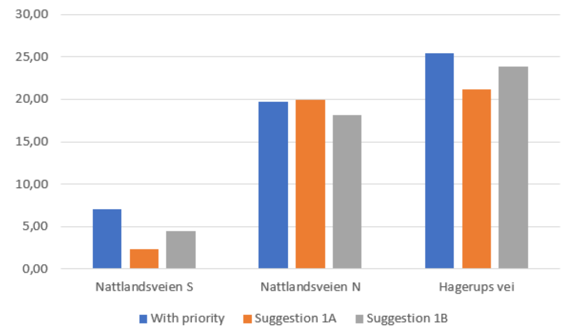
Furthermore, when looking at the bus delay, improvement 1A is suddenly the one showing the best results, where it was the opposite for the average vehicle delay. The bus delay is decreasing on the southern and western approaches. However, for the northern approach, it is getting a small increase. Even though one would think that this improvement would not lead to an increase in bus delay as it is increasing the green time for this movement, such a small difference in bus delay can also be a result of the number of vehicles in front of the bus creating shock waves leading to more queues. There may also be the case that as the detector detecting the bus and triggering the priority is located too close to the intersection, meaning that a bus being in the queue behind the detector will not trigger the priority, but rather increase the delay time. For the second improvement, which goal is to clear the approach of conflicting vehicles turning right and vehicles going straight through to the southern approach, the delay for the northern approach is being reduced. However, as for the increase in improvement 1A, the decrease for this improvement is also not very large and can be a cause of external factors that are not related to an error or unreliability of the bus priority scheme. Therefore, one can raise the question of how effective the bus priority for the intersection is, as the results from the simulations of the improvements are very similar to the field study, which all are not as good as the scenario where the priority was not included. There may be the case that the bus priority, which is extending the green times for the associated phases, is just making fewer vehicles able to enter the intersection on the opposing movements in the other phases, creating more queue, which distracts the buses. However, once the bus priority is triggered, and the green time is extended to the necessary duration, the approaches experiencing this should be able to benefit as it will help to clear the approach for vehicles. Based on



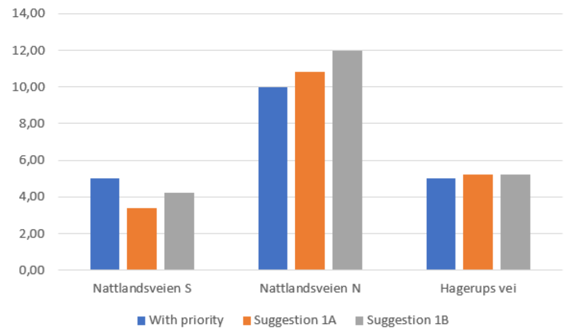
a) Average vehicle delay



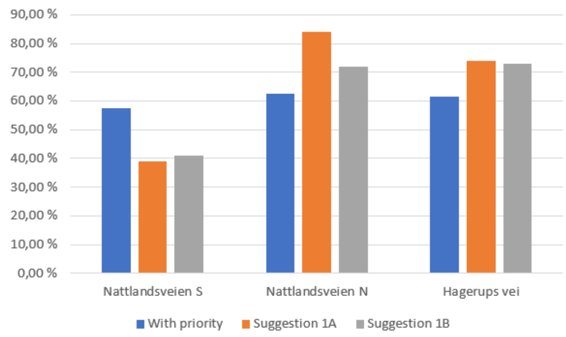
b) Total delay



c) Bus delay



d) Maximum queue



e) Number of stops

Figure 9.1: Improvements comparison for intersection 1

this, there may be argued that the bus priority is not very effective and should not be implemented at this intersection. On the other hand, if one is to promote public transport and make this transport mode more attractive than a private vehicle, having a priority system for the buses may be the way to go nonetheless, if done the right way, i.e., that it makes the travel times for buses shorter. Then it would also be necessary to focus on the amount of priority that should be given, which can be discussed regarding how much disbenefit one wants to give other vehicles. As explained by McLeod and Hounsell (2003), too much priority could potentially lead to a lot more disbenefit for the other travellers, making it a choice of how to balance the positives and negative for the different travel modes.

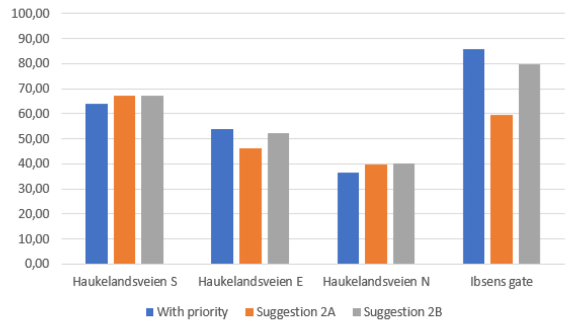
Looking at the rest of the vehicles and how they are affected by the bus priority, both with and without the improvements, the delay gets worse when the priority is implemented. As was mentioned by Kyoungho and Rakha (2006), with a high traffic volume, especially of transit vehicles, e.g., buses, more detriments for the other vehicles could occur. And, as the northern and southern approach are experiencing many buses, this may lead to more disbenefits for the other travellers, especially on the western approach. Yet, when including the improvements, the delay is decreasing again for several of the approaches, at least for some of the improvements. This can be supported by the work done by Liu et al. (2018), Høsser (2017), and Shaaban and Ghanim (2018), where the implementation of bus priority did not lead to a worsening of the performance measures for the rest of the vehicles, but rather remained unchanged. On the other hand, where the literature is more focused on the delay, not much is mentioned about queue lengths and the number of stops. For these performance measures, the northern and western approaches are showing worse performances than for the priority scenario. However, as with the delay, both average vehicle delay and bus delay, the differences are not that big, but can instead be a result of lack of data, i.e., more field data or more simulations would give a closer value. It can also be that the increase in traffic volume in the simulations could make for more queues and stop, which is not unthinkable. Also, when the bus priority is being implemented, there is an increase in green times for the prioritized movements. This would make the percentage of green time for other movements lower. For instance, looking at what can be considered a cross street at intersection 1, the western approach, a lower green time percentage could lead to an increase in the performance results (Skabardonis & Christofa, 2011), which can be observed with the increase of negative values for the performances of this approach when implementing the bus priority. Yet, when this approach also experiences a priority, which it does with the buses that are arriving from this approach, the performance measures are becoming better again. Though, as the improvements for the intersection cannot be considered to have the main purpose to improve the results for this approach, being able to clear the northern approach in a faster way could also lead to the necessary green time on the northern approach to be shortened, even though the improvement and priority is to extend the green time for phase A. For instance, if the approach is cleared for vehicles, there is no need to continue with phase A. Then, phase B can start earlier.

To decide whether the improvements are worth continuing working with, or to be implemented in a real-life scenario, depends on what the target for the urban transport network is. If the goal is to continue with giving priority to public transport and making this a more attractive offer to travellers, both improvements are showing positive results as they do reduce the bus delay. They also give a small reduction to the average delay, which benefits all travellers using the roads. Improvement 1A is showing better results for buses on two out of three approaches, with one approach almost having no delay. On the other hand, improvement 1B shows better results for the northern approach, which is the approach that contributes to the most delay at the intersection. For the number of stops and maximum queue, 1A gets shorter maximum queues, but there is a need for more stops. As the results are also very close to the priority scenario, it would be helpful to see the improvements tried out at the intersection to see whether there is an improvement, or if the differences are indeed very small, as the simulations have shown. It also needs to be considered the small amount of data gathered from the field study. With the small amount of data, there may be that the collected data is not representative of the intersection and that several recordings would have been more helpful to get a clearer view of how the situation is at the intersection. In that way, it would also have been possible to be more certain whether the priority works better than what was found in the data set that was used. Also, as these data recordings were undertaken during the Covid-19 pandemic, the traffic may not have been representative of the intersection either. During both recordings, there were strict regulations in the municipality of Bergen, meaning that fewer people were supposed to travel to and from work, but rather work from home. And, with traffic conditions, there may not be the case that the results would be the same as what has been found in these field studies. As mentioned by Xu et al. (2010), an increase in traffic volume could lead to an increase in the delay and more disbenefits for the intersection. The fact that the weather conditions also were very different from the first to the second recording should be mentioned. One would think that with warmer temperatures, no ice on the road, and more sunlight per day, people would tend to drive faster, possibly utilize smaller gaps and decrease the headway between other vehicles. But this may have proved not to be the case as the results worsened when the weather got better. However, as with better weather, there was also an increase in the presence of cyclists, which could hinder the vehicles in some way, making them travel slower than if the cyclists were not present. If the recordings would have had a similar number of cyclists, and possibly too with more similar weather conditions, the comparison between the two situations could have been more realistic and reliable. Therefore, as both improvements show good results to some degree, both could be interesting to study further, and the one to go for would be more a question of if one wants to prioritize the buses more than the benefit of the whole intersection.

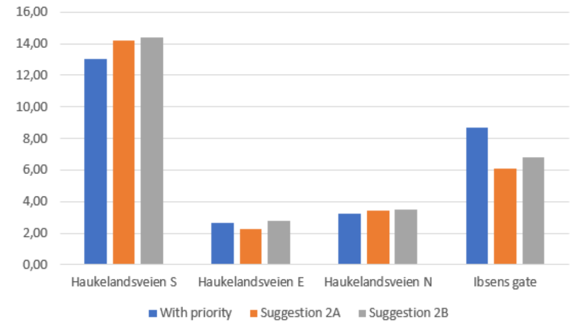
In most cases, it looks like the buses can enter the intersection within the appropriate green time with the green time extension. However, the extension of green time is making the green time percentage for other vehicles lower, but the green time for the other phases and movements would still be triggered, meaning that if a bus arrives during another phase than its own, it will still have to wait as usual. Therefore, to be able to make the buses wait even longer, a green time reduction for opposing movements and phases could have been a thing to have a look into. For instance, if a priority is triggered, the other phases would only use their minimum green times. This could have made the delay for the other approaches, which will only receive the minimum green time, higher as fewer vehicles would be able to clear the approach during a phase. However, prioritizing the buses could have made the waiting time lower. And, as the buses also may have a lot of other traffic around itself, the priority could also benefit the other vehicles by decreasing the delay for these vehicles too. In chapter 1.3 of this thesis, it says that the focus for the third objective is to look at mostly the signal planning and not focus too much on larger geometrical design changes to the intersections. Though, if one were to look at potential changes to the geometrical design for intersection 1, there are a few things that could be looked at; even though the intersection is located very close to apartment buildings, meaning that adding an extra lane or increase the lane width by using more land area than what is already in use would be difficult, making changes related to this could be interesting. As mentioned for improvement 1B, the goal is to not have the two lanes on the northern approach block each other. Therefore, one could consider making the refuge on the northern approach smaller or eventually remove it. When the refuge starts, the lanes become very narrow, thus potentially creating the blocking. Removal of the refuge would allow the lanes to remain wide enough to cater for both buses and cars next to each other. On the other hand, this change would remove the potential safety island for pedestrian crossing the northern approach. With no refuge, one would have to cross the entire approach in one go. For traffic safety reasons, the required green time for this pedestrian crossing would probably be having to be increased, which would give the phases for the movements on the northern approach a lower green time percentage. Another option would be to remove the northern pedestrian crossings entirely. This would mean that the pedestrian would eventually have to cross the road at another pedestrian crossing either 220 meters north of the intersection, or 180 meters south of the intersection. This could also open the possibility of removing the refuge. However, this is an option that is a large disbenefit for pedestrian, and could therefore face some opposition, especially as it can go against the goal of having more trips done by other travel modes than private cars.

9.2 Intersection 2

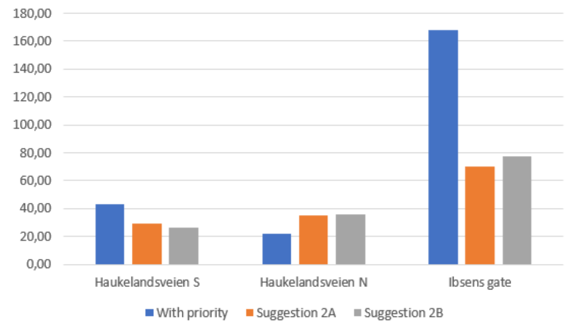
For intersection 2, the focus of the improvements was to improve the problems that occurred on the western approach by 1) increasing the minimum and maximum time for phase C, and 2) changing the phase order for phases B and C to allow for the left-turning vehicles to enter the intersection at the same time as the rest of the arriving vehicles. Looking at improvement 2A, the average delay for this approach is being reduced by almost half a minute, which can be observed in Figure 9.2 a). For the rest of the approaches, this improvement is not showing the greatest changes. The average vehicle delay only changes with a few seconds on the other approaches. However, the change in average vehicle delay for the western approach results in an overall reduction in the total delay of almost three vehicle hours, despite the total delay for the southern approach increasing by approximately one hour. Improvement 2B is not showing as good results as improvement 2A. The improvement is showing a decrease in average and total delay for the western approach as well and for the total delay for the entire intersection with one and a half vehicle hour. However, the reduction in average delay for the western approach is not as large as the reduction in improvement 2A. Here, it is only with six seconds, thus 20 seconds lower than for the first improvement. Based on the delay results for the western approach, improvement 2A is



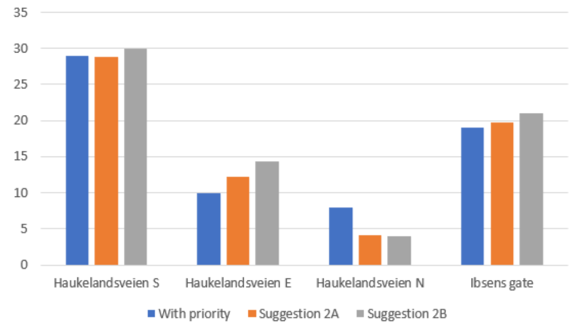
a) Average vehicle delay



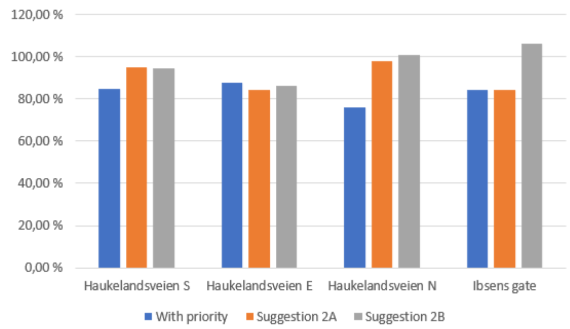
b) Total delay



c) Bus delay



d) Maximum queue



e) Number of stops

Figure 9.2: Improvements comparison for intersection 2

therefore showing a much better result than improvement 2B. Looking at the other approaches, the southern approach shows the same results for both improvements, which is an increase by a few seconds. However, this increase, with the large traffic volume on the approach, is enough to increase the total delay for the approach by over one vehicle hour. For the eastern and northern approaches, the changes in both average vehicle delay and total delay remains mostly the same with only some small changes seen in Figure 9.2. Furthermore, when looking at the results regarding the bus delay, which is shown in Figure 9.2 c), this was in the priority scenario in some way affected by the downstream queue on the northern approach, especially for the southern and western approaches. Looking at these two approaches, the bus delay is significantly being reduced for both improvements. For the western approach, the bus delay is in both improvements decreased with over one and a half minute, while as for the southern approach, the relative difference is also large. For the northern approach, which was the only approach showing an improvement from the no priority scenario, the delay has been increased in both cases, from 21.63 seconds to 34.77 and 36.18 seconds for improvement 2A and 2B, respectively. Regarding the downstream queue that occurred during the field data, this phenomenon proved difficult to recreate during the calibration process, and the jam that was created from this queue was only lasting for a short period in the simulations. Therefore, one can discuss the reliability of the results obtained from the Aimsun Next simulations as they in some ways were a bit different from the real-life observations. On the other hand, the model is calibrated to replicate this situation, and with the calibration parameters used for this, it is also acceptable to assume that they do represent the real-life to a degree and is possible to use to determine whether the improvements are good or not. Also, as the model is an attempt to recreate a real-life situation, an exact replication would be very hard to get, especially with the lack of time and data for the thesis. However, when using the results from the simulations, from Figure 9.2 d) and e), one can observe that where the improvements in most cases showed better results than for the priority scenario regarding the delay, the performances related to the maximum queue and number of stops are showing a more negative trend. Though the northern approach is showing an improvement in the maximum queue for both improvements, that is the only time the improvements are showing better results. The maximum queue for the other three approaches remains mostly the same, with a small increase in some places. Regarding the number of stops, some of the approaches are even showing a result meaning that a vehicle, on average needs to stop more than once while in the model section. The increase in the number of stops can be related to the calibration parameters for the model, especially the reaction times to traffic lights and stops. These values have been set, for some approaches, to be very high so that the model could be calibrated correctly. However, this would also lead to the vehicles possibly not reacting as fast as they would in real life, and not utilize gaps and entering the intersection during the yellow signal. A larger reaction time would also maybe contribute to more shock waves, stopping the traffic further behind in the model sections.

Looking at the effect the improvements are having on the buses, both the southern and western approaches are benefiting from the improvements as the bus delay is reduced for both. In the priority scenario, the western approach was experiencing a very high delay, which was a very large increase from the no priority scenario. The southern approach also experienced a large increase from the no priority scenario to the priority scenario. Both these increases were in some way influenced by the downstream queue on the northern approach during the field recordings. In the simulations, this downstream queue was present at times, but not on the same scale as in the real-life situation. This can be observed in the results in Figure 9.2 c) as the delay for the buses were greatly reduced. The phenomenon of a downstream queue next to bus stops was discussed by Lian et al. (2019), where a larger number of buses arriving at a downstream bus stop could lead to more disbenefits for the intersection. Even though the construction work on the northern side of the tunnel also contributes to the downstream queue in some way, having an overload of buses at the downstream bus stop also contributes to more disbenefits for the intersection. If there were two downstream lanes instead of only one, i.e., the buses could stay in a separate lane from the other vehicles, the influence of the bus overload could have been less prominent. Also, regarding the western approach, during the field recordings, it looked like the priority did not always work. The buses sometimes had to wait for several cycles, even though they had passed the detectors that were triggering the priority. In the simulations, where this is programmed to be triggered every time, the bus priority will always work. Therefore, this would most likely mean that the buses would benefit from the improvements used in Aimsun Next. Furthermore, where the southern and western approaches are both getting a reduced delay, the northern approach is getting an increase in bus delay for both improvements. Also, none of the improvements were focusing on improving the performance for the buses on this approach, meaning that more benefits on the other movements would lead to fewer benefits for this approach.

Apart from the delay for all vehicles and the bus delay, the maximum queue length increases for the eastern and western approaches, while staying somewhat the same for the southern approach. For the northern approach, the maximum queue is being reduced by 50% for both improvements. In both improvements, the green time for some of the phases is being extended, meaning that the percentage of green time for other phases will be lower. Therefore, as with intersection 1, it is no surprise that this results in long queues, as the approaches have more time to build up the queue before their green time. The extended waiting time for some approaches can also be observed when looking at the number of stops for the different approaches. For this performance, only the eastern approach is showing an improvement, with a slight reduction for both improvements. Improvement 2A is the one that shows the best results regarding this performance of the two improvements. 2B on the other hand gives some results that means that the vehicles on average stop more than once for both the northern and western approaches. Even though the northern approach is part of the route where the main traffic flow goes, i.e., between the northern and southern approaches, the green times for the northern movements in this phase does not have as long green times as, for instance, the movements on the southern approaches. As the left turn on the northern approach has a lower flow than the left turn on the southern approach, the green time on this is shorter than for the southern movement's left turn. Due to this, the through movement for the southern approach can start before the through movement on the northern approach, giving the through movement on the northern approach a shorter green time than for the through movement on the southern approach. Because of this, the probability of more vehicles needing to stop is increased. And, combined with the length of the phases B and C in the improvements, it is understandable that this performance result is increasing even more. Regarding the high value for improvement 2B on the western approach, this improvement is increasing the waiting time for the movements on the western approach as the eastern approach movements receives more green time as the northern pedestrian crossing needs to be catered for.

When it comes to if the improvements suggested for intersection 2 is worth implementing or trying out in a real-life scenario, it needs to be looked at the goal for the transport network, likewise with for intersection 1. Even though both improvements gives a negative result for bus delay on the northern approach, which is the approach with the most buses, the new value for bus delay is still lower than the average vehicle delay for the approach. Also, this increase in delay is not as large as the reduction in delay that is obtained for, especially, the western approach, where both improvements reduce the delay by between 90 and 100 seconds. In addition, the reduction in bus delay for the southern approach is very significant and is somewhat the same as the increase for the northern approach. Therefore, as both these improvements are giving better results for buses, they can both be worth considering. Furthermore, looking at the entire intersection with all vehicles and approaches, improvement 2A shows the best results for all the performance results. Both 2A and 2B gives a reduction in total delay, however, 2A gives a reduction over one vehicle more than 2B. Whereas for the maximum queue and number of stops, the results for 2A is a little bit better than 2B, even though they are both worse than the real-life priority scenario. Therefore, since both improvements are showing both better, but also worse results, it needs to be looked at what the goal is to achieve. As both are reducing the total delay and bus delay, they are both interesting to proceed with. However, as improvement 2A is showing better results in most cases, this improvement looks to be the most promising of the two. This means that changing the phase order of phases B and C may not prove to be the most efficient way of solving the problem on the western approach. It may reduce the benefits to some degree, but only focusing on extending the green time for the approach looks to be sufficient for improving the bad results observed in the priority scenario.

As this intersection have recently been redeveloped, getting a new approach lane system for some of the approaches, changes to the geometrical design would most likely be complicated. However, there may be that some changes to the geometric design could have helped to improve the traffic management at the intersection. For instance, for phase C[16], which includes the eastern approach movements, the southernmost pedestrian crossing on the eastern approach, and the pedestrian crossing on the northern approach, it is the latter that are requiring the most time as the length of the pedestrian crossing is long, crossing five lanes, three approaching and two exiting lanes, without a middle refuge to stop at. Therefore, this phase needs to have enough time to cater for this movement. However, if one were to remove this crossing, the required green time for phase C would have been decreased, getting less waiting time for the other busier approaches. This change could increase the delay for the eastern approach, but with the low traffic volume, reducing the delay on the other approaches can make the change justified. However, removing the pedestrian crossing would raise the question of where the pedestrians can cross the road. Now, an alternative route is to go over the tunnel to the north. Though, this would make the travel time extensively longer, also raising the potential of a rising number of

[16] Phase C in the original signal phase plan

jaywalkers crossing this approach. This alternative route would also probably have to undergo some improvements as it is not designed for universal accessibility. Based on this, removing the pedestrian crossing would also not be an improvement that contributes to the goal of less private vehicle trips and more use of public transport, cycling and walking, as it is making the latter less efficient. On the other hand, looking at the traffic management at the intersection, this alteration could be interesting as it makes the green time for phase C not dependant on the pedestrian crossing. Another option that could be worth looking into is to rearrange the lane system on the western approach. Now, at the intersection, the western approach is having four lanes, where two are turning right, one through movement, and one turning left. The rightmost lane is a bus lane but was in the recordings rarely used by buses. Redesigning the lane assignment to, for instance, one more left turning lane for buses, could potentially remove some of the upstream queues. This suggestion could potentially let more vehicles come closer to the intersection and allow for other vehicles to not being stuck where the lanes merge into one lane further upstream. However, if this is not combined with some changes in green time, or other signal phasing management, the approach would probably fill up, nonetheless. The bus lane could also be under-utilized at many times as there are not many buses on this approach. Also, the right turning lane that will be the only right turning lane has a very sharp turn, making it hard for some vehicles to make the turn without interfering with the adjacent lane. This can also be a reason why only a few buses were using this lane in the field recordings.

10 Conclusion

The goal of the thesis was to evaluate the effects a bus priority scheme had on a signalized intersection, as well as looking at potential improvements to optimize the priority even more. Two intersections in the municipality of Bergen were used. Based on the theory, a bus priority should make the benefits for buses better than for a situation without the priority. This includes reducing the delay and number of stops. Also, the other vehicles that used the same route as the buses could benefit from the priority as the priority the bus is receiving can be utilized by them. However, in some situations, the priority can create more traffic problems, and make the results from the priority even worse than a normal no priority design. For instance, if a non-arterial road receives a lot of priority, the arterial road can experience more waiting time than what it should do based on the share of the traffic volume. Also, too many buses on an arterial road can lead to the priority being triggered too often, also increasing the disbenefits for the non-arterial roads as they are having a less green time percentage.

On the other hand, being able to clear the way for the buses before they arrive at the intersection will make for a shorter requirement time for the priority to be triggered. Therefore, making efforts to prioritize approaches with a lot of queues and delays so that these are not blocking the buses can make for better efficiency of the priority. So, increasing the green time for vehicles that are blocking the buses can contribute to decreasing the disbenefits for the signalized intersection. This was shown in the two intersections used for this thesis. Other improvements that could help the priority and the efficiency of the intersections could include removing pedestrian crossings as these are critical when interfering with their opposing movements. However, removing these would mean removing facilities that are to be used for a more sustainable urban network, where the goal is to use fewer private vehicles, and rely more on urban transport, bikes, and walking.

Yet, due to limited time and resources, there was not gathered a lot of field data. Therefore, to get a clearer view over the intersection and to exclude large sample deviations, more extensive field studies for the BAS is needed to conclude on how well the priority is performing.

11 Further work

As mentioned in the thesis, to the north of intersection 2, there was some construction work going on while the field studies were being undertaken. This construction work could have had some impact on the efficiency of the intersection, especially considering the downstream queue on the northern approach. Therefore, more extensive work on how this work was impacting the intersection and how this could have been avoided would have made it possible to be more certain of how the priority was affecting the intersection. This problem may not only refer to this type of construction work, but also to how other types of external factors further away from the intersection are affecting the traffic management and performances for the intersection.

Also, this thesis has been made during the Covid-19 pandemic, meaning that the traffic volume on the roads was not necessarily how it would be under normal circumstances. And, as mentioned in the literature chapter, an increase in traffic volume could lead to a large change in the performance results when a bus priority scheme is implemented. Therefore, looking at the intersections under normal traffic conditions would be helpful to investigate how the priority is working.

In the end, the goal with the bus priority is to make the buses a more reliable and competitive transport mode to private vehicles. Therefore, examining if there is a shift in the share of trips away from private vehicles can be helpful to see whether the priority is meeting its goal.

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Attachment A – OD matrices

A1 – Intersection 1

Without priority

Light vehicles

O\D	South	North	West	Sum
South		246	88	**334**
North	472		284	**756**
West	123	189		**312**
Sum	**595**	**435**	**372**	**1402**

Trucks

O\D	South	North	West	Sum
South		2	0	**2**
North	2		2	**4**
West	0	1		**1**
Sum	**2**	**3**	**2**	**7**

Bicycles

O\D	South	North	West	Sum
South		2	0	**2**
North	17		2	**19**
West	2	2		**4**
Sum	**19**	**4**	**2**	**25**

Buses (no PT)

O\D	South	North	West	Sum
South		1	0	**1**
North	2		1	**3**
West	0	2		**2**
Sum	**2**	**3**	**1**	**6**

Pedestrians

O\D	West S	North W	South E	Sum
West N	0	0	18	**18**
South W	0	15	0	**15**
North E	16	0	0	**16**
Sum	**16**	**15**	**18**	**49**

With priority

Light vehicles

O\D	South	North	West	Sum
South		245	84	**329**
North	482		299	**781**
West	122	205		**327**
Sum	**604**	**450**	**383**	**1437**

Trucks

O\D	South	North	West	Sum
South		1	0	**1**
North	3		2	**5**
West	0	0		**0**
Sum	**3**	**1**	**2**	**6**

Bicycles

O\D	South	North	West	Sum
South		0	6	**6**
North	51		5	**56**
West	6	2		**8**
Sum	**57**	**2**	**11**	**70**

Buses (no PT)

O\D	South	North	West	Sum
South		1	0	**1**
North	0		0	**0**
West	0	3		**3**
Sum	**0**	**4**	**0**	**4**

Pedestrians

O\D	West S	North W	South E	Sum
West N	0	0	29	**29**
South W	0	12	10	**22**
North E	10	0	0	**10**
Sum	**10**	**12**	**39**	**61**

A2 – Intersection 2

Without priority

Light vehicles

O\D	South	East	North	West	**Sum**
South		140	327	227	**694**
East	71		31	60	**162**
North	133	60		41	**234**
West	93	161	105		**359**
Sum	**297**	**361**	**463**	**328**	**1449**

Trucks

O\D	South	East	North	West	**Sum**
South		0	8	1	**9**
East	3		1	4	**8**
North	5	1		8	**14**
West	1	1	9		**11**
Sum	**9**	**2**	**18**	**13**	**42**

Bicycles

O\D	South	East	North	West	**Sum**
South		18	24	3	**45**
East	0		0	0	**0**
North	1	0		1	**2**
West	0	3	0		**3**
Sum	**1**	**21**	**24**	**4**	**50**

Buses (no PT)

O\D	South	East	North	West	**Sum**
South		0	3	2	**5**
East	0		0	0	**0**
North	9	0		2	**11**
West	7	0	0		**7**
Sum	**16**	**0**	**3**	**4**	**23**

Pedestrians

O\D	South W	North W	East N	South E	**Sum**
South E		25	133	0	**158**
West N	20		50	30	**100**
North E	15	5		80	**100**
South W	0	12	15		**27**
Sum	**35**	**42**	**198**	**110**	**385**

With priority

Light vehicles

O\D	South	East	North	West	**Sum**
South		156	299	235	**690**
East	67		28	72	**167**
North	155	57		35	**247**
West	79	167	95		**341**
Sum	**301**	**380**	**422**	**342**	**1445**

Trucks

O\D	South	East	North	West	**Sum**
South		0	6	1	**7**
East	2		3	2	**7**
North	8	4		8	**20**
West	1	1	8		**10**
Sum	**11**	**5**	**17**	**11**	**44**

Bicycles

O\D	South	East	North	West	**Sum**
South		40	71	10	**121**
East	0		0	0	**0**
North	7	2		1	**10**
West	0	5	0		**5**
Sum	**7**	**47**	**71**	**11**	**136**

Buses (no PT)

O\D	South	East	North	West	**Sum**
South		0	1	0	**1**
East	0		0	0	**0**
North	10	0		3	**13**
West	5	0	0		**5**
Sum	**15**	**0**	**1**	**3**	**19**

Pedestrians

O\D	South W	North W	East N	South E	**Sum**
South E		17	100	0	**117**
West N	43		83	25	**151**
North E	20	10		92	**122**
South W	0	12	12		**24**
Sum	**63**	**39**	**195**	**117**	**414**

Attachment B – Buses and timetables

B1 – Intersection 1

Bus	Direction	Stops	Frequency	Starts
2	North to south	North	10 min	14:59
3	North to West	North, West	10 min	14:54
21	North to south	North	30 min	14:47
25	North to West	North, West	30 min	14:53
80	North to south	North	10 min	14:59
604	North to west	North, west	60 min	15:17

Bus	Direction	Stops	Frequency	Starts
2	South to north	North	10 min	14:52
3	West to north	North	10 min	14:47
21	South to north	North	30 min	14:34
			10 min	15:24
25	West to north	North	30 min	14:45
80	South to north	North	10 min	14:43

B2 – Intersection 2

Bus	Direction	Stops	Frequency	Starts
2	North to south	North	10 min	07:14
3	North to south	North	10 min	07:01
12	North to south	North	10 min	07:31
20	North to south	North, south	15 min	07:06
21	North to south	North	15 min	07:16
27	North to west	North	30 min	No morning route
28	North to west	North	60 min	No morning route
80	North to south	North	10 min	07:18
604	North to south	North	60 min	No morning route

Bus	Direction	Stops	Frequency	Starts
2	South to north	North	10 min	07:26
3	South to north	North	20 min	07:11
			10 min	08:12
12	South to north	North	14 min	07:31
			10 min	07:45
20	Start north	North	20 min	07:05
21	South to north	North	14 min	07:30
			10 min	07:44
27	West to north	North	20 min	07:15
			9 min	07:35
			20 min	07:53
			Stopp	08:12
28	West to north	North	20 min	07:26
			Stopp	08:06
80	South to north	North	10.5 min	07:25

Attachment C – Signal planning data for Aimsun Next

C1 – Intersection 1

Phase	Movement(s)	Minimum green time	Maximum green time	Passage time
1	Through from south Through from north	10 sec	60 sec	3 sec
3	Left turn from west Right turn from west	4 sec	23 sec	3 sec
5	Left turn from south Right turn from west Pedestrian crossing north	15 sec	15 sec	3 sec
7	Pedestrian crossing west	21 sec	21 sec	3 sec
8	Right turn from north	8 sec	40 sec	3 sec
10	Left turn from south Right turn from west	4 sec	12 sec	3 sec

Interphase	Duration
2, 4, 6, 9, 11	5 sec

Detector ID	Location	Allocated to phase
1122	Southern approach	5
1123	Western approach	3,5
1129	Western approach	3
1130	Northern approach	1
1131	Northern approach	8
1132	Southern approach	1

C2 – Intersection 2

Phase	Movement(s)	Minimum green time	Maximum green time	Passage time
1	Right turn from east Left turn from north	12 sec	12 sec	3 sec
3	Through from south Two northernmost pedestrian crossings east	7 sec	7 sec	3 sec
4	Through from south Two northernmost pedestrian crossings east Pedestrian crossing west	20 sec	38 sec	3 sec
6	Through from east Southernmost pedestrian crossing east Pedestrian crossing north	25 sec	25 sec	3 sec
8	Left turn from west	6 sec	8 sec	3 sec
10	Left turn from south	10 sec	24 sec	3 sec
11	Through and right turn from north	20 sec	29 sec	3 sec
13	Left turn from east	7 sec	8 sec	3 sec
15	Through from west Right turn from west	6 sec	30 sec	3 sec
17	Right turn from west	6 sec	24 sec	3 sec
18	Right turn from south	6 sec	38 sec	3 sec
20	Right turn from east	6 sec	12 sec	3 sec

Interphase	Duration
2, 5, 7, 9, 12, 14, 16, 19	5 sec

Detector ID	Location	Allocated to phase
579	Southern approach	10
581	Eastern approach	20
582	Northern approach	11
583	Northern approach	1
585	Western approach	15, 17
588	Western approach	8
589	Eastern approach	13
590	Southern approach	3, 4
591	Southern approach	3, 4
592	Southern approach	18
654	Eastern approach	6
655	Western approach	15

Attachment D – Priority settings for Aimsun Next

D1 – Intersection 1

Priority parameter	Priority 0	Priority 1
Public transport lines	2 northbound	3 northbound
	2 southbound	3 westbound
	21 northbound	25 northbound
	21 southbound	25 westbound
	80 northbound	604 westbound
	80 southbound	
Phase	1	8
		3
Priority request detectors	281	283
	283	285
Priority end detectors	1106	1108
	1109	1109
Delay	0	0
Inhibit	0	0
Minimum dwell	12	10
Maximum dwell	60	30
Reserve	0	0
Type	Serve all	Serve all

D2 – Intersection 2

Priority parameter	Priority 0	Priority 1	Priority 2
Public transport lines	2 northbound	2 southbound	27 northbound
	3 northbound	3 southbound	28 northbound
	12 northbound	12 southbound	
	20 northbound	20 southbound	
	21 northbound	21 southbound	
	80 northbound	80 southbound	
Phase	4	11	8
Priority request detectors	639	641	643
Priority end detectors	640	642	640
Delay	5	20	0
Inhibit	0	0	0
Minimum dwell	30	20	5
Maximum dwell	45	29	50
Reserve	0	0	0
Type	Serve all	Serve all	Serve all

Attachment E – Calibration parameters

E1 – Intersection 1

Global parameters

Parameter	Value
Warmup period	10 minutes
Simulation step	0.50 sec
Reaction time at stop	0.70 sec
Reaction time at traffic light	0.70 sec
Queue entry speed	0.00 m/s
Queue exit speed	2.00 m/s

Local parameters

Approach	Parameter	Value
South	Acceleration factor	Increase x5
	Additional reaction time at stop	-1.00 sec
	Additional reaction time at traffic light	-1.00 sec
North	Acceleration factor	Increase x5
	Additional reaction time at stop	-1.00 sec
	Additional reaction time at traffic light	-1.00 sec
West	Acceleration factor	Increase x2
	Additional reaction time at stop	0.00 sec
	Additional reaction time at traffic light	0.00 sec

Vehicle parameters

Bicycle

Parameter	Mean	Deviation	Minimum	Maximum
Length	1.80	0.10	1.55	1.90
Width	0.75	0	0.75	0.75
Max desired speed	30.0km/h	10.0km/h	10.0km/h	40.0km/h
Speed limit acceptance	1.00	0.10	0.80	1.00
Max acceleration	3.00m/s^2	0m/s^2	3.00m/s^2	3.00m/s^2
Normal deceleration	4.00m/s^2	0m/s^2	4.00m/s^2	4.00m/s^2
Max deceleration	6.00m/s^2	0m/s^2	6.00m/s^2	6.00m/s^2
Reaction time			0.8	
Reaction time at stop			1.2	
Reaction time in front of vehicle at traffic light			1.6	

Car

Parameter	Mean	Deviation	Minimum	Maximum
Length	4.80	0.50	3.50	5.00
Width	1.80	0.20	1.60	2.00
Max desired speed	110.0km/h	10.0km/h	80.0km/h	150.0km/h
Speed limit acceptance	1.00	0.30	0.50	1.10
Max acceleration	3.10m/s^2	0.20m/s^2	2.60m/s^2	3.40m/s^2
Normal deceleration	4.00m/s^2	0.25m/s^2	3.50m/s^2	4.50m/s^2
Max deceleration	6.00m/s^2	0.50m/s^2	5.00m/s^2	7.00m/s^2
Reaction time			0.5	
Reaction time at stop			1.0	
Reaction time in front of vehicle at traffic light			1.0	

Bus

Parameter	Mean	Deviation	Minimum	Maximum
Length	15.00	3.00	12.00	22.00
Width	2.55	0	2.55	2.55
Max desired speed	90.0km/h	10.0km/h	70.0km/h	100.0km/h
Speed limit acceptance	0.95	0.10	0.80	1.05
Max acceleration	1.00m/s^2	0.30m/s^2	0.80m/s^2	1.80m/s^2
Normal deceleration	2.00m/s^2	1.00m/s^2	1.50m/s^2	4.50m/s^2
Max deceleration	5.00m/s^2	1.00m/s^2	4.00m/s^2	6.00m/s^2
Reaction time			0.5	
Reaction time at stop			1.0	
Reaction time in front of vehicle at traffic light			1.0	

Truck

Parameter	Mean	Deviation	Minimum	Maximum
Length	12.00	2.00	8.00	20.00
Width	2.55	0.20	2.00	2.80
Max desired speed	85.0km/h	10.0km/h	70.0km/h	100.0km/h
Speed limit acceptance	1.00	0.05	0.80	1.05
Max acceleration	1.00m/s^2	0.50m/s^2	0.60m/s^2	1.80m/s^2
Normal deceleration	3.50m/s^2	1.00m/s^2	2.50m/s^2	4.80m/s^2
Max deceleration	5.00m/s^2	0.50m/s^2	4.00m/s^2	6.00m/s^2
Reaction time			0.8	
Reaction time at stop			1.0	
Reaction time in front of vehicle at traffic light			1.0	

E2 – Intersection 2

Global parameters

Parameter	Value
Warmup period	10 minutes
Simulation step	0.5 sec
Reaction time at stop	0.7 sec
Reaction time at traffic light	0.7 sec
Queue entry speed	0.00 m/s
Queue exit speed	2.00 m/s

Local parameters

Approach	Parameter	LT/TH	Bus lane	RT
South	Acceleration factor	No change	Decrease x0.5	Decrease x0.5
	Additional reaction time at stop	0.50 sec	1.00 sec	1.00 sec
	Additional reaction time at traffic light	0.00 sec	1.00 sec	1.00 sec
		LT/TH	**RT**	
East	Acceleration factor	Decrease x0.5	Decrease x0.5	
	Additional reaction time at stop	1.00 sec	1.00 sec	
	Additional reaction time at traffic light	0.00 sec	1.00 sec	
		LT/TH/RT		
North	Acceleration factor	No change		
	Additional reaction time at stop	0.00 sec		
	Additional reaction time at traffic light	0.00 sec		
		LT/TH	**RT**	
West	Acceleration factor	Decrease x0.5	Decrease x0.5	
	Additional reaction time at stop	2.00 sec	1.00 sec	
	Additional reaction time at traffic light	1.00 sec	1.00 sec	

Vehicle parameters

Bicycle

Parameter	**Mean**	**Deviation**	**Minimum**	**Maximum**
Length	4.80	0.50	3.50	5.00
Width	1.80	0.20	1.60	2.00
Max desired speed	110.0km/h	10.0km/h	80.0km/h	150.0km/h
Speed limit acceptance	1.00	0.30	0.50	1.10
Max acceleration	3.10m/s^2	0.20m/s^2	2.60m/s^2	3.40m/s^2
Normal deceleration	4.00m/s^2	0.25m/s^2	3.50m/s^2	4.50m/s^2
Max deceleration	6.00m/s^2	0.50m/s^2	5.00m/s^2	7.00m/s^2
Reaction time		0.8		
Reaction time at stop		1.2		
Reaction time in front of vehicle at traffic light		1.6		

Car

Parameter	**Mean**	**Deviation**	**Minimum**	**Maximum**
Length	4.80	0.50	3.50	5.00
Width	1.80	0.20	1.60	2.00
Max desired speed	110.0km/h	10.0km/h	80.0km/h	150.0km/h
Speed limit acceptance	1.00	0.30	0.50	1.10
Max acceleration	3.10m/s^2	0.20m/s^2	2.60m/s^2	3.40m/s^2
Normal deceleration	4.00m/s^2	0.25m/s^2	3.50m/s^2	4.50m/s^2
Max deceleration	6.00m/s^2	0.50m/s^2	5.00m/s^2	7.00m/s^2
Reaction time		0.5		
Reaction time at stop		1.0		
Reaction time in front of vehicle at traffic light		1.0		

Bus

Parameter	Mean	Deviation	Minimum	Maximum
Length	15.00	3.00	12.00	22.00
Width	2.55	0	2.55	2.55
Max desired speed	90.0km/h	10.0km/h	70.0km/h	100.0km/h
Speed limit acceptance	0.95	0.10	0.80	1.05
Max acceleration	1.00m/s^2	0.30m/s^2	0.80m/s^2	1.80m/s^2
Normal deceleration	2.00m/s^2	1.00m/s^2	1.50m/s^2	4.50m/s^2
Max deceleration	5.00m/s^2	1.00m/s^2	4.00m/s^2	6.00m/s^2
Reaction time		0.5		
Reaction time at stop		1.0		
Reaction time in front of vehicle at traffic light		1.0		

Truck

Parameter	Mean	Deviation	Minimum	Maximum
Length	12.00	2.00	8.00	20.00
Width	2.55	0.20	2.00	2.80
Max desired speed	85.0km/h	10.0km/h	70.0km/h	100.0km/h
Speed limit acceptance	1.00	0.05	0.80	1.05
Max acceleration	1.00m/s^2	0.50m/s^2	0.60m/s^2	1.80m/s^2
Normal deceleration	3.50m/s^2	1.00m/s^2	2.50m/s^2	4.80m/s^2
Max deceleration	5.00m/s^2	0.50m/s^2	4.00m/s^2	6.00m/s^2
Reaction time		0.8		
Reaction time at stop		1.0		
Reaction time in front of vehicle at traffic light		1.0		

Attachment F – Calibration

F1 – Intersection 1

Calibration **Intersection 1**

Delay

Delay no aps

Approach	Observed, c	Modelled, m	Difference	Delay diff
South	8,36	8,23	-0,13	Ok
North	17,13	17,83	0,7	Ok
West	18,02	18,17	0,15	Ok

Max error	
5	seconds

Delay with aps

Approach	Observed, c	Modelled, m	Difference	Delay diff
South	10,49	9,6	-0,89	Ok
North	22,17	20,74	-1,43	Ok
West	21,8	19,64	-2,16	Ok

Queue

Max queue no aps

Approach	Observed, c	Modelled, m	Difference	Queue diff
South	6	3,4	-2,6	Ok
North	11	8,4	-2,6	Ok
West	8	5,2	-2,8	Ok

Max error	
3	vehicles

Max queue with aps

Approach	Observed, c	Modelled, m	Difference	Queue diff
South	5	5,2	0,2	Ok
North	10	12,6	2,6	Ok
West	5	6,4	1,4	Ok

Stops

Number of stops no aps

Approach	Observed, c	Modelled, m	Difference	Stops diff
South	51,00 %	48,00 %	-0,03	Ok
North	51,90 %	78,00 %	0,261	Ok
West	82,60 %	74,00 %	-0,086	Ok

Max error	
30,00 %	vehicles

Number of stops with aps

Approach	Observed, c	Modelled, m	Difference	Stops diff
South	57,60 %	51,00 %	-0,066	Ok
North	62,50 %	85,00 %	0,225	Ok
West	61,40 %	77,00 %	0,156	Ok

F2 – Intersection 2

Calibration Intersection 2

Delay

Delay no aps

Approach	Observed, c	Modelled, m	Difference	Delay diff
South	40,58	33,91	-6,67392	Ok
East	52,47	61,38	8,912143	Ok
North	34,58	33,12	-1,46	Ok
West	60,58	73,01	12,42601	Ok

Max error	
15	seconds

Delay with aps

Approach	Observed, c	Modelled, m	Difference	Delay diff
South	64,06	63,27	-0,7922	Ok
East	53,87	44,30	-9,57435	Ok
North	36,61	35,75	-0,86	Ok
West	85,92	80,03	-5,89258	Ok

Queue

Max queue no aps

Approach	Observed, c	Modelled, m	Difference	Queue diff
South	29	19,00	-10	Ok
East	11	11,00	0	Ok
North	9	3,8	-5,2	Ok
West	18	20,60	2,6	Ok

Max error	
10	vehicles

Max queue with aps

Approach	Observed, c	Modelled, m	Difference	Queue diff
South	29	27,00	-2	Ok
East	10	8,20	-1,8	Ok
North	8	4,8	-3,2	Ok
West	19	20,80	1,8	Ok

Stops

Number of stops no aps

Approach	Observed, c	Modelled, m	Difference	Stops diff
South	84,40 %	78,28 %	-0,061	Ok
East	89,40 %	97,14 %	0,077	Ok
North	79,40 %	94,00 %	0,146	Ok
West	92,60 %	99,66 %	0,071	Ok

Max error	
30,00 %	vehicles

Number of stops with aps

Approach	Observed, c	Modelled, m	Difference	Stops diff
South	84,50 %	91,48 %	0,070	Ok
East	87,50 %	81,33 %	-0,062	Ok
North	75,90 %	93,00 %	0,171	Ok
West	84,20 %	99,19 %	0,150	Ok

Evaluation and Modelling of Bus Priority at Signalized Intersections

NTNU
Kunnskap for en bedre verden

Vestland fylkeskommune