Optimization of Signal Controlled Bicycle Crossings

Adaption to an Increase in Bicyclists in Gothenburg

Master's thesis in Infrastructure and Environmental Engineering

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Gothenburg, Sweden 2019

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Abstract

The city of Gothenburg has a strategic goal aiming to increase the total amount of trips made by bicycle with a factor of 3 by 2025 compared to 2011's numbers. This report has aimed towards evaluating how the signal controlled crossings in Gothenburg will handle the mentioned increase and how they can be optimized to handle said increase by trying to answer three questions *Is there a certain commuter path that is more prone to queuing than others?*, *In what way can the existing traffic signals on such paths be optimized in order to reduce queuing in the future?*, and *How would such optimization for bicycles affect the overall traffic situation?*. In order to answer the questions, site investigations were made on 9 different locations divided between three areas that were carefully selected to represent the bicycle infrastructure in Gothenburg, that was under risk of congestion, on a wider level. Each intersection was visited at least twice, one morning and one afternoon, and information on how the bicyclists used the intersection was collected and then used as a base for simulation of the future in the simulation software PTV Vissim. The results show that without any measures two of the three different areas studied cannot handle the increase in total bicyclists and entails longer travel times or long queues. By either implementing green waves, prolonged green times, sections of all green, or bicycle priority into the signal sequences the capacity in the intersections increased but the optimizing measures lead instead to deterioration for other means of transport that was not traveling in the same direction as the bicycles. Concluding the results it can be said that there is more needed to facilitate the total increase in bicyclists in Gothenburg than changes to the signal sequences. Either a redesign is needed at problem areas or the total car traffic needs to be decreased if the overall flow of the traffic is to be maintained in the future.

Optimisering av Signalkontrollerade Cykelöverfarter
Anpassning till en ökning av antalet cyklister i Göteborg
Examensarbete inom masterprogrammet Infrastruktur och Miljöteknik
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Sammanfattning

Göteborgs stad har som strategiskt mål att öka det totala antalet cykelresor med en faktor 3 till år 2025 jämfört med 2011 års siffror. Denna rapport har syftat till att utvärdera hur de signalkontrollerade korsningarna i Göteborg kommer att hantera ökningen av cyklar och hur de kan optimeras för att hantera ökningen genom att försöka svara på tre frågor *Finns det en viss pendlingsväg som är mer utsatt för köande än andra?*, *Hur kan de befintliga trafiksignalerna på sådana vägar optimeras för att minska köandet i framtiden?* och *Hur skulle en sådan optimering för cyklar påverka trafiksituationen i sin helhet?*. För att svara på frågorna gjordes platsundersökningar på 9 olika platser fördelade på tre områden som var noggrant utvalda för att representera cykelinfrastrukturen som är utsatt för trängsel i Göteborg på en bredare nivå. Varje korsning besöktes minst två gånger, en morgon och en eftermiddag, och information om hur cyklisterna använde korsningen samlades in och användes sedan som en bas för framtidsimuleringar i PTV Vissim. Resultaten visar att utan några åtgärder kan två av de tre områdena som studerades inte hantera den totala ökningen av cyklister och medför längre restider eller långa köer. Genom att antingen införa gröna våg, förlängda gröntider, allgrönt eller cykelprioritering i signalsekvenserna ökade kapaciteten i korsningarna men optimeringsåtgärderna leder även till försämring för andra transportmedel som inte färdades i samma riktning som cyklarna. Slutvis utifrån resultaten kan slutsatsen dras att det behövs mer för att hantera den totala ökningen av cyklister i Göteborg än förändringar i signalsekvenserna. Antingen behövs en ombyggnad för problemområden eller att den totala biltrafiken minskas om flödet i trafiken ska bibehållas i framtiden.

Preface

This project has been carried out during the spring of 2019 as a Master's Thesis at the master programme Infrastructure and Environmental Engineering and concludes our studies at Chalmers University of Technology.

Before you, our reader, continues to explore the results of our work on the future of the bicycle infrastructure in Gothenburg we would like to acknowledge some people who have made this thesis possible.

First, we would like to thank our supervisor at WSP Sweden, Sebastian Hasselblom, without whom this thesis would not have existed. Sebastian has provided guidance when needed and it was with the help of Sebastian that the subject of the thesis was developed. Additionally, we would also like to thank Carl Johan Schultze at WSP Sweden for guidance and functioning as a stand-in supervisor whenever Sebastian was not available at the office.

Secondly, we would like to thank PTV Group, and Jan Dietrich in particular, for the providence of a license to use the simulation software and help with getting said license to work. Without this help, the work with simulations of the future would have become far more complex than needed.

We would also like to thank Fredrik Larsson and Lilia Halsen Bidar at the Traffic and Public Transport Authority in Gothenburg for helping us collect data on bicycle passages from previous years and signal sequences respectively, data that has played a big part in the study.

Lastly, we would like to thank our respective family and friends for moral support during both this thesis and all our years at Chalmers. Thank you for putting up with us.

<div align="center">
Johan Bergman & Christofer Sernheim Sandäng, Gothenburg, May 2019
</div>

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1 | INTRODUCTION

This chapter introduces the reader to the thesis by providing a background to the study and information on what the study works towards accomplishing.

1.1 | Background

According to Nationalencyklopedin (2019), the bicycle's history in Sweden sets foot in the middle of the 19th century. Back then there were only a sparse amount of bicycles in Sweden produced mainly out of wood and steel. 20 years later the first bicycle factory was built producing Penny-farthings at first and thereafter the so-called Safety Bicycles which the modern bicycle is based off.

Despite the bicycle's long history in Sweden the bicycle as a mean of mass transportation was later passed by the car unlike what happened in many other countries where the bicycle still is the more common mean of transport. At the beginning of the 21st century, bicycles only made up one-tenth of the total trips in Sweden while half of the trips made by cars were shorter than 5 kilometers (Nationalencyklopedin, 2019).

However, things are starting to change and cities around Sweden has started to invest in bicycle infrastructure to encourage more people to leave the car at home in favor of the bicycle. The reasons are many and one is the environmental aspect. To prevent and reduce the global warming there are a several measures that can be done, one of them is to enhance and encourage more bicycling.

A study about transportation modes showed that an increment in bicycle usage would result in climate change mitigation (Massink, Zuidgeest, Rijnsburger, Sarmiento, & Maarseveen, 2011) by a reduction in CO_2 emission. Due to this, the city of Gothenburg, located in the western parts of Sweden as shown in Figure 1.1, passed a strategy program for bicycle traffic called *For a close big city* (Månson & Junemo, 2015) in the year of 2015. The vision is that the city of Gothenburg should become an attractive bicycle city where the bicycle is a competitive mean of transport. One of the main goals is that the number of trips made by bicycle should triple compared to the year 2011's numbers by 2025. This leads to an sought after increase in bicycle traffic of approximately 8 percent per year.

Today the traffic signal system in Gothenburg more often than not favors the car where bike lanes and car lanes intersect (Månson & Junemo, 2015), resulting in a possible build-up of queues of bikes at the signals during rush hour traffic and there is little to none information on how the issue would be affected by the wanted increase in total bicycle traffic.

In order to shed some light on the issue, the report will seek to investigate how signal controlled crossings, where bicycles and cars intersect, would be affected by the increase and how the signals' sequences can be optimized to cope with the mentioned increase as optimization is to be preferred over reconstruction according to the Swedish Transport Administration's 4 step principle which states in what order changes to the infrastructure should be evaluated (Trafikverket, 2018).

Figure 1.1: Map showing location of the city of Gothenburg in the red circle (Google Maps, 2019k).

1.2 | Problem Description

The wanted increase in numbers of bicyclists using the bicycle infrastructure in Gothenburg as it is today would lead to longer queues at crossings but the actual impact has yet to be studied. According to the Swedish Transport Administration's 4 step principle (Trafikverket, 2018), optimization is to be favored over reconstruction or new establishment and to adapt the existing traffic signals to an increase in bicyclists would, therefore, be of interest in order to cope with the wanted modal shift in the transport sector.

1.3 | Purpose

The aim of the report is to evaluate how traffic signals at bicycle and motor vehicle-crossings can be optimized to cope with an increase in bicycle traffic, resulting in a more continuous flow for bicycle commuter traffic in the future.

In order to evaluate the issue, the report will work towards answering the following questions:

- Is there a certain commuter path that is more prone to queuing than others?

- In what way can the existing traffic signals on such paths be optimized in order to reduce queuing in the future (2025)?

- How would such optimization for bicycles affect the overall traffic situation?

1.4 | Scope

For the report, only bicycle commuter traffic in Gothenburg is to be evaluated which entails that areas outside of Gothenburg will not be studied for more than as reference cases. In this report, intersections in Stockholm will be used for reference.

According to the city of Gothenburg (2019a), the city has 813 kilometers of bicycle lanes with several crossings where bicycles and motor-driven vehicles intersect. This leads to a large amount of signal controlled crossings that are possible to evaluate in accordance with the aim. To evaluate all signal controlled crossings is a task that would require more time than is available for this project and due to this only a sample of selected crossings are to be evaluated. These crossings are carefully selected in order to properly represent commuter paths that may be at risk of bicycle queuing in the future.

In order to further limit the project in time, each investigated crossing will, in most cases, only be visited twice, at least one morning and one afternoon. In order for the measurements to properly represent a normal day, the sites will not be visited during heavy rain weather and only during weekdays, excluding Fridays as the commuter pattern tends to divert from normal on Fridays as commuters leaves their jobs early or runs errands before the weekend (personal communication with traffic analyst S. Hasselblom, Febuary 4. 2019).

Furthermore, the project is carried out during winter and spring resulting in data gathered on site only representing either of those two seasons. This leads to simulations of summer and autumn traffic being based on qualified assumptions based on total traffic measured by the city instead of on-site investigations.

In addition, the bicycle lanes in Sweden are used by more vehicle types than bicycles, for example, electric wheelchairs and electric scooters. The simulation software, however, only accounts for bicycles and therefore all vehicles using the bicycle lanes will be counted for as bicycles in order to get a proper view of the total flow.

1.5 | Thesis Outline

The report is divided into 8 chapters and varying amounts of sub-chapters with the Chapter 1 containing an introduction to the subject.

Following the introduction chapter is Chapter 2 which contains a theoretical framework with information on the history, present and future situation for bicycles and bicyclists, information on congestion reducing methods in the bicycle traffic, simulation models for bicycle traffic and lastly information regarding intersections under investigation.

Chapter 3 presents the methodology that the project has used, divided between the different parts of the study.

Chapter 4 contains the results obtained from site investigations, how the simulation models were set up and what results were obtained from the simulations of the future, with and without optimizing measures.

Chapter 5 analyzes the obtained results and concretizes what the results obtained points towards.

Chapter 6 brings up a discussion regarding the significance of the obtained results for the market and also a discussion on sources of error, how they may have affected the result and how they came into existence.

Finishing of the report is Chapter 7 containing the conclusions of the report in relation to the aim and finally, Chapter 8 presenting suggestions on future research.

2 | THEORETICAL FRAMEWORK

This chapter will provide a theoretical framework on bicycle traffic and theories surrounding it and available simulation models for bicycles as to give the reader a broader knowledge on the subject in order to better understand the results.

2.1 | The Bicycle's Place in Society

The bicycles place in society and its popularity has varied since its release. To better understand the situation today an understanding of how the development has looked up until today is of great importance. Therefore, the following sections will give a brief understanding of where it all started, what the prerequisites are today and what the goals are for tomorrow.

2.1.1 | History of Bicycle Traffic in Sweden

At the beginning of the bicycle's history, the bicycle was mainly a symbol of status for the upper class but at the turn of the 20th century the bicycle had started to gain importance on the Swedish countryside as a way to move over distances on, sometimes, bad roads (Nationalencyklopedin, 2019). During this time a bicycle cost close to 13 000 SEK, recalculated to 2018's monetary value but due to the possibilities of traveling between cities gave, the bicycle was still a sought-after possession.

After Henry Ford invented the T-Ford, a car model, at the beginning of the 20th century the bicycle got a competitor on the transport market but due to two world wars and gasoline being rationed during the second of them the bicycle became the most frequent mean of transport with over 70 percent of the total trips in Stockholm being made by bike during the 1930s and increasing to 80 percent by the 1950s (Everett, 2018).

In 1934 an organization called *The bicycle promotion (Cykelfrämjandet)* was established (Nationalencyklopedin, 2019). With new towns in the United Kingdom as archetypes they, out of many things, started to promote bicycle paths in the cities after the end of the second world war.

However, according to Everett (2018), the economic growth in Sweden after the second world war also led to the middle class being able to afford a car and Sweden soon became the country in Europe with the most cars per capita. The blossoming car traffic led to more bicycle accidents in the cities and the share of trips made by bicycle quickly dropped to 20 percent in Stockholm by the 1970s. At the same time traffic planners also started to separate car traffic and bicycle traffic and from this point on bicycle traffic should instead intermingle with pedestrians. Planning for car traffic had now become the norm.

At the end of the 1970s, *the Swedish Bicycle Association (Svenska Cykelsällskapet)* was founded (Nationalencyklopedin, 2019). The organization worked towards increased bicycling in the society as well as quality assessment and inventory of bicycle paths.

According to Everett (2018), this worked to some extent and during the 1980s, after demonstrations against the increased traffic accidents involving bicycles, cars, and specifically children, the politicians and city planners started to give bicycles their designated paths that wove together into a network giving bicycles free way.

The decreased bicycling from the 1950s to the 1980s has still not yet recovered and at the beginning of the 21st century only approximately one billion trips were made by bicycle in Sweden out of the total 10 billion trips (Nationalencyklopedin, 2019).

Even though there is an increase in bicycling today, the number of people who decides to commute by bicycle varies from one day to another. A literature overview published in 2010 by Heinen et al. mentions several aspects that affect the total usage. These aspects are, for example, the climate, the environment, and car ownership. In other words, you are more likely to commute by bicycle if you live in a city with moderate temperatures with few rain-days that have a well functioning bicycle infrastructure and you do not own a car.

Getting more people to commute by bicycle can also save lives. A study by Johansson et al. (2017), states that if everyone that lives within 30 minutes of bicycling from work in Stockholm used a bicycle instead of a car to commute the reduce in air pollution would save 449 years of life annually.

2.1.2 | Present Situation for Bicycle Traffic in Gothenburg

According to the latest numbers from Göteborgs Stad (2019a), the city has 813 kilometers of bicycle paths divided between *separated bicycle paths*, *local bicycle paths* and *reduced speed mixed traffic streets*. In the city, more than 100 000 trips are made by bicycle every day which corresponds to 7 percent of the total trips made pointing towards a slight increase from the year before compared with numbers presented in the latest *Traffic and Travel Development Report* released by Göteborgs Stad (2017b) as can be seen in Table 2.1.

Table 2.1: The modal distribution since 2011, in percent out of over 100 000 total trips per day (Göteborgs Stad, 2017b).

	By Foot	By Bicycle	By Public Transport	By Car
2017	20	6	28	45
2016	20	6	28	46
2015	21	6	27	46
2014	21	7	27	46
2013	21	6	27	45
2012	22	5	25	48
2011	22	5	25	48

The report states that, even though it is hardly visible in the modal distribution, the number of trips made with bicycles has increased with 20 percent since 2011 resulting in an average increase of 3.1 percent per year. Contrary to the overall increase in trips made by bicycle since 2011 the number of trips has decreased since the top notation in 2014. The total number of trips decreased with 4 percent between 2016 and 2017 making the overall increase since 2011

9 percent lower than the highest notation. The yearly change between 2011 and 2017 can be seen in Figure 2.1.
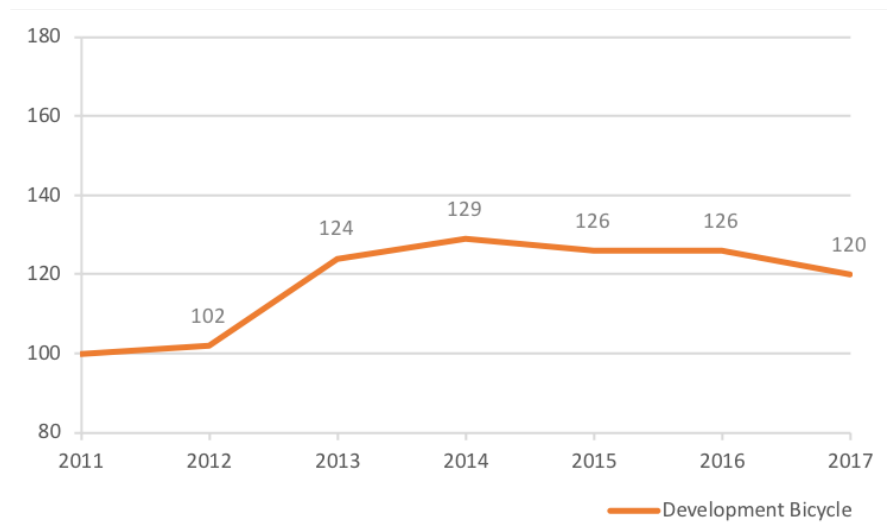
Figure 2.1: Development of total yearly bicycle traffic in Gothenburg with 2011 as index 100 (Göteborgs Stad, 2017b).

The over 100 000 trips made by bicycle every day within the city is, however, not condensed on only one road and the number of bicycle passages varies widely from place to place. The city of Gothenburg has 25 measuring stations to track where the people of Gothenburg bicycles the most (Göteborgs Stad, 2017b). The larger bicycle paths within the city have the highest flows during weekdays as can be seen in Figure 2.2.
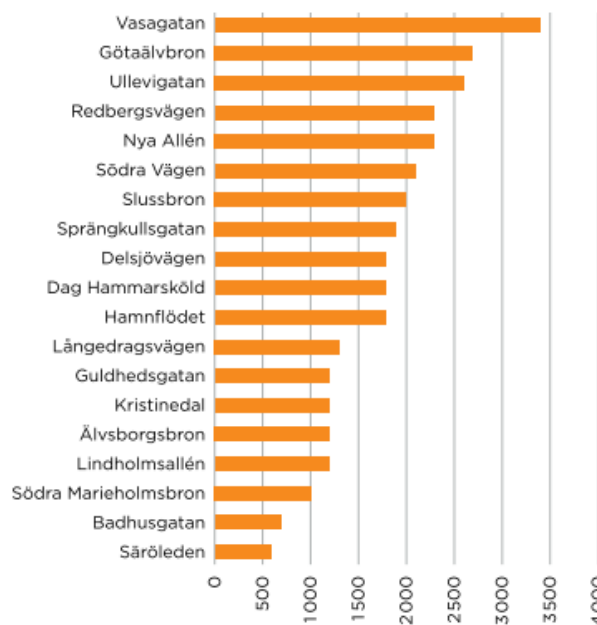
Figure 2.2: Average number of bicycle passages during weekdays per measuring station (Göteborgs Stad, 2017b).

By evaluating the data collected by the city of Gothenburg's measuring stations it can be seen that the bicycle mainly is used for transport to and from work (Göteborgs Stad, 2018). Studying all bicycle passages per hour, four hours stand out in the share of total passages during 2018 as can be seen in Figure 2.3. These four hours make up the two different commuter windows with the morning window spanning from 7 AM to 9 AM (07:00-09:00) and the evening window spanning from 4 PM to 6 PM (16:00-18:00).
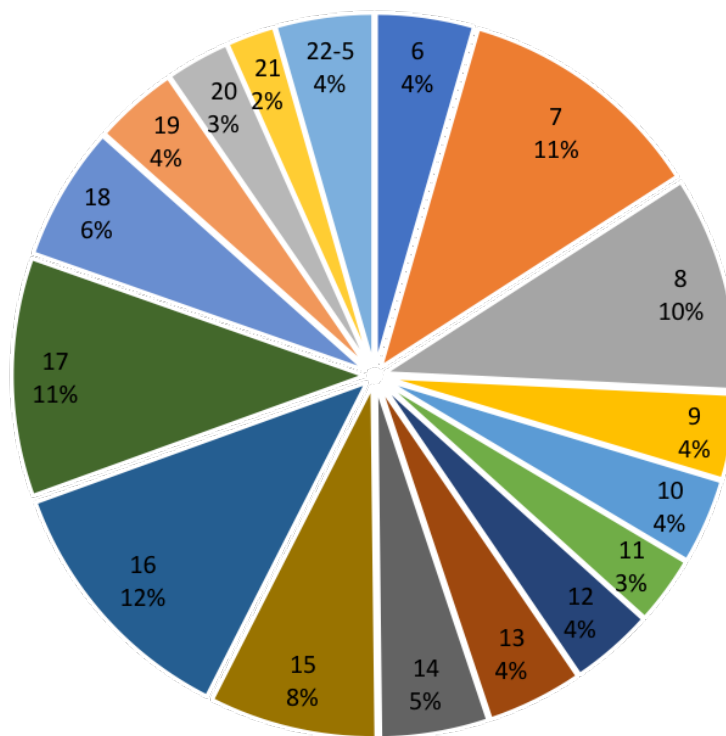
Figure 2.3: Hourly share of total bicycle passages in 2018 from 0 to 23 (Göteborgs Stad, 2018).

2.1.3 | Future Vision on Bicycle Traffic in Gothenburg

In 2015 the city of Gothenburg approved a new strategy program for the bicycle traffic in the city called *Bicycle program for a close big city 2015-2025* (Månson & Junemo, 2015). The strategy program revolves around a vision of Gothenburg becoming an attractive city for bicyclists and that the bicycle itself becomes a competitive mean of transport within and into the city.

In order to fulfill the vision, two different goals are to be strived for:

- Tripled bicycling in 2025 compared to 2011.

- In 2025, three out of four Gothenburgians sees Gothenburg as an bicycle friendly city.

For the investigation, the former goal of a tripling of the total bicycle traffic is of interest as a tripling could lead to increased congestion in the bicycle infrastructure.

Tripling the total bicycle traffic by 2025 compared to 2011 would require an average yearly increase of 8.2 percent resulting in a gradually accelerating increase, as is visible in Figure 2.4,

and would, in the end, require bicycle traffic to account for 12 percent of the total trips (Månson & Junemo, 2015).
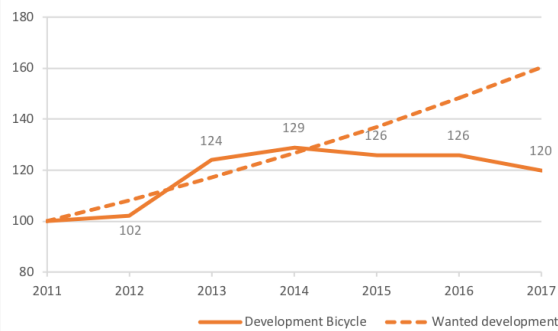
(a) Development and wanted development from 2011 to 2017
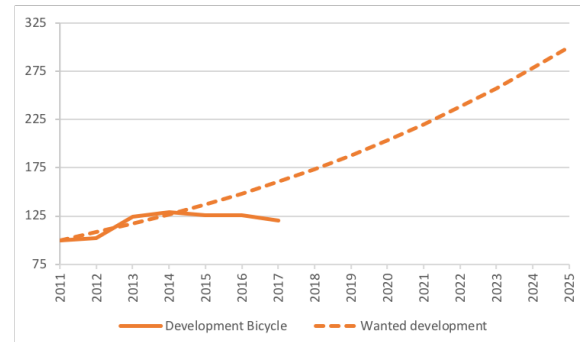
(b) Wanted development between 2011 and 2025

Figure 2.4: Wanted development of total bicycle traffic according to *Bicycle program for a close big city 2015-2025* using 2011 as index 100 (Månson & Junemo, 2015).

In order to fulfill the goals, four focus areas have been identified in the bicycle program (2015) consisting of *Infrastructure, Operation, and Maintenance, Support and Services* and *Communication*. To meet the goals these four focus areas must interact with one another where the infrastructure for bicycles is coherent, well designed and accessible all year around. At the same time, the city of Gothenburg should provide support and services that facilitate bicycling and also communicates what the city is doing to make bicycling in the city more attractive for the inhabitants.

2.2 | The Theories Behind Congestion Reducing Measures

As the number of bicyclists in Gothenburg presents an increasing trend, the bicycle paths become more congested which results in longer queues and higher frequency in start-stops. According to Månson and Junemo (2015) there are different ways to prevent queues and improve continuous cycling, for instance:

- Traffic signal gives green light to the bicyclists, and after a few seconds, the other road users traveling in the corresponding direction get a green light. This configuration will not only give a head start for the bicyclist but also enhance traffic safety as bicyclists becomes more visible when they are in the middle of the crossings.

- Traffic lights with detectors that turn green when bicyclists approach a crossing. This type of system will help bicyclists to enter and pass the bicycle path faster.

- Momentarily all bicycle crossings in a certain intersection get a green light. To give priority only for bicyclists to pass the intersection, with an appropriate and regular interval, will improve safety and increase the potential cycle traffic load.

- Implementation of Green Waves.

Regarding green wave (GW), GW is a way to optimize traffic signals in order to minimize traffic jam and improve passability for the vehicles, (Wu, Deng, Du, & Ma, 2014). The purpose is to make it possible for vehicles to drive through an intersection with a certain speed without the need to stop.

Since the GW concept was first introduced in the US in the 1920s it has mostly been used for motorized vehicles in traffic intersections (Zyga, 2013). Due to high bicycle traffic flow in Amsterdam and Copenhagen, the concept has been frequently implemented in bicycle intersections in these cities. Different configurations have been tested and implemented in both Europe and the US. The two main modes are controlled either by sensors or timers. For sensors, the Green Wave starts when a vehicle approaches a traffic light. The signal system detects it by sensors which in turn tells the traffic light to switch to green. As the vehicle reaches the next intersection the same procedure can be initiated and the green lights are rolling forward like a wave, see Figure 2.5. In GW configured traffic light systems the lights are programmed to prioritize bicyclists to a certain extent in relation to other traffic.
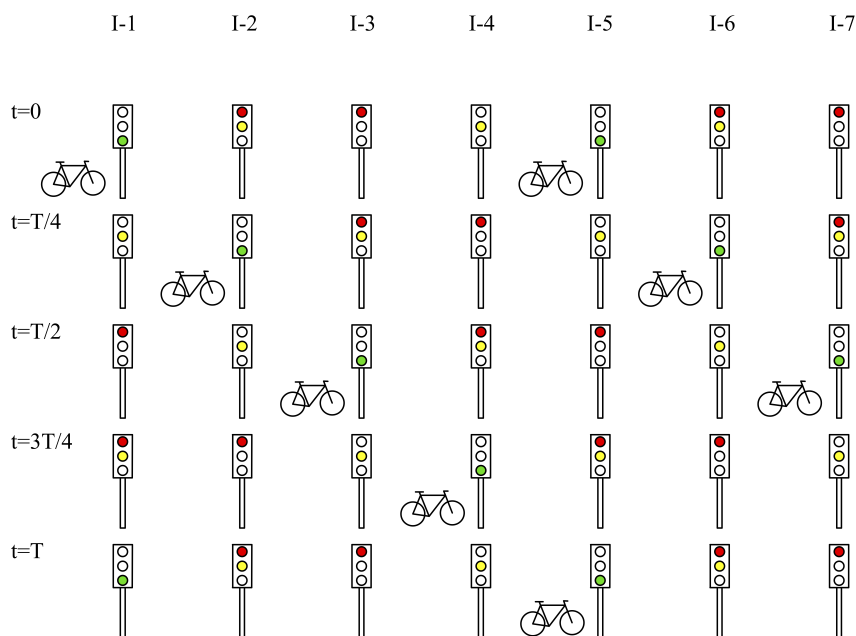
Figure 2.5: Series of traffic signals turns green as the bicycle moves forward, a so called Green Wave. In the figure, each row is a time step and each column an intersection. Authors' own copyright.

The GW implementation has positive effects on traffic intersections and its flow. The advantages are improved efficiency, decreased CO_2 and NO_X emissions, less time in queues and reduced fuel consumption for motor vehicles (Zyga, 2013). Other benefits of using Green Wave in traffic control systems could be to control traffic speed, enable higher traffic loads and facilitating bicycle traffic.

2.3 | Simulation Models for Bicycle Traffic

The volume of bicycle traffic has fluctuated the last century and the interest in bicycles grew slow at the beginning of the 20th century before speeding up (Jin, Qu, Zhou, et al., 2015). One reason for this increase in interest can be derived from the implementation of public bike sharing. Compared to other transportation modes the bicycle-sharing fleet implies advantages in availability, comfort, and economy. The other reason for the increment of bicycle trips can be the higher use of bicycles that is powered by electricity with additional human force. The increasing interest for bicycles worldwide has led to researches developing simulation models specifically for bicycles to strengthen simulations (Jin, Qu, Xu, et al., 2015).

2.3.1 | Bicycle-specific Simulation Models

There have been several attempts at deriving following models specifically for bicycles. According to Jin, Qu, Xu, et al. (2015), there have been several different flow models of bicycle-related traffic using cellular automata (cell based simulation model) produced during the 21st century taking into consideration different simulation scenarios and vehicle types. The models mentioned in the report is presented in Table 2.2 and abbreviations used in the table is explained below.

RB Regular Bicycle
ES Electric Bicycle
NS Nagel-Schreckenberg
EBCA Extended Burgers Cellular Automata

Table 2.2: Dedicated bicycle traffic flow models according to Jin, Qu, Xu, et al. (2015).

Researchers	Release year	Simulation Scenario	Vehicle type(s)	Bicycle traffic modeling type
Gould and Karner	2009	Separated bicycle path	RB, EB	NS
Zhang et al.	2013	Separated bicycle path	RB, EB	NS
Zhao et al.	2013	Separated bicycle path	RB, EB	Improved NS
Yang et al.	2013	Separated bicycle path	RB	NS and dynamic floor field
Jiang et al.	2014	Separated bicycle path	RB, EB	Improved NS
Jiang et al.	2004	Separated bicycle path	RB, EB	EBCA
Jia et al.	2007	Separated bicycle path	RB, EB	EBCA
Li et al.	2008	Separated bicycle path	RB, EB	EBCA
Vasic and Ruskin	2012	Non-separated roadway and intersection	Car, RB	NS model and Intersection rule
Zhang et al.	2014	Intersection	Car	NS
			RB	EBCA
Luo et al.	2015	Non-separated roadway	Car	NS
			RB	Improved NS
Ding et al.	2015	Non-separated roadway	Bus/Car	NS
			RB	EBCA

The report also presents a multi-value automata model which is called IEBCA (Improved Extended Burgers Cellular Automata). This model is appropriate for non-lane-based bicycle traffic and is said to be more realistic than the ECBA since the model is taking the maximum speed of electric bikes into consideration. The model is based on the BCA (Burgers Cellular Automata) model which has the evolution equation:

$$U_j(t+1) = U_j(t) + min(U_{j-1}(t), L - U_j(t)) - min(U_j(t), L - U_{j+1}(t)) \qquad (2.1)$$

Where $U_j(t)$ is the number of vehicles in cell j at time t and L is the number of bicycle lanes.

Additionally, as an effect from the increase in both interest and usage of the bicycle during the last years researchers have also started to look into how to represent the acceleration of bicycles, a field that was previously rather unexplored. By using GPS-trackers on test subjects Ma and Luo (2016) developed three different models in order to meet the demand.

2.3.2 | Bicycle Simulation in PTV Vissim

The simulation software Vissim, which is later used in this study, provides three/two different models for car following to use when simulating driver behavior (PTV AG, 2018):

- Wiedemann 74
- Wiedemann 99
- (No interaction)

Wiedemann is a psychophysical car following model that allows for a vehicle to be in one of four modes of driving, *Free driving, Approaching, Following* or *Braking.* The car following model affects the acceleration of the vehicle which in each mode is affected by the speed, speed difference to other vehicles, distance to other vehicles and individual characteristics given to each driver/vehicle (PTV AG, 2018).

Wiedemann 99 is based on Wiedemann 74 but allows for the user to change 10 different parameter values (CC0-CC9) which impacts the driving behavior instead of only three. What each parameter is and what they affect is presented in the list below (PTV AG, 2018):

CC0 Standstill distance - states the desired distance between two vehicles at standstill.

CC1 Headway time - Distribution of time in seconds that a driver wants to keep to the vehicle in front

CC2 Following variation - Changes how much more than the safety distance a vehicle is allowed to have before forced to move closer to the vehicle in front.

CC3 Threshold for entering Following - Affects how early a vehicle starts to decelerate before reaching the safety distance.

CC4 & CC5 Negative and positive Following threshold - Affects differences in speed when a vehicle is in the *Following* mode.

CC6 Speed dependency of oscillation - Changes how the distance to a vehicle in front affects the speed variation.

CC7 Oscillation acceleration - Changes a vehicle's acceleration when in the oscillation process.

CC8 Standstill acceleration - Changes the preferred acceleration from a standstill.

CC9 Acceleration at 80 km/h - Changes the preferred acceleration when traveling at 80 km/h.

According to Aghabayk, Sarvi, Young, and Kautzsch (2013), the first seven parameters are used when calculating thresholds for following and the latter three are directly used in calculating the driver behavior. The thresholds affecting the driving behavior can be seen in Figure 2.6 and is determined by six equations, Equation 2.2 to 2.7.

In the equations L is the length of the vehicle in front, v is the speed of the vehicle being calculated if the vehicle at hand is slower than the leading vehicle otherwise v is equal to the leading vehicles speed with some margin of error, Δx is the distance between the vehicle's front bumper and the vehicle in front's front bumper, and δ is a variable given a value of 1 when the vehicle's speed is greater than CC5, otherwise δ is equal to 0.

The desired distance between two vehicles when at standstill (AX) is calculated as:

$$AX = L + CC0 \qquad (2.2)$$

The minimum safety distance (BX) when following is calculated as:

$$BX = AX + CC1 \times v \qquad (2.3)$$

The upper limit for distance of the following process (SDX) is calculated as:

$$SDX = BX + CC2 \qquad (2.4)$$

The point at longer distance at which a vehicle perceive that it is traveling faster than the vehicle in front (SDV$_i$) is calculated as:

$$(SDV)_i = -\frac{\Delta x - (SDX)_i}{CC3} - CC4 \qquad (2.5)$$

The point at shorter distance at which a vehicle perceives that it is traveling faster than the vehicle in front is calculated as:

$$CLDV = \frac{CC6}{17000} \times (\Delta x - L)^2 - CC4 \qquad (2.6)$$

The point at shorter distance at which a vehicle perceives that it is traveling slower than the vehicle in front (OPDV) is calculated as:

$$OPDV = -\frac{CC6}{17000} \times (\Delta x - L)^2 - \delta CC5 \qquad (2.7)$$
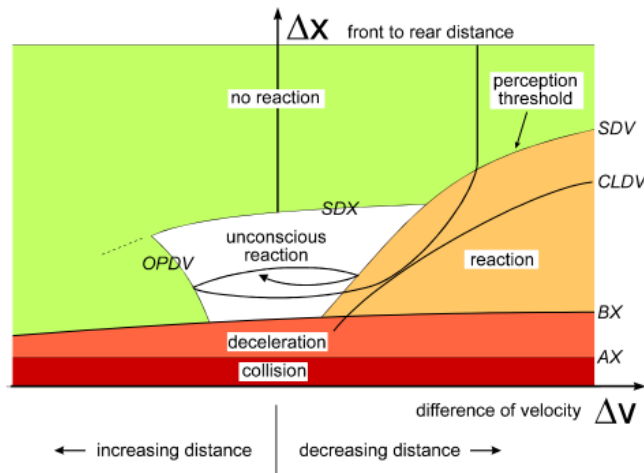
Figure 2.6: Thresholds affecting the driving behavior of vehicles according to Wiedemann (PTV AG, 2011).

According to COWI (2013), bicycle traffic should due to its complexity be simulated using Wiedemann 99 when using PTV Vissim since Wiedemann 99 allows for more precise changes in the driving behavior compared to Wiedemann 74.

In addition to the following model used, also parameters affecting lane change affect the driving behavior of a vehicle (PTV AG, 2018).

2.4 | General Information on Intersections Being Studied

In the study, bicycle crossings located within three different areas of varying size were studied:

- Nya Allén including seven intersections
- The intersection between Annedalsmotet and Dag Hammarskjöldsleden
- The intersection between Skånegatan and Ullevigatan

Together the three areas give an opportunity to evaluate different measures to reduce future congestion and at the same time offer the opportunity to analyze the bicycle traffic in Gothenburg on a wider level.

2.4.1 | Intersections along Nya Allén

Nya Allén stretches from Ullevigatan to Järntorgsgatan, as can be seen in Figure 2.7, providing a connection for bicycle traffic between the north-eastern and the south-western parts of the city center mostly running through park areas. Nya Allén is a part of the bicycle commuter network in Gothenburg (Månson & Junemo, 2015) and was Gothenburg's fifth most trafficked bicycle path in 2017 (Göteborgs Stad, 2017b). Due to its many signal controlled crossings, Nya Allén gives the opportunity to evaluate the implementation of a green wave for the bicycle traffic in segments.
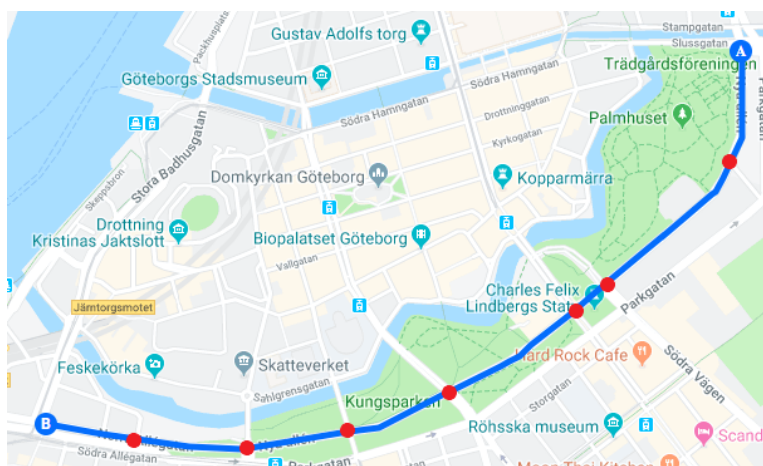
Figure 2.7: City of Gothenburg with Nya Allén marked in blue stretching from Ullevigatan (A) to Järntorgsgatan (B) with investigated intersections shown as red dots (Google Maps, 2019m).

Excluding the intersections located at the beginning and the end of Nya Allén the bicycle path has seven intersections using signal controllers for safe passages, shown in Figure 2.7 as

red dots. Nya Allén consists of bidirectional bicycle paths located on each side of the one-way road with the path closest to Parkgatan being the one studied as it stretches all the way to Järntorget whereas the other side ceases to exist at Pusterviksgatan.

Following the road from point A to B, as defined in Figure 2.7, the first intersection studied is the intersection between Nya Allén and Sten Sturegatan, shown in Figure 2.8.
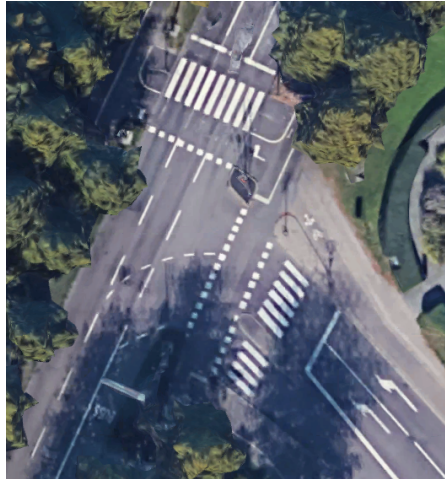
Figure 2.8: Intersection between Nya Allén and Sten Sturegatan (Google Maps, 2019f).

The intersection is a T-intersection for motor vehicles where the bidirectional bicycle path crosses the connecting road (Sten Sturegatan) and continue south. Additionally, there is a bidirectional bicycle path connecting the two sides of Nya Allén in the northern part of the intersection creating a two-dimensional flow for the bicycle traffic. The intersection is trafficked by public transport in the form of buses traveling along Nya Allén.

All bicycle crossings are signal controlled and are given green light in conjunction with the motor vehicles traveling in the corresponding direction.

Continuing along the road, the next intersection is between Nya Allén and Södra Vägen (shown in Figure 2.9). The intersection is identical to the previous one regarding crossings for bicycles and the associated turning options but for car traffic, the intersection is trafficked by public transport in the form of buses traveling both along Nya Allén as well as turning onto Södra Vägen towards Heden and vice versa.

Figure 2.9: Intersection between Nya Allén and Södra Vägen (Google Maps, 2019g).

Less than 100 meters south-west lies the next intersection between Nya Allén and Kungsport-savenyen as shown in Figure 2.10.

Figure 2.10: Intersection between Nya Allén and Kungsportsavenyen (Google Maps, 2019c).

The intersection is a four-way intersection trafficked by public transport in the form of trams and buses. Regarding the bicycle traffic, there is a bidirectional crossing on both sides of Nya Allén with the southernmost being the one being studied. Additionally, there are two one-directional bike lanes connecting on each side of Kungsportsavenyen running in the same directions as the other traffic.

Trams are given priority in the intersection and all traffic is controlled by signals where bicycles are given green light in conjunction with the corresponding motor vehicles.

Continuing along the path, the next intersection is Nya Allén - Raoul Wallenbergs Gata, as visible in Figure 2.11, which is a four-way intersection with the same properties as the intersection between Nya Allén and Kungsportsavenyen. The intersection is during the time of the study affected by roadwork on the northern side of the intersection eliminating the possibility for motor vehicles to travel in the north-south direction, thus not allowing trams to traffic the intersection during the study. In order to get a more realistic result, the simulation will take the north-south traffic into consideration based on previous conditions.

Regarding the bike lanes, the easternmost connection has two one-directional connections leaving the main bidirectional bike lane using the same signal control and the westernmost is a one-directional connection for merging with the main lane. All directions are given green at the same time as the corresponding motor traffic which at the moment is time-based but trams used to have priority in the intersection and will, therefore, be simulated as such.

Figure 2.11: Intersection between Nya Allén and Raoul Wallenbergs Gata (Google Maps, 2019d).

The fifth intersection along Nya Allén is the intersection between Nya Allén and Viktoriagatan (see figure Figure 2.12). The intersection is identical with the previous intersection in terms of properties but is not affected by any road work during the study.

Figure 2.12: Intersection between Nya Allén and Viktoriagatan (Google Maps, 2019h).

Intersection number six along Nya Allén is between Nya Allén and Sprängkullsgatan where Viktoriabron connects to Nya Allén from the north (see Figure 2.13).

Figure 2.13: Intersection between Nya Allén and Sprängkullsgatan (Google Maps, 2019e).

The intersection between Nya Allén and Sprängkullsgatan is a four-way intersection with signal-controlled bidirectional bicycle crossings in all directions giving bicyclist many options for travel within the intersection. The intersection is also trafficked by buses traveling in the east-west direction as well as east-south but all traffic is given the same priority.

Lastly, the seventh intersection along Nya Allén and the last intersection before reaching the end destination at Järntorget is the intersection between Norra Allén, an extension of Nya Allén, and Pusterviksgatan, as shown in Figure 2.14.

Figure 2.14: Intersection between Norra Allén and Pusterviksgatan (Google Maps, 2019b).

This is the intersection where the additional bicycle lane on the other side of Allén ends and merges with the main lane. This is done with a bidirectional connection in the eastern part of the intersection and a one-directional connection in the western part. All crossings are signal controlled and time-based. The road connecting from the south is a one-directional connection allowing for traffic to cross the intersection or make a left turn towards Järntorget.

2.4.2 | Annedalsmotet - Dag Hammarskjöldsleden

Located in the south-western parts of the city (see Figure 2.15a), Annedalsmotet connects to Dag Hammarskjöldsleden forming an intersection where a one-dimensional bicycle flow is

controlled by signals. The intersection, shown in Figure 2.15b, allows for bicycles to cross the main road and the bus lane in order to travel toward or from the city center.

(a) Map showing the location of Annedalsmotet in Gothenburg using a red mark (Google Maps, 2019j).

(b) Intersection between Annedalsmotet and Dag Hammarskjöldsleden (Google Maps, 2019a).

Figure 2.15: Location and overview of the intersection at Annedalsmotet.

Dag Hammarskjöldsleden was the 10th most trafficked bike path according to Göteborgs Stad (2017b) and the one direction flow of bicycles gives the opportunity to evaluate how longer green times in the signal sequences or detectors in the ground can affect the total congestion and flow. The intersection is also a part of Gothenburg's bicycle commuter network (Månson & Junemo, 2015).

2.4.3 | Skånegatan - Ullevigatan

Ullevigatan was the third most trafficked bicycle road according to the numbers from 2017 (Göteborgs Stad, 2017b) only succeeded by Vasagatan and Götaälvbron. The intersection is located in the north-eastern part of the city center and shown in Figure 2.16a. Due to many roads interweaving the intersection becomes large and the distances from one side to the other long, visible in Figure 2.16b.

(a) Map showing the location of the intersection between Skånegatan and Ullevigatan, marked in red (Google Maps, 2019l).
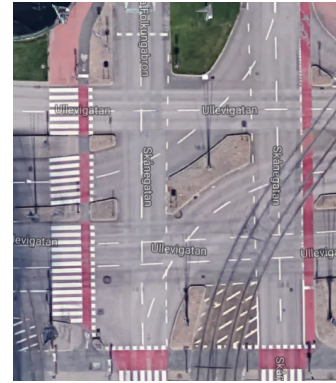
(b) Intersection between Skånegatan and Ullevigatan (Google Maps, 2019i).

Figure 2.16: Location and overview of the intersection between Skånegatan and Ullevigatan.

The intersection is highly trafficked by public transport with both trams and buses and the flow of cars is high. The bicycle lane in the southern part of the intersection is a bidirectional crossing along Ullevigatan whereas the other two bicycle lanes are one-directional lanes connecting to the main lane.

The high flow of all types of traffic results in a high risk of congestion. A possible solution to evaluate in this intersection is *all green* or *pre-green* in order to reduce the congestion for bicycles in the future.

3 | METHODOLOGY

In order to fulfill the aim of the report and answer the questions stated in section 1.3, the project was divided into different parts where the methods used for the specific parts are presented below.

3.1 | The Study's Methodological Approach

In the book *Social Research Methods* Bryman (2012) writes that two methodological approaches are dominant within science, qualitative ant quantitative. This study primarily uses a quantitative methodology as information gathered sees the system as a whole and not the specific individuals using the bicycle network and quantifies the results as numbers on a protocol. A smaller behavioral study within the study uses a qualitative methodology where individuals are observed and studied based on how they behave.

3.2 | Initial Information Gathering

In order to gain an understanding of the problem at hand, an initial information gathering was conducted. Initial information was gathered using both literature studies as well as discussion with traffic analysts at WSP Sweden, considered to have knowledge in the field. In these discussions, no formal interview questions were asked but instead topics discussed and the knowledge gathered from the discussions were mainly used as basis for further research.

The initial information gathered was used to select intersections that were relevant for the study and could be used to draw a more wide conclusion on the situation in Gothenburg overall.

Through discussions with traffic analysts at the company WSP Sweden in Gothenburg and data on bicycle traffic in Gothenburg from previous years obtained from the city of Gothenburg, 9 different intersections were selected for further study based on the assumption that high flows and intersections lead to congestion and thus queuing while at the same time representing different types of problem areas in the bicycle infrastructure. Some intersections that had higher flows than the investigated was excluded due to:

- Lack of signal controls for bicycles.
- Non-separated bicycle lanes making measures hard to implement.
- Construction work carried out in the intersection during the study period.
- Similarity with already chosen intersections.

3.3 | Site Investigations

The intersections that were selected based on the initially gathered information was visited in order to gather information on how the bicyclists behave in the intersections, such as turn ratios.

Based on data on bicycle traffic from previous years it was determined that the most highly trafficked times, and thus the times most prone to congestion, was divided between two commuter windows. The first window being the morning traffic between 7 AM and 9 AM and the second being the evening traffic between 4 PM and 6 PM. Based on this the intersections were only studied during said windows resulting in a minimum number of site investigations being two per intersection.

The measuring of the traffic was conducted using pre-constructed forms collecting equivalent information at every intersection in order to achieve inter-rater reliability when the intersections were measured by different individuals. Inter-rater reliability means that different data collectors, also called raters, collects the data in the same way (Mchugh, 2012). Something achieved by using pre-constructed forms.

The intersections were only visited during weekdays, excluding Fridays, in order to achieve test-retest reliability since the commuter pattern diverts from the normal during Fridays (personal communication with traffic analyst S. Hasselblom, February 4, 2019). Test-retest reliability ensures that the results is not highly dependent on the situation during the data collection (Rousson, Gasser, & Seifert, 2002). In addition, the behavior of the bicyclists were observed but not measured quantitatively.

During the site investigations, data on how many bicyclists used the intersections per quarter of an hour as well as how they used the intersection (relative flows) were measured in order to collect data to use when setting up the simulation model. Examples of the forms used is attached to the report in Appendix A.

One intersection was revisited to evaluate if seasons affected the behavior of bicyclists in the intersections. Which intersection to revisit was decided together with the analysts at WSP and the dates the intersections were visited is shown in Table 3.1. Generally, the weather was favorable during this period, which encouraged more commuters to take the bicycle, thus the result could be said to be relatively representative.

Table 3.1: Dates when intersections were visited. All dates are during 2019.

Area	Intersection	Date of Visit		
		AM	PM	Extra
Nya Allén	Sten Sturegatan	Feb. 6	Feb. 4	
	Södra Vägen	Feb. 7	Feb. 11	
	Kungsportsavenyen	Feb. 12	Feb. 13	May 8
	Raoul Wallenbergs Gata	Feb. 14	Feb. 18	
	Viktoriagatan	Feb. 20	Feb. 21	
	Sprängkullsgatan	Feb. 26	Feb. 25	
	Pusterviksgatan	Feb. 28	Feb. 28	
Ullevi	Skånegatan - Ullevigatan	Mar. 12	Mar. 19	
Annedal	Annedalsmotet - Dag Hammarskjöldsleden	Mar. 27	Mar. 21	

For behavioral comparison and broader discussion intersections in Stockholm were visited but not measured. The observed behavior of bicyclists in Stockholm was only used as a mean for

comparisons and the behavioral study was conducted as a qualitative study where observed behaviors were noted but not counted.

3.4 | Simulations of the Future

Simulations of the bicycle traffic were conducted based on the information gathered from both site investigations and the initial information gathering. The simulations were conducted on a micro level using the simulation software *PTV Vissim 11*.

Simulations of the future were based on the city of Gothenburg's goal of a tripling in total bicycle traffic by 2025 compared to 2011 but with the same bicyclist behavior as measured during the site investigations. Different seasons were simulated based on previous data of the number of bicyclists during the seasons from previous years.

Simulations in Vissim were carried out 10 times per scenario, where a scenario was a different setup of flows, public transport departure times, relative flows and signal sequences. In the simulation, vehicle entry times changed based on a random seed which started at 3 and was increased with 10 steps per run. This was done to limit the possibility of the result not representing the actual situation and instead, more realistically show how the system handles the calculated flows. The simulations were carried out during 6000 simulation seconds corresponding to 6000 seconds with results evaluated being taken out during one hour between simulation second 1800 and 5400. Results were evaluated based on travel time and queue lengths where the 85th percentile was calculated as to get a result that could be regarded as a normal peak in accordance to standards at WSP Sweden.

The bicyclist's behavior was simulated based on COWI's report on *Micro simulation of cyclists in peak hour traffic* (2013) which uses, the in Vissim implemented, car following model Wiedemann 99 and changes the parameter values to better represent the bicyclist's behavior. In accordance to COWI's report, several driving behaviors for bicyclists were used depending on the situation in the model where different behaviors were taken into consideration when a bicyclist was approaching or in an intersection, leaving an intersection or traveling between intersections. These behaviors were compared to the observed when calibrating the models and tweaked when needed to better represent the observed behavior.

The base parameter values used in Wiedemann 99 for the three cases in accordance with COWI's report is presented in Table 3.2. What each parameter affects is presented in subsection 2.3.2. In addition to parameters affecting the following behavior, different settings for lateral placement behavior were also changed depending on the three cases where Equalization is a mix of Bicycle Path and Intersection.

Table 3.2: Parameter values for the three used bicycle driving behaviours as presented by COWI (2013). A line means no changes compared to Bicycle Path.

Used where?	Bicycle Path Other	Intersection 75 m before and through intersections	Equalization 50 m after an intersection
CC0	0.2 m	-	-
CC1	Distribution 4 (mean 0.5 s)	-	-
CC2	2 m	-	-
CC3	-20 s	-	-
CC4/CC5	(-)0.25 m/s	-	-
CC6	1 1/(m·s)	-	-
CC7	0.2 m/s^2	-	-
CC8	1.8 m/s^2	-	-
CC9	0.01 m/s^2	-	-
Other		Standstill distance = 0 m	

3.5 | Setup and Calibration of Models

Each model calibration differs slightly from one another and the calibrations they have in common is presented below followed by more specific calibration of the individual models.

The simulation software Vissim is mainly designed to simulate car traffic, and bicycles are in short terms simulated as small cars with changed behavior and appearance. COWI's report *Micro simulation of cyclists in peak hour traffic* is seen as guidelines for a realistic simulation of bicycles, and parameter settings for bicycles as well as the driving behavior on bicycle lanes presented in the report have been copied in this project's simulations with little to no changes.

Signal control sequences for the signal heads in the intersection as they behave today was provided by Trafiksystem Väst and was implemented as such and optimizing measures used this as a base when implemented. Prioritization for different modes of transport was coded using the, for PTV Vissim, add-on software VISVAP.

During on-site investigations, car traffic was not measured but have instead been estimated using data previously collected by the city of Gothenburg where maximum evening flow has been measured and presented per segment of the road (Göteborgs Stad, 2019b). The intersection at Annedalsmotet-Dag Hammarskjöldsleden is an exception to this where cars and buses were counted as well during the site investigation. These flows were also used for in simulations of 2025.

3.5.1 | Nya Allén

The model of Nya Allén was set up by recreating the system on top of a map of the area. An example of this can be seen in Figure 3.1 where the intersection between Nya Allén and Kungsportsavenyen is zoomed in.

The default lane width of 3.5 meters was used for motor vehicles whereas bidirectional bicycle paths were modeled as two separate paths consisting of two 1.5 meter wide lanes in each direction on top of each other where the left lane was set as an overtaking lane. One-directional bicycle paths were given a width of 1.2 or 1.5 meters depending on location. Due to the model

consisting of several intersections interlinked, the three previously mentioned behaviors were implemented in accordance to COWI (2013).
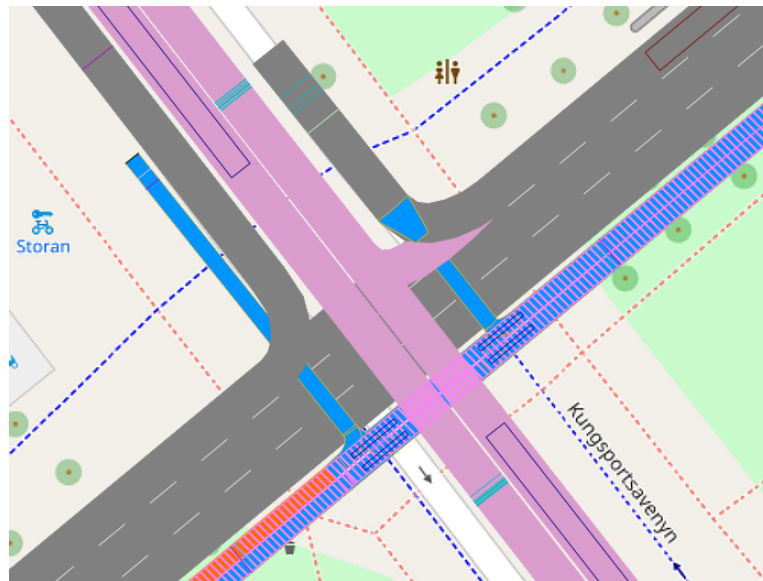
Figure 3.1: The intersection between Nya Allén and Kungsportsavenyen as modeled on top of a map of the area (OpenStreetMap contributors, 2019a). In the figure, grey roads for motorized vehicles, pink for public transport exclusive, blue for bicyclists traveling in an intersection, and orange for bicyclists leaving an intersection. CC BY-SA.

Using relative flows, total flow and maximum queue length gathered during site investigations the simulation model was calibrated against known maximum hourly flows from the winter season of 2017 presented in data provided by the city of Gothenburg (Göteborgs Stad, 2017a). The model was calibrated against 2017's flows in order to enable for an increase to the wanted flows of 2025 in accordance with the strategic plan by multiplying flows with a factor of 2.5 derived from differences in index as shown in Figure 2.4.

The total bicycle flow from all connecting roads was calibrated using Microsoft Excel and the measured relative flows by adequately changing incoming flows to correlate with maximum hourly flows. A part of this calibration can be seen in Figure 3.2 where incoming flows were changed to make the values shown under *Measuring Station* correspond to each other.
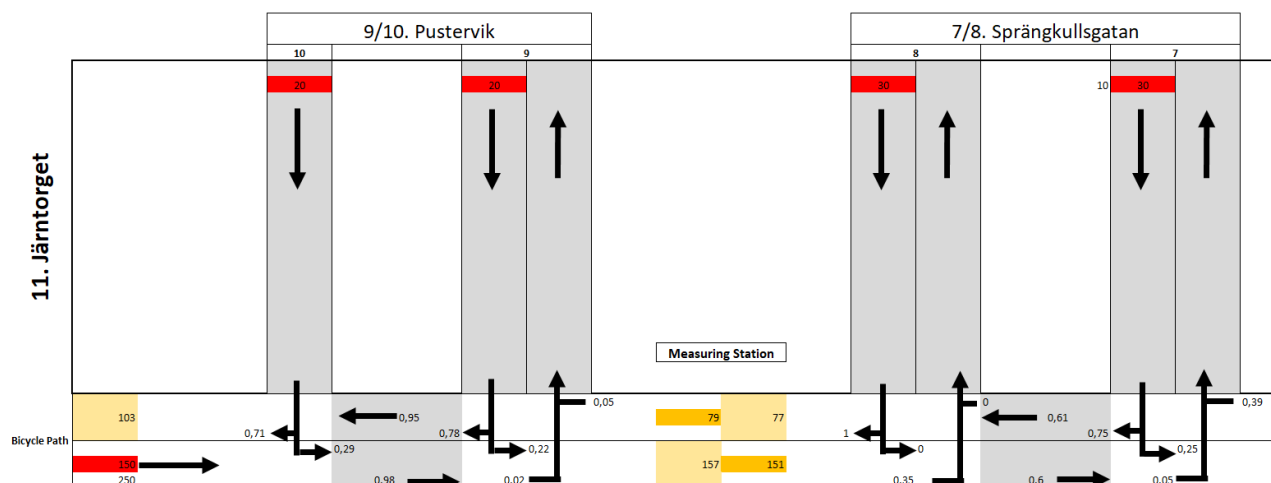
Figure 3.2: Part of the calibration of bicycle flows along Nya Allén. Light yellow areas are flows calculated using relative flows and red marked flows. Authors' own copyright.

Visual calibration was conducted by running the simulation of the current situation and noting down observed errors in behavior of both model and bicyclists. In this process, it was noted that the parameters affecting overtaking inhibited bicyclists from overtaking on areas where they should have overtaken bicyclists in front and to make overtaking easier for the bicyclists some parameters were changed in comparison with COWI's guidelines on modeling bicycles in peak hour traffic. More precisely:

- Bicycles were allowed to overtake on both sides of the bicycle in front of them in the whole system and not only at intersections.

- The preferred lateral distance between bicycles was reduced at intersections to allow for a more dense queue.

- Bicycle lanes between intersections were given a "slow lane rule" meaning slower vehicles keeps right in the lane.

3.5.2 | Annedalsmotet-Dag Hammarskjöldsleden

Like the setup of the model of Nya Allén, the model of the intersection at Annedalsmotet-Dag Hammarskjöldsleden was set up by recreating the system on top of a map of the area. However, as visible in Figure 3.3, in this case, a satellite picture from Google maps was used as a background instead of the built-in OpenStreetMap as the latter did not fully show the set up of the area.
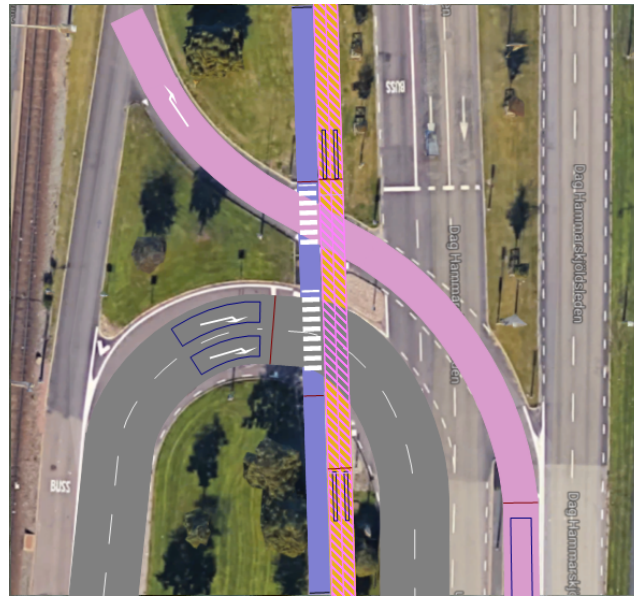
Figure 3.3: The intersection at Annedalsmotet-Dag Hammarskjöldsleden as modeled on top of a map of the area (Google Maps, 2019a). In the figure, grey areas are for cars, pink for buses, purple for pedestrians, and yellow for bicyclists in the intersection.

Here the lanes were set up in the same way as in the intersections along Nya Allén but with a width of 1.2 meters per bicycle lane and in addition a walking path was added with a width of 2 meters to more closely resemble the actual situation.

In comparison with the model of Nya Allén, the model of the intersection at Annedalsmotet-Dag Hammarskjöldsleden was a small model resulting in fewer calibration measures compared to COWI's report needed to be taken. In this case, no changes of the bicyclists' driving behavior were needed but instead only the flows needed to be calibrated.

Calibration of flows was conducted using Microsoft Excel and comparing measured flows on site with maximum hourly flows from 2017. Measured afternoon flows from site closely resembled the maximum day during winter 2017. This lead to the conversion factors for afternoon traffic between measured flows and different seasons as well as the year 2025 being based on differences between seasons of 2017 as can be seen in Table 3.3. Morning flows used the same conversion factors but first had to be decreased by an iteratively created factor to decrease the measured flow to be in line with maximum flows of winter 2017. This factor was set to 1.72.

Table 3.3: Bicycle flow conversion factors between winter of 2017 and other seasons as well as the year 2025 for the intersection at Annedalsmotet-Dag Hammarskjöldsleden.

Season	Time of Day	Maximum Flow From City Center	Maximum Flow Towards City Center	Factor Winter to Season	Total Factor 2017-2025 (Based on indexes)	Total Factor 2025 (Product of the two previous)
Winter	AM	76	118	1.00	2.5	2.50
	PM	144	60	1.00	2.5	2.50
Spring	AM	136	400	1.73	2.5	4.32
	PM	296	144	1.56	2.5	3.91
Summer	AM	149	492	2.04	2.5	5.11
	PM	386	170	1.96	2.5	4.89
Autumn	AM	123	307	1.41	2.5	3.53
	PM	287	80	1.24	2.5	3.10

3.5.3 | Skånegatan-Ullevigatan

The setup of the intersection between Skånegatan and Ullevigatan was a one intersection model set up in the same way as the previous intersections and is shown in Figure 3.4. The default width of lanes of 3.5 meters was used for car traffic and trams and for bicycles the width of the lanes were dependent on whether or not the bicycle path was bidirectional or not. The bidirectional paths were set up as previously with a width of 1.5 meters per lane and one-directional paths were set to 1.2 meters in width.

The complexity of the signal system led to the signal system controlling trams in the intersection being simplified using give-way rules where all other vehicle types were told to give way to the trams instead of using stop signals for the trams. This was assumed to not significantly affect the capacity of the intersection.
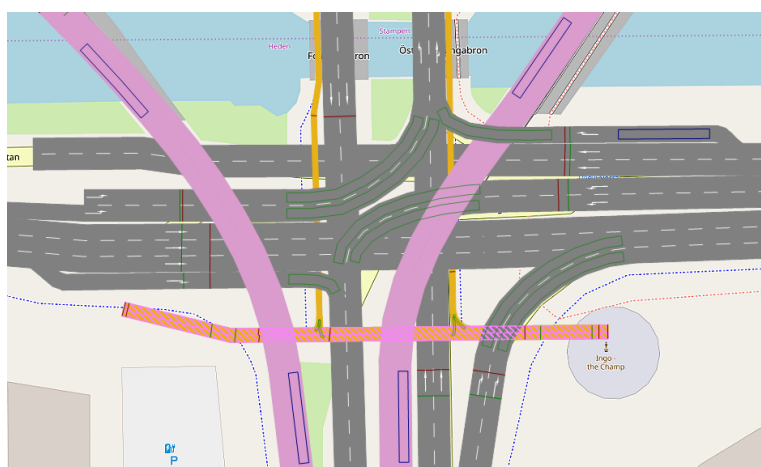
Figure 3.4: Simulation model of the intersection between Skånegatan and Ullevigatan (OpenStreetMap contributors, 2019b). In the figure, pink areas are for trams, gray for motorized vehicles, and yellow for bicyclists in the intersection. CC BY-SA.

Regarding parameters affecting the driving behavior, one change was made compared to COWI's report for this intersection. The changed parameter was the preferred lateral distance when overtaking on the bicycle lanes. This parameter was changed to the default in Vissim in order to simulate a more dense queue.

Calibration of flows was conducted using Microsoft Excel and comparing measured flows on site with maximum hourly flows from 2017. Measured flows were decreased by an iteratively created factor of 1.56 to resemble winter values from 2017 in order to then increase the flow depending on season and year using conversion factors based on differences between winter 2017 and other seasons as well as the year 2025. These conversion factors are shown in Table 3.4.

Table 3.4: Bicycle flow conversion factors between winter of 2017 and other seasons as well as the year 2025 for the intersection between Skånegatan and Ullevigatan.

Season	Time of Day	Maximum Flow From City Center	Maximum Flow Towards City Center	Factor Winter to Season	Total Factor 2017-2025 (Based on indexes)	Total Factor 2025 (Product of the two previous)
Winter	AM	109	181	1.00	2.5	2.50
	PM	165	108	1.00	2.5	2.50
Spring	AM	225	393	2.12	2.5	5.29
	PM	373	225	2.17	2.5	5.43
Summer	AM	383	484	3.09	2.5	7.73
	PM	444	357	3.00	2.5	7.50
Autumn	AM	224	378	2.07	2.5	5.18
	PM	327	214	1.98	2.5	4.95

3.6 | Ethical Concern

When evaluating the ethical concerns related to research carried out in a social field it is, according to Bryman (2012), important to thoroughly analyze the chosen method in regards to four different areas:

1. Harm to participants

2. Lack of informed consent

3. Invasion of privacy

4. Deception

Using the stated method, the participants, bicyclists in this case, is never at any *risk of being harmed* due to the study as long as the site investigations are carried out in a way that the data collectors do not in any way affect the usability of the bicycle path. In other words, the collectors need to place themselves away from the bicycle path so that they do not hinder the bicyclists.

Regarding the area *lack of informed consent* the participants were never able to properly give their consent on participating in the study but since the data collection was kept anonymous and simply a matter of numbers or notes on a paper, no measurements can be traced back to an individual bicyclists. Therefore, it was decided that consent was not needed as long as there was no possibility of *invasion of privacy*. However, when asked the data collectors clearly described what they were doing and how the data was to be used in order to prevent the curious participants from being *deceived*.

4 | RESULTS FROM THE STUDY

In this chapter results gathered from both site investigation and collected from computer simulations are presented.

4.1 | Results from Site Investigations

In this section the result from the site investigations is presented. The raw data collected during the site investigations is presented in Appendix B.

4.1.1 | Traffic Flows

The diagram shown in Figure 4.1 is based on data from site investigations conducted along Nya Allén, Ullevigatan and Dag Hammarskjöldsleden. Each bar represents the total traffic volume per hour through one specific intersection. The shown values are the theoretical maximum hourly flow, calculated as the two highest adjacent quarterly flows multiplied by two.
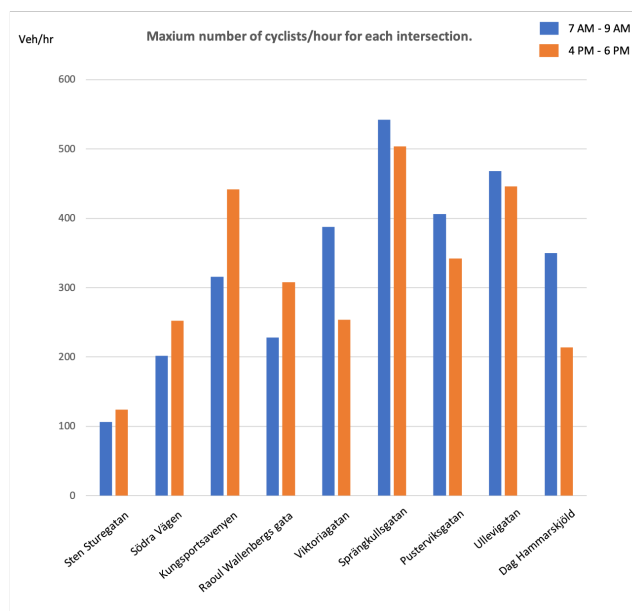
Figure 4.1: Bicyclists per hour using each specific intersection. Authors' own copyright.

The results indicate that the share of the total bicyclists is approximately equally distributed between morning and afternoon. The total bicyclist that crosses all intersections in any direction during the morning was 4400, and the corresponding number for the afternoon was 4650. Regarding the stretch between Viktoriagatan and Pusterviksgatan at Nya Allén, the investigation resulted in the total flow 3800 bicyclists for all directions in the intersections for both morning and afternoon. The same number for the stretch Sten Sturegatan to Raoul Wallenbergs Gata was 3000 bicyclists. Due to increasing precipitation, the investigation at

Sten Sturegatan could not be fully completed in the afternoon and the investigation had to be aborted early and lasted only from 4 to 5 PM. However, based on the collected data a peak in flow could still be seen and the location was not revisited.

In addition to the total flow of bicyclists, the maximum queue length measured in the number of bicyclists was measured during the sessions and was used to calibrate the simulation model. The maximum number of bicyclists in a queue is presented in Figure 4.2. The shown value is the total number of bicyclists and not the number of bicyclists in a line.
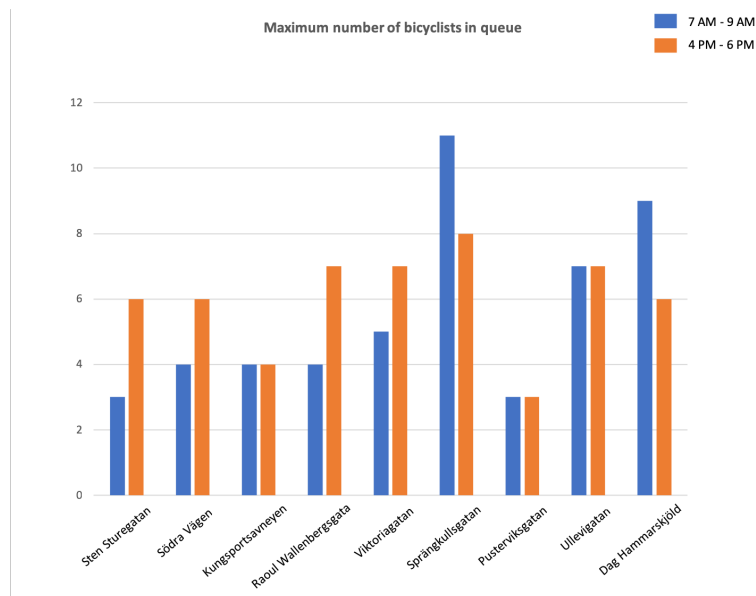
Figure 4.2: Maximum number of bicyclists in queue at each specific intersection. Authors' own copyright.

4.1.2 | Relative Flows

Each bicycle path can be crossed in different ways depending on what final destination the bicyclist has. From a certain starting point, where the bicyclist enters the intersection, one to three different turn options are available. With data gathered of flows that correspond to respective turn alternative, relative flows were determined. In Figure 4.3 the share of the bicyclists that runs straight ahead through a certain intersection is presented. The actual number of bicyclists turning a certain direction can be seen in Appendix B.
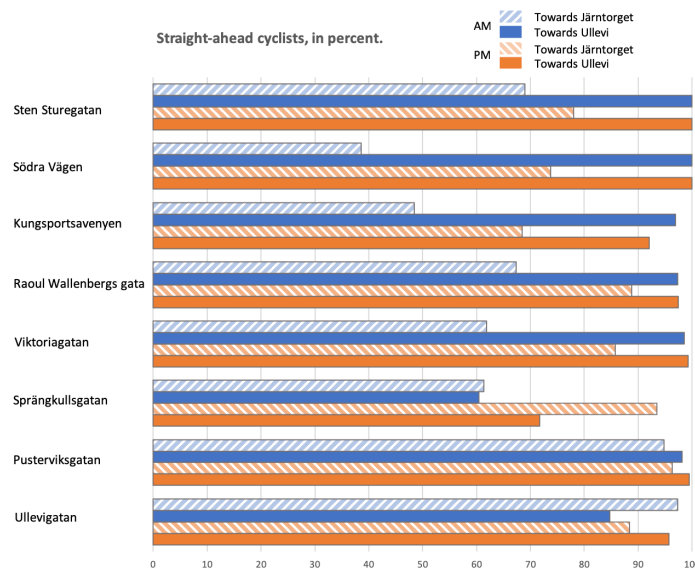
Figure 4.3: Share of bicyclist entering an intersection from each side of the main bicycle path that continues straight ahead through the intersection. Authors' own copyright.

According to the chart, the majority of bicyclists that passes Pusterviksgatan runs straight through the intersection without turning left or right, corresponding to a relative flow between 95-100 %. The data also indicates that Sprängkullsgatan has the lowest number of bicyclists that goes straight ahead, with an average of 72 % (based on data during morning/afternoon in both directions). As the filled bars indicate, the majority of the commuters that bicycles between Järntorget and Ullevigatan tend to go straight ahead through the intersections. Whilst the patterned bars shows that a large share of the bicyclists that goes in direction Ullevigatan-Järntorget turns left or right more frequently.

The revisit to the intersection between Kungsportsavenyen and Nya Allén to evaluate if the relative flows had changed depending on season showed that the relative flows were similar but not identical to what was earlier observed and it was assumed that this was more likely due to day-to-day variations rather than due to season. This was also assumed to be the fact for all intersections.

4.1.3 | Observed Behavior of Bicyclists in Gothenburg and Stockholm

From the site investigations, the behavior of the bicyclists when using the intersections were also observed in order to more precisely mimic the behavior in the simulations.

During site investigations in Gothenburg several protruding behaviors were observed:

- Bicyclists have stands close to one another in queues.
- Defying red lights is common.
- Bicycling in the opposite direction on one-directional paths is common where the total length of the path is shorter that way.
- Some bicyclists cut corners instead of crossing two bicycle crossings.

During site investigations in Stockholm some behavior that is not intended in the bicycle infrastructure were observed, namely:

- Bicyclists using walking paths and zebra crossings to get to where they want.

- Bicyclists cutting corners to shorten their path.

- Bicyclists defying red lights.

- Bicyclists moving in the wrong direction on the paths.

However, not only bad behaviors were observed but also one positive behavior that were not common in Gothenburg. The bicyclists in Stockholm also more commonly signaled their turns using hand gestures before changing direction. Overall the same bad behaviors that could be observed in Gothenburg was also observed in Stockholm but at a lesser rate. The bicyclists in Stockholm seemed more keen on following the rules in the signaled intersection. If only observing the behaviors of E-scooter riders in Stockholm, the rates of unwanted behaviors were more close to the Gothenburgians.

4.2 | Simulations of the Future and Possible Measures of Optimization

In this section, the future situation with an increase in total bicyclists using the bicycle paths are presented both without any changes to the traffic signals of today as well as with optimizing measures. Results will be presented for the summer season as summer is the most highly trafficked season and is, therefore, the season that stresses the system the most. Results from summer should be regarded as the worst case scenario.

4.2.1 | Implementation of Green Wave along Nya Allén

For the bicycle system along Nya Allén, the results are presented as a comparison between the morning traffic with and without any optimizing measures. The result from the evening showed similar results but with queues building up in the opposite direction.

The change in bicyclist using the system can be visualized as an OD-matrix showing the expected number of bicyclists going from one place (Origin) to another (Destination) during one hour based on measured relative flows and total flows. For this, all possible origins and destinations were numbered according to the following:

1. Ullevigatan
2. Sten Sturegatan
3. Södra Vägen
4. Kungsportsavenyen
5. Raoul Wallenbergs Gata
6. Viktoriagatan
7. Sprängkullsgatan East
8. Sprängkullsgatan West
9. Pusterviksgatan East
10. Pusterviksgatan West
11. Järntorget

Comparing the OD-matrix for summer morning 2017, shown in Table 4.1, with the OD-matrix for summer morning 2025, shown in Table 4.2, paints a picture on how significant the increase in bicyclists would be if the vision of a tripling in total trips reaches its goal.

Table 4.1: OD-Matrix showing expected number of bicyclists along Nya Allén traveling from one place to another in one hour during summer morning 2017.

From/To	1	2	3	4	5	6	7	8	9	10	11	Sum
1		34.4	46.8	15.5	4.7	3.7	2.3	0.0	0.2		3.5	111.1
2	26.7		10.8	3.6	1.1	0.8	0.5	0.0	0.0		0.8	44.4
3	22.2	0.0		0.0	0.0	0.0	0.0	0.0	0.0		0.0	22.2
4	7.1	0.0	0.0		27.0	20.8	13.2	0.0	1.0		19.7	88.9
5	0.0	0.0	0.0	0.0		16.9	10.7	0.0	0.8		16.0	44.4
6	23.4	0.0	0.0	0.7	0.7		7.6	0.0	0.6		11.3	44.4
7	15.5	0.0	0.0	0.5	0.5	0.2			2.5		47.5	66.6
8	0.0	0.0	0.0	0.0	0.0	0.0			3.3		63.3	66.6
9	5.5	0.0	0.0	0.2	0.2	0.1	0.5	3.4			34.7	44.4
10	7.2	0.0	0.0	0.2	0.2	0.1	0.6	4.5			31.5	44.4
11	182.5	0.0	0.0	5.6	5.8	2.0	16.3	114.3	6.7			333.2
Sum	290.1	34.4	57.6	26.4	40.3	44.5	51.9	122.2	15.2	0.0	228.2	

Table 4.2: OD-Matrix showing expected number of bicyclists along Nya Allén traveling from one place to another in one hour during summer morning 2025. 2.5 times higher flows compared to 2017.

From/To	1	2	3	4	5	6	7	8	9	10	11	Sum
1		86.1	116.9	38.9	11.8	9.1	5.8	0.0	0.5		8.6	277.7
2	66.6		27.1	9.0	2.7	2.1	1.3	0.0	0.1		2.0	111.1
3	55.5	0.0		0.0	0.0	0.0	0.0	0.0	0.0		0.0	55.5
4	17.8	0.0	0.0		67.4	52.0	33.1	0.0	2.6		49.2	222.1
5	0.0	0.0	0.0	0.0		42.2	26.9	0.0	2.1		39.9	111.1
6	58.5	0.0	0.0	1.8	1.9		19.1	0.0	1.5		28.3	111.1
7	38.8	0.0	0.0	1.2	1.2	0.4			6.2		118.7	166.6
8	0.0	0.0	0.0	0.0	0.0	0.0			8.3		158.3	166.6
9	13.7	0.0	0.0	0.4	0.4	0.1	1.2	8.6			86.6	111.1
10	18.0	0.0	0.0	0.6	0.6	0.2	1.6	11.3			78.9	111.1
11	456.3	0.0	0.0	14.1	14.5	4.9	40.8	285.7	16.7			833.0
Sum	725.2	86.1	144.0	66.0	100.7	111.1	129.8	305.6	38.0	0.0	570.5	

The most notable difference and also the difference that stresses the system the most is the increase of 500 bicyclists, from 333 to 833 bicyclists, coming from Järntorget. The increase in total bicyclist using the system at the same time leads to longer traveling times as visible in Table 4.3. The significant increases in traveling time for bicyclists is mainly due to a queue building up at the intersection with Sprängkullsgatan when the flows are increased. This phenomenon is shown in Figure 4.4.

Table 4.3: 85th percentile for travel time in minutes for stretches along Nya Allén and connecting roads in 2017 and 2025.

Stretch	Summer Morning 2017	Summer Morning 2025
Bicycle Järntorget-Ullevigatan	7.92	18.64
Bicycle Ullevigatan-Järntorget	7.59	8.36
Bicycle Kungsportsavenyen-Järntorget	5.30	5.64
Bicycle Järntorget-Kungsportsavenyen	6.27	17.39
Bus Blå Express	4.62	4.94
Car Raoul Wallenbergs Gata-Sprängkullsgatan	2.25	2.43
Car Sten Sturegatan-Viktoriagatan	4.04	3.65
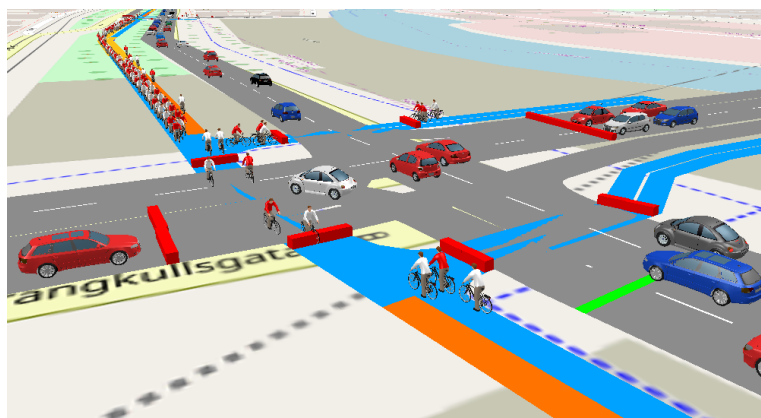
Figure 4.4: Queue building up from the intersection between Nya Allén and Sprängkullsgatan due to the increased flow in morning summer traffic by 2025 (OpenStreetMap contributors, 2019a). CC BY-SA.

The queue eventually stretches back all the way to Järntorget resulting in the system not being able to handle the total increase in bicycles traveling from Järntorget and Pusterviksgatan West where during the whole simulation an average of approximately 10 and 5 bicyclists per hour and a maximum of 40 and 16 respectively were not able to enter the system as they could not fit. This results in them never entering the simulation.

The proposed solution for optimizing the signal controls for the increased number of bicyclists in the system along Nya Allén is an implementation of a segmented Green Wave in combination with longer green time for the signal at Sprängkullsgatan West which was the signal that resulted in the queue building congestion. To show the possible improvement for the bicycle traffic a Green Wave for bicyclist only over-prioritized by trams was implemented. As expected the traveling times for bicycles using the system were decreased as can be seen in Table 4.4. This is mostly due to a decrease in queuing at Sprängkullsgatan.

Table 4.4: 85th percentile for travel time in minutes for stretches along Nya Allén and connecting roads in 2025 with and without Green Wave implementation.

Stretch	Summer Morning 2025	Summer Morning 2025 with Green Wave
Bicycle Järntorget-Ullevigatan	18.64	13.00
Bicycle Ullevigatan-Järntorget	8.36	6.99
Bicycle Kungsportsavenyen-Järntorget	5.64	4.91
Bicycle Järntorget-Kungsportsavenyen	17.39	12.48
Bus Blå Express	4.94	3.32
Car Raoul Wallenbergs Gata-Sprängkullsgatan	2.43	2.46
Car Sten Sturegatan-Viktoriagatan	3.65	12.48

The reduction in travel time for bicycles, however, results in worsening effects for other means of transport. The car traffic along Nya Allén benefits from the GW for the bicyclists as they are traveling in the same direction and thus gets more green time. Cars on connecting roads have a harder time entering the system which is shown both in travel time for cars driving between Raoul Wallenbergs Gata and Sprängkullsgatan, which increases further, as well as in the error messages from the simulations where on average approximately:

- 10 cars per hour could not enter from the northern side of Raoul Wallenbergs Gata.

- 60 cars per hour could not enter from the northern side of Viktoriagatan.

4.2.2 | Bicycle Priority or Prolonged Green Time at Annedalsmotet-Dag Hammarskjöldsleden

For the intersection located at Annedalsmotet-Dag Hammarskjöldsleden results from comparisons of optimizing measures and the current set up during afternoon traffic will be presented. As in the case with Nya Allén, similar results were gained when observing the second commuting window but with the queues building up in the opposite direction.

Since this model only consisted of one intersection the increase in bicycle flow by 2025 can more easily be presented in a table showing the different flows. This information can be found in Table 4.5.

Table 4.5: Hourly bicycle flow at Annedalsmotet-Dag Hammarskjöldsleden.

Direction	Summer Afternoon 2017	Summer Afternoon 2025
Northbound	160	390
Southbound	290	735

The increased flow of bicycles leads to longer queues, as can be seen in Table 4.6, with the 85th percentile in queue lengths more than doubling in both directions.

Table 4.6: Queue lengths in number of bicycles at Annedalsmotet-Dag Hammarskjöldsleden in 2017 and 2025.

Queue Position	Summer Afternoon 2017		Summer Afternoon 2025	
	85th percentile	Average	85th percentile	Average
Northbound	2	0	5	1
Southbound	5	1	11	4

A queue length of 11 bicycles, in this intersection, is not a large queue as the design allows for such queue to fit within the system but in order to test some optimizing measures for a straight crossing, as the intersection at hand, implementation of higher priority for bicycles as well as prolonging the green time for bicycles was tested. Regarding the higher priority for bicycles, it was set up so that only buses were over-prioritized in the intersection and the prolonged green time increased the maximum green time for bicycles with 25 seconds while the green time for motor vehicles was lowered by 15 seconds.

Queue lengths after implementing said optimizing measures can be seen in Table 4.7 and show that implementing a bicycle priority in the intersection has the largest impact on the queue length whereas a prolonged green time only affects the average queue length in one direction, this is probably due to certain waves in the simulation consisting of 5 and 11 bicyclists resulting in said 85th percentile.

Table 4.7: Queue lengths in number of bicycles at Annedalsmotet-Dag Hammarskjöldsleden in 2025 with and without optimizing measures.

Queue Position	Summer Afternoon 2025		Summer Afternoon 2025 Bicycle Priority		Summer Afternoon 2025 Prolonged Green Time	
	85th percentile	Average	85th percentile	Average	85th percentile	Average
Northbound	5	1	3	1	5	1
Southbound	11	4	8	2	11	3

Changing the sequences in favor of the bicyclists, however, affects the overall capacity of the intersection and implementation of optimizing measures leads to the simulated system not being able to handle the total car flow anymore. More precisely:

- Bicycle prioritization leads to on average 186 vehicles per hour not being able to enter the system.

- Prolonged green time leads to on average 17 vehicles per hour not being able to enter the system.

Without any changes to the signal control, the system managed to handle all vehicle flows in its current set up and no error messages were given from the simulation.

4.2.3 | Implementation of All Green at Skånegatan-Ullevigatan

Results from the intersection between Skånegatan and Ullevigatan is presented for the afternoon traffic and alike previous intersections the results from the morning traffic were similar but with problematic queues building up in the opposite direction.

The intersection has bicycles coming in to the intersection from three directions and the change in flow from 2017 to 2025 is presented in Table 4.8 and as this is the third most trafficked bicycle path in the city it is also here that we have the single highest flow coming from one direction used in this project's simulations. This high flow consists of 510 bicycles per hour in 2017 and is increased to 1275 bicycles per hour by 2025.

Table 4.8: Hourly bicycle flow in the intersection between Skånegatan and Ullevigatan

Direction	Summer Afternoon 2017	Summer Afternoon 2025
Westbound	300	750
Eastbound	510	1275
Southbound	120	300

Even using 2017's flows there were longer queues building up among the bicyclists leaving the city center, suggesting that the bicycle infrastructure already is close to its capacity and increasing the flow with the factor of 2.5 (index 120 to 300) to 2025's values results in the queue never getting the time needed to disperse as can be seen in Table 4.9.

Table 4.9: Queue lengths in number of bicycles in the intersection between Skånegatan and Ullevigatan in 2017 and 2025.

Queue Position	Summer Afternoon 2017		Summer Afternoon 2025	
	85th Percentile	Average	85th Percentile	Average
Westbound	5	1	11	4
Eastbound	17	11	251	244

Having a queue of 251 bicycles is not reasonable so an optimizing measure is needed if this intersection is going to work in the future and in addition the increased bicycle flow leads to the system not being able to handle on average 256 bicycles per hour trying to enter from the western side and approximately 20 bicycles per hour from the other directions.

The proposed optimizing measure being tested in this intersection was the implementation of 20 seconds of all green for bicycles before motor vehicles are given green light. Implementing such measure lowers the queue length as can be seen in Table 4.10 and allows for the system to handle almost all bicycles. On average only 30 bicycles per hour is unable to enter the system in total according to the error log of the simulation.

Table 4.10: Queue lengths in number of bicycles in the intersection between Skånegatan and Ullevigatan in 2025 with and without optimizing measures.

Queue Position	Summer Afternoon 2025		Summer Afternoon 2025 with All Green	
	85th Percentile	Average	85th Percentile	Average
Westbound	11	4	8	2
Eastbound	251	244	247	173

However, a queue with a standard peak of 247 bicycles and an average of 173 is still a long queue and implementing all green for the bicycles prolongs the cycle time for motor vehicles resulting in the system overflowing with cars. The implementation leads to:

- On average 290 cars per hour are unable to enter the system from the west.

- On average 410 cars per hour are unable to enter the system from the east.

- On average 90 cars per hour are unable to enter the system from the south.

5 | ANALYSIS OF THE RESULTS

In the analysis of the results, the results obtained from both site investigations and simulations of the future are analyzed with a basis in how they correlate to the research questions presented at the beginning of the report but also on a more broad spectrum. The different tested optimizing measures are to be analyzed and also the need for optimizing measures.

5.1 | Analysis of Results Obtained from Site Investigations

The raw data collected from the site investigations shows an overall increasing trend in the number of bicyclists using the intersection going from Sten Sturegatan, which was the first to be visited, and on-wards. This is in line with what previous data has shown, that the closer one gets to summer the more likely one is to take the bike. Some measurements does not follow the same trend but that is presumptively due to slightly colder days or wind that made people leave the bicycle at home.

Regarding queue lengths, the results show that, along Nya Allén, the lengths are of rather constant sizes suggesting that the queue lengths often is determined by how many bicyclists are able to pass a previous intersection during one sequence cycle. The queue, however, becomes longer at intersections with more connecting roads, such as Sprängkullsgatan where two bidirectional paths connects to the main path.

The relative flows mainly suggest that the intended main direction of the path is the way people use the intersection. Therefore implementing optimizing measures is mainly a possibility in the main direction if they are to have any effect. The data also suggests that, along Nya Allén, a commuter route can be identified in the direction from Järntorget towards Ullevigatan, rather than the opposite direction. This means that, overall, a higher percentage is traveling straight through the intersections when traveling towards Ullevigatan than when traveling towards Järntorget during both morning and evening traffic. This could be due to people running errands on their way home rather than on their way to work and therefore diverts from the main path.

The observed behavior indicates that the Gothenburgian bicyclists and the bicyclists in Stockholm are to some extent alike in their behavior. When suitable for the bicyclist the proposed behavior in a signaled crossing is left behind and rules are broken in order to more quickly get through the intersection. However, the bicyclists in Stockholm did this at a lesser rate making them more law-abiding which in its turn means that simulations based on bicyclists following the rules would be closer to reality in Stockholm than in Gothenburg.

5.2 | Analysis of Results Obtained from Simulations

Looking at results obtained from simulation, of the three studied areas it can be said that only one of the three areas would cope with the wanted increase in bicyclists by 2025, namely Annedalsmotet where the normal peak of queue length in 2025 was lower than the current peak at Ullevigatan and should be regarded as usable even in the future.

This would mean that there is no need for any optimization measures at specifically Annedalsmotet in order to handle the increase in total bicycle traffic with a factor of 2.5 by 2025, but looking at both Nya Allén and Skånegatan-Ullevigatan the results indicate a deterioration in usability of the bicycle network wherein the foremost case the travel times more than doubles and in the latter case the queues become longer than the average bicyclist is believed to have patience for.

5.2.1 | Nya Allén and the Usage of Green Waves

The increase in flow and the subsequent congestion increases the total travel time between the two ends of the system with a factor of 2.4, almost identical to the increase in traffic flow. The increase in travel time to above 18 minutes results in walking being almost as fast and therefore a congestion-reducing method is needed for the future if the bicycle should still be regarded as a viable mean of transport.

At Nya Allén it can be said that the implementation of a segmented green wave in combination with longer green time at bottlenecks does a lot for the usability of the path during peak hours in 2025 but there is still an increase in total travel time between the two ends of the path with approximately 5 minutes due to congestion which could lead to people considering other means of transport. At the same time, the implementation of this optimizing measure puts significant stress on the traffic at a whole and would require a decrease in the total car traffic flow in order to not uphold the overall traffic.

The increase in travel time with 5 minutes with the green wave could still be regarded as an increase that makes people considering other means of transport and in order to evade an increase in travel time a redesign of the system may be needed. If the design of the bicycle path were to change, in a way that increases the capacity (for example by broadening the lanes), the green wave could be given more restrictions such as minimum green time for connecting roads and through that cope with both the bicycle flow as well as other traffic flow without affecting travel times negatively.

5.2.2 | Annedalsmotet-Dag Hammarskjöldsleden and the Usage of Prioritization or Prolonged Green Time

The one-dimensional flow intersection at Annedalsmotet does not show signs of overloading even when the flow is increased. As stated earlier the intersection shows no indication of a need for congestion reducing measures. However, in order to later evaluate congestion reducing measures on a wider spectrum, some measures are still analyzed.

Evaluating the implemented measurements at Annedalsmotet-Dag Hammarskjöldsleden it can be said that bicycle prioritization directly under-prioritized public transport without any restrictions in minimum green time in an intersection with only a one-dimensional flow for every mean of transport is only reasonable in areas with a lower flow of cars. This since the flow of cars is directly affected when bicycles are prioritized through a reduction in the total green time in the motor vehicle's travel direction. A high flow of cars would then make the system overflow if the cars are not given time to empty their link before filling up again.

Instead, in areas with a high flow of cars, introducing prolonged minimum green times could be a good measure for intersection with one-dimensional flows if the times are optimized for

the specific intersection since this gives better control on how many of either vehicle type is let through during each cycle. This could lead to higher waiting times for bicycles as no vehicle type is prioritized but instead have to wait a fixed time. Implementation of prolonged green time does, however, not show any noticeable impact on the queue length at the simulated intersection and this is probably due to the results showing the number of bicyclists in some of the clusters of bicyclists arriving at the same time.

5.2.3 | Ullevigatan-Skånegatan and the Usage of All Green

The situation at Ullevigatan-Skånegatan shows that the peak flow of today is already stressing the system in the complex and highly trafficked intersection with standard peak queue lengths of 18 bicycles. The lack of space for queuing due to pedestrian areas and trams crossing the bicycle path leads to the situation already being close to the peak of what the system can handle without overflowing and blocking other areas.

At first 18 bicycles in a queue sounded unreasonable but a revisit to the area during late spring showed queues of 11 bicycles implying that a queue of 18 bicycles during summer is reasonable. Increasing the flow with a factor of 2.5 from this situation is too much for the system to handle and even though implementing two windows of 20 second all green in every traffic signal sequence cycle lowers the average queue length with over 70 bicyclists, the normal peak is barely changed and in addition the traffic flow as a whole becomes severely affected.

All green is still a good optimizing measure with a high potential effect, as can bee seen in the reduction of queue length, but the intersection at hand cannot handle the increase in flow of bicycles without completely ruining the flow of motor vehicles, no changes to the signal system can make the intersection handle the increased bicycle flow at its peak. If the bicycle flow were to reach this peak a rebuild of the bicycle infrastructure in the intersection is needed unless bicycles are persuaded into choosing other roads. Otherwise many commuters that usually commute through this intersection will move over to other means of transport.

5.3 | Analysis of the Results on a Broader Spectra

Analyzing the results obtained from the study in a broader perspective, the results could be said to be applicable to one of three situations in other parts of Gothenburg. Namely areas where:

- Several intersections are close to each other with a distinct main road.

- A single intersection with a one dimensional flow.

- A single intersection with a two dimensional flow.

This is the fact at several other places in the city and the optimizing measures could, with smaller tweaks, be implemented at other intersections in order to improve the situation for the bicyclists in the future.

Furthermore, based on the observations that the same unwanted behaviors among bicyclists in signal controlled intersections existed in Stockholm as well, even though it existed at a lesser rate, the result could be applicable in intersections fulfilling either situation in Stockholm and the results could even be more likely in Stockholm as a higher percentage of users followed

the rules as the bicyclists in the simulation does. Given that the results could be regarded as applicable to both Gothenburg and Stockholm it could potentially be applicable to other big cities in Sweden.

6 | Discussion

In this chapter the result of the study is discussed in relation to its validity and significance.

6.1 | Regarding the Chosen Methodology

Overall the chosen methodology was the better way to tackle the issue at hand but in hindsight, there are some parts that could have been done differently given the outcome.

All site investigations were carried out by the two authors resulting in the total time that the investigations were spread out over were rather long resulting in outdoor temperature possibly affecting the total number of bicyclists in the system leading to the actual measured flow not being used directly in the simulation. If more people were to carry out the site investigations, more intersections could be investigated at the same time and thus give results that could directly be implemented in the simulation model.

During the spring in Gothenburg, the number of electric scooters in the system increased significantly. Electric scooters were counted as bicycles during the site investigations and this increase could have affected the results in a way that only the future can tell.

Due to the supervisor's knowledge, only Vissim was investigated as a mean of simulating bicycle traffic. However, there is other simulation software that utilizes other following models and thus could give other results.

6.2 | Expected Result versus Actual Result

The result obtained from the simulations of the future were both better than the expected result in some areas and worse in others. Overall it was expected to see a deterioration of the usability of the bicycle network when the number of bicyclists was increased which overall was reflected in the simulation results but at for example Annedalsmotet the effect of the increased number of bicycles were lower than expected.

Regarding the results at Skånegatan-Ullevigatan, the authors could not imagine how the intersection was to react to the increased flow. It was expected to see longer queues in the future but not as long as the result implies. The authors had quite frankly not fully understood what it meant to pass the serviceability limit for an intersection, 250 bicycles in a queue showed the authors what that meant.

The prolonged travel times along Nya Allén was expected due to the congestion the increase in bicyclists were to bring but it was expected that the travel times were to be reduced to more normal levels with the introduction of a segmented green wave. This turned out not to be the case and it was probably due to the, in some intersections, long interstage times (time between green light in two different directions) where the safety times in place were long in order to reduce the risk of collisions. This meant that even though a bicycle was approaching, the signal could not give it green light early enough before it had to reduce its speed and sometimes come to a full stop.

It was also assumed before the behavioral observations in Stockholm that the bicyclists in Stockholm would more commonly break the rules but this showed to be false based on the results and the assumption were probably mainly due to prejudice and not actual knowledge.

6.3 | Results Significance in the Field

On a broad scale, improving the bicycle network is an ongoing work among both researchers and cities around the world. The results obtained from the simulations in this report is in line with what is expected from the tested congestion reducing measures, as the city of Gothenburg states in the strategy program, and this project did not intend to only show that this was the case but also show the potential for the different congestion reducing measures given different situations in the network, something that previous research has lacked.

This report has shown the impact of implementing some congestion reducing measures in the Gothenburgian bicycle traffic which gives analysts and city planners a basis on which decisions can be made for the future development of the bicycle traffic.

6.4 | Sources of Error and Their Effect on the Results

The simulations simplify both the system and the behavior of the bicyclists. For example, the simulation is based on bicyclists following the traffic rules where in reality some bicyclists defy red light signals, uses one-directional bicycle paths in the wrong direction, and cuts corners, leaving for bicycles designated areas. Overall some of this behavior should, however, decrease in relation to the increase in bicyclists as there would be less space for bicyclists to, for example, move in the wrong direction. Defying red light will probably still be a fact among bicyclists trying to improve their travel time when stressing to and/or from work.

Additionally, the behavior when queuing was not fully able to be resembled in the simulation as the simulation software did not allow for bicyclists to basically stand on each other in the queues but instead only allowed for the bicyclists to queue next to each other. The software also did not allow for the bicyclists to squeeze past a queue if the queue is heading in another direction than the bicyclist.

In the end, the sources of error are not assumed to have affected the result negatively. If the identified errors have an effect on the calculated flows it would likely have increased the flow rate leading to fewer problems in the intersections from time to time and not made the simulated results worse.

6.5 | Likelihood of the Simulated Future to be the Future

The simulations are based on the goal for 2025 being met but looking at the development curve and the stagnating increase in bicycles the last years it could very well be that the goal is not going to be met and if so the stress on the system is going to be lower than simulated. Reaching the goal would probably require a change in the perception of bicycles among the people as well and not only building better infrastructure. However, preparing for the wanted increase is still good in regards to future proofing the infrastructure with bicycle traffic being

one of the most environmentally friendly means of transport and therefore something to strive for.

Additionally, the simulated queue lengths in 2025 at Skånegatan-Ullevigatan at a glace seems unrealistic. The queue lengths are based on that no one takes another route which would probably be the case in reality. The queue becomes as long due to the system not having time to empty the demand during one cycle. If some bicyclists decide to take another route, the intersection could handle the bicyclists in a better way.

7 | CONCLUSION

At the beginning of the report, three research questions were presented that the report aimed towards answering. One of the main conclusions regarding these three questions is that there is not one definitive answer to any of the questions and that the answers vary depending on the current setup of the infrastructure in the studied area.

The first question presented was ***Is there a certain commuter path that is more prone to queuing than others?*** As stated in the methodology, through interviews with traffic analysts in Gothenburg it was deemed that bicycle commuter paths with high traffic flows and intersections lead to a risk of congestion resulting in queues and/or prolonged travel time. The high flow along with the start and stop behavior caused by the intersections results in queuing and this phenomenon has been validated by the simulations.

The second question presented was ***In what way can the existing traffic signals on such paths be optimized in order to reduce queuing in the future (2025)?*** Different congestion reducing measures were presented in the literature study and tested in the simulations. Not all studied areas were in need of optimizing measures even after the increase in traffic flow but depending on the situation in the analyzed area, different optimizing measures can be used for the signal controls in order to reduce congestion. In areas with several coherent intersections a, to some extent restricted, green wave can be implemented in order to facilitate the bicycle flow and in areas with longer distances between signal controlled crossings measures such as all green, bicycle prioritization or prolonged green time can be used to reduce queue lengths. However, optimizing measures of the signal controls can only take you so far and the results indicated that in some situations the flows become too high in the future for the intersection to handle in the current design. Other congestion reducing measures could be more efficient but have to be analyzed further before being considered.

The third and last question presented was ***How would such optimization for bicycles affect the overall traffic situation?*** As visible in the results from the simulations, implementation of any optimizing measure will affect the overall traffic situation with a positive outcome for some and negative outcome for others. For example, making changes to the signal sequences in order to facilitate the bicycle flow along the main road will benefit both the bicycles and cars running along the main road but will hindrance all traffic connecting to the main road. Due to this, it is of importance to closely study how and whom changes will affect and to know how much it is reasonable to take into account negative outcomes for less prioritized means of transport before implementing any changes to the signal system.

Concluding, the results obtained from the simulations could be said to be applicable to similar intersections in bigger cities of Sweden, such as Stockholm, Malmö and more.

8 | FUTURE RESEARCH

In this project, only optimizing measures for the signal control systems has been evaluated. Preparing for the future will, with high probability, also include changes in how the system is built regarding widths of lanes and other measures. A future research could evaluate how changes in the design of the system could affect the total capacity and could in combination with changes to the signal system show the city of Gothenburg how the city could prepare for the increase in total bicyclists using the system.

Furthermore the project also used a simulation following model which is mainly built for cars. A future research could evaluate the same situation but using a, for bicycles, more realistic following model and compare the differences between the two.

During the study it was also rumored about an upcoming major change to the design of the bicycle network along Nya Allén and if such plans are published, a future research could evaluate how changes to signal controls in the new system could affect the overall traffic flow.

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A | EXAMPLE OF INTERSECTION PROTOCOL

Intersection control form (to be filled in after session)

Intersection: _Sten Sturegatan_
Date: _6 / 2_
Time of day: _7 - 9_
Weather: _Cold -1° C and cloudy_
Filled in by: _Christofer_

Public Transport:

Is the intersection trafficked by public transport?
- ☒ Yes
    - If yes, what type(s)?
        - ☐ Tram
        - ☒ Bus
- ☐ No

Is the public transport prioritized in the intersection?
- ☐ Yes
- ☒ No
- ☐ Can't say

Intersection Type:

What type of detection system for bicycles?
- ☐ Manual
- ☐ Coils
- ☒ None/Time based

What kind of bicycle lanes are used?
- ☐ One way
- ☒ Bidirectional

Traffic notations:
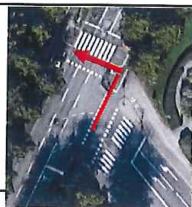
Longest queue (bicycles): ___3___
- In which direction: ~~Towards~~ City
  From

Intersection Sten Sturegatan-Nya Allén

	552	555	556
07:00-07:15	—	2	0
07:15-07:30	5	0	1
07:30-07:45	6 1	8 1	11 2
07:45-08:00	8 2	4 1	1
08:00-08:15	9 1	7 3	1
08:15-08:30	9 2	0	1
08:30-08:45	13 2	0	0
08:45-09:00	18 5	9 2	0

0	0	0

Intersection Sten Sturegatan-Nya Allén

	SS1	SS4	SS3
07:00-07:15	2 2	6 6	
07:15-07:30	7 5	12 6	
07:30-07:45	11 4	17 5	
07:45-08:00	19 8	30 13	
08:00-08:15	27 8	45 15	
08:15-08:30	32 5	54 9	
08:30-08:45	37 5	66 12	
08:45-09:00	40 5	76 10	

0	0	0

Intersection control form (to be filled in after session)

Intersection: _Ster Sture – NA_   Weather: _Snow/rain_
Date: _4 / 2_
Time of day: _16 – 17_
Filled in by: _Johan_

Public Transport:

Is the intersection trafficked by public transport?
- ☑ Yes
  - If yes, what type(s)?
    - ☐ Tram
    - ☑ Bus
- ☐ No

Is the public transport prioritized in the intersection?
- ☐ Yes
- ☑ No
- ☐ Can't say

Intersection Type:

What type of detection system for bicycles?
- ☐ Manual
- ☐ Coils
- ☑ None/Time based

What kind of bicycle lanes are used?
- ☐ One way
- ☑ Bidirectional

Traffic notations:

Longest queue (bicycles): _6_
- In which direction: _Towards City_

Intersection Sten Sturegatan-Nya Allén

SS1   SS4   SS3

16:00-16:15	11	6	
16:15-16:30	2̶1̶ 13	1̶0̶ 4	
16:30-16:45	7̶ 7	3̶9̶ 29	
16:45-17:00	8	4̶7̶ 8	
17:00-17:15			
17:15-17:30			
17:30-17:45			
17:45-18:00			

0	0	0

Intersection Sten Sturegatan-Nya Allén

552   555   556

16:00-16:15	2	0	1
16:15-16:30	2 4	2	0
16:30-16:45	0	0	1
16:45-17:00	4 7	3 1	1
17:00-17:15			
17:15-17:30			
17:30-17:45			
17:45-18:00			

0	0	0

B | Collected Data from Site Investigations

Below is attached an abbreviation translator for relations in Figure B.1 followed by a compilation of data collected during site investigations in Table B.1.

Figure B.1: Relation translation for Table B.1. Attributes according to corresponding figure in section 2.4.

Table B.1: Data collected from site investigations.

Sten Sturegatan — AM / PM

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
SS1	40	58	69	32		39	50	78	48	6
SS2	18		31	14		11		22	14	
SS3	0	76	0	0		0	47	0	0	
SS4	76		100	56	3	47		100	74	
SS5	9	15	60	8		3	6	50	4	
SS6	6		40	6		3		50	4	
All	149			106		103			124	

Södra Vägen

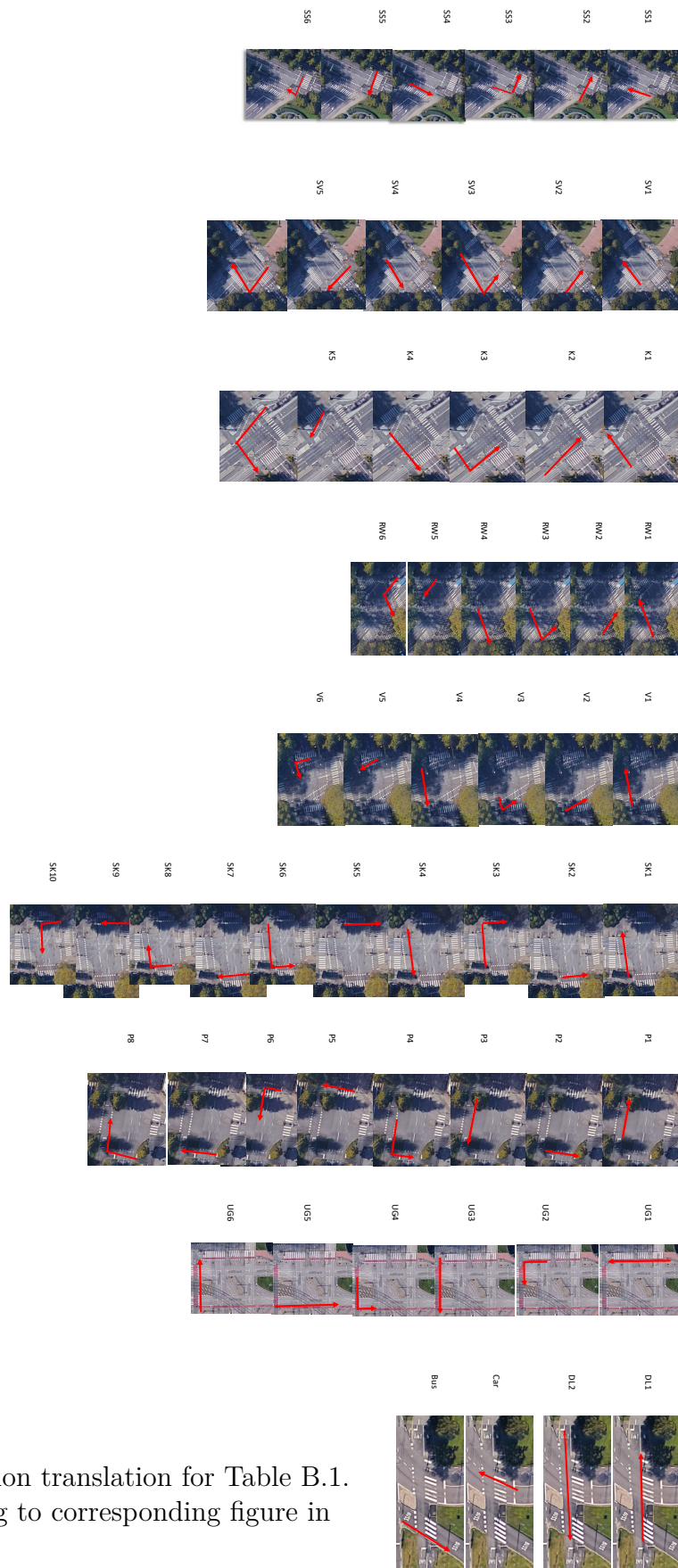| Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
SV1	68	176	39	44		157	213	74	98	6
SV2	108		61	76		56		26	36	
SV3	0	109	0	0		0	112	0	0	
SV4	109		100	72	4	112		100	68	
SV5	15	15	100	10		89	89	100	60	
SV6	0		0	0		0		0	0	
All	300			202		414			252	

Kungsportsavenyen

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
K1	107	221	48	64	4	161	235	69	118	
K2	114		52	76		74		31	46	
K3	6	196	3	6		10	125	8	10	
K4	190		97	146		115		92	82	
K5	48	52	92	34		281	289	97	180	
K6	4		8	4		8		3	8	
All	469			316		649			442	4

Raoul Wallenbergs Gata

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
RW1	99	147	67	76		278	313	89	186	
RW2	48		33	34		35		11	22	
RW3	6	224	3	6		5	196	3	8	
RW4	218		97	130	4	191		97	112	7
RW5	1	1	100	2		23	23	100	14	
RW6	0		0	0		0		0	0	
All	372			228		532			308	

Viktoriagatan

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
V1	120	194	62	92	5	180	210	86	106	7
V2	74		38	52		30		14	26	
V3	5	337	1	6		1	131	1	2	
V4	332		99	240		130		99	82	
V5	8	18	44	8		44	90	49	34	
V6	10		56	10		46		51	34	
All	549			388		431			254	

Sprängkullsgatan

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
SK1	122	199	61	86		299	320	93	208	8
SK2	77		39	64		21		7	26	
SK3	0		0	0		0		0	0	
SK4	352	582	60	218	11	162	226	72	106	
SK5	201		35	140		50		22	38	
SK6	29		5	30		14		6	14	
SK7	1	4	25	2		2	16	13	4	
SK8	3		75	6		14		88	14	
SK9	39	39	100	28		241	247	98	142	
SK10	0		0	0		6		2	10	
All	824			542		809			504	

Pusterviksgatan

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
P1	181	191	95	126		316	328	96	188	
P2	10		5	8		12		4	10	
P3	363	370	98	236	3	200	201	100	122	
P4	7		2	8		1		0	2	
P5	10	14	71	10		28	28	100	20	
P6	4		29	6		0		0	0	
P7	5	23	22	4		9	49	18	8	
P8	18		78	18		40		82	42	
All	598			406		606			342	3

Ullevigatan

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
UG1	80	83	96	68		66	82	80	52	
UG2	3		4	4		16		20	10	
UG3	166	196	85	102		381	398	96	248	7
UG4	30		15	8		17		4	22	
UG5	10	368	3	28		31	267	12	14	
UG6	358		97	288	7	236		88	148	
All	647			468		358			446	

Dag Hammarskjöldsleden - Bicycles

Relation	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Bicyclists	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
DL1	130	505	26	100		247	358	69	146	6
DL2	375		74	252	9	111		31	76	
All	505			350		358			214	

Dag Hammarskjöldsleden - Motor vehicles

Relation	Tot.Vehicles	For 2 directions	Relative Flows	MaxFlow/h	Number in queue	Tot.Vehicles	For 2 directions	Relative Flows	MaxFlow/h	Number in queue
Car	1189	1236	96	692		1654	1695	98	1112	
Bus	47		4	28		41		2	30	
All	1236			716		1695			1122	