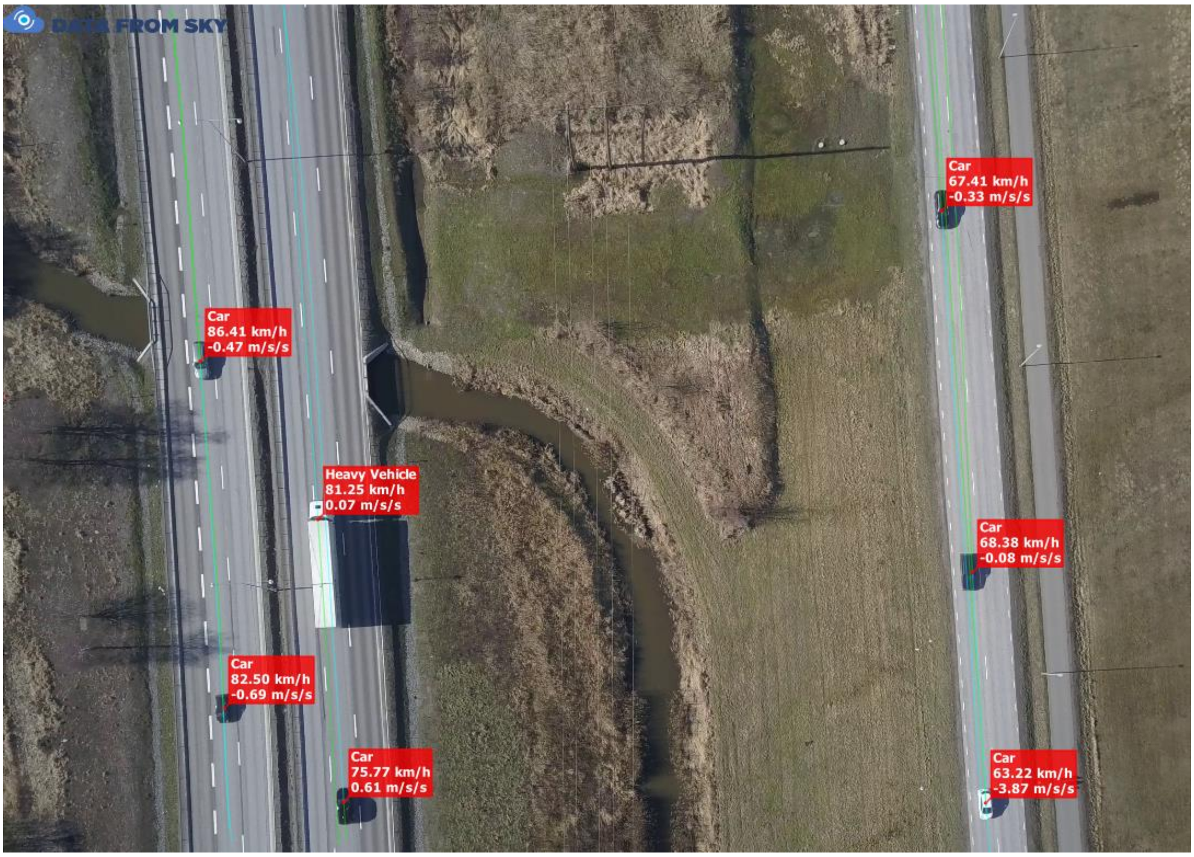

Longitudinal driver behaviour in different road environments

A microscopic video-based study in Gothenburg

Master's thesis in Infrastructure and Environmental Engineering

MARIANA BATISTA

Department of Architecture and Civil Engineering
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Cover:
Visualisation snapshot of the traffic analysis at Söderleden and Jolengatan from the DataFromSky software viewer.

Department of Architecture and Civil Engineering
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ABSTRACT

Longitudinal driver behaviour can be related to the road infrastructure and interaction between vehicles. Consequently, it is important to study driver behaviour taking into consideration both the roadway and the traffic participants. This thesis investigates how the road environment influences longitudinal driver behaviour by using a microscopic video-based approach in Gothenburg. Three road segments were selected, Bifrostgatan, Jolengatan and Söderleden, as they present different road characteristics. Then, traffic data was collected by drone and processed by DataFromSky to study time headway, speed and acceleration in the car-following regime. The trajectories of the vehicles were also visually examined to understand if the road infrastructure influences driver behaviour. Furthermore, statistical analysis was used to investigate the longitudinal driver behaviour parameters and non-parametric tests were performed to compare headway and speed in the road environments. The study showed that longitudinal driver behaviour can be affected by infrastructures attributes, such as the presence of bike lane, speed reduction sign and lane width. In Bifrostgatan drivers were inclined to be more cautious, driving slower, on the lane closer to the bike lane. In Jolengatan, the traffic sign seems to influence the vehicles' movement dynamics, being the only environment where drivers were respecting the speed limit. In Söderleden, drivers perceived the road in a different way, perhaps due to the lane width, and in some lanes, they were driving in a rate 25% above the speed limit. From the non-parametric tests, it was concluded that time headway is different among the three road environments, but Bifrostgatan and Jolengatan have similar headway distributions, which might be because they play the same function in the network. It was observed higher time headways in Bifrostgatan and Jolengatan than in Söderleden. On the other hand, speed characteristics were significantly different in all the road segments, not only because they have different speed limits, but also because drivers tend to vary behaviour within the road segment. Thereafter, a traffic simulation environment was created for Bifrostgatan on PTV VISSIM. The parameter CC1 of the Wiedemann 99 car-following model was calibrated based on the data collected. According to the results, it can be said that the road environment can be calibrated taking into consideration vehicle composition, flow and speed distribution as input data and time headway for the calibration of CC1.

Key words: Longitudinal driver behaviour, Car-following, Road environment, DataFromSky, PTV VISSIM, Bifrostgatan, Jolengatan, Söderleden.

Contents

Preface

This master's thesis is the result of a degree project work of 30 credits for the master's programme in Infrastructure and Environmental Engineering at Chalmers University of Technology. The project has been conducted in collaboration with Alten Sverige during the spring term 2019 under the supervision of Eric Bjärkvik.

I would like to acknowledge and thank some of the people that have helped me throughout this project. First, I would like to thank my supervisor Eric for all his support, guidance and valuable advice during the thesis work. I would also like to thank my examiner Xiaobo Qu for the assistance he has provided. This project used Alten Sverige's drone to collect traffic data, therefore I would like to thank Alten Sverige and also Erik Djupström, who took his time to help me with the data collection.

Furthermore, without DataFromSky, this project could not have been done. DataFromSky was responsible for processing the videos, consequently providing me with the information I needed to perform my analysis. Therefore, I would like to thank Lenka Šedivá, who made this collaboration possible.

Finally, I would like to thank my family and friends for supporting me during this project but also throughout my studies at Chalmers University of Technology.

Göteborg, May 2019
Mariana Batista

Abbreviations

CF	Car-following
CV	Coefficient of variation
DHW	Distance headway
LFV	Luftfartsverkets
NVDB	National Road Database for Sweden
THW	Time headway
TTC	Time to collision

1 Introduction

Traffic is a complex dynamic system composed of people, vehicles and infrastructure. The relationship among them has a great impact on the traffic conditions in a city. Therefore, it is not always straightforward to understand the underlying reasons for congestion (O'Flaherty, 1997). In the next years, congestion levels are expected to be reduced due to the introduction of autonomous cars. These vehicles can be useful to increase traffic capacity because of an optimised driver behaviour that can also improve safety and fuel consumption. The parameters incorporated in the autonomous system, particularly the ones related to driving style, can influence traffic systems and flow efficiency. As a result, it has been crucial to focus on understanding driver behaviour to design better autonomous driver models, driver assistance systems and, consequently, improve the road infrastructure (Hoogendoorn et al., 2014; Wu et al., 2011).

Longitudinal driver behaviour relates to car-following situations, as when drivers are following a vehicle and trying to keep a specific safe headway by adapting the movement dynamics to the vehicle in front. Several studies have already identified that driver behaviour can change according to the type of leading vehicle, road characteristics and traffic conditions (Brackstone et al., 2009; Ericsson, 2000; Van Winsum & Heino, 1996). However, a deep understanding of how drivers interact with each other is furthermore crucial to investigate if the road environment influences this behaviour at some level.

As stated by Van Winsum & Heino (1996), time headway is a key parameter for car-following behaviour in microscopic traffic analysis, being applied in planning, analysis and design of road systems. Moreover, there are many factors influencing driver behaviour in a road segment, as the number of lanes, lane width, traffic signs, speed limit and the presence of cyclists and pedestrians (Brackstone et al., 2009; Ericsson, 2000). Consequently, predicting and classifying behaviour is not always trivial. By evaluating headway in different road environments, essential information can be retrieved about the interaction between drivers and show if they are meeting the expectations of the road design (Ma & Andréasson, 2006; Wang et al., 2010).

The main purpose of this thesis is to gain in-depth insight into longitudinal driving behaviour in correlation to the road environment. The assumptions are that driver behaviour may be road type specific and that variation in headway as well as movement dynamics characteristics are evident among different road environments. The assumption is directly connected to headway, speed and acceleration as they are influential parameters to study the potential effects of traffic environment on safety, emissions, fuel consumption and traffic flow. By analysing three different road segments in greater Gothenburg, an initial analysis to support the design of automated vehicles in specific traffic environments can be developed. Furthermore, the results might also provide a good overview of the situation to traffic planners as infrastructure features are investigated in specific road environments.

1.1 Aim and objectives

The aim of this thesis is to identify if longitudinal driver behaviour is affected by the road environment in Gothenburg. In order to understand and compare driver behaviour parameters in different traffic environments, the project has the following objectives:

- Perform a literature study on road environment, car-following, longitudinal driver behaviour and traffic analysis;
- Choose at least three areas with different road type characteristics and infrastructure attributes in greater Gothenburg;
- Collect and analyse data from the chosen areas to characterise driver behaviour based on road infrastructure, headway, speed and acceleration;
- Perform a statistical analysis to investigate if there is a variation in vehicles headway and speed in the road environments;
- Analyse the trajectories of vehicles to study if the movement dynamics characteristics can be influenced by the road environment;
- Use the information collected for one road environment to create a traffic simulation environment on PTV VISSIM and calibrate it to represent the current traffic.

1.2 Research questions

This research attempts to answer the following key questions:

- Is longitudinal driver behaviour different in the road environments?
- Does road infrastructure impact driver behaviour?
- How is the road environment perceived by drivers? Do they respect the speed limit?
- Is the collected data enough to calibrate a model on PTV VISSIM?

1.3 Limitations

Longitudinal driver behaviour accounts for several parameters, as reaction time on traffic, headway, speed limit, acceleration, time to collision etc. Capturing the important motivations and other elements of driver choice is crucial in order to produce accurate models and subsequent traffic flow predictions. When the leading vehicle brakes in traffic, the time distance between vehicles will decrease immediately, generating a reaction delay for the following driver to take further actions (Snowdon and Waterson, 2013; Zhao, 2014).

Changing in reaction time can be determinant for headway as it has been shown that if drivers are aware of vehicles in front decelerating or about to decelerate, they might start to increase their headway on purpose in order to maximise safety zone (Van der Hulst, 1999). However, without naturalistic driving data, it is difficult to account the driver's reactions to the analysis. Therefore, for this thesis, reaction time is not taken into consideration to characterise driver behaviour. It is also important to point out that the car-following regime is considered when characterising longitudinal driver behaviour, so all data collected is first filtered based on a critical time headway (see details in section 3.5)

According to TRB (2000), a road segment is defined as the length of the road out of the influence of intersections, junctions, on- or off-ramps and weaving areas. The analysis performed in this thesis considers the road environments as road segments. The influence of traffic control on driver behaviour is then not investigated. Moreover, as detailed in section 3.2, the case study areas are located in Mölndal, which belongs to the greater Gothenburg. Therefore, the findings might not be a good representation or equivalent when considering different parts of the city. The study is also only concentrated on the traffic situations recorded by the drone. As described in section 3.3, the videos were limited to 10 minutes, consequently the data collected might not be representative for all traffic conditions presented on these road environments in different days or times of the day.

2 Literature study

In order to investigate longitudinal driver behaviour in different road environments, a comprehensive understanding on how vehicles interact with each other on the roadway is important. Therefore, a general introduction to road environment, driver behaviour and traffic analysis is presented in this chapter. Thereafter, a few examples of previous studies that have a similar purpose as this master's thesis are reviewed.

2.1 Road Environment

The road environment is characterised by its design, function, pedestrian and cyclists' movements, traffic control measures and the infrastructure that surrounds it. The road features can be determinant to the interaction between road users, influencing drivers attitude due to the presence of traffic signs, pedestrian crossing zones, bike lanes and/or public transportation. Drivers make decisions in accordance to the environment they are inserted. For example, they decide whether to overtake a vehicle or drive at a specific speed based on the way the road environment is perceived (Aronsson, 2006; Fuller & Santos, 2002).

The structure of road environments is crucial to traffic engineering as drivers tend to adapt their behaviour depending on changes in the road section. For example, when increasing lane width, widening the shoulder or resurfacing the road, drivers might adjust their speed to higher rates. People usually agree on how a highway looks like and tend to have consistent behaviour on this environment. Therefore, if an urban street for a speed limit of 50 km/h is designed as a 4-lane road, drivers will probably interpret this environment as a type of highway and behave accordingly. Nevertheless, when considering other types of environments, as urban streets or arterial roads, there is no consensus among the drivers on how they are structured. As a result, driver behaviour can vary based on the features presented in the road section (Findley, 2016; Fuller & Santos, 2002).

2.1.1 Road classification

Road classification has established a form to categorise roads according to their function and hierarchies of movement, becoming an important parameter for designing the road network. A common practice is to categorise roads based on the network hierarchy. By accounting specific characteristics and implying *major* and *minor* associations, each road type has a ranked position considering the whole network (Marshall, 2005).

According to TRB (2000), when considering the hierarchy of the traffic network, urban roads are ranked between local streets and multilane suburban highways. As a result, the street function, traffic control conditions and the characteristics of the roadway developments are the parameters differentiating and categorising each road type in an urban traffic network. That is why classifying road segments according to their function as opposed to the network hierarchy is a simpler way to categorise roads. In this way, roads that provide more mobility than accessibility are classified higher on functionality. The usual classification includes arterial, collector and local roads, as illustrated in Figure 1 (Meyer, 2016).

In the 1950s, roads were classified into three main functional types in the United States: arterial roads, collector roads and local roads and streets. However, as the same type of road could have a major or minor role in the network, subdivisions were also considered in this classification. Nowadays, considering the development of the urban space and incorporation of new vehicles and activities, classifying roads has become more challenging. Many roads can be considered to have multi-functions, and that is why the British manual Transport in the Urban Environment has further categorised roads based on their intended function rather than their functional form (Marshall, 2005; O'Flaherty, 1997). Table 1 describes the details of both classifications, from the United States and the British manual.

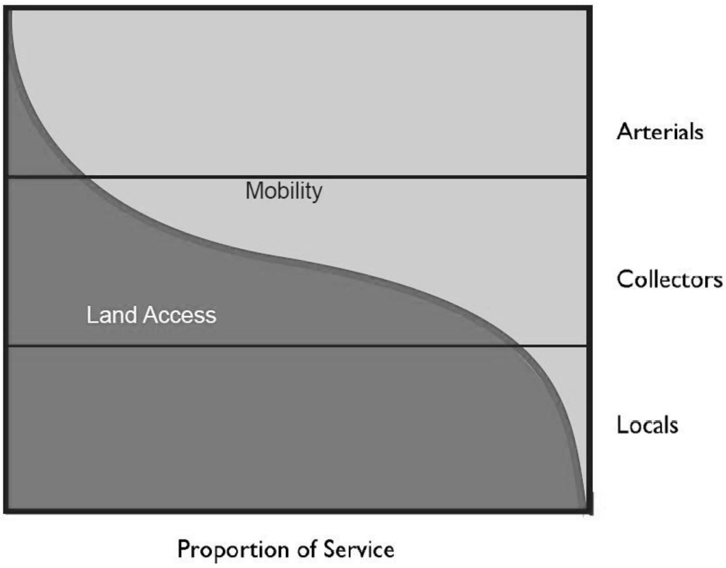

Figure 1. Road category based on proportion of service (Meyer, 2016)

Table 1. Road classification in the United States and UK (Marshall, 2005; O'Flaherty, 1997)

Country	Road type		Function
United States	Arterial	Major	Primary route for longer-distance high-speed through-vehicle movements with no direct frontage access.
		Minor	As major but with some direct frontage access.
	Collector	Major	Provide through-vehicle movements and frontage access for arterial and local roads with some access service.
		Minor	As major but with more access service.
	Local roads and street		Provide frontage access according to the land use that they serve, residential, commercial and industrial streets.
United Kingdom	Distributor	Primary	Fast moving long distance through traffic with no pedestrians or frontage access.
		District	Medium distance traffic to primary network. Present public transport services. Connect different parts of the urban area.
		Local	Frontage access where vehicles are near the beginning or end of their journey.
	Pedestrian	Street	Strictly for walking, meeting and trading.
		Route	Shared space with cyclists and pedestrians
	Cycling route		Only cycling allowed.

Trafikverket classifies roads based on their importance to the road network, following the categories in ISO 14825:2004 Intelligent transport systems. This classification is called *Funktionell vägklass* (Functional road class in English) and ranges from 0 to 9. Class 0 represents the most important roads whereas class 9 represents the least important ones. The classification considers all parties concerns in the traffic development, as the municipality, administrative boards, traffic agencies etc. The road sections are classified taking into consideration its neighbouring roads, therefore, a road section with a specific class is usually connected to at least one section of the same or higher class. This classification is used on the National Road Database for Sweden (NVDB) to characterise roads in the country (Nilsson et al., 2017).

It is also important to point out that the road design can be based on the road classification. Even though, the lane width depends on the traffic volume, speed and roadside geometry, it can also be correlated directly to the road type. Narrower lane width tends to reduce traffic speeds, therefore local roads are usually narrower than highways, for example. It is not a universal agreement, but lane width tends to vary from 2.7 to 4.5 metres. In arterial roads, it is common to see the lane width ranging from 3.3 to 3.75 metres. In collector roads, the range can be from 3.0 to 3.6, whereas in local roads, from 2.7 to 3.3 metres (Meyer, 2016; Texas Department of Transportation, 2010; TRB, 2000)

2.1.2 Driver factors

Driver behaviour can be influenced by several external conditions, such as road type, the number of lanes, traffic conditions and type of leading vehicle. Vehicles in a car-following regime are discrete elements with motion characteristics connected to each other via the driver's processing of information. When studying longitudinal driver behaviour, the relative distance and speed between vehicles can reflect the environment that surrounds the driver. Braking or accelerating are clear representations of different human reactions in traffic. Therefore, the way people decide to drive in certain situations can be described as the result of the driver's decisions to cope with the road environment (Ericsson, 2000; Murphey, 2008).

On the other hand, driver behaviour is also directly linked to human factors and individual preferences. Consequently, human performance in traffic is a fundamental parameter when analysing the road network. It deals with perception-reaction time, control movement time and responses to other vehicles. Changes in speed and acceleration are perceived by drivers and can directly impact how drivers follow the leading vehicle in a given time in the traffic environment. Therefore, speed, headway, time gap acceptance and thresholds for overtaking or merging into traffic are parameters connected to driver behaviour (Koppa, 2001).

The way drivers perceive the traffic environment has also a great impact on how people behave. Some studies in traffic psychology have found out that driver behaviour can be correlated to the environment factors, like the other drivers' behaviour, cultural background, road infrastructure and the presence of traffic control devices (Fuller & Santos, 2002; Itkonen et al., 2017). Driver behaviour is also subjected to individual differences and human factors, as fatigue, emotion, stress, distraction and effects of different substances. Therefore, human behaviour is not easy to predict. Instead, it must be studied to try to identify trends among different drivers (Fuller & Santos, 2002).

2.2 Traffic analysis

Traffic analysis can report the current situation and allow the calibration of models to simulate the future performance of the traffic system, being essential to the development of transport systems (O'Flaherty, 1997). The level of analysis can range from macroscopic to mesoscopic and microscopic, in which the difference relies on the degree that traffic flow phenomena is characterised (TRB, 2000).

Macroscopic studies relate to the traffic network as a whole, employing flow, average speed and density as rate variables. On the other hand, microscopic studies investigate the individual parts of vehicles, capturing information of every trajectory. In this way, vehicles can be traced in the network in order to understand how they behave in terms of acceleration, deceleration, gap acceptance etc. Consequently, the mesoscopic studies are in between microscopic and macroscopic analysis, in which the movement of clusters or platoons of vehicles are then of interest (Mannering & Washburn, 2013; TRB, 2000).

2.2.1 Traffic parameters

Traffic network is usually composed of intersections and roads. When looking only at the road segments and disregarding the influence of intersections on traffic, drivers are then only interacting with vehicles in the same roadway. Nevertheless, there are some important microscopic and macroscopic traffic characteristics worth evaluating in road segments (Hoogendoorn, n.d.; TRB, 2000).

The microscopic characteristics are related to each individual vehicle, which makes vehicle's trajectories, distance and time headway the main variables. On the other hand, the macroscopic characteristics refer to the average behaviour of the flow, considering the fundamental diagrams to evaluate intensity, density and speed as the main attributes of the traffic flow (Dijker et al., 2007; Hoogendoorn, n.d.). More details regarding these parameters are provided below.

<u>Vehicle trajectory</u>
Tracking the position of a vehicle over time is a fundamental technique to study vehicle trajectory. It provides a summary of vehicular motion in one dimension. As illustrated in Figure 2, by representing the distance along a certain road segment as a variable *x* and the necessary time for a vehicle to cross that section as a variable *t*, the vehicle trajectory can be defined as a function *x(t)* (Hoogendoorn, n.d.).

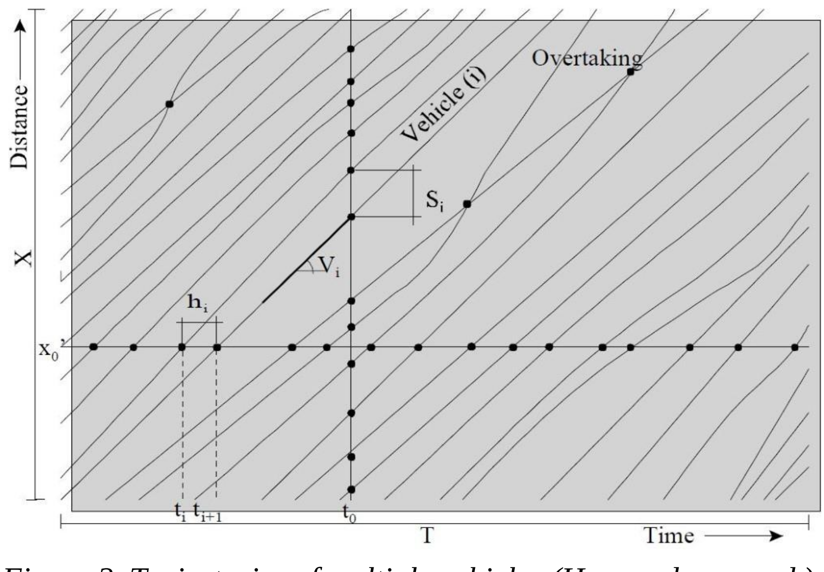

Figure 2. Trajectories of multiple vehicles (Hoogendoorn, n.d.)

Distance headway

In Figure 2, distance headway (DHW) is represented by the variable *S*. It can be defined as the distance between two successive vehicles, considering the same reference point of both vehicles, bumper to bumper, for example (Figure 3). As a consequence, distance headway is an instantaneous variable established at a specific time instant (Hoogendoorn, n.d.; Van Winsum & Heino, 1996).

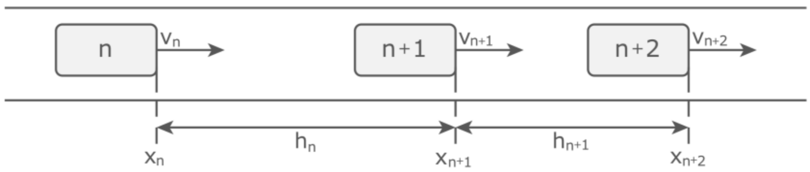

Figure 3. Vehicle position, velocities and headways (Zhao, 2014)

Time headway

In Figure 2, time headway (THW) is represented by the variable *h*. It has a similar definition to distance headway but instead of distance it considers the time interval between two successive vehicles. Mathematically, time headway can be calculated dividing the distance headway by the speed of the following vehicle (Hoogendoorn, n.d.; Van Winsum & Heino, 1996).

In TRB (2000), it is described that the inverse of flow rate can be a reference for the average time headway. Nevertheless, vehicles do not travel at constant headways. Even though drivers tend to move in groups, or platoons, varying headways are observed between successive vehicles. Therefore, in order to have a better picture of the traffic environment, it is important to take into consideration time headways from all vehicles crossing a road segment.

Intensity

The number of vehicles crossing a specific road section in a pre-determined time interval is defined as intensity. It can be also referred to as flow, represented by the variable *q*. Intensity is then determined as the number of vehicles divided by the unit of time, which can be expressed as 24 hours, one hour, 5 minutes etc (Hoogendoorn, n.d.).

Density

Density can be defined as the number of vehicles on a unit of road length at a specific time instant. Compared to intensity, density is more difficult to be determined as the road segment needs to be analysed using photography or video from a high point. It can then be considered as an instantaneous quantity, valid only for a certain time for a particular area (Hoogendoorn, n.d.).

Speed

Speed is a fundamental parameter for traffic performance. Speed data is used to determine control measures, establish road design elements, analyse capacity, assess safety and monitor speed trends. Spot speed, for example, is collected to study measure speeds at a specific location under the traffic and environmental conditions presented at the time of data collection. There are two approaches to measure speed in traffic, time- and space-mean speed. Direct measurements using laser or radar devices provide time-mean speed whereas indirect measurements result in space-mean speed by calculating the speed from time measurements of a vehicle travelling a known distance (Findley, 2016).

2.2.2 Longitudinal driver behaviour

Considering the driver control task, the longitudinal driver behaviour can take into account two distinguished subtasks, roadway and vehicle interaction (Figure 4). The roadway subtask is related to the decisions made by drivers regarding the available infrastructure and its elements, such as the number of lanes, curves and on- or off-ramps, in order to drive safely and comfortably. On the other hand, the vehicle interaction subtask relates to the decisions regarding other traffic participants on the road (Ossen, 2008).

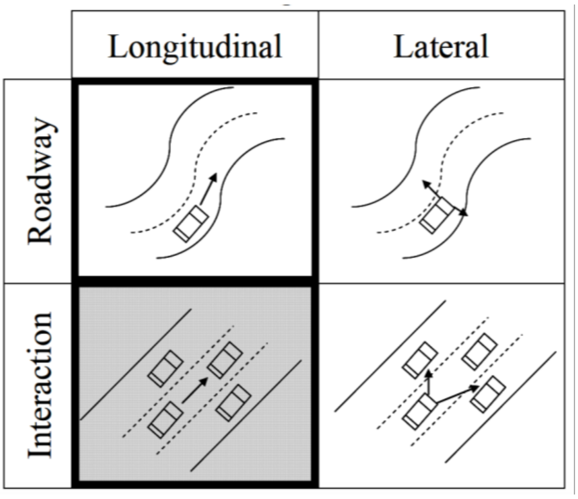

Figure 4. Classification of essential subtask of driving task (Ossen, 2008)

The longitudinal roadway subtask is closely related to speed limit, as drivers attempt to keep their vehicles on the roadway, on the appropriate lane, taking into consideration an adequate speed to avoid an unsafe situation. However, when dealing with other vehicles, drivers need to keep a safe distance to the leading vehicle and adapt their speed in order to prevent collisions and have a comfortable ride along the roadway (Minderhoud, 1999).

As a result, longitudinal driver behaviour can be classified in two regimes: free-flow and car-following. In the free-flow regime, the driver has a voluntary choice of behaviour, being only constrained by the roadway features (TRB, 2000). The car-following regime relates to the vehicle interaction subtask, and it is further explained in section 2.2.3.

2.2.3 Car-following

Car-following is a very common behaviour in road environments that characterises a fundamental form of interaction between vehicles in the same lane. Since it has a great impact on traffic flow, understanding what characterises this behaviour is important to identify measures capable of alleviating congestion and improving traffic system performance (Itkonen et al., 2017).

Several traffic parameters and models can be used to identify a car-following regime. However, in these circumstances, as drivers tend to maintain a desired distance from the lead vehicle, some practical methods have also been developed to establish a critical time gap or headway to represent car-following conditions. Studies have shown that a critical time headway usually ranges from 3 to 6 seconds (Brackstone et al., 2009; Dijker et al., 2007). TRB (2000) states that it is hard to empirically establish a critical headway, therefore they proposed a surrogate measure in which vehicles following other vehicles with a time headway of less than 3 seconds are considered to be in a car-following regime.

Drivers attempt to adjust speed and distance to the following vehicle based on their wishes to minimise the trip duration and maximise safety, consequently the car-following behaviour can vary under different conditions. There are four distinct regimes for car-following: approaching, stable following, braking and accelerating. In the approaching regime, the driver starts to adapt its speed to the vehicle in front before getting to the stable following regime, in which the driver follows the vehicle in front with a safe headway accelerating and decelerating accordingly. In the braking regime, the driver has a much higher speed than the vehicle in front and tend to brake hard to avoid accidents. The opposite happens in the accelerating regime, when the driver accelerates to a desired speed before starting the approaching regime (Galante et al., 2016; Ma & Andréasson, 2006)

Car-following behaviour is closely associated with time/distance headway and speed. A study conducted at the Holland Tunnel in 1966 analysed over 24,000 vehicles on a single lane roadway in order to obtain statistical estimations for desired headway. Based on this study, desired headway and speed could be correlated according to Figure 5 (Luttinen, 1996).

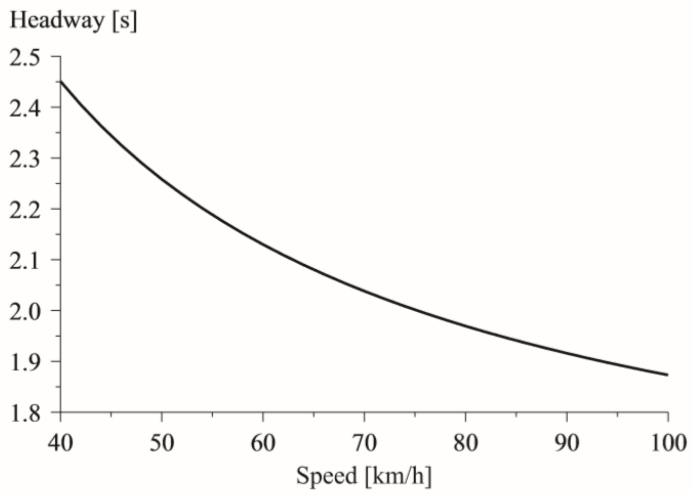

Figure 5. Relationship between speed and desired headway (Luttinen, 1996)

Luttinen (1996) also described the variation of headways based on car-following models in seven factors according to when the driver is approaching the leading vehicle (factors 5-7), when the driver has finished the approaching phase and is then following the leading vehicle (factors 1-4) and when the driver changes from the free-flow regime to car-following (factors 1, 6 and 7):

1. Difference in reaction among drivers;
2. Delayed response to speed variations of the leading car;
3. Oscillation due to delayed response;
4. Difference in length of leading vehicles;
5. Transition between the approaching phase and the beginning of car-following;
6. Difference in the initial headway, when the car-following process starts;
7. Difference in the initial relative speed, when the car-following process starts.

The attempt to maintain the desired headway can be represented in models by relative speed (DV) between two vehicles, the angular velocity of the lead vehicle (Ht) or the Time to

Collision (TTC). TTC is defined as the space between two vehicles (DX) divided by the relative speed. Therefore, the adjustments of the vehicle speed over time can be demonstrated as following spirals in the DX-DV plane, as shown in Figure 6 (Brackstone et al., 2009; Wang et al., 2014b).

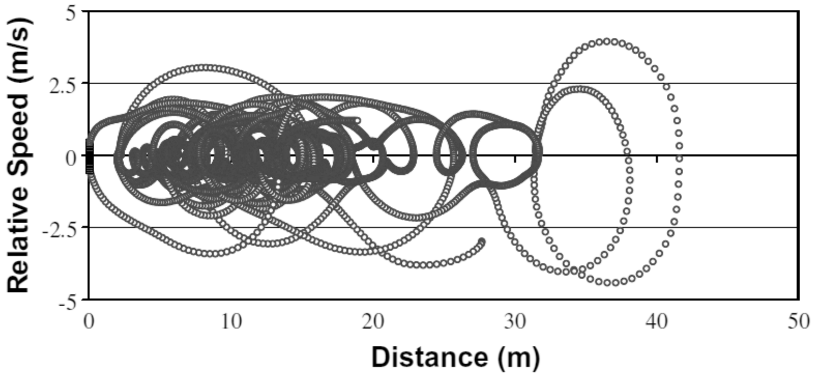

Figure 6. An example of a typical following relationship (Brackstone et al., 2009)

Models for drivers' car-following behaviour are applied in the development of advanced vehicle control systems as well as traffic simulations (see section 2.2.4). In traffic engineering, the headway and speed distribution are crucial for the development of new models and automatic supporting systems, as the statistical properties can provide a comprehensive understanding of driver behaviour in different scenarios (Maurya et al., 2015). Therefore, researchers have been studying it since 1950. In the beginning, only the relationship between relative distance/speed with the following car was studied, but car-following behaviour can be also influenced by surrounding traffic conditions, weather, vehicle type and driver's characteristics, for example (Geng et al., 2016).

2.2.4 Simulation

The purpose of building a traffic simulation environment is to identify and understand how the traffic system works and can change over time. Simulations are important to predict the output of a real system based on different conditions and situations. However, in order to use the simulation as a representation of the real traffic system, there must be a validation of the simulation model to represent the traffic characteristics as close as possible to reality (Barceló, 2010).

Performing a validation study in which the output results from the simulation is compared to the input data is extremely important. The validation of the model involves an iterative process in which the input parameters are set side by side to the actual traffic measurements. For that, validation criteria must be defined by formulating a particular hypothesis that can be tested using statistical techniques. When the results fail to pass a hypothesis test, problems can be then identified to review and repair the model accordingly (Barceló, 2010; Hoogendoorn, n.d.). Figure 7 illustrates the methodological scope for simulation.

Moreover, simulation software use specific models to represent traffic behaviour. Therefore, understanding the model limitations and assumptions is crucial to calibrate the simulation (Hoogendoorn, n.d.). Car-following is represented by Wiedemann's models on PTV VISSIM, which is based on a psycho-physical driver's perception. This model assumes four different driving regimes: free driving, approaching, following and braking. For urban traffic and merging areas, the default model is the Wiedemann 74 whereas for freeway traffic with no merging, it is the Wiedemann 99 (PTV Group, 2018). Some details for each Wiedemann's car following models are provided further in this section.

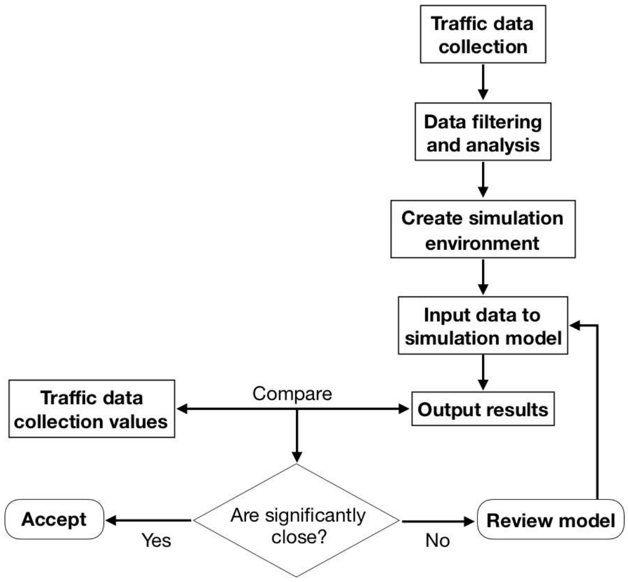

Figure 7. Overview of the simulation process (adapted from Barceló, 2010)

Desired speed, acceleration/deceleration and safe following distance are the main parameters for car-following behaviour on PTV VISSIM. The fundamental concept of the Wiedemann's model regards faster drivers decelerating when they start to reach their individual perception to a vehicle travelling slower, which depends on relative speed and distance to the vehicle in front. Drivers will then only accelerate when they reach another perception threshold, consequently, there is a slight and steady acceleration and deceleration (Lu et al., 2016; PTV Group, 2018). Figure 8 shows a representation of the Wiedemann's car-following model.

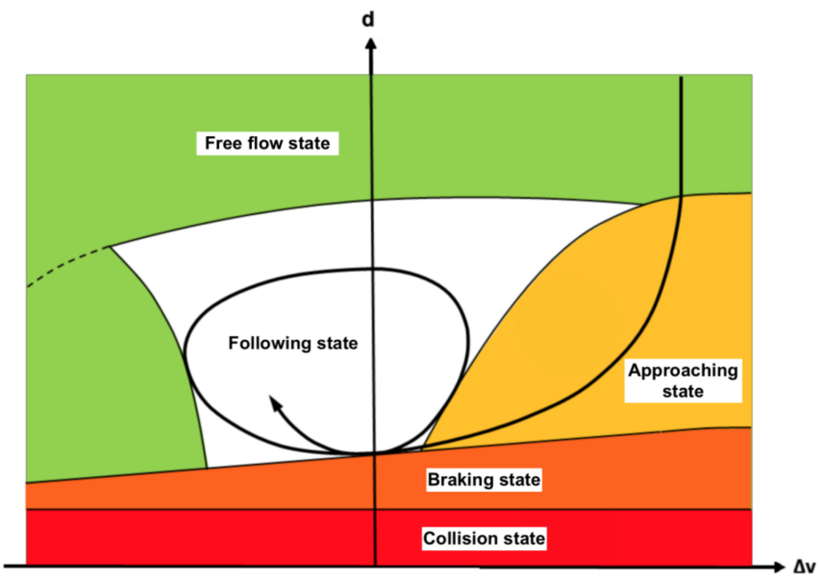

Figure 8. Representation of Wiedemann's car following model, where d is distance and Δv is change in speed (adapted from PTV Group, 2018)

Wiedemann 74

The parameters for the Wiedemann 74 model are (PTV Group, 2018):

- Average standstill distance (ax): average desired distance between two cars. The default value is 2.0 and the tolerance lies from -1.0m to +1.0m (normally disturbed with a standard deviation of 0.3m);
- Additive part of safety distance (bx_{add}): used for the computation of the desired safety distance *d*. The default value is 2.0;
- Multiplicative part of safety distance (bx_{mult}): same as bx_{add} but it is a greater value, with greater distribution of safety distance. The default value is 3.0.

The desired distance *d* is calculated according to equation 1 and 2.

$$d = ax + bx \tag{1}$$

$$bx = (bx_{add} + bx_{mult} * z) * \sqrt{v} \tag{2}$$

where *v* is the vehicle speed in m/s and *z* is a is normally distributed value with mean of 0.5 and standard deviation of 0.15.

Wiedemann 99

The parameters for the Wiedemann 99 model are (PTV Group, 2018):

- Standstill distance (CC0): desired standstill distance between two vehicles in metres. It has no variation. The default value is 1.5m;
- Following distance (CC1): time distribution of speed-dependant part of desired safety distance dx_{safe}, the distance in seconds that a driver wants to maintain at a certain speed. The default value is 0.9s;
- Longitudinal oscillation (CC2): if this value is 10m, for example, the following distance behaviour translates to values between dx_{safe} and $dx_{safe} + 10m$. The default value is 4.0m;
- Perception threshold for following (CC3): the number of seconds before the safety distance is reached. It defines the start of the deceleration process. The default value is -8.0;
- Negative speed difference (CC4): defines the negative speed difference during the following regime in m/s. The default value is -0.35;
- Positive speed difference (CC5): defines the positive speed difference during the following regime in m/s (corresponds to the negative value in CC4);
- Influence speed on oscillation (CC6): influence of distance on speed oscillation during the following regime in 1/m*s. When this value is 0, it means the speed oscillation is independent of the distance. The default value is 11.44;
- Oscillation during acceleration (CC7): oscillation during the acceleration regime. The default value is 0.25 m/s^2;
- Acceleration starting from standstill (CC8): desired acceleration when starting from standstill. The default value is 3.50 m/s^2;
- Acceleration at 80 km/h (CC9): desired acceleration at 80 km/h. The default value is 1.50 m/s^2.

The parameter CC1 is believed to have a great impact on the calibration of the Wiedemann 99 model. However, it is important to highlight that it cannot be taken as time headway, as

CC1 does not account for the vehicle length nor the standstill distance (CC0). Therefore, CC1 can be calculated according to equation 3 (Dong et al., 2015).

$$CC1_i = THW_i - \frac{Length_{(i-1)}}{Speed_{(i-1)}} - \frac{CC0}{Speed_i} \tag{3}$$

where *i* refers to vehicle *i* and *(i-1)* to the vehicle in front of vehicle *i.*

2.3 Related studies

Ericsson (2000) found out that street type has a strong impact on driving pattern. The study was carried out in Lund and investigated driving patterns using a factorial analysis of variance to compare different street types, drivers and traffic conditions. The research concluded that drivers tend to adopt a specific behaviour according to the road category. The streets were classified as main street in a residential area, local street, radial arterial and streets in the city centre. The results showed that average speed and acceleration levels had a significant variation for all the streets selected. Moreover, in the streets in the city centre, more oscillation and percentage of time at low speeds were presented.

Wang et al. (2014a) studied longitudinal driving behaviour by measuring relative speed, DHW, THW, TTC and acceleration from a host vehicle in freeways, distributor and local access roads. They identified that longitudinal driving behaviour varies with road categories, which influences the relationship between the host vehicle speed and DHW in a car-following situation. The lower the host vehicle speed, the shorter the DHW. On the other hand, the host vehicle speed not always reflected in a change of THW, as drivers tend to be consistent in this matter. That was also seen in Brackstone et al. (2009) and Taieb-Maimon & Shinar (2006), in which the results showed a limited dependence of THW on speed as drivers are willing to keep time headway constant and consistent.

Marsden et al. (2003) compared driver behaviour in a motorway in England, France and Germany by using an instrumented vehicle and performing an analysis of differences between typical headway on car-following and approach regimes. They observed a great variation in the amount of time drivers spent in a close following situation at speed above to 80 km/h. Moreover, it was observed that time headway vary with speed and variation in headway characteristics were evident among the countries. On the other hand, Ayres et al. (2001) showed that in free-flow traffic, with a constant speed, the time headway was varying according to the traffic volume, in which physical parameters on the road, as traffic signs, lane width and curvature were influencing the drivers' speed choice. But for congested situation, time headway remained constant, ranging from 1 to 2 seconds.

Brackstone et al. (2009) concluded that driver following behaviour does not change depending on road characteristics, instead it is influenced by the type of leading vehicle. The study shows that drivers tend to follow closer trucks and vans than cars, with a clear distance reduction at higher speeds. It is important to point out though that this study examined only two types of high-speed roads. Kong & Guo (2016) further studied the car-truck interaction in China. By recording traffic in four segments in a freeway, it was observed that the median headway between cars is the smallest whereas the one between trucks, the highest. Depending on the traffic flow, cars can follow trucks with a larger headway than trucks follow cars. Nevertheless, by performing a statistical analysis, it was found out that the headways are statistically different, in which the percentage of trucks in the road segment can have a significant influence on the headway.

3 Methodology

The master's thesis project was developed in collaboration with Alten Sverige and supervised by Eric Bjärkvik. After an intense literature study about road environment, car-following parameters, driver behaviour and similar studies, the project was divided into five parts: site selection, data collection, data processing, data analysis and traffic simulation. The details for each part are presented in the sections below.

3.1 Overview

For this thesis, the most important parameters for the investigation of longitudinal driver behaviour are vehicles' headway and speed. In order to consider information from all vehicles crossing a road segment, recording traffic was decided to be the best method. In this case, though, the challenge was to process the videos as they would need automated data processing to track vehicles and extract the parameters of interest. In an attempted to find a simple approach to data processing, DataFromSky developed by RCE systems s.r.o. in 2014 was found as the perfect solution. They offer a method to understand road-user behaviour by measuring speed, vehicle gap and acceleration data from videos and allowing trajectory data interpretation on a software viewer (DataFromSky, 2018). Nevertheless, in order to benefit from the DataFromSky method, traffic needed to be recorded by drone.

Due to local regulations, some zones require special permission from local air traffic services for drone flying, as areas close to airports. Based on Transportstyrelsen (2017), Luftfartsverkets (LFV) provides a custom map (Figure 9) that highlights areas where flying a drone is not allowed in Sweden. Consequently, selecting the case study locations was based on this map to avoid any complication. Apart from that, the recommendation from LFV was to choose roads close to industrial or rural areas and fly the drone away from residential buildings or where it could be people.

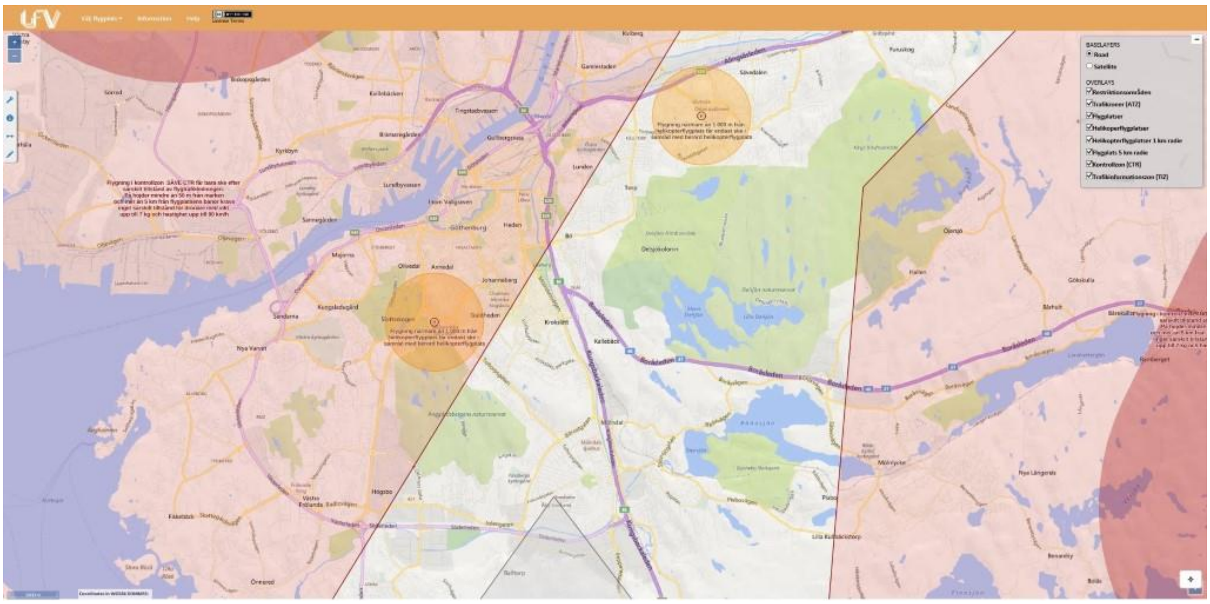

Figure 9. Drone chart for Gothenburg (LFV, 2019)

3.2 Site selection

Selecting the locations was a crucial part of the project as they define the object of study. In this part, the goal was to select at least three different road segments in order to investigate driver behaviour in distinct environments, as in a highway, arterial road, collector and/or local street. Due to the limitations imposed by LFV (2019) for drone flying, it was decided to look for locations closer to parks, agriculture fields and industries. Also, in order to avoid several trips, the proximity of the road segments was taken into consideration.

Söderleden, Jolengatan and Bifrostgatan were then selected as the road segments (Figure 10) based on the following reasons:

- Located in an appropriate area for drone flying;
- Present different speed limit and road characteristics;
- Very close to each other;
- Söderleden and Jolengatan could be recorded simultaneously.

Figure 10. Söderleden, Jolengatan and Bifrostgatan locations (adapted from Lantmäteriet, 2019)

They are located in Mölndal, which belongs to greater Gothenburg, and in general, the area closer to the roads segments is characterised by residential houses and green spaces (a golf club, crop fields, a cemetery and some recreational parks). However, there are also some shopping centres close to Söderleden and Jolengatan, such as car dealer stores, auto repairs shops and a big building material store.

3.2.1 Söderleden

Söderleden is part of E6.20 highway, being the stretch between Mölndal and Järnbrottsmotet. The road has six lanes in total but there is a trench that physically separates the road in three lanes for each direction. Apart from being an important route for the south/west road network of the Gothenburg area, it is a regional route for heavy vehicles and goods transportation (SWECO, 2009; Trafikverket, 2019a). Table 2 provides additional details about the road characteristics.

Table 2. Details for Söderleden (Trafikverket, 2019b)

Functional road class	1
Number of lanes per direction	3
Total number of lanes	6
Speed limit	80 km/h
Width of the road per direction	12 m
Restriction (no-entry)	Tractors
Dangerous goods transportation	Recommended as primary road

As Söderleden has two stretches going in different directions, it was decided that it would be better to differentiate them by number (Figure 11). Therefore, in this thesis, “Söderleden 1” refers to the lanes going in the west direction, towards Järnbrottsmotet, whereas “Söderleden 2” refers to the lanes going in the east direction, towards Mölndal.

Söderleden represents an important road for the region, hence it is expected that it offers a great capacity, accommodating high traffic flow throughout the day. The chosen section for analysis is approximately 110 metres long and it is surrounded by vegetation, with a creek passing under the road, as it can be seen in Figure 11. There are fences separating the lanes from the vegetation not allowing pedestrians or cyclists to cross the road. It is also important to notice that there is no shoulder or emergency stop lane in the section.

Figure 11. Screenshot of the recorded video showing Söderleden and Jolengatan

3.2.2 Jolengatan

Jolengatan is a stretch parallel to Söderleden. As it can be seen in Figure 11, the road section is surrounded by vegetation and there is a sidewalk closer to the road, physically separated by a trench, where pedestrians and cyclists share the space. The road characteristics can be seen in Table 3.

The data from NVDB (Trafikverket, 2019b) states that the width of Jolengatan is 5 metres (Table 3), however, when checking the measurement of each lane on Lantmäteriet (2019), it was found that they are approximately 3.5 metres. As a result, the width of Jolengatan should be at least 7 metres. Therefore, in this thesis, it is assumed then that the width of Jolengatan is 7 metres.

Table 3. Details for Jolengatan (Trafikverket, 2019b)

Functional road class	3
Total number of lanes	2
Speed limit	70 km/h
Width	5 m

It is important to point out that the road section is approximately 150 metres away from a speed reduction area, in which drivers should adjust their speed to 50 km/h. As there are traffic signs signalising it to the drivers, it is expected that they will accelerate and decelerate accordingly when entering and leaving Jolengatan. The road segment as well as the position of the reduction speed sign are illustrated in Figure 12. After the speed reduction sign, and even further away from the chosen road section, there is also entry areas and bus stop on both lanes.

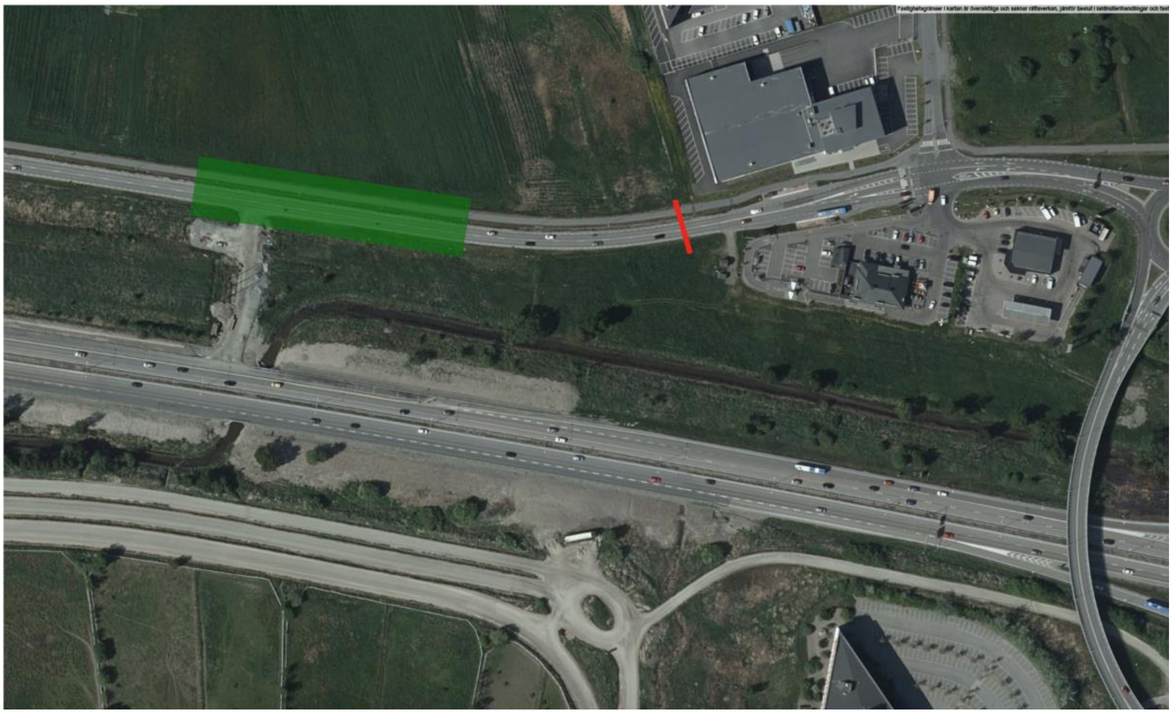

Figure 12. Case study area in Jolengatan represented in the green rectangle and the position of the reduction speed sign represented by the red line (adapted from Lantmäteriet, 2019)

3.2.3 Bifrostgatan

Bifrosgatan is a long street with approximately 1.9 km that connects Jolangatan/Aminogatan to Göteborgsvägen. The area is mainly residential, with many green spaces, parking lots and close to Fässberg cemetery. The street characteristics are described in Table 4.

Table 4. Details for Bifrostgatan (Trafikverket, 2019b)

Functional road class	3
Total number of lanes	2
Speed limit	50 km/h
Width	9 m
Restriction (no-entry)	Trucks

The chosen section for analysis is approximately 135 metres long. It is also between Frölundagatan and Frejagatan, located approximately 200 metres away from both a roundabout and traffic lights in the southbound and northbound direction, respectively. As it can be seen in Figure 13, there is an elevated bike lane alongside one of the lanes (the right lane in the northbound direction).

Figure 13. Screenshot of the recorded video showing the road section in Bifrostgatan

3.3 Data collection

A DJI Mavic Pro drone was used to collect the data. The drone belongs to the category 1A according to Transportstyrelsen (2017). Therefore, as it weights around 743 grams, it was not necessary to have a permission to fly it in the road sections. Traffic was then recorded in 4K at 30 FPS.

The data was collected on 11th March 2019, close to 1 p.m. The date and time of the day was selected based on the availability of Erik Djupström, who is the person responsible for the drone at Alten. The drone could fly for approximately 20 minutes, so it was decided to record each road section for 10 minutes as Söderleden and Jolengatan could be recorded at the same time. Söderleden and Jolengatan were recorded first at 12:45 a.m., and Bifrostgatan was then recorded around 1 p.m.

3.4 Data processing

The recorded videos were sent to DataFromSky on 25th March 2019. Due to the academic collaboration, DataFromSky was able to process the videos with a state of art algorithmic solutions, and deliver high-frequency data for position, speed and acceleration of each vehicle in the road segment on 09th April 2019.

DataFromSky was able to process 9 minutes and 23 seconds of each video. The output from the videos was then read on DataFromSky software viewer, which also allows manipulating and analysing the data. Parameters as vehicle type, speed, acceleration and movement dynamics can be extracted for each vehicle crossing the road section. It is also possible to draw a virtual line (called gate) on the road segment in order to register and count crossing vehicles as well as get information regarding flow, time and distance headway.

By taking advantage of the software viewer, time and distance headway data could be analysed as well as graphs for speed and acceleration for the travelled distance of each vehicle crossing the road segments. The raw data and the analysis performed on the software were exported to CSV files to be further investigated using Python and Excel.

3.5 Data analysis

The data analysis can be divided into four main categories: gates, preliminary analysis, data filtering and statistical analysis. As each category also includes particularities, more details about them are provided in the sections below.

3.5.1 Gates

As mentioned in section 3.4, it is possible to create virtual lines (gates) on the DataFromSky software viewer to get additional data, as headway measurements. Therefore, it was decided to create three gates in each lane of the road sections.

First, it was given a specific nomination for each lane in the road sections. In Bifrostgatan, the lanes were called B1 and B2. In Jolengatan, they were called J1 and J2. Consequently, the lanes in Söderleden 1 were called S1, S2, S3 and in Söderleden 2, they were called S4, S5 and S6. Then, in each of these lanes three gates, referred as *a*, *b* and *c*, were created as shown in Figure 14 and Figure 15.

From each gate, it was possible to retrieve data regarding flow as well as speed, acceleration, time and distance headway for each vehicle crossing them. On that account, different parts of the road sections could be analysed separately and compared to each other to evaluate if drivers tend to maintain consistent behaviour along the road section.

Figure 14. Bifrostgatan gates

Figure 15. Gates in Söderleden (left side) and Jolengatan (right side)

3.5.2 Preliminary analysis

The preliminary analysis focused on determining the number of vehicles crossing the case study areas, especially estimating the number of samples in each lane. Therefore, an overview of the demand and capacity of the road environments on that specific moment of the day can be assessed. In consequence, taking into account that DataFromSky processed 9 minutes and 23 seconds of the recorded videos, the corresponding flow for each lane can be calculated dividing the number of passing vehicles by the respective duration of the processed video.

Furthermore, the mean speed in each road section was analysed. The intention was to find out if drivers tend to keep their vehicles under the speed limit. Then, a simple statistical analysis was performed for speed in each gate, calculating the maximum, minimum, mean and standard deviation values, to check if the drivers were inclined to vary speed along the road section. More than that, a rough idea of how speed tends to vary in regard to the infrastructure attributes on the road sections could be estimated, as for example, due to the lane width, the bike lane in Bifrostgatan and the speed reduction sign in Jolengatan.

The vehicles trajectories taken from the DataFromSky software viewer were also studied in this section. The trajectories lines on the software were investigated considering all vehicles that crossed the road sections during the video. By overlaying all the trajectories, a summary of the vehicle's motion could be visually evaluated. Also, some curious trajectories observed on the videos were selected in order to evaluate if certain behaviours could be derived from the infrastructure surrounding the drivers.

3.5.3 Data filtering

Setting the boundaries to car-following regime can be very tricky. There is no specific guideline or methodology to establish when vehicles are engaged in car-following, as the relationship among speed, acceleration and headway can be very dynamic and it is usually represented in models. On the other hand, as mentioned in section 2.2.3, some studies have attempted to define ranges of critical time headways that could lay the foundation of the car-following regime.

For this thesis, it was decided to take into consideration TRB (2000) and establish 3 seconds as the critical time headway. Therefore, in order to define the vehicles engaged in car-following, the datasets of all gates were filtered for vehicles following each other with a time headway of less than 3 seconds. The data was filtered on Python and the analysis were performed in both Python and Excel.

3.5.4 Statistical analysis

Having a better understanding of how drivers are behaving in each road environment can be translated into some statistics estimations. Therefore, the first analysis performed among the vehicles engaged in car-following was to further evaluate time headway, speed and acceleration/deceleration. Maximum, minimum, median, mean, standard deviation and coefficient of variance values for those parameters were calculated. The coefficient of variance can be an interesting measurement to investigate how much of variation is presented in that specific dataset. This kind of information is important to understand if drivers keep consistent behaviours when facing the same situation.

As seen in section 2.3, DHW can present a higher variation than THW. Consequently, as this research does not present a large car-following dataset, it was decided to work solely with THW in order to try to identify more common behaviours. Even so, the relationship between DHW and THW was represented in a plot to have an overview of the distance range between vehicles in each road environment.

In section 2.2.3 and 2.3, it was discussed that the relationship between speed and headway is fundamental for car-following. With that in mind, this relationship was also intended to be further investigated in this research. However, it is important to mention that the researches in which this relationship was analysed had large datasets, taking into consideration several observations throughout the year. For this thesis, since it was only considered an observation of 10 minutes in each road environment, the amount of data is not really representative to develop a correlation between parameters. Despite that, it was still decided to represent speed and headway in a plot to check if any conclusions could be drawn.

The distribution of THW and speed were then examined for each gate to analyse their frequency in the road environments. Furthermore, a non-parametric test, considering a significance level of 0.05, was performed to analyse whether the vehicles headway and speed in these three road environments were different.

It was chosen to perform Kruskal-Wallis and Mann-Whitney U tests as they are both non-parametric tests that examine whether independent samples originate from the same distribution. The main difference between them is that the Mann-Whitney U test only compares two samples, whereas the Kruskal-Wallis test can be used to compare more than two samples. Based on previous studies, THW tends not to have a normal distribution, thus choosing non-parametric tests was also important to have a better effect on the data. Furthermore, these tests can be used on samples of equal or different sizes as they are based on a ranking method.

By performing these non-parametric tests, the data could be interpreted to evaluate if drivers attempt to change their behaviour depending on the road environment. If it is proved that the distribution of THW and/or speed in the road environments is different, it can be assumed that drivers do not adopt the same criteria when following a vehicle in these road segments. THW and speed were first evaluated considering the three road environments. Then, they were further analysed within the road environment, to understand if there is variation regarding the lanes and position along the road section.

3.6 Traffic simulation

Bifrostgatan was chosen to be modelled on PTV VISSIM as a case study due to its simplicity and urban road segment characteristics. During the literature study, it was seen in many studies that highways and arterial roads were often simulated as road segments whereas urban environments were usually simulated to evaluate intersections. Therefore, calibrating an urban collector road based on data collected by drone was seen as an interesting modelling practice.

First, to construct the model, a background image taken from Lantmäteriet (2019) to illustrate the road environment in Bifrostgatan was insert and scaled in PTV VISSIM. Then, taking this image as a reference, the road network was created using *links*. These elements called *links* represent individual traffic lanes with a specific width and direction of movement. Therefore, respecting the details in Table 4 and the road network configuration, the road environment was created, as it can be seen in Figure 16. It is important to notice that the links were extended until the area where vehicles would sort of merge, close to the roundabout and the traffic lights, in order to represent the entire road segment between these traffic control measures.

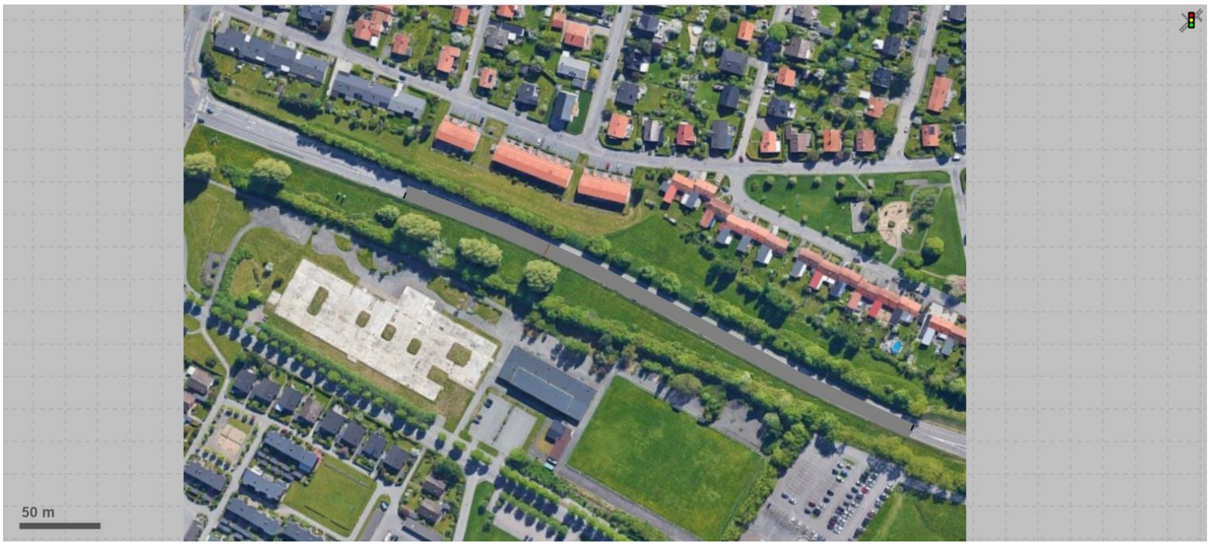

Figure 16. Overview of the traffic environment created on PTV VISSIM

After that, the vehicle compositions and the relative flows should be added to the links. The results show that on lane B1, there are 69 cars and 1 bus passing there during the data collection, whereas on lane B2, there are 55 cars, 1 bus and 1 heavy vehicle. The vehicle counts were then translated in percentage and used as an input in relative flows. Thereafter, the results were divided in time intervals of 1 minute and multiplied by 60 in order to determine the exact vehicle volumes by time interval in vehicles per hour, as it can be seen in Figure 17.

Count: 10	Cont	TimeInt	Volume	VehComp	VolType
1		0-60	660,0	1: B1	Exact
2		60-120	300,0	1: B1	Exact
3		120-180	480,0	1: B1	Exact
4		180-240	300,0	1: B1	Exact
5		240-300	360,0	1: B1	Exact
6		300-360	600,0	1: B1	Exact
7		360-420	240,0	1: B1	Exact
8		420-480	660,0	1: B1	Exact
9		480-540	420,0	1: B1	Exact
10		540-MA	180,0	1: B1	Exact

Count: 10	Cont	TimeInt	Volume	VehComp	VolType
1		0-60	480,0	2: B2	Exact
2		60-120	600,0	2: B2	Exact
3		120-180	420,0	2: B2	Exact
4		180-240	300,0	2: B2	Exact
5		240-300	120,0	2: B2	Exact
6		300-360	120,0	2: B2	Exact
7		360-420	240,0	2: B2	Exact
8		420-480	480,0	2: B2	Exact
9		480-540	420,0	2: B2	Exact
10		540-MA	240,0	2: B2	Exact

Figure 17. Screenshots of the vehicle inputs by time interval for B1 (left) and B2 (right)

The next step was to define the desired speed distribution based on the results from DataFromSky. As before, the vehicle composition should also be taken into consideration when analysing speed. As there was only one bus and heavy vehicle crossing each lane, there was no speed distribution for them and the desired speed for those was taken as the rate they were travelling on the lanes. On the other hand, the speed distribution for cars was analysed and the cumulative speed distribution curve for each lane was plotted and used as the input in PTV VISSIM. The curves were manually matched on the software and can be seen in Figure 18.

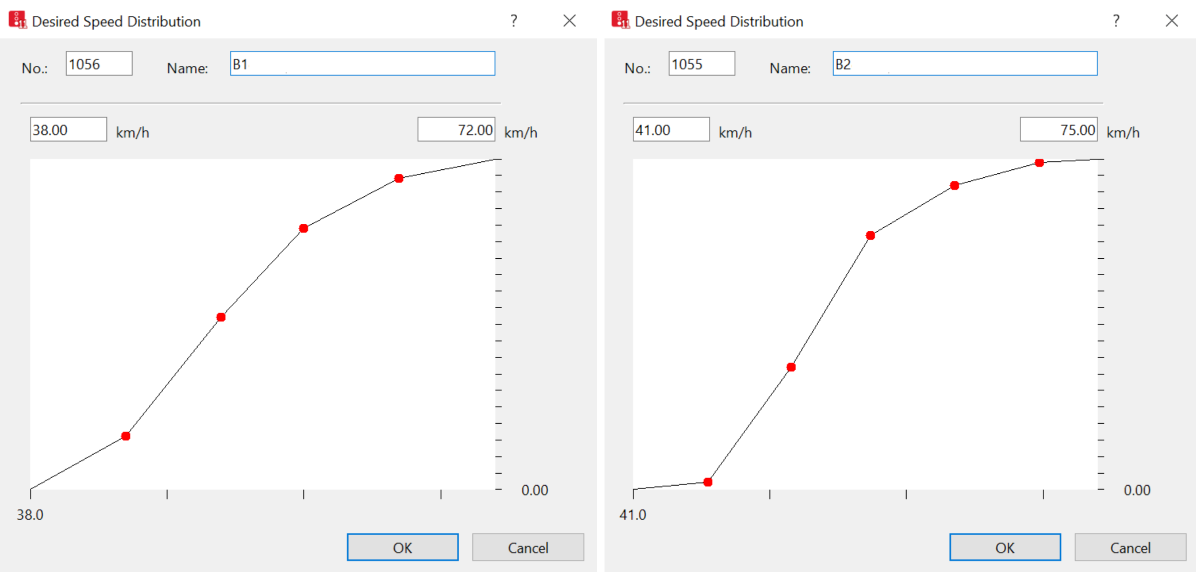

Figure 18. Desired speed distribution for cars in B1(left) and B2 (right)

As described in section 2.2.4, there are two models for car-following behaviour on PTV VISSIM. In the case of Bifrostgatan, the recommendation from PTV Group (2018) is to use Wiedemann 74 model. However, taking into consideration the data collected during this research, it would not be possible to properly calibrate this model. Therefore, since the section in Bifrostgatan is a road segment, with no merging or interaction with traffic control measures, it was decide to use the Wiedemann 99 model for the simulation, particularly because there would be enough information to calibrate parameter CC1 according to equation 3 in section 2.2.4. Either way, it was decided to run the simulation using the default parameters of each model before calibrating the Wiedemann 99 model to check if they would represent the road environment similarly.

In order to evaluate the traffic performance on the simulation, a data collection point was then inserted on the same position as the gates B1b and B2b. As a consequence, the speed output from the simulation could be compared to the real observed speed on the data analysis. The simulation outputs are compiled as an average result obtained from 5 simulation runs. The validation of the model is then based on the speed distribution taking into consideration speed data for time intervals of 1 minute.

4 Results

The results from data analysis and simulation are presented in this chapter. The preliminary analysis shows an overview of the results from DataFromSky for each road environment, regarding vehicle type, speed and vehicles' trajectories. Then, these results were filtered for car-following behaviour and a statistical analysis was performed to analyse the microscopic parameters in Bifrostgatan, Jolengatan and Söderleden. After studying the three road environments, information from the data analysis was used as an input in PTV VISSIM to calibrate a model for Bifrostgatan.

4.1 Preliminary analysis

From the DataFromSky software viewer, it is possible to export information concerning the count of vehicles crossing the road segment based on their type, such as cars, medium vehicles, heavy vehicles, bus and motorcycle. Table 5 shows a summary of vehicle count in each road section.

Table 5. Number of vehicles crossing each road environment during the data collection

Vehicle type	Bifrostgatan	Jolengatan	Söderleden 1	Söderleden 2
Cars	110	137	304	286
Medium vehicles	12	17	23	29
Heavy vehicles	1	6	26	26
Bus	2	-	1	1
Motorcycle	1	-	-	-
Undefined vehicle[1]	1	-	-	-
Total count	127	160	354	342

[1]it refers to the PostNord compact electric vehicle.

However, in order to have a better overview of the traffic flow, the number of vehicles crossing each lane in each road environment is a fundamental information. Therefore, Table 6 summarises the number of vehicles crossing each lane in Bifrostgatan, Jolengatan and Söderleden, and Figure 19 illustrates the mean flow for each of them.

Table 6. Number of vehicles for each lane

Road segment	Bifrostgatan		Jolengatan		Söderleden 1			Söderleden 2		
Lane	B1	B2	J1	J2	S1	S2	S3	S4	S5	S6
Cars	62	48	79	58	53	177	74	74	122	90
Medium vehicles	6	6	5	12	3	16	4	7	13	9
Heavy vehicles	-	1	3	3	5	16	5	-	21	5
Bus	1	1	-	-	-	1	-	-	-	1
Motorcycle	-	1	-	-	-	-	-	-	-	-
Undefined vehicles	1	-	-	-	-	-	-	-	-	-
Total count	70	57	87	73	61	210	83	81	156	105

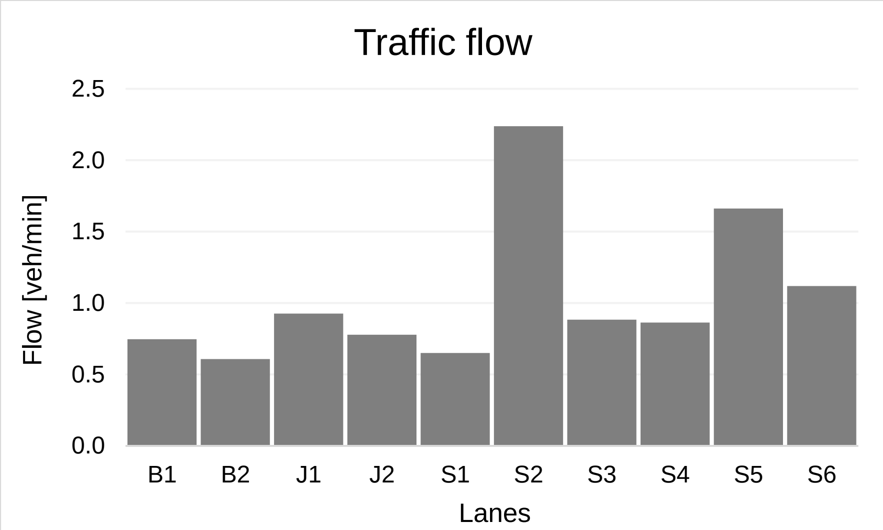

Figure 19. Traffic flow of each lane in the road environments

4.1.1 Speed

The mean speed of different vehicle types in Bifrostgatan, Jolengatan and Söderleden can be seen in Table 7. Furthermore, the maximum, mean and minimum speed, considering the total vehicle count in each gate of the road sections, together with the standard deviation, can be seen in Appendix A.

Table 7. Mean speed in km/h of the vehicles crossing the road environments

Vehicle type	Bifrostgatan	Jolengatan	Söderleden 1	Söderleden 2
Cars	53.74	64.03	87.55	87.03
Medium vehicles	54.99	67.29	86.91	86.79
Heavy vehicles	55.71	61.62	83.52	82.69
Bus	50.10	-	77.63	74.91
Motorcycle	50.41	-	-	-
Undefined vehicle	41.53	-	-	-
All vehicles	53.99	64.29	87.19	86.66

On the DataFromSky software viewer, it is possible to overlay a parameter on the road segment to understand how it varies over time and position. Therefore, the mean speed along the road sections can be seen in Figure 20 and Figure 21.

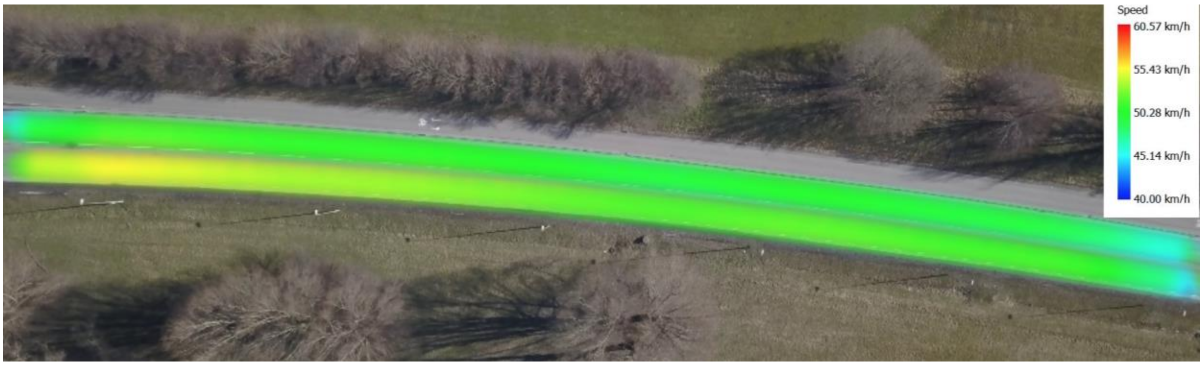

Figure 20. Mean speed in road section for Bifrostgatan

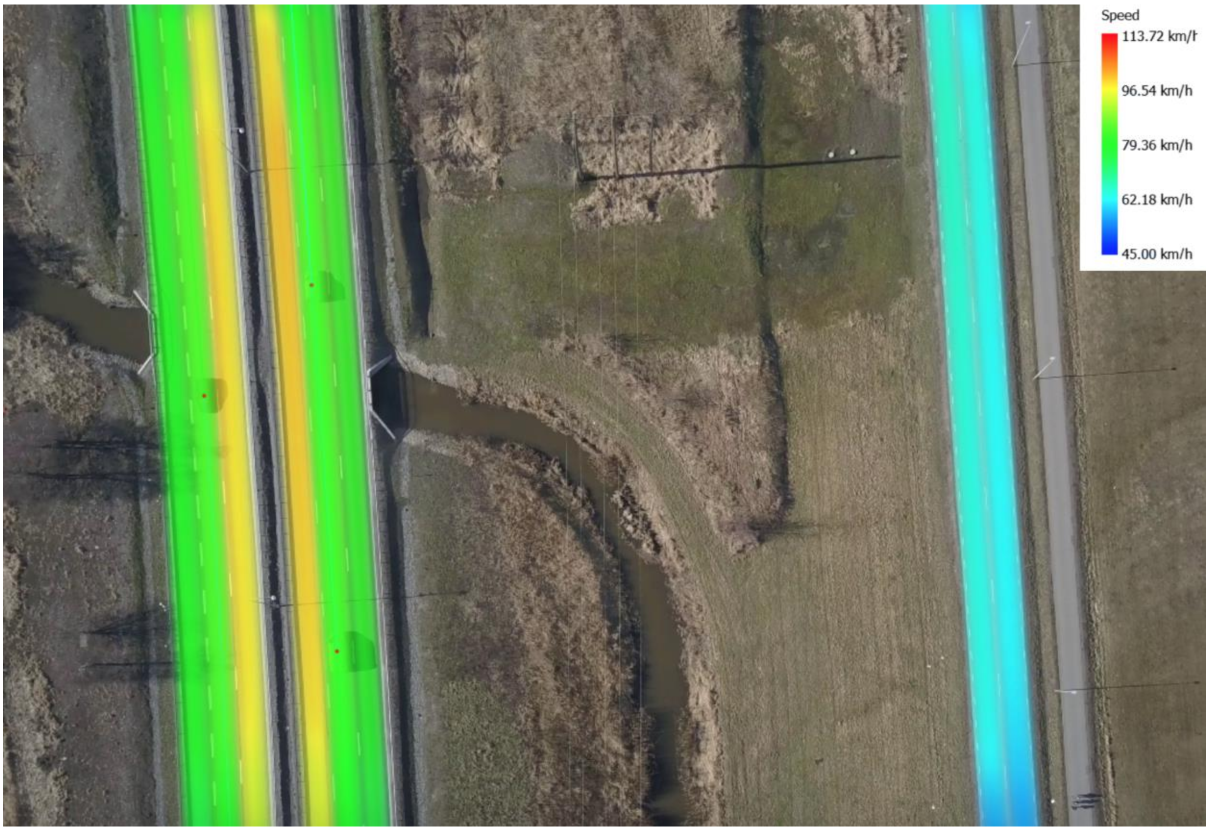

Figure 21. Mean speed in road sections for Söderleden (right side) and Jolengatan (left side)

4.1.2 Trajectories

The trajectories of the vehicles for every vehicle crossing the road sections can be seen on the DataFromSky software viewer. Figure 22 and Figure 23 illustrates the trajectories of all vehicles crossing the road sections in Bifrostgatan, Jolengatan and Söderleden. Moreover, in Appendix B, there are some visualisation snapshots from the software that illustrate some specific vehicle's trajectory worth mentioning in the research.

Figure 22. Trajectories of the vehicles in Bifrostgatan

Figure 23. Trajectories of the vehicles in Söderleden (left side) and Jolengatan (right side)

4.2 Statistical analysis

The statistical analysis for the vehicles engaged in car-following is presented in this section. Furthermore, the vehicles time headway and speed are further investigated using Kruskal–Wallis and Mann–Whitney U tests in order to check if the distributions of these parameters are different within the gates, lanes and road environments.

4.2.1 Vehicle in car-following

In order to identify the vehicles in a car-following regime, the data was filtered as described in section 3.5.3. Consequently, the number of vehicles engaged in car-following considering vehicles crossing each gate is shown in Table 8. These results were then compared to the number of vehicles crossing each lane (Table 6) to calculate the percentage of vehicles engaged in car-following.

The initial intention was to categorise car-following according to the type of leading vehicle, as seen in many researches during the literature study. However, the number of samples was not large enough to provide significant results to the research, in which most of the vehicles interaction was between cars. As a result, car-following is analysed taking into consideration all types of vehicles that are following each other under a time headway of less than 3 seconds.

Table 8. Vehicles engaged in car-following

Road environment	Gate	Nº of samples	% of vehicles in CF
Bifrostgatan	B1a	28	40.0
	B1b	29	41.4
	B1c	30	42.9
	B2a	30	52.6
	B2b	32	56.1
	B2c	35	61.4
Jolengatan	J1a	40	46.0
	J1b	38	43.7
	J1c	38	43.7
	J2a	30	41.1
	J2b	32	43.8
	J2c	30	41.1
Söderleden 1	S1a	19	31.1
	S1b	21	34.4
	S1c	24	39.3
	S2a	147	70.0
	S2b	140	66.7
	S2c	140	66.7
	S3a	34	41.0
	S3b	33	39.8
	S3c	29	34.9
Söderleden 2	S4a	42	51.9
	S4b	43	53.1
	S4c	41	50.6
	S5a	80	51.3
	S5b	85	54.5
	S5c	86	55.1
	S6a	55	52.4
	S6b	53	50.5
	S6c	54	51.4

4.2.2 Headway

The time headway for the vehicles engaged in car-following were analysed to evaluate how drivers behave in each road environment, the summary of the statistical results can be seen in Table 9. Furthermore, the time headway distributions for each gate can be found in Appendix C.

Then, Figure 24 illustrates the relationship between time and distance headway in the road sections taking into consideration the gate in the middle of each lane (referred as *b*) to represent the road environment characteristics.

Table 9. Statistical results of vehicle time headway per gate

Road environment	Gate	Max [s]	Min [s]	Median [s]	Mean [s]	σ [s]	CV
Bifrostgatan	B1a	2.87	0.47	1.75	1.71	0.62	0.37
	B1b	2.94	0.47	1.70	1.72	0.62	0.36
	B1c	2.90	0.53	1.69	1.79	0.63	0.35
	B2a	2.94	0.50	1.47	1.68	0.76	0.45
	B2b	2.80	0.63	1.48	1.63	0.68	0.42
	B2c	2.94	0.60	1.74	1.73	0.65	0.37
Jolengatan	J1a	2.97	0.67	1.97	1.88	0.63	0.33
	J1b	2.90	0.90	1.77	1.87	0.59	0.32
	J1c	2.87	0.93	1.85	1.92	0.62	0.32
	J2a	2.97	0.63	1.57	1.69	0.55	0.32
	J2b	2.94	0.47	1.69	1.67	0.57	0.34
	J2c	2.84	0.63	1.77	1.67	0.57	0.34
Söderleden 1	S1a	2.57	0.63	1.40	1.53	0.71	0.46
	S1b	2.70	0.77	1.50	1.57	0.67	0.43
	S1c	2.84	0.77	1.45	1.53	0.62	0.40
	S2a	2.97	0.43	1.40	1.51	0.65	0.43
	S2b	2.97	0.47	1.43	1.51	0.60	0.40
	S2c	2.97	0.47	1.45	1.54	0.61	0.39
	S3a	2.90	0.30	1.60	1.68	0.69	0.41
	S3b	2.97	0.37	1.53	1.68	0.71	0.42
	S3c	2.77	0.40	1.53	1.56	0.62	0.40
Söderleden 2	S4a	2.97	0.50	1.42	1.59	0.70	0.44
	S4b	2.94	0.37	1.37	1.61	0.73	0.46
	S4c	2.97	0.77	1.47	1.72	0.74	0.43
	S5a	2.87	0.37	1.52	1.51	0.62	0.41
	S5b	2.90	0.43	1.57	1.58	0.60	0.38
	S5c	2.97	0.53	1.58	1.61	0.60	0.37
	S6a	2.94	0.47	1.70	1.72	0.77	0.45
	S6b	2.97	0.43	1.60	1.70	0.70	0.42
	S6c	2.97	0.63	1.60	1.72	0.69	0.40

The results from Kruskal-Wallis test considering the gate in the middle of each lane (referred as *b*) showed that at a significance level of 0.05, the time headway distributions of the three road environments were significantly different (p-value = 0.006). Nevertheless, as Bifrostgatan and Jolengatan were seen to have similar range of values for THW, a Mann-Whitney U test was performed to check if their distributions can be considered similar by coming from the same population sample. The test was positive, with a p-value of 0.403.

Then, the Kruskal-Wallis test was performed in each lane to compare time headway distributions among the three gates (*a*, *b* and *c*) and the results can be seen in Table 10. Thereafter, in order to study the gates in different lanes but located in the same position along the road section, the Mann-Whitney U and Kruskal-Wallis tests were performed and the results are summarised in Table 11.

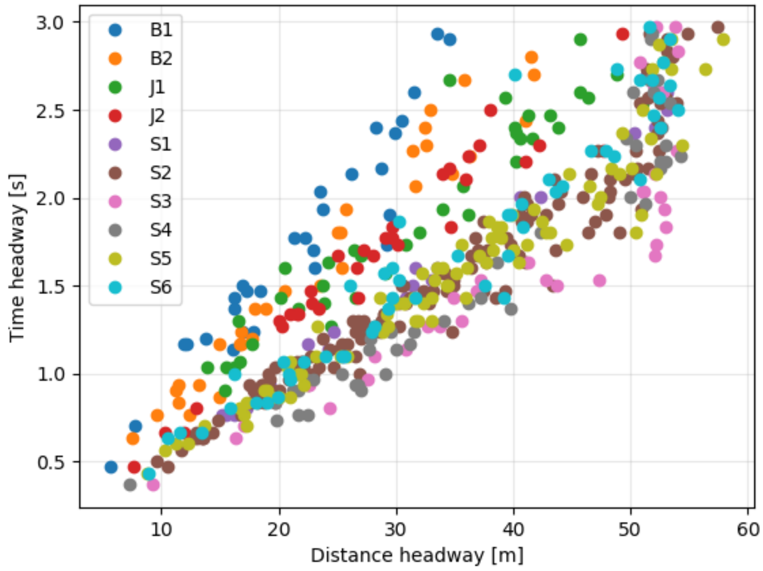

Figure 24. Relationship between time and distance headway

Table 10. Results from Kruskal-Wallis test for THW distribution per lane

Road environments	Gates	p-value
Bifrostgatan	$B1_{(a,b,c)}$	0.862
	$B2_{(a,b,c)}$	0.796
Jolengatan	$J1_{(a,b,c)}$	0.921
	$J2_{(a,b,c)}$	0.997
Söderleden 1	$S1_{(a,b,c)}$	0.952
	$S2_{(a,b,c)}$	0.793
	$S3_{(a,b,c)}$	0.735
Söderleden 2	$S4_{(a,b,c)}$	0.618
	$S5_{(a,b,c)}$	0.593
	$S6_{(a,b,c)}$	0.989

Table 11. Results from Mann-Whitney and Kruskal-Wallis tests for THW distribution

Road environment	Gates	p-value
Bifrostgatan	B1a - B2a	0.369
	B1b - B2b	0.253
	B1c - B2c	0.334
Jolengatan	J1a - J2a	0.061
	J1b - J2b	0.098
	J1c - J2c	0.072
Söderleden 1	S1a - S2a - S3a	0.340
	S1b - S2b - S3b	0.356
	S1c, S2c, S3c	0.952
Söderleden 2	S4a - S5a - S6a	0.341
	S4b - S5b - S6b	0.662
	S4c - S5c - S6c	0.773

4.2.3 Speed

For the speed of the vehicles engaged in car-following, Table 12 shows the summary of the statistical results. In Appendix D, the speed distribution for each gate is presented. Furthermore, in an attempt to find a relationship between headway and speed, plots of speed against time and distance headway, taking into consideration the gate referred as *b* in each road environment, are illustrated in Appendix E.

Table 12. Statistical results of vehicle speed per gate

Road environment	Gate	Max [km/h]	Min [km/h]	Median [km/h]	Mean [km/h]	σ [km/h]	CV
Bifrostgatan	B1a	60.08	36.56	44.91	45.48	4.94	0.11
	B1b	61.29	37.84	45.12	46.17	5.42	0.12
	B1c	61.39	38.41	46.60	47.92	6.02	0.13
	B2a	64.95	44.02	49.36	50.57	4.87	0.10
	B2b	63.60	44.83	50.34	51.60	4.72	0.09
	B2c	73.62	47.85	54.99	55.77	5.84	0.10
Jolengatan	J1a	73.40	35.37	56.05	55.17	8.59	0.16
	J1b	73.41	47.17	61.98	61.33	6.52	0.11
	J1c	74.90	48.04	60.98	61.46	5.96	0.10
	J2a	68.15	42.88	51.12	52.70	6.36	0.12
	J2b	73.92	54.01	59.42	60.76	4.52	0.07
	J2c	79.45	54.62	60.47	61.25	5.47	0.09
Söderleden 1	S1a	82.72	68.45	74.71	74.85	3.97	0.05
	S1b	87.24	72.66	77.50	78.22	3.85	0.05
	S1c	89.83	71.92	79.02	79.55	3.96	0.05
	S2a	106.38	65.68	78.46	78.99	6.92	0.09
	S2b	106.85	70.42	81.56	82.85	6.75	0.08
	S2c	101.72	70.43	82.86	83.41	6.34	0.08
	S3a	115.02	83.44	94.35	96.46	8.50	0.09
	S3b	116.49	87.95	99.39	100.64	8.28	0.08
	S3c	115.05	88.65	99.84	100.82	7.77	0.08
Söderleden 2	S4a	111.83	78.40	92.20	93.40	9.86	0.11
	S4b	112.95	79.32	96.81	97.32	9.04	0.09
	S4c	111.07	83.49	96.74	96.73	7.84	0.08
	S5a	97.43	65.79	79.00	79.42	7.50	0.09
	S5b	103.31	66.43	81.72	82.30	6.71	0.08
	S5c	102.16	70.38	81.83	82.48	6.63	0.08
	S6a	102.29	58.31	74.07	74.75	9.24	0.12
	S6b	99.83	59.24	77.76	77.76	7.99	0.10
	S6c	100.75	58.37	78.63	78.71	7.80	0.10

The results from Kruskal-Wallis test considering the gate in the middle of each lane (referred as *b*) showed that at a significance level of 0.05, the speed distributions of the three road environments were significantly different (p-value <0.001), as already expected as they have different speed limits. Then, the Kruskal-Wallis test was performed in each lane to compare speed distributions among the three gates (*a*, *b* and *c*) and the results can be seen in Table 13.

Table 13. Results from Kruskal-Wallis test for speed distribution per lane

Road environments	Gates	p-value
Bifrostgatan	$B1_{(a,b,c)}$	0.209
	$B2_{(a,b,c)}$	<0.001
Jolengatan	$J1_{(a,b,c)}$	<0.001
	$J2_{(a,b,c)}$	<0.001
Söderleden 1	$S1_{(a,b,c)}$	0.001
	$S2_{(a,b,c)}$	<0.001
	$S3_{(a,b,c)}$	0.027
Söderleden 2	$S4_{(a,b,c)}$	0.093
	$S5_{(a,b,c)}$	0.011
	$S6_{(a,b,c)}$	0.020

Thereafter, in order to study the gates in different lanes but located in the same position along the road section, the Mann-Whitney U and Kruskal-Wallis tests were performed and the results are summarised in Table 14.

Table 14. Results from Mann-Whitney and Kruskal-Wallis tests for speed distribution

Road environment	Gates	p-value
Bifrostgatan	B1a - B2a	<0.001
	B1b - B2b	<0.001
	B1c - B2c	<0.001
Jolengatan	J1a - J2a	0.019
	J1b - J2b	0.206
	J1c - J2c	0.308
Söderleden 1	S1a - S2a - S3a	<0.001
	S1b - S2b - S3b	<0.001
	S1c - S2c - S3c	<0.001
Söderleden 2	S4a - S5a - S6a	<0.001
	S4b - S5b - S6b	<0.001
	S4c - S5c - S6c	<0.001

4.2.4 Acceleration

The number of vehicles accelerating and braking in each gate can be seen in Table 15. Moreover, information regarding their statistics can be seen in Appendix F. Nevertheless, some of the values in Appendix F are marked in red as the rates seem to be too out of range. The results might have been compromised during the analysis performed by DataFromSky due to some noise in the data and too small time steps on the data processing.

Since it was hard to manipulate the data, those high rates could not be excluded from the data analysis. However, as it can be seen in Appendix F, most of these rates are located in the gates *a* and *c*. Therefore, in order to have a better picture of the variation of acceleration and deceleration in the road segments, Figure 25 and Figure 26 illustrate the maximum, minimum and mean rates along with the standard deviation, taking into consideration the gates referred as *b*.

Table 15. Number of vehicles accelerating and braking in each gate

Road environment	Gate	Accelerating	Braking
Bifrostgatan	B1a	27	1
	B1b	26	3
	B1c	12	18
	B2a	5	25
	B2b	5	27
	B2c	10	25
Jolengatan	J1a	37	3
	J1b	26	12
	J1c	8	30
	J2a	1	29
	J2b	5	27
	J2c	15	15
Söderleden 1	S1a	18	1
	S1b	13	8
	S1c	13	11
	S2a	137	10
	S2b	86	54
	S2c	79	60
	S3a	32	2
	S3b	15	18
	S3c	14	15
Söderleden 2	S4a	4	38
	S4b	10	33
	S4c	22	17
	S5a	11	69
	S5b	19	66
	S5c	41	45
	S6a	7	48
	S6b	12	41
	S6c	26	28

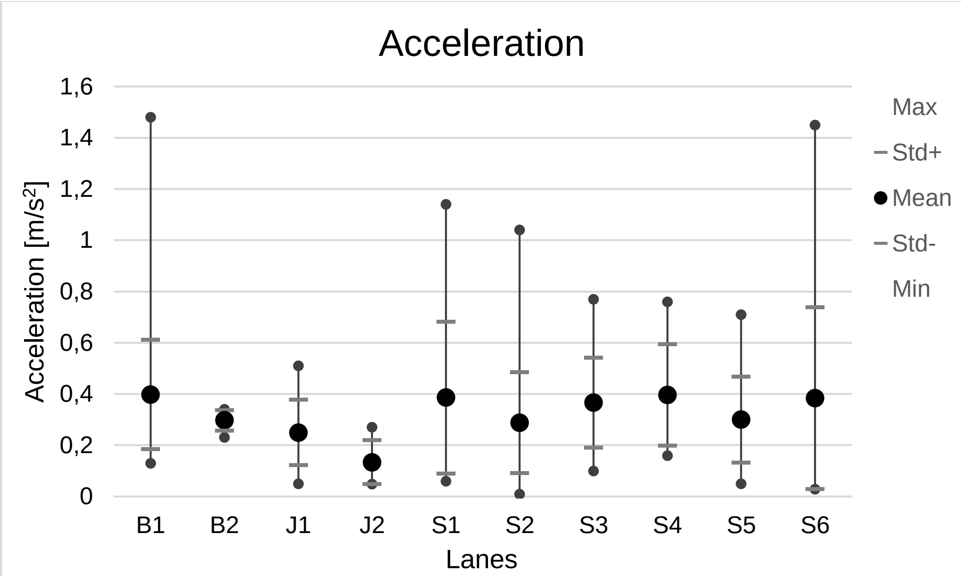

Figure 25. Acceleration variation in each lane

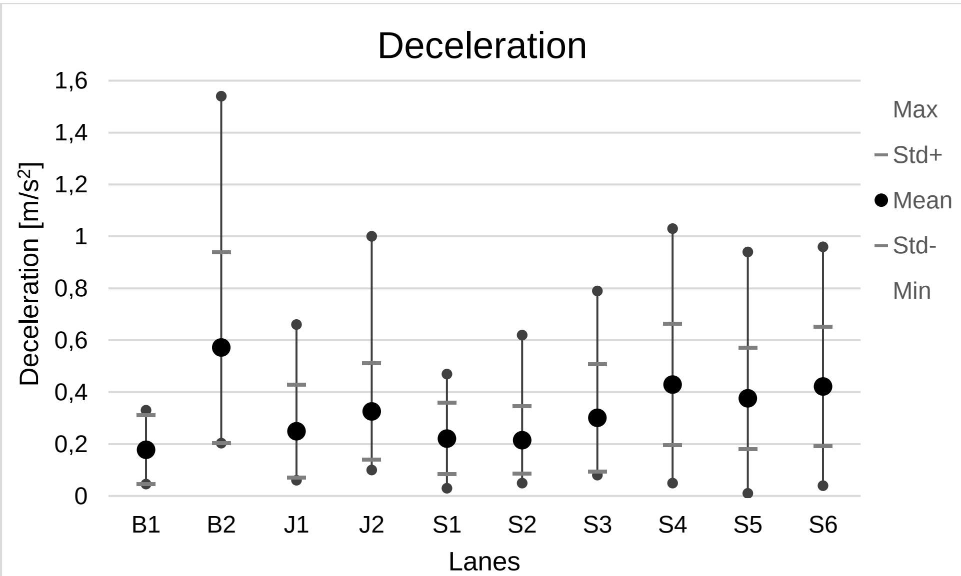

Figure 26. Deceleration variation in each lane

4.3 Calibration of the model

For the traffic simulation, five replication runs were performed using seeds from 42 to 62 with an increment of five units. The first two simulations considered the default parameters for the Wiedemann's car-following models. The average of the simulation results of the five replications were then compared to the observed data, see Appendix G.

As it can be seen in Appendix G, the output from the simulation is not really representative to the observed data. Overall, it was found an error of more than 4% for each lane. Therefore, in order to better represent the driver behaviour in Bifrostgatan, the car-following model needed to be calibrated. As described in sections 2.2.4 and 3.6, the parameter CC1 should be calibrated. For that, the length of the leading vehicle in the car-following regime needed to be estimated as it is a parameter in equation 3 (see section 2.2.4). This information was then retrieved from the DataFromSky software viewer, as they set an average length for each vehicle type when processing the videos (Table 16), which was considered to be a good reference.

Table 16. Average vehicle length set by DataFromSky

Vehicle type	Length [m]
Undefined	5.00
Car	5.00
Medium vehicle	5.83
Heavy vehicle	12.50
Bus	12.50
Motorcycle	2.50

Then, by taking into consideration the data for time headway and speed for each vehicle and the respective leading vehicle in the car-following regime, along with their length and the default value of 1.50 metres for CC0, CC1 was calculated for each vehicle in Bifrostgatan. The mean CC1 considering data from both lanes was found as 1.3 seconds. CC1 was then set to 1.3 seconds on PTV VISSIM, and the five replication runs were simulated again. The results can be seen in Figure 27 and Figure 28. The error after the calibration was slightly below 2% for the two lanes.

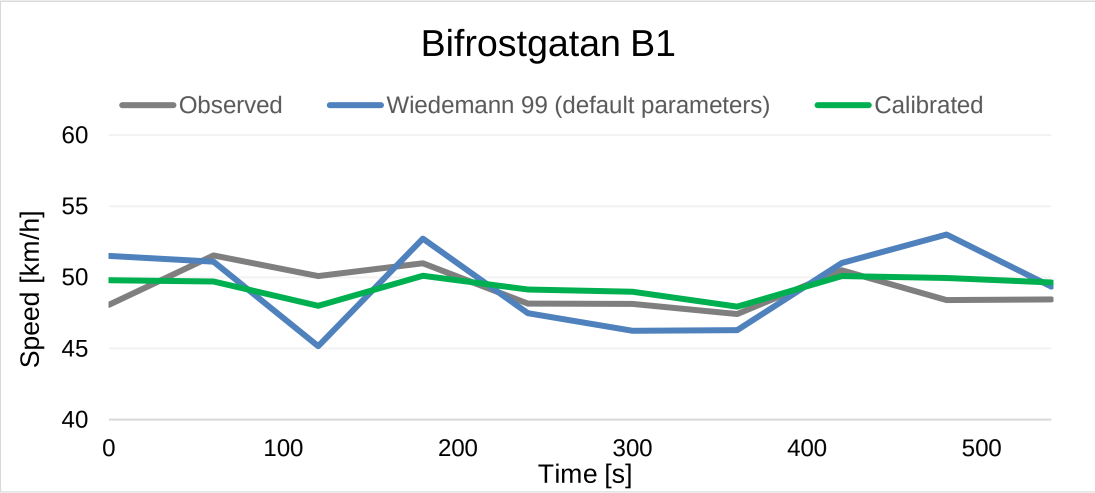

Figure 27. Comparison between observed speed and the output from the simulations for B1

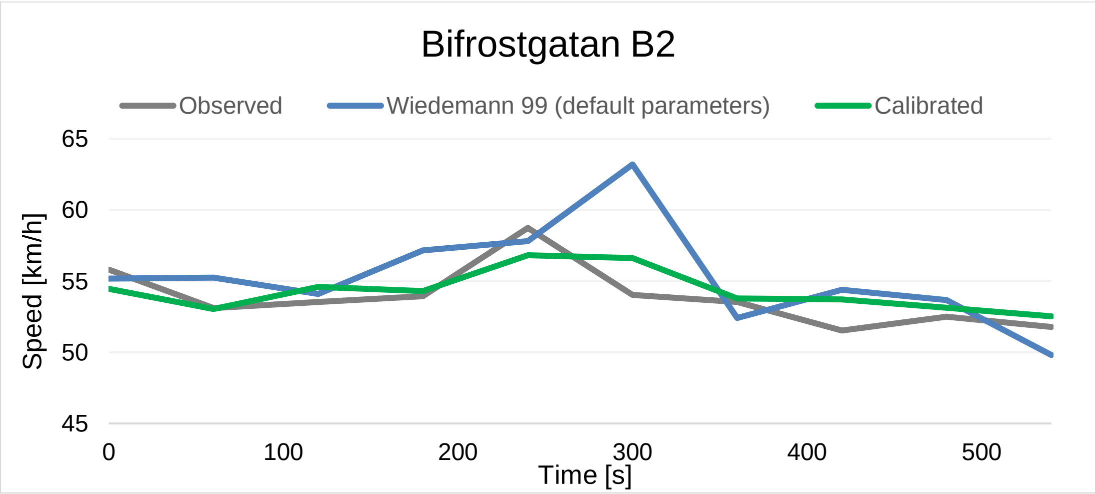

Figure 28. Comparison between observed speed and the output from the simulations for B2

5 Discussion

In this chapter, the results are discussed to explore how the longitudinal driver behaviour is affected by the road environment in Gothenburg. The three road environments are analysed in regard to the infrastructure attributes and thereafter compared to each other to understand if drivers tend to adopt different behaviours depending on where they are. The calibration of the model on PTV VISSIM as well as its limitations is also discussed.

5.1 Road environments

Bifrostgatan, Jolengatan and Söderleden are classified as classes 3, 3 and 1, respectively, on the functional road classification used by Trafikverket, as seen in section 3.2. Consequently, taking into consideration the road characteristics and their role in the network, Bifrostgatan and Jolengatan could be categorised as collector major roads and Söderleden as an arterial major road based on the American classification in Table 1 (see section 2.1.1).

Concerning infrastructure attributes, the main differences among these road environments are the lane width and speed limit. For example, even though Bifrostgatan and Jolengatan are classified on the same functional level, Bifrostgatan has a road width of 9 metres (approximately 4.5 metres/lane) and 50 km/h as speed limit, while Jolengatan has a road width of 7 metres (approximately 3.5 metres/lane) and 70 km/h as speed limit. On the other hand, as Söderleden can be classified as an arterial road, the number of lanes (3 lanes/direction) is a specific characteristic to this road segment, as opposed to Bifrostgatan and Jolengatan that only have one lane per direction. Furthermore, the speed limit in this environment is 80 km/h and the lanes are approximately 4 metres wide.

It is important to point out that during the data collection, the traffic conditions could be considered as free flowing in the three road sections. No congestion was seen during the 10 minutes, and vehicles were not constrained by any specific situation. Therefore, as expected, the traffic demand in Söderleden was much higher than in Jolengatan and Bifrostgatan, as it can be seen in Table 5. Nevertheless, it was seen that there is an over demand in specific lanes, at least during those 10 minutes of data collection. In Söderleden 1, the demand on lane S2 was around 3 times higher when compared to S1 and S3 (Table 6). A similar situation could be seen in Söderleden 2, where lane S5 had a higher demand than S4 and S6. Therefore, it seems that drivers might prefer to drive in the lanes located in the middle.

During the data collection, many situations as illustrated in Figure B9 in Appendix B were seen, where drivers remained in a car-following regime while driving in the lane in the middle even though the other two lanes were free and they could easily overtake the vehicles. Furthermore, most heavy vehicles were seen travelling on the lanes in the middle (Table 6), which might have influenced drivers to remain in a car-following regime when following this type of vehicle.

It is also interesting to point out a curious observation during the data collection in Bifrostgatan. According to Trafikverket (2019b), as it can be seen in Table 4, trucks are not allowed in this road environment. Nevertheless, as shown in Figure B1 in Appendix B and Table 6, there was one truck (heavy vehicle) travelling on lane B2.

5.2 Speed limit

Jolengatan was the only road environment in which the mean speed of all vehicle types was under the speed limit (70 km/h), as it can be seen in Table 7. Nevertheless, it is important to remember that, as discussed in section 3.2.2, the road section in Jolengatan is located close to a speed reduction area. As seen in Figure A2 in Appendix A, it is noticeable that the mean speed is lower on the gate located closer to the speed reduction sign (gate *a*) when compared to the other gates. Therefore, it can be concluded that drivers tend to respect the traffic sign in this road environment, reducing their speed accordingly.

Furthermore, as it can be seen in Figure 21, a slightly higher mean speed rate is seen in the middle of the road section as opposed to the area in the bottom of the picture, which is the area closer to the speed reduction sign. In addition, in Table 15, it can be observed that on the gate J1a, 92.5% of the vehicles engaged in car-following are accelerating while on the gate J2a, 97% of the vehicles are braking. Therefore, it can be confirmed that vehicles in Jolengatan adopt their speed due to the speed reduction sign.

On the other hand, a different situation was seen in Bifrostgatan and Söderleden. In both road environments, most of the vehicles were found not to be respecting the speed limit (Table 7). By analysing the mean speed considering the total count of vehicles (see Appendix A), it was observed that the vehicles tend to drive within or above the speed limit depending on the lane and/or gate the data was retrieved. In this sense, it is interesting to relate the lane width to vehicles travelling above the speed limit. As seen in section 2.1.1, usually collector roads present a range of lane width between 3.0 to 3.6 whereas arterial roads from 3.3 to 3.75. Both Bifrostgatan and Söderleden have lane width wider than these ranges, respectively. Roads with wide lanes might be perceived by driver as an environment appropriate to drive fast, or at least, faster than the posted speed limit.

It was curious to notice that in Bifrostgatan drivers on the lane closer to the bike lane (lane B1) tend to drive slower than the drivers on lane B2. This behaviour was observed when analysing the speed of all vehicles crossing the road section, as seen in Figure 20 and Figure A1 in Appendix A, as well as when considering only vehicles engaged in car-following (Table 12). Taking that into account, it could be assumed that the presence of the bike lane on the road segment might induce drivers to be more cautions, even though the bike lane is elevated, being physically disconnected from the lane.

In Söderleden it was observed that drivers tend not to respect speed limit (80 km/h). It was noticed that many vehicles were travelling with a rate close to 100 km/h. In addition, a large variation in speed was observed when considering the inner lanes (S3 and S4) as opposed to the outer lanes (S1, S2, S5 and S6), as seen in Figure A3 and Figure A4 in Appendix A. It can then be concluded that drivers perceived S3 and S4 as “fast speed lanes”, in which the mean speed is around 100 km/h (Figure 21), 25% higher than the speed limit. It is also interesting to point out that the lane width (4 metres) might give the sense of security to the drivers to move faster and could be one of the reasons for them to be driving above the speed limit.

5.3 Analysis of trajectories

For the vehicles’ trajectories, even though only a visual analysis was carried out, some interesting conclusions can be drawn about how drivers tend to position their vehicles on the lanes. By looking at Figure 23, it can be said that vehicles in Jolengatan tend to follow the same trajectories and keep more or less the same position, on the centre of the lane, when travelling in this road segment (see Appendix B for more pictures). That might be due to the fact that the lane can be considered narrow when compared to Bifrostgatan or Söderleden, for example, and overtake is also not allowed in that section.

On the other hand, when looking at the trajectories in Söderleden (Figure 23), it can be seen that there is a lot of variation in the trajectories of the vehicles. That might be partially due to lane change behaviour but also to lateral separation effects, when vehicles are not positioned on the centre of the lane all the time. In this case, drivers might want to have a better view of the traffic ahead, either to find opportunities to overtake or to pay attention in the movement dynamics of the other vehicles in front. Consequently, many drivers tend not to follow the same trajectory as the leading vehicles. It was observed that in the inner and outer lanes, for example, many vehicles tend to drive closer to the edge, as it can be seen in Figure B7 and Figure B8 in Appendix B.

In Bifrostgatan, the situation is a bit peculiar. First, by taking a look at Figure 22, it can be noticed that vehicles on lane B1 tend to travel closer to the centre of the lane whereas vehicles on lane B2, on the edge of the lane. If the lane width is taken into consideration (approximately 4.5 metres), it can be said that it seems to be really wide for a speed limit of 50 km/h. Jolengatan has narrower lanes and higher speed limit, as a result, drivers there tend to keep their vehicles on the centre of the lane. It seems that drivers on lane B1 only tend to drive on the centre of the lane because of the bike lane, as it is elevated, they might be afraid to be too close to it and perhaps damage their vehicles.

Furthermore, when analysing particular cases as Figure B2 and Figure B3 in Appendix B, it can be seen that even the bus tends to keep the same behaviour as the overall vehicles in Bifrostgatan. Also, as discussed in section 5.2, the average speed on lane B1 is lower than on B2. Therefore, it can be concluded that the elevated bike lane closer to B1 might be influencing the driver behaviour. It seems that drivers tend to perceive this infrastructure feature in a cautious way.

5.4 Longitudinal driver behaviour characteristics

The interaction between vehicles was investigated taking into consideration the longitudinal driver behaviour for vehicles engaged in car-following. From Table 8, it can be seen that in Bifrostgatan and Jolengatan, more than 40% of the vehicles were engaged in car-following. In Söderleden 1, when considering lane S2, it can be seen that approximately 70% of vehicles were following another vehicle whereas this percentage dropped to 30% on the other lanes. On the other hand, it was seen that in Söderleden 2, more than 50% of the vehicles were engaged in car-following in all the lanes.

5.4.1 Time headway

The result from Kruskal-Wallis test showed that the time headway distribution in the three road environments does not come from the same population. However, Bifrostgatan and Jolengatan can be considered similar, probably because according to the road classification they develop the same function in the traffic network. Therefore, it can be concluded that drivers tend to adopt different time headways depending on the type of the road segment. If looking only at the mean time headways (Table 9) though, the difference does not seem to be significant. Nevertheless, when taking into consideration the distributions, some evident variation in frequency can be seen (Appendix C).

Taking into consideration the road classification, collector roads as opposed to an arterial road, in Bifrostgatan and Jolengatan, the time headways were slightly higher than in Söderleden. The mean time headway in Bifrostgatan and Jolengatan ranged from 1.6 to 1.9 seconds whereas in Söderleden, from 1.5 to 1.7 seconds. Variation on time headway tended to be higher on Söderleden though, as higher CV were found in this road section. As a result, drivers might be more inclined to vary their choices on time headway more intensively when in a "fast moving" environment.

On the other hand, it was seen that drivers tend to be consistent to their choice of headway along the roadway, as Kruskal-Wallis test showed no significant statistical difference in time headway within gates for all the road environments (Table 10). However, when comparing time headway in different lanes, the p-value in Jolengatan was really low when compared to the other road segments. Yet, the results do not show any statistical evidence that could state a variation among lanes (Table 11).

As described in section 3.2.2, there is a speed reduction sign in Jolengatan, which might influence drivers to vary their time headways in this environment. That is because, depending on the lane, drivers need to adjust speed from 50 km/h to 70 km/h, or vice-versa. As a result, drivers are usually accelerating in lane J1 and braking in lane J2, which might influence the interaction between vehicles. For example, it is observed that drivers on lane J1 tend to adopt a mean time headway of 1.9 seconds whereas on lane J2, a time headway of 1.7 seconds.

5.4.2 Speed

Comparing the mean speed of the vehicles engaged in car-following to the overall mean speed in the road sections (see section 4.1.1), it was noticed that vehicles were crossing some gates under the speed limit, particularly in Bifrostgatan and Söderleden. The mean speed of vehicles engaged in car-following in lanes B1, S1 and S6 is below the speed limit (Table 12) whereas, when considering all vehicles crossing these road sections, the mean speed tends to be within the speed limit (see Appendix A). That might be because some vehicles might engage in a car-following regime due to slower vehicles, as shown in Figure B4 and Figure B5 in Appendix B.

From the statistical results in Table 12, it is evident that speed has lower CV than time headway (Table 9), which might be due to the speed limit, so drivers tend not to vary their speed as much and tend to drive within a desired speed. The Kruskal-Wallis test confirmed that the three road environments were indeed different regarding speed distribution. Nevertheless, surprisingly, it was found out that speed is not that consistent along the roadway (Table 13). Lanes B1 and S4 were the only ones that did not show statistical evidence of different speed distribution within the lane (p-value > 0.05). Consequently, it can be concluded that even though the road sections were not very long, and the traffic conditions could be considered as free flowing, drivers still tended to vary speed rates within the road section.

Furthermore, when comparing speed distribution in different lanes (Table 14), Jolengatan was the single road section that did not result in a significant statistical level of difference in all cases, only in gate *a* where the p-value was 0.019. The gates J1a and J2a are located closer to the speed reduction sign as already discussed previously, therefore, the different speed distribution in this position might be resulted from the movement dynamics of vehicles accelerating and braking accordingly to the sign. Nevertheless, in the other gates in Jolengatan, it can be assumed that the infrastructure, such as lane width or the presence of the sidewalk, is not influencing drivers and so they tend to keep similar behaviour regardless of the direction they are travelling.

Söderleden is considered to be an arterial road with fast-moving traffic, in which drivers tend not to travel at the same rate when engaged in car-following, as demonstrated by the varying median and mean speed values for the six lanes and eighteen gates in Table 12. Consequently, it is not surprising to see that the speed distribution varies within the road segment (Table 14). As for Bifrostgatan, the discussion in section 5.2 has highlighted how drivers tend to be more cautious on lane B1, driving slower, probably due to the bike lane. In this case, seeing that the speed distribution of the two lanes do not follow the same distribution (Table 14) might also count as an evidence on how an infrastructure attribute can influence behaviour in a road segment.

Many studies have already analysed the relationship between speed and headway (see section 2.2.3), and in this research despite the small amount of data, it was still decided to take a look at this relationship (see Appendix E). However, as expected, no clear correlation could be seen between these parameters. In some cases, as in lane S2 in Söderleden, as there were more data, some tendency could be observed in the plot (Figure E3 in Appendix E) but not sustained by a strong relationship. Therefore, in order to have a better picture of the situation, more data should have been collected and evaluated. This research was limit to only 10 minutes of traffic observation, not even considering different days or times of the day. The results were then very limited to the situation recorded and, unfortunately, it was not enough to identify a relationship between parameters.

Another interesting observation in the correlation topic is the different ranges of DHW when considering the same THW in the road sections. In Figure 24, it can be seen that for Bifrostgatan, for example, DHW tends to range from 5 to 40 metres, whereas in Söderleden from 5 to 57 metres. Clearly, this difference can be linked to the different speed in these road sections, as for example, for a DHW of 20 metres, the THW is 1.5 seconds and 0.9 seconds for Bifrostgatan and Söderleden, respectively. Taking the mean speed into consideration, the same results can be calculated by dividing DHW and speed. Therefore, the data collected is indeed reliable, with more data, a correlation between parameters could certainly be achieved to provide a better overview of the road environment and develop models to differentiate longitudinal driver behaviour in different road types.

5.4.3 Acceleration

As already mentioned in section 4.2.4, there were some uncertainties in the acceleration and deceleration values as part of the data might have been compromised. Due to some noise in the data together with small time step during the data processing, the rates might have been not properly extracted from the videos. This was seen especially in gates *a* and *c*, which represent the beginning and end of each lane and where the vehicles started to appear on the videos. Also, as it can be seen in Appendix F, there were even CV over 1.0 for gates *a* and *c* whereas for gates *b*, CV ranged from 0.5 to 0.8. However, unfortunately, it was not feasible to exclude the unrealistic rates from the statistical analysis for gates *a* and *c*. It was not possible to manipulate this kind of data on the software, as the results delivered by DataFromSky were already incorporated in the files.

When it comes to the behaviour connected to vehicles accelerating and decelerating, it is curious to notice that, depending on the gate, there is a clear gap between the number of vehicles accelerating and braking (Table 15). In Jolengatan, for example, most of the vehicles on lane J1 are accelerating whereas on lane J2 they are braking, as assumed and already discussed in section 5.2. Nevertheless, this was the road segment with the least variation in acceleration as drivers seem to behave similarly in response to the traffic sign.

Figure 25 and Figure 26 showed the mean rate for acceleration and deceleration for gates *b*, which is mainly between 0 and 0.8 m/s^2. It was interesting to notice that in lane B2, vehicles seem to adopt similar behaviour for acceleration but varying a lot the behaviour for deceleration, being the lane where vehicles have the highest CV and rate in deceleration (Appendix F). Furthermore, from the CV values in Appendix F, it could be seen that the variation in acceleration and deceleration tends to be really high. Overall, there is no evident driving characteristic appointing to numerical differences in the way drivers accelerate or brake in each road environment. The only conclusions drawn can be based on Table 15, on the number of vehicles accelerating and braking in each gate. Vehicles seem to attempt to adapt their movement dynamics in the road environment by either accelerating or braking in response to respectively larger headways or slower vehicles in front.

During the car-following regime in Bifrostgatan, drivers on lane B2 might have encountered more slower vehicles, tending to present more varying brake behaviour in order to keep a safe headway to the vehicle in front. The opposite was seen in lane B1, especially on gates *a* and *b*, where more vehicles accelerating than braking were observed. Vehicles might be in the accelerating regime when crossing these gates, and then reaching the stable following on gate *c*, where there is a similar number of vehicles accelerating and braking (Table 15).

A similar situation can be seen in Söderleden 1. It seems that vehicles crossing gates *a* and *b* are in the accelerating regime, then reaching the stable following in gate *c*. The opposite can be said for Söderleden 2 though (Table 15). Taking the direction of movement in Söderleden 2, vehicles travel from gate *c* to *a*, therefore it was observed that vehicles tend to be in a stable following regime while crossing gate *c* but when reaching gates *b* and *a*, they might be facing a braking regime.

5.5 VISSIM model

The first simulation runs were performed taking into consideration the default parameters for the car-following models Wiedemann 74 and 99. As it can be seen in Appendix G, Wiedemann 99 seemed to be more fitting to the observed data even though the results were not very representative to the reality. The average calculated error between the observed data and the simulated output was 4% for both models, which might not seem to be very high, but since the curves barely look alike, it cannot be considered a good representation of the traffic in Bifrostgatan.

On the other hand, after calibrating the parameter CC1, it could be seen in Figure 27 and Figure 28 that the difference between reality and simulation was smaller than before. The average error for both lanes dropped to 2%. It is still not perfect, and it does not result in an output identical to the observed traffic, however, it is much closer than when considering the default parameters for the car-following model. It is also important to point out that as PTV VISSIM is a stochastic microscopic simulator, more replication runs as well as different seeds were tested. Nevertheless, better results were not achieved.

Wiedemann 74 car-following model is the one recommended by PTV VISSIM to simulate urban environments. Bifrostgatan can be considered as an urban collector road, so using this model would have been the ideal choice. However, considering the data collected, calibrating the parameters for this model was not possible. Therefore, implementing the Wiedemann 99 as the car-following model for Bifrostgatan and calibrating the parameter CC1 was considered the best solution for this case. Looking at the outcome in Figure 27 and Figure 28, it can be assumed that the model worked well for Bifrostgatan and could be applied as a good representation of the observed traffic.

The only validation criterion to the calibration of the model was the speed profile. Investigating acceleration and even microscopic variables as headway would perhaps give a better picture of how accurate the model is. Of course, validating speed is already a good representation of the current traffic behaviour, but in order to optimise driver behaviour for future purposes, as supporting driving systems, having an accurate model of the driver behaviour in the road segment is important to perform realistic simulations.

It is also important to highlight that, with the data available, only one parameter out of the ten parameters in the Wiedemann 99 model was calibrated. Keeping the default values for the other nine parameters can be considered as the main limitation in the simulation. Even though CC1 is considered to be one of the most influential parameters in the model, it would be interesting to investigate if by calibrating another parameter, the error could be further reduced.

One of the most important outcomes from the simulation is the fact that the calibration could support further investigation in the road environment. As the calibration has shown to provide a good representation of the reality, this simulation environment can be applied in studies and analysis on the traffic system in Bifrostgatan. Therefore, the simulation environment created could be used to investigate longitudinal driver behaviour, as time headway and distance headway, in regard to the incorporation of autonomous vehicles in the road section, for example.

6 Conclusion

Headway, speed and acceleration are important parameters to characterise longitudinal driver behaviour. From the research, it can be concluded that the choice of time headway seems to be particular to each road type. It was observed higher THW in the collector roads, Bifrostgatan and Jolengatan, whereas lower values for the arterial road, Söderleden. Even though Bifrostgatan and Jolengatan present different infrastructure attributes, the non-parametric test showed that the time headway distributions for these two segments come from the same population. Therefore, drivers have similar choice of THW there.

Investigating the speed in each road environment showed that drivers can have different perception of the road section depending on the infrastructure features. For example, in Bifrostgatan, drivers tended to be more cautious (driving slower) on the lane closer to the bike lane. On the other hand, in Söderleden, drivers seemed to perceive the road environment more like a traditional fast-moving highway, not really respecting the speed limit, which could also be related to the lane width.

Acceleration did not provide any specific conclusion for the research. Partially because the data might have been compromised during the data processing, but also no clear characteristic behaviour was observed among the road environments. Based on the number of vehicles accelerating and braking, only an overall picture of which car-following regime approach the vehicles are along the roadway could be assessed. In this case, more data would be necessary to try to correlate acceleration with another parameter, such as relative speed or even headway, to investigate if there is a particular behaviour differentiating the road segments.

Additionally, it was possible to create a simulation environment for Bifrostgatan on PTV VISSIM. The model was validated using the speed profile, and by calibrating only one of the parameters of Wiedemann 99 car-following model, the results showed an average error of 2% between the real data and the simulation output. By collecting more specific data in the road segment, this simulation environment can be further improved to represent the reality even better. Also, this model can be applied in studies and analysis in Bifrostgatan, either to investigate specific changes in the infrastructure attributes or to further examine driver behaviour in response to specific scenarios.

7 References

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Appendix A

Speed characteristics in the road segments

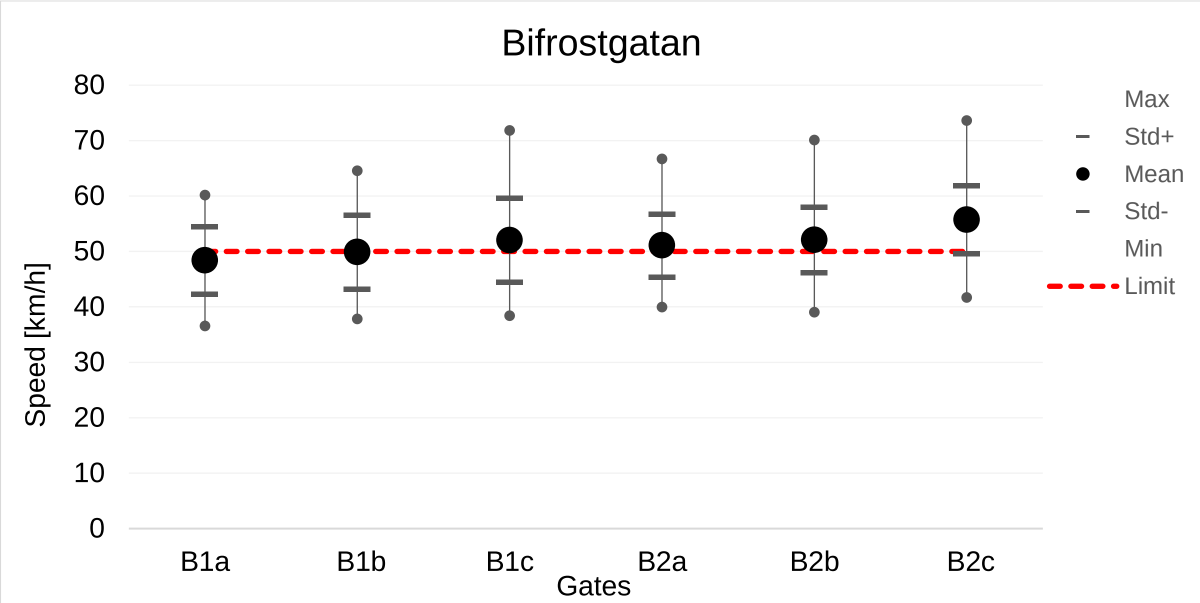

Figure A1. Summary of speed characteristics in Bifrostgatan

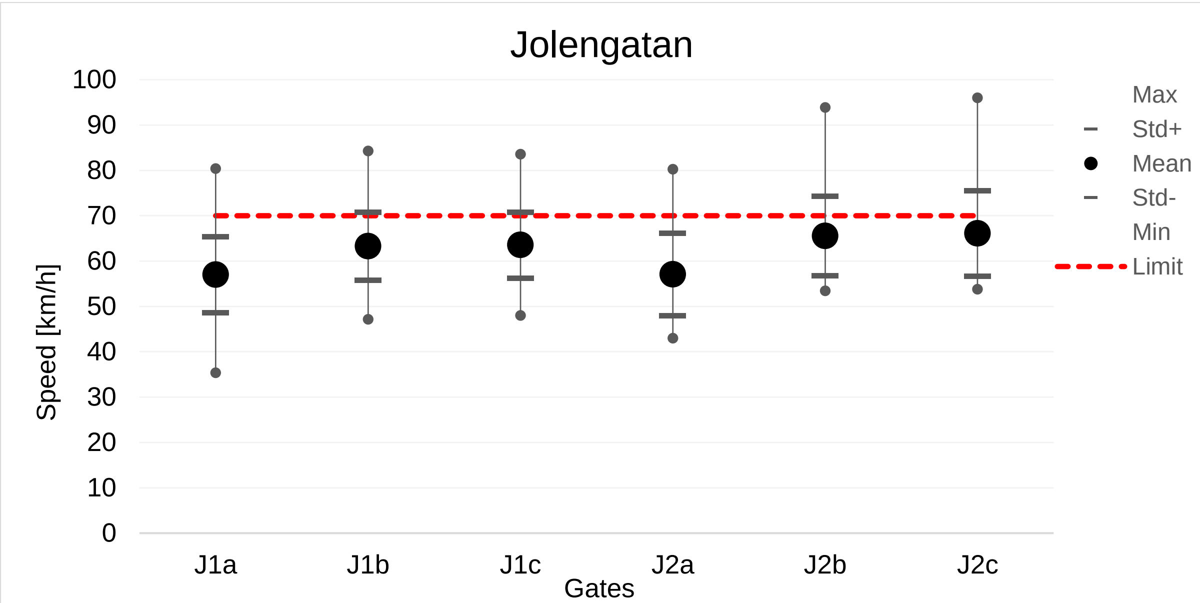

Figure A2. Summary of speed characteristics in Jolengatan

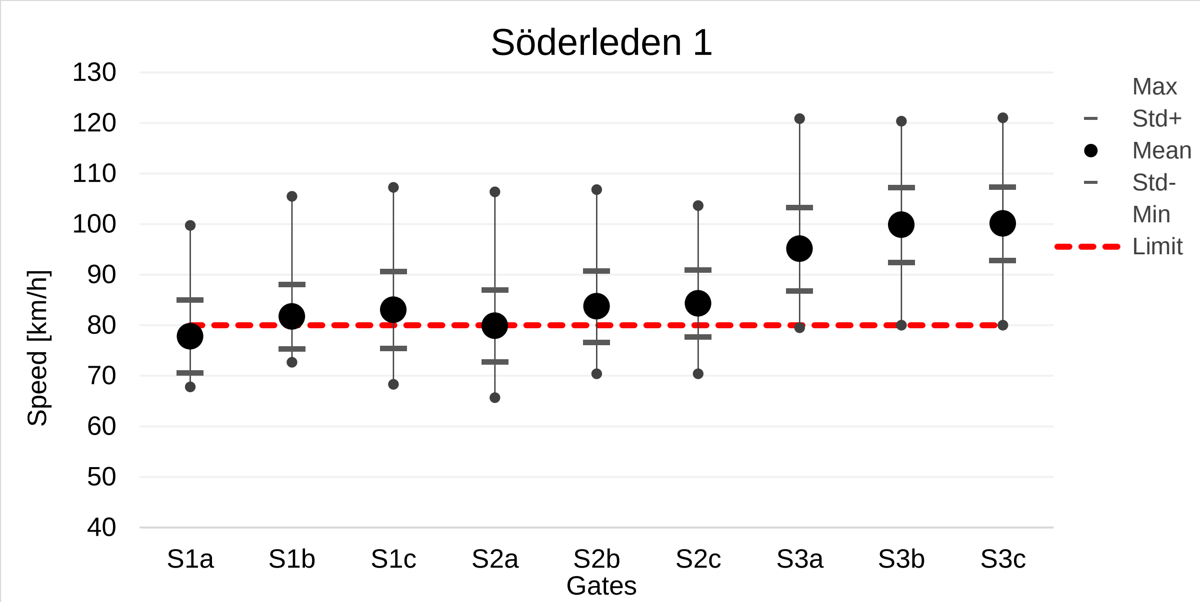

Figure A3. Summary of speed characteristics in Söderleden 1

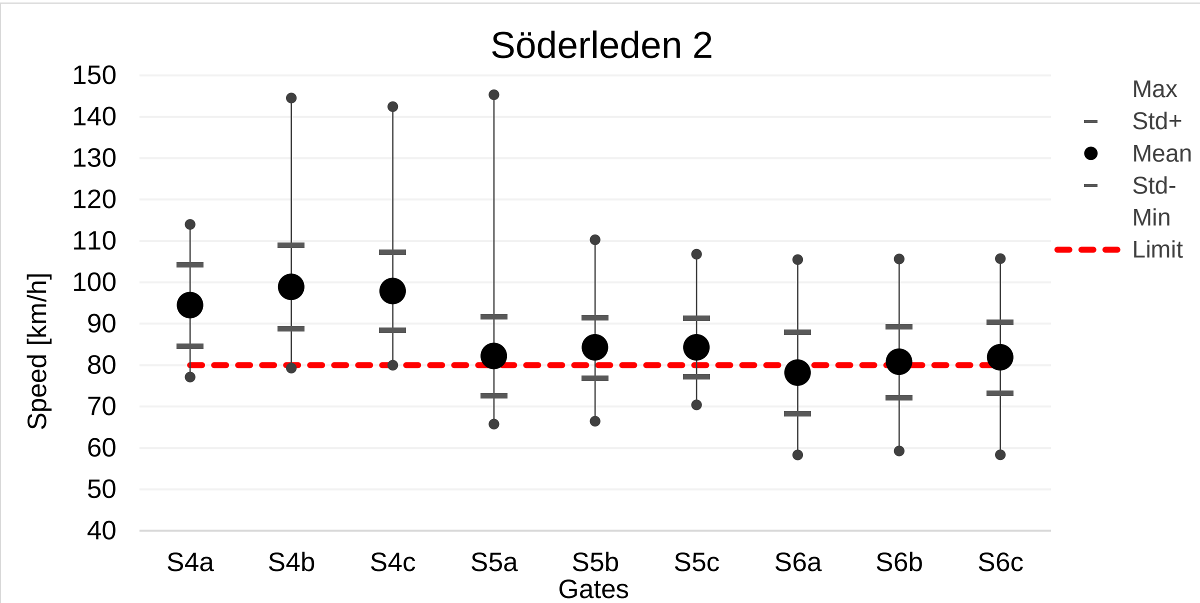

Figure A4. Summary of speed characteristics in Söderleden 2

Appendix B

Visualisation snapshots from DataFromSky software

Figure B1. Heavy vehicle travelling in Bifrostgatan

Figure B2. Bus trajectory on lane B2 in Bifrostgatan

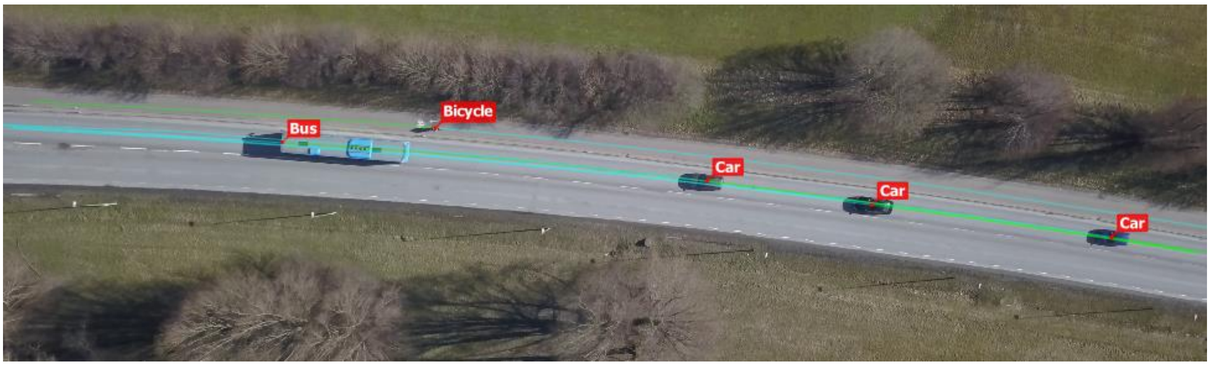

Figure B3. Bus trajectory on lane B1 in Bifrostgatan

Figure B4. Undefined vehicle in Bifrostgatan

Figure B5. Vehicles engaging in car-following because of the the undefined vehicle


Figure B6. Examples of vehicles engaged in car-following in both Söderleden and Jolengatan

Figure B7. Car in Söderleden 1 travelling on the edge of the inner lane S3

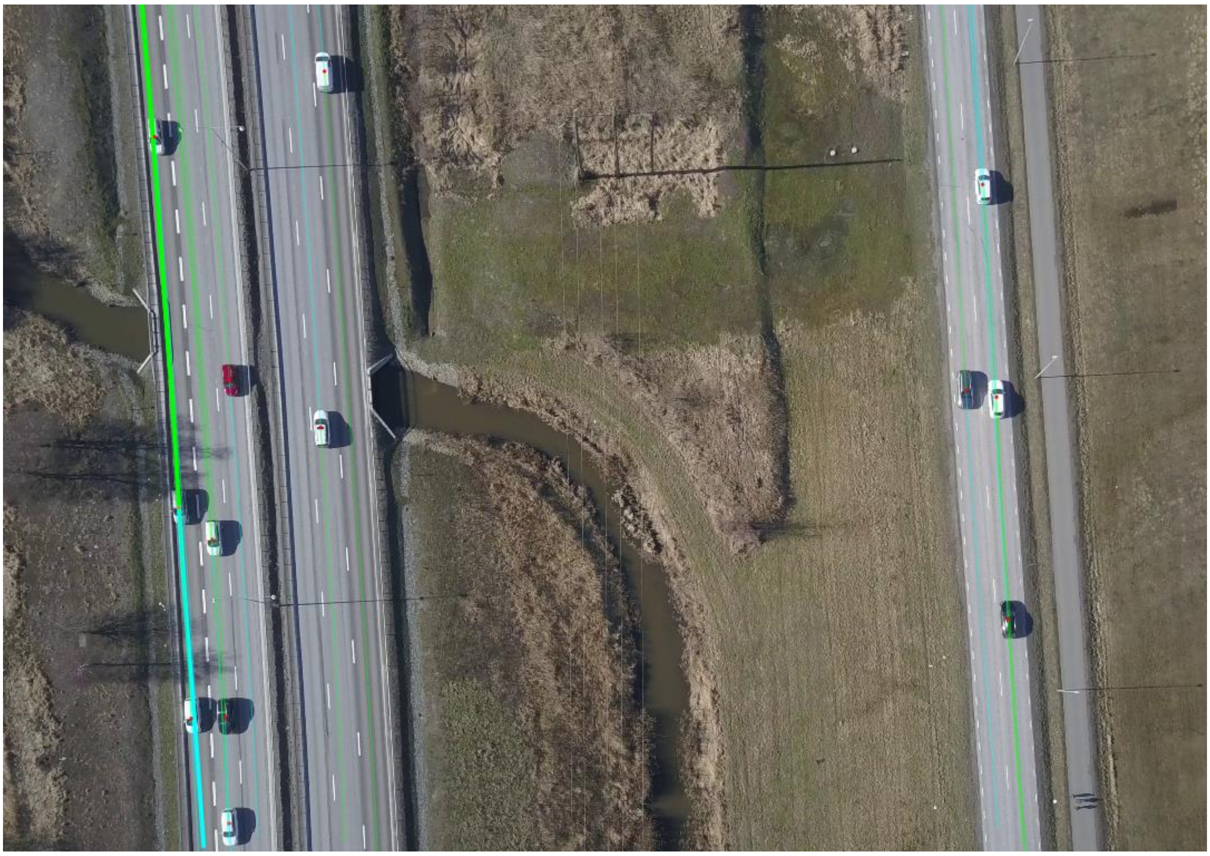

Figure B8. Car in Söderleden 2 travelling on the edge of the outer lane S6

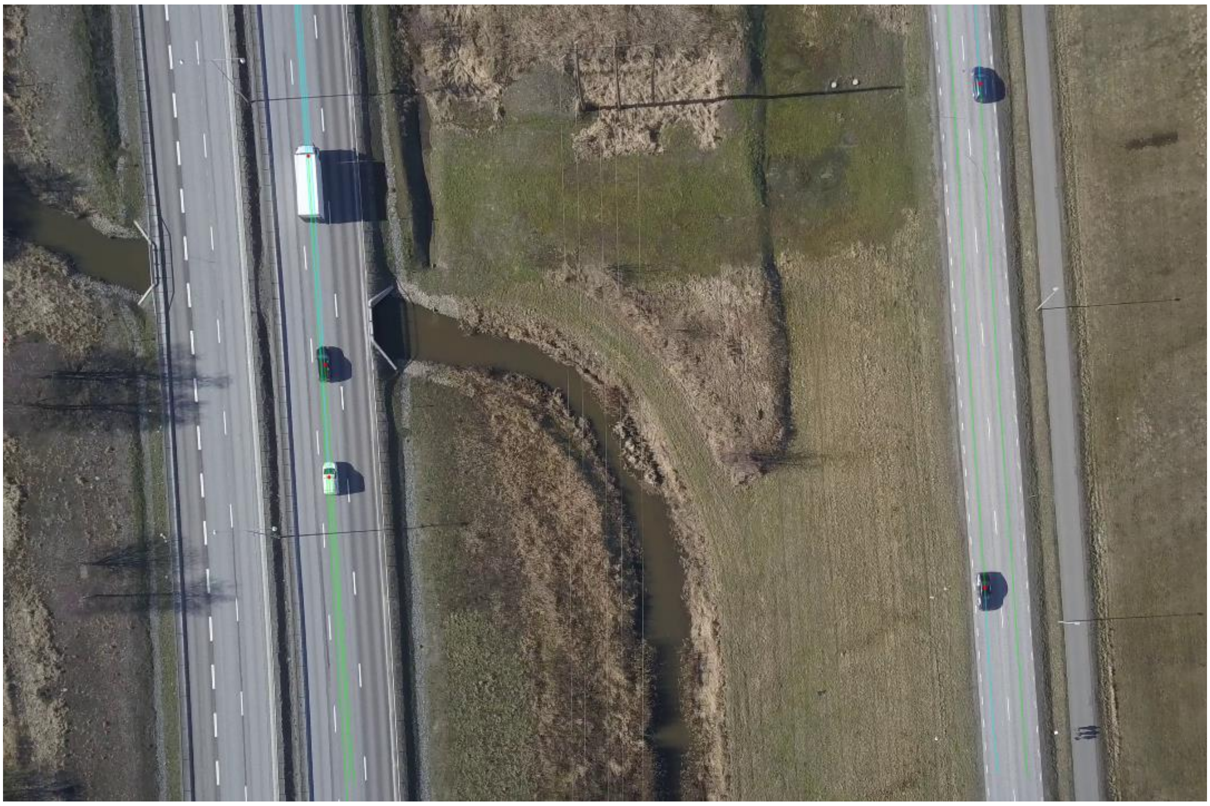

Figure B9. Vehicles engaged in car-following behind a heavy vehicle

Appendix C

Time headway distributions

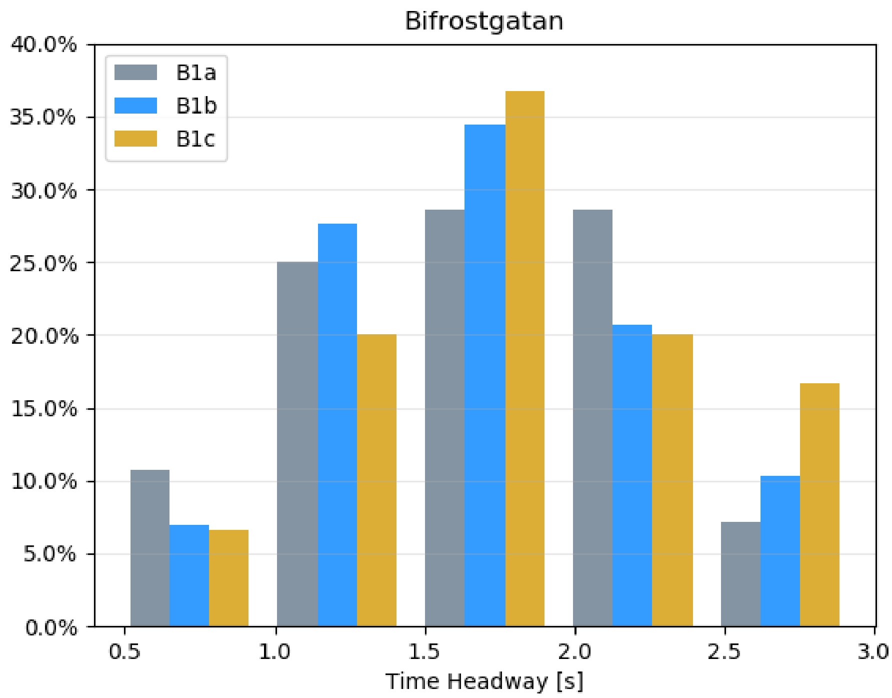

Figure C1. Time headway distribution for gates in lane B1 in Bifrostgatan

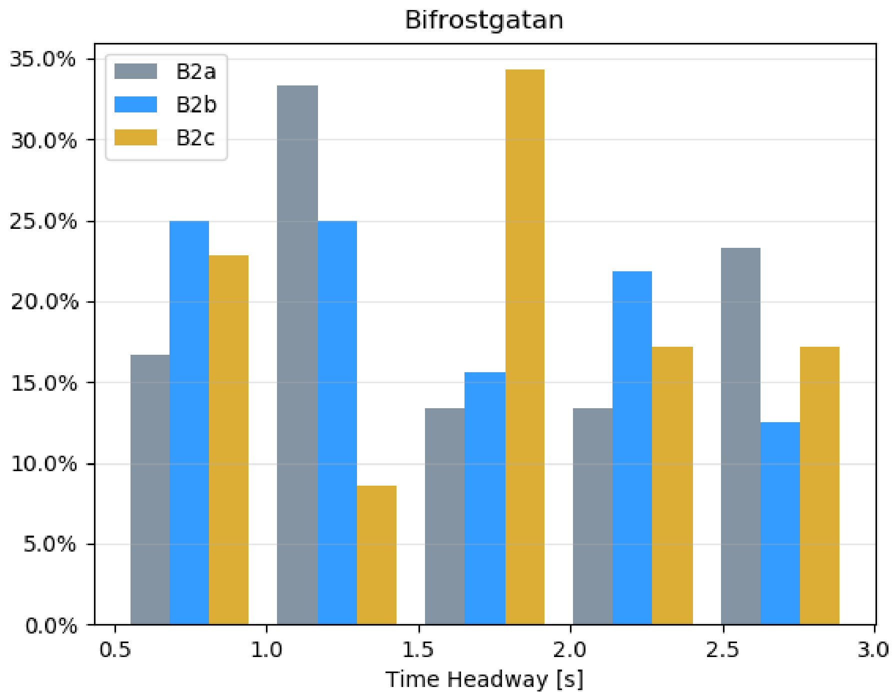

Figure C2. Time headway distribution for gates in lane B2 in Bifrostgatan

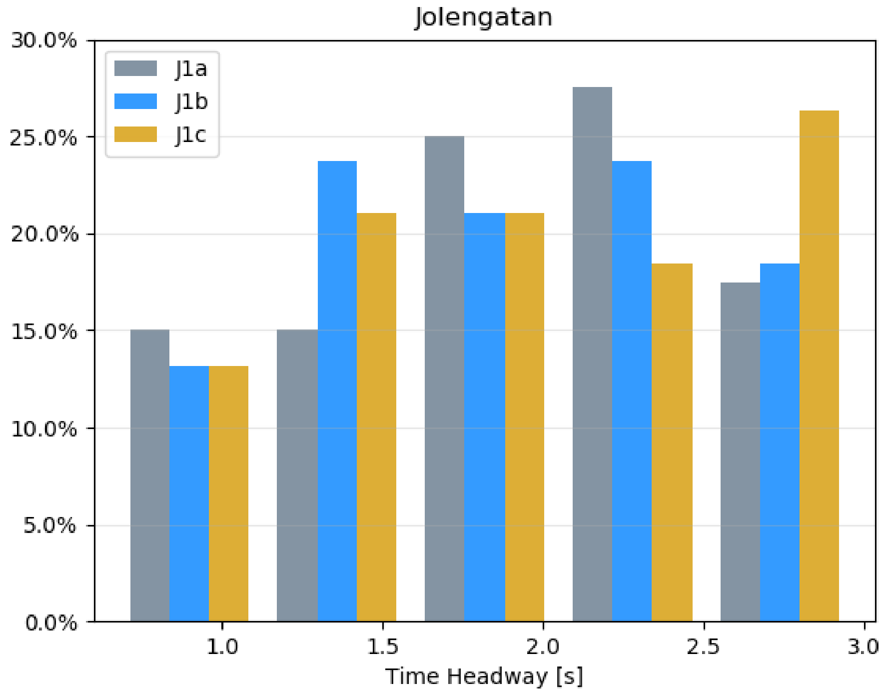

Figure C3. Time headway distribution for gates in lane J1 in Jolengatan

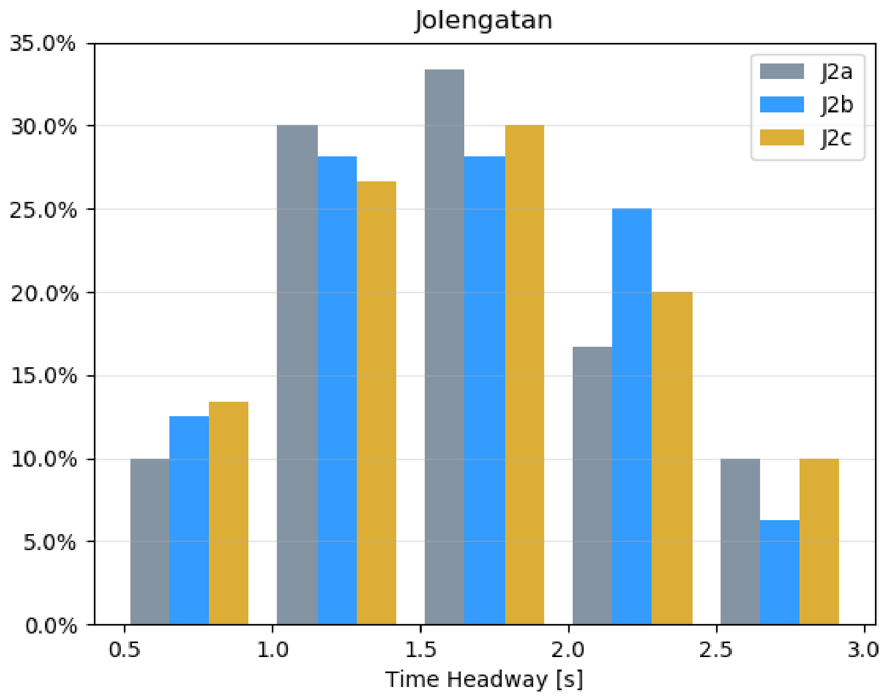

Figure C4. Time headway distribution for gates in lane J1 in Jolengatan

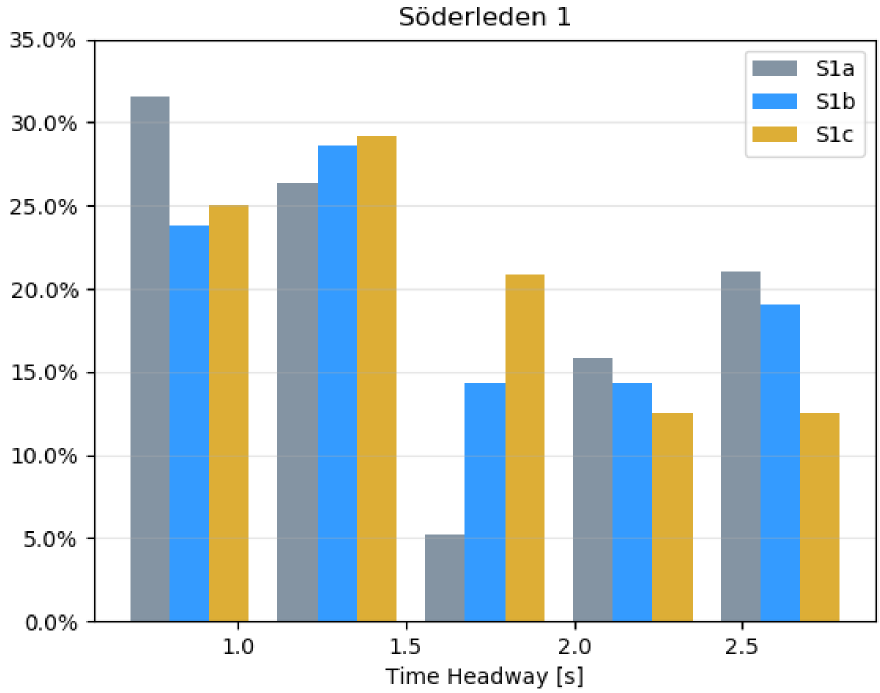

Figure C5. Time headway distribution for gates in lane S1 in Söderleden

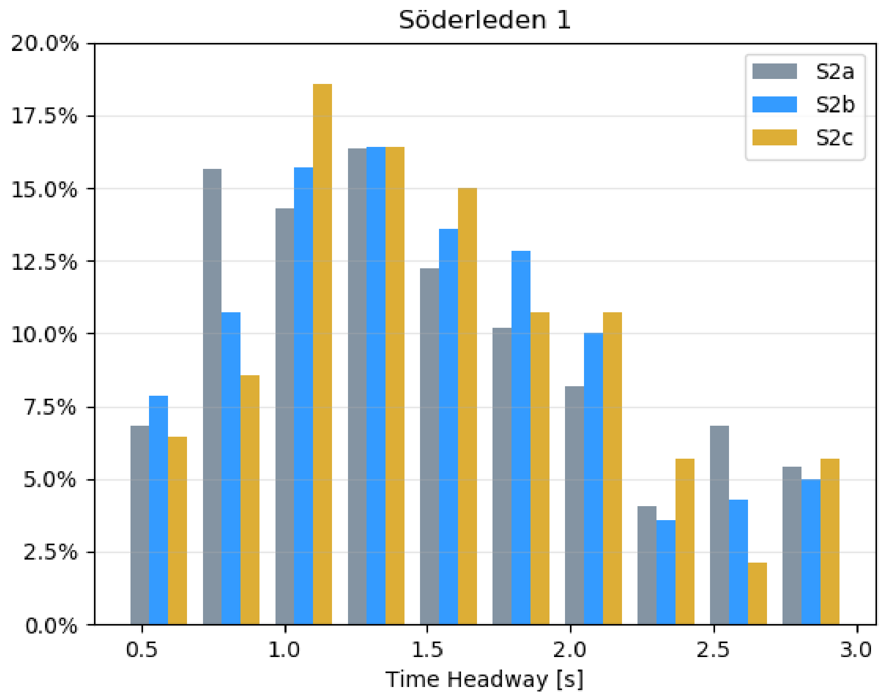

Figure C6. Time headway distribution for gates in lane S2 in Söderleden

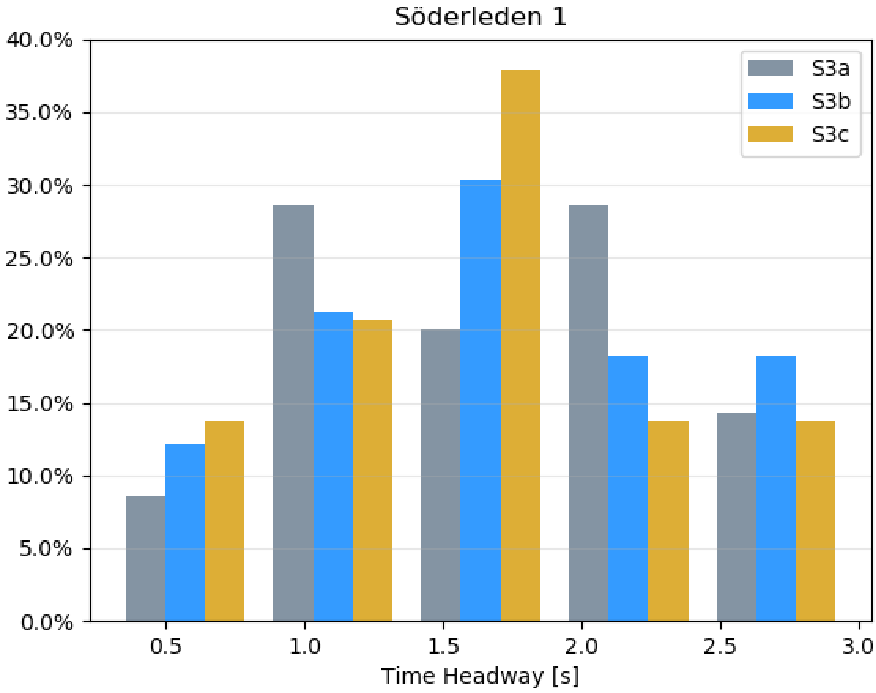

Figure C7. Time headway distribution for gates in lane S3 in Söderleden

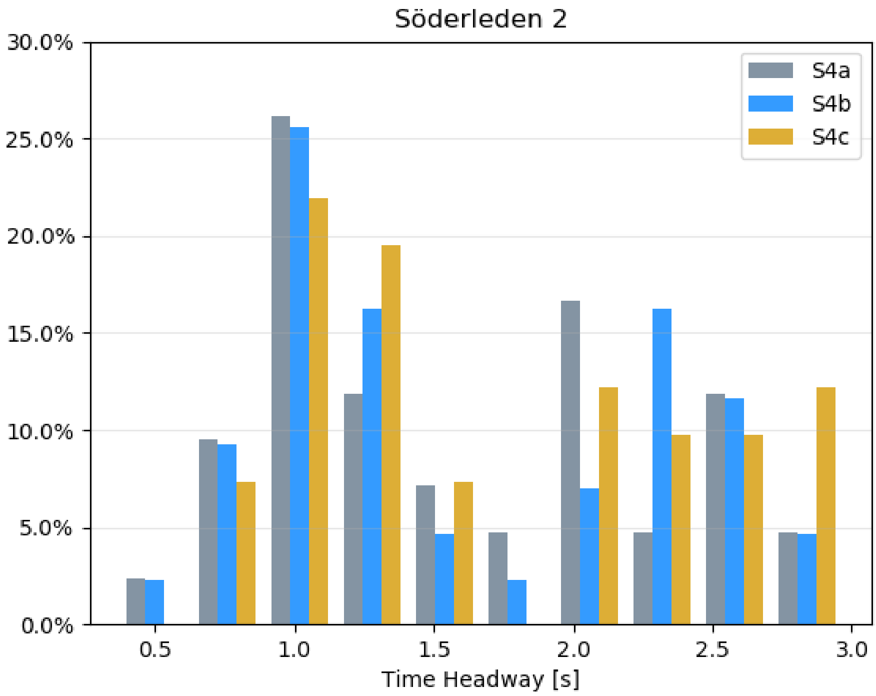

Figure C8. Time headway distribution for gates in lane S4 in Söderleden

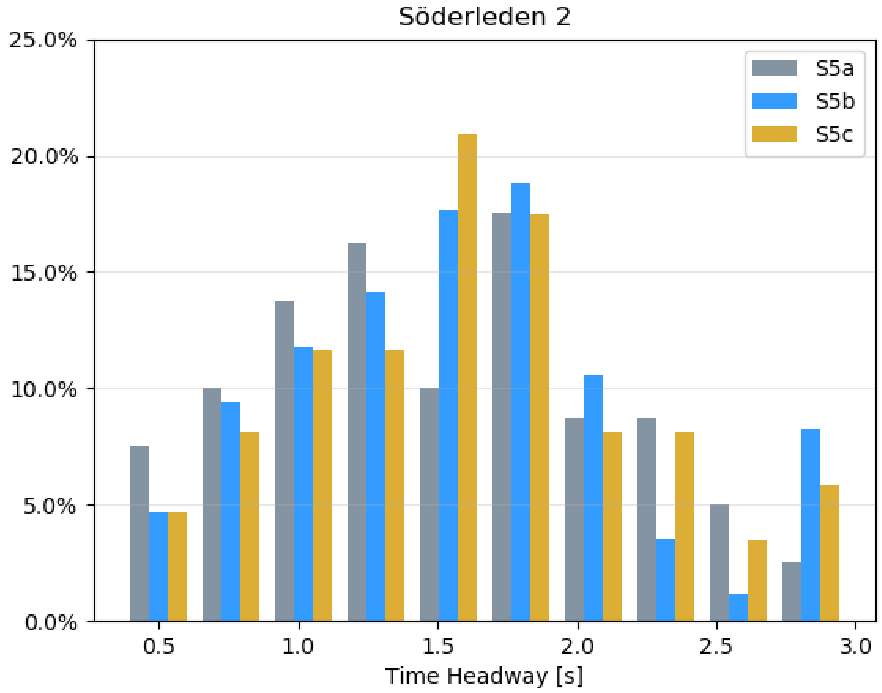

Figure C9. Time headway distribution for gates in lane S5 in Söderleden

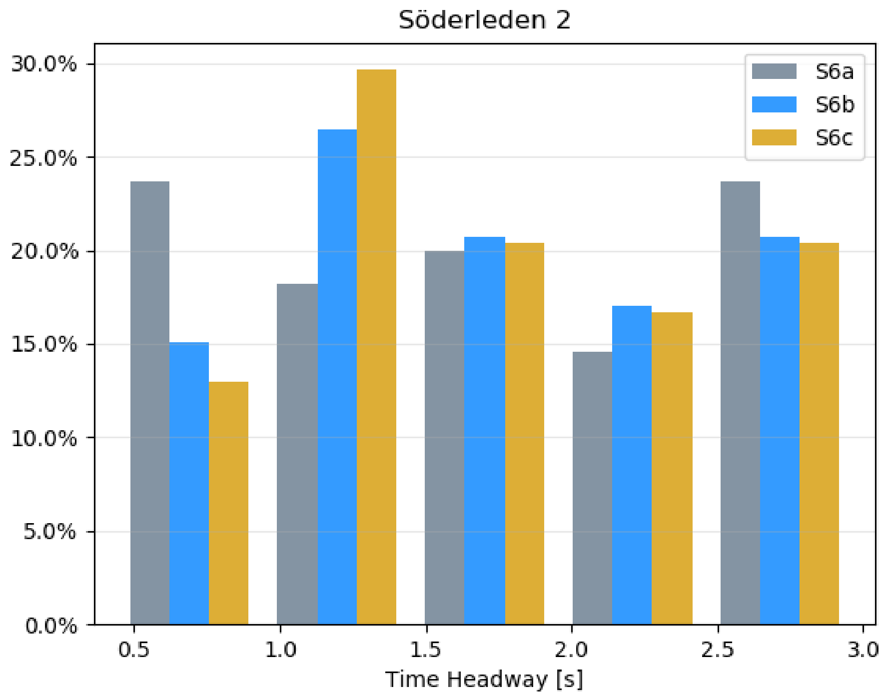

Figure C10. Time headway distribution for gates in lane S6 in Söderleden

Appendix D

Speed distributions

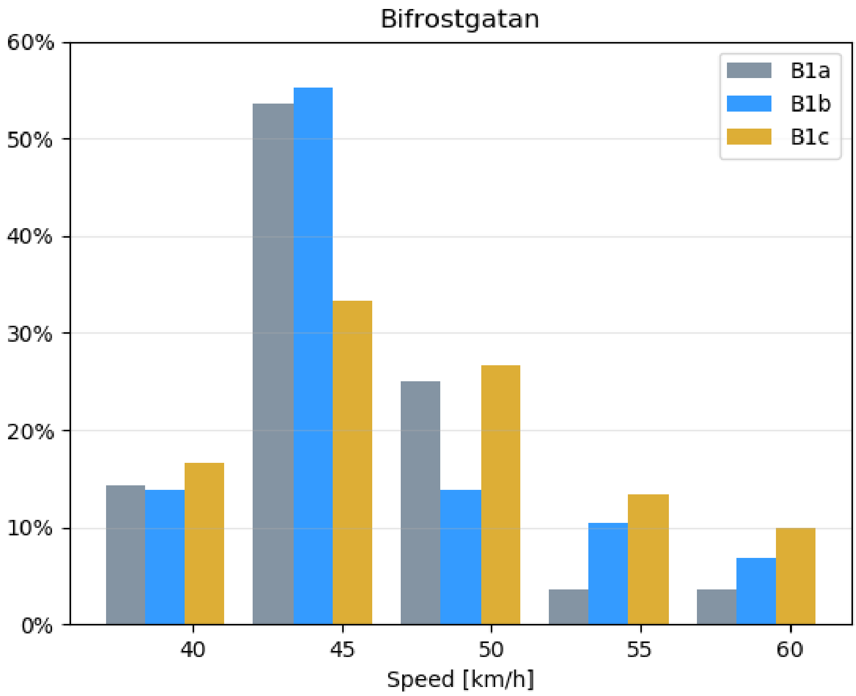

Figure D1. Speed distribution for gates in lane B1 in Bifrostgatan

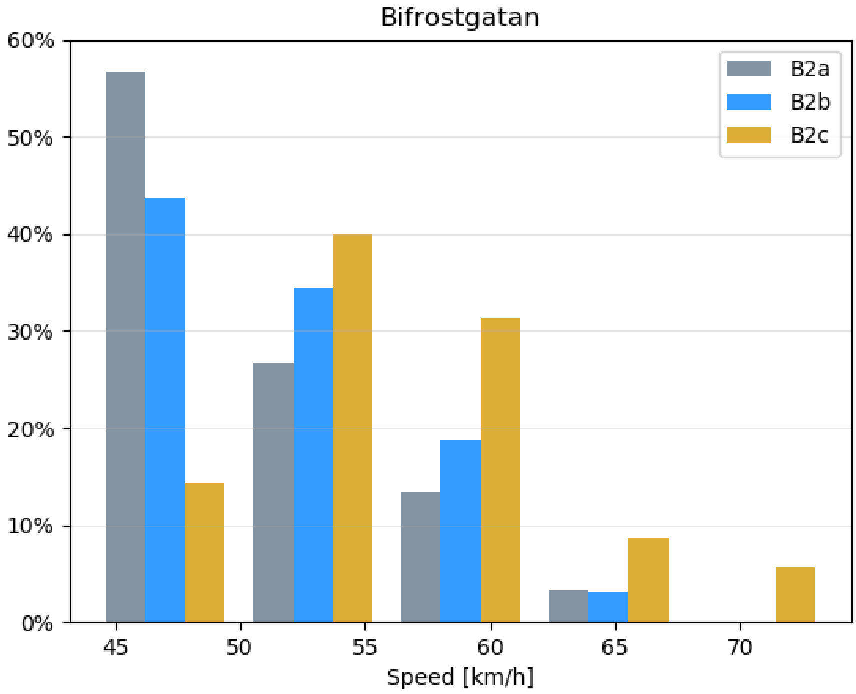

Figure D2. Speed distribution for gates in lane B2 in Bifrostgatan

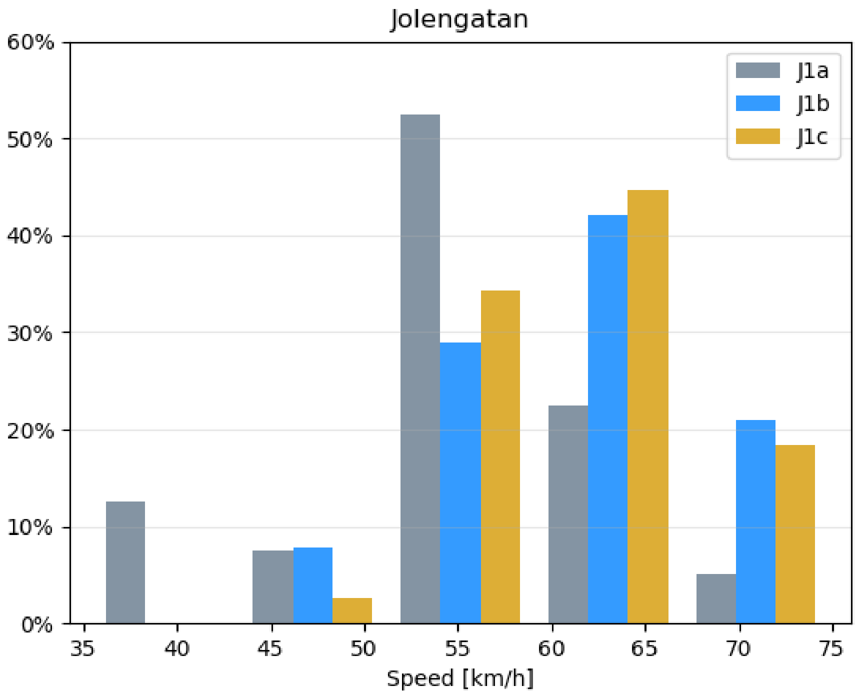

Figure D3. Speed distribution for gates in lane J1 in Jolengatan

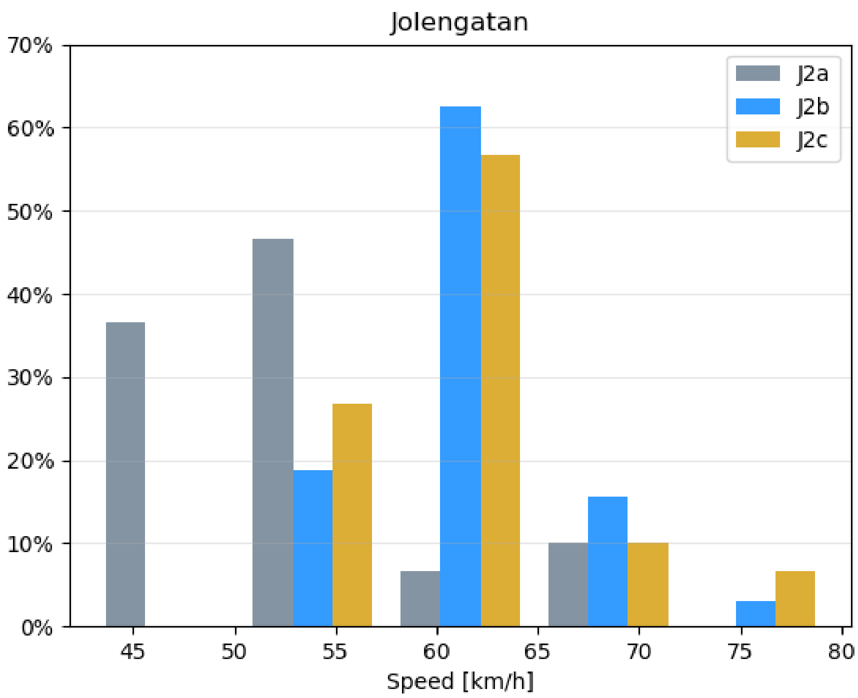

Figure D4. Speed distribution for gates in lane J2 in Jolengatan

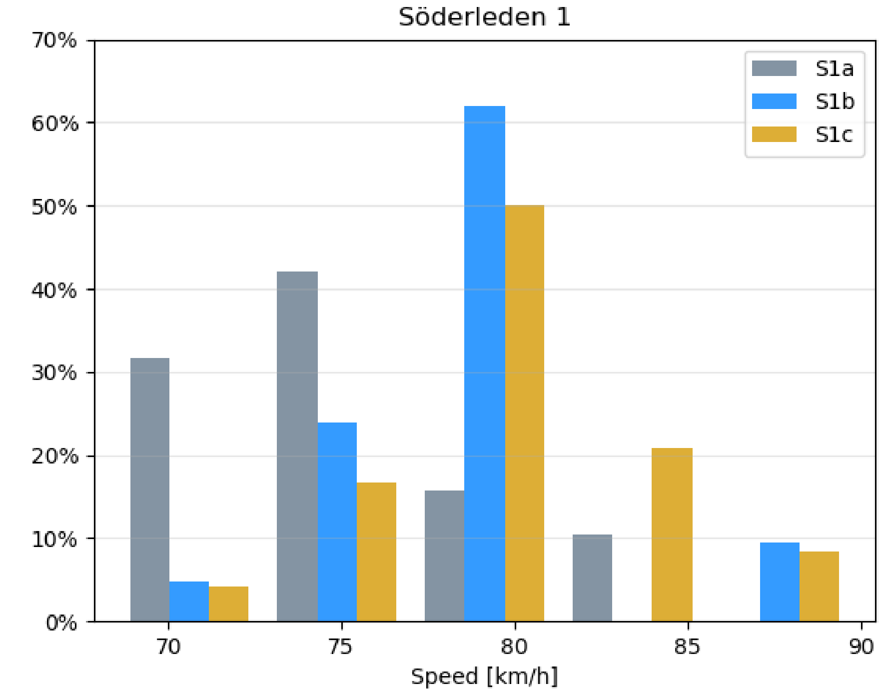

Figure D5. Speed distribution for gates in lane S1 in Söderleden

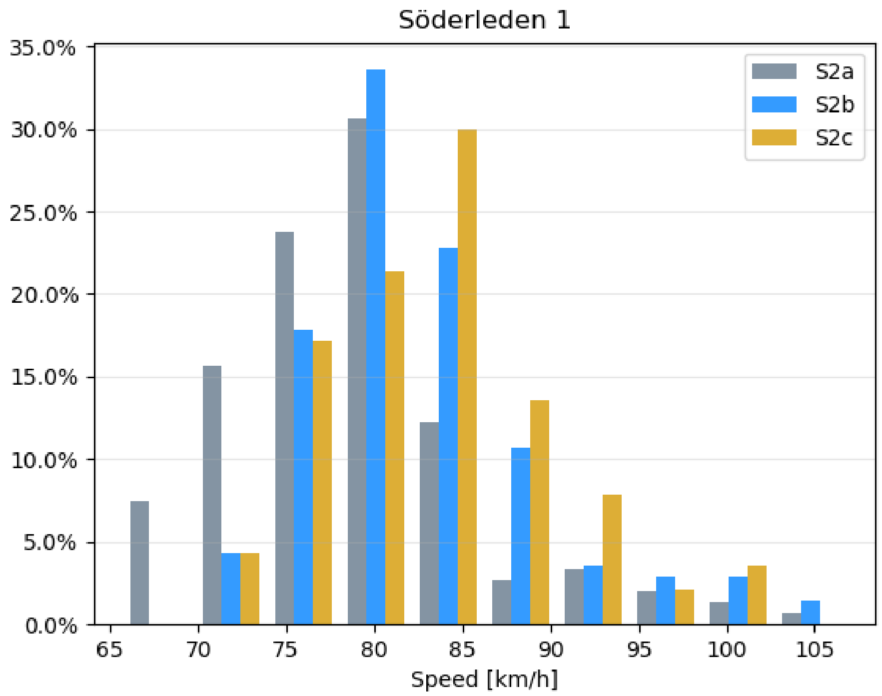

Figure D6. Speed distribution for gates in lane S2 in Söderleden

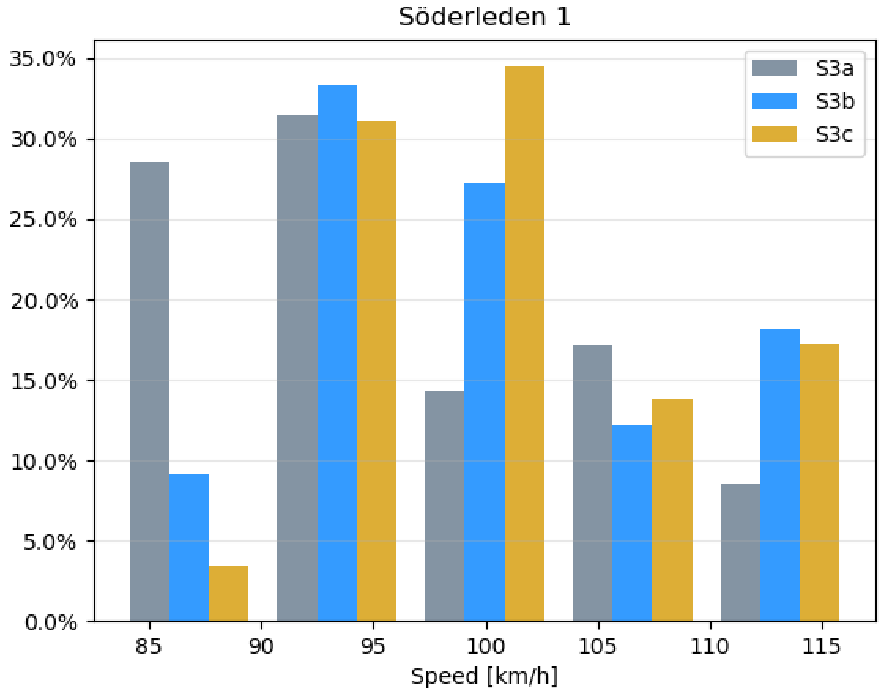

Figure D7. Speed distribution for gates in lane S3 in Söderleden

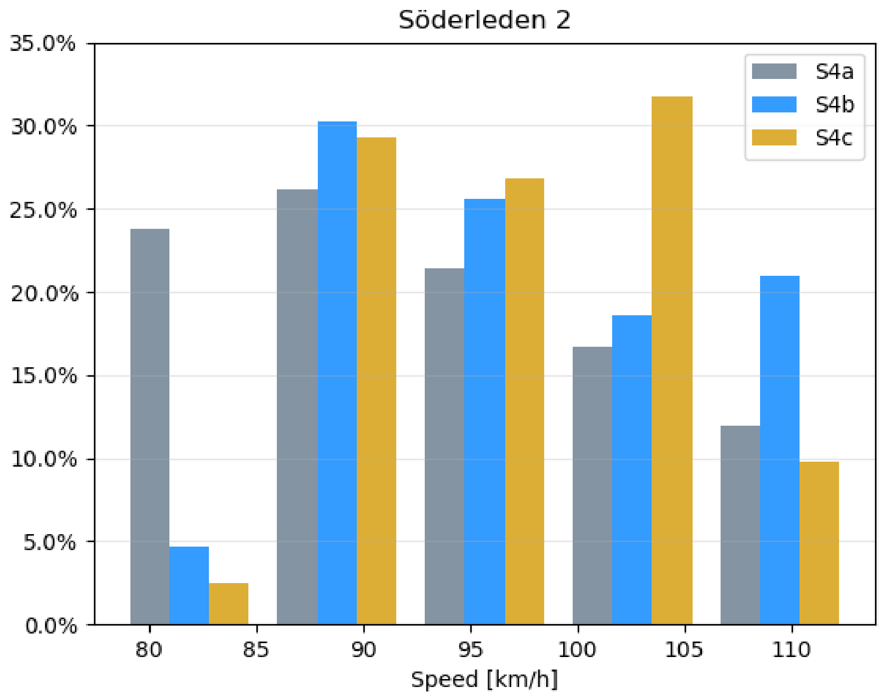

Figure D8. Speed distribution for gates in lane S4 in Söderleden

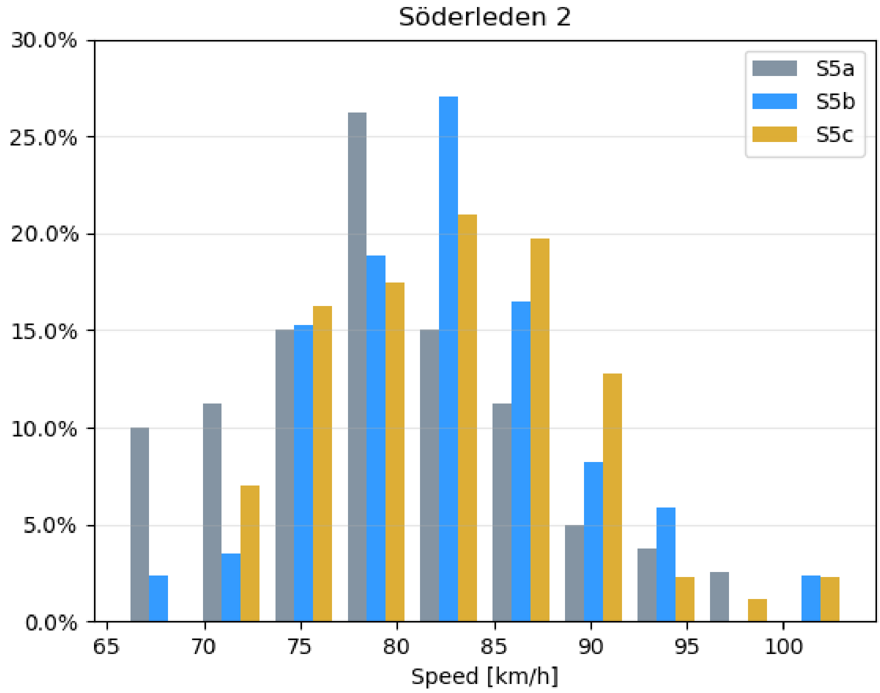

Figure D9. Speed distribution for gates in lane S5 in Söderleden

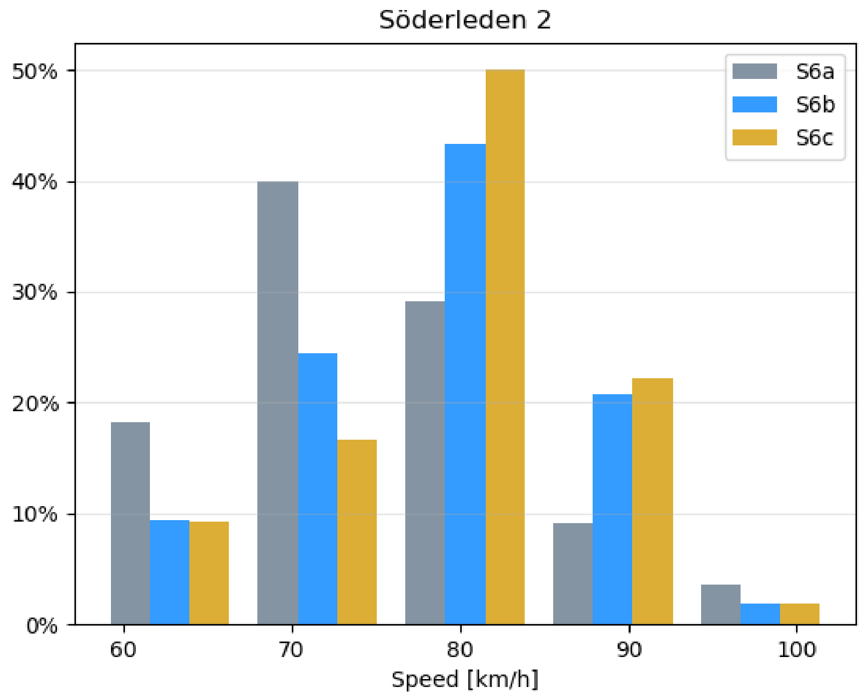

Figure D10. Speed distribution for gates in lane S6 in Söderleden

Appendix E

Relationship between speed and headway

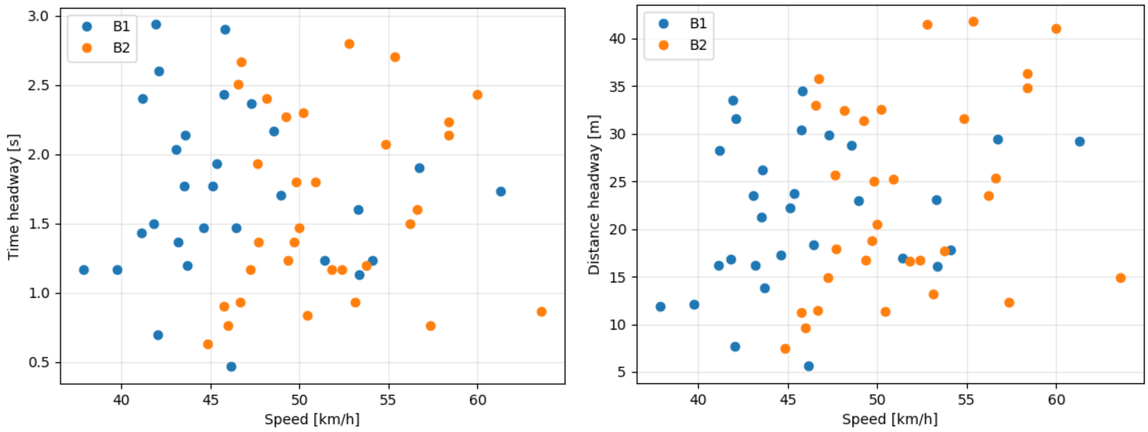

Figure E1. Relationship between speed and THW (left) and DHW (right) in Bifrostgatan

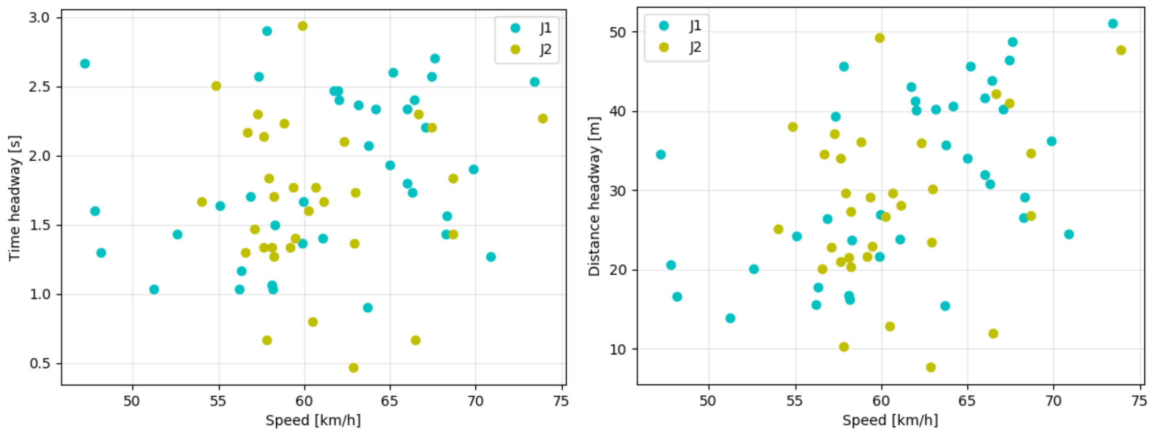

Figure E2. Relationship between speed and THW (left) and DHW (right) in Jolengatan

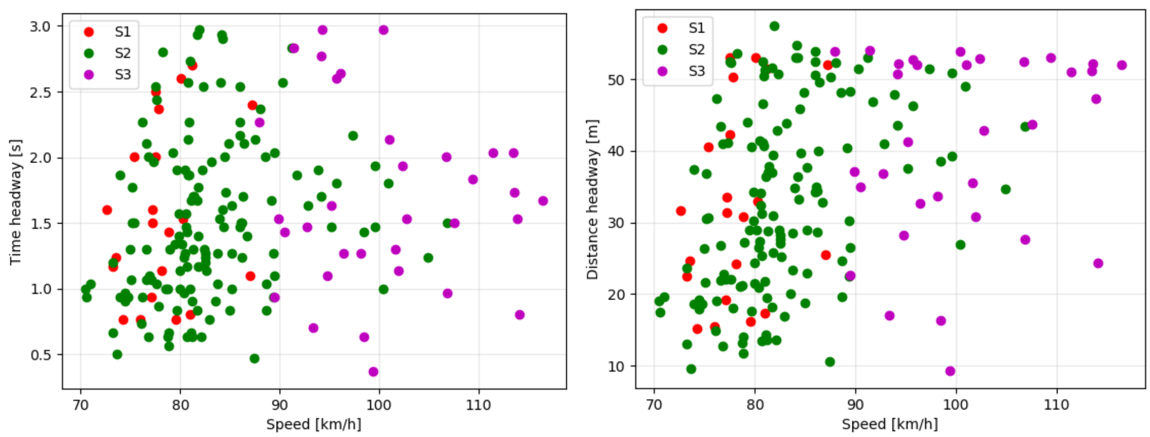

Figure E3. Relationship between speed and THW (left) and DHW (right) in Söderleden 1

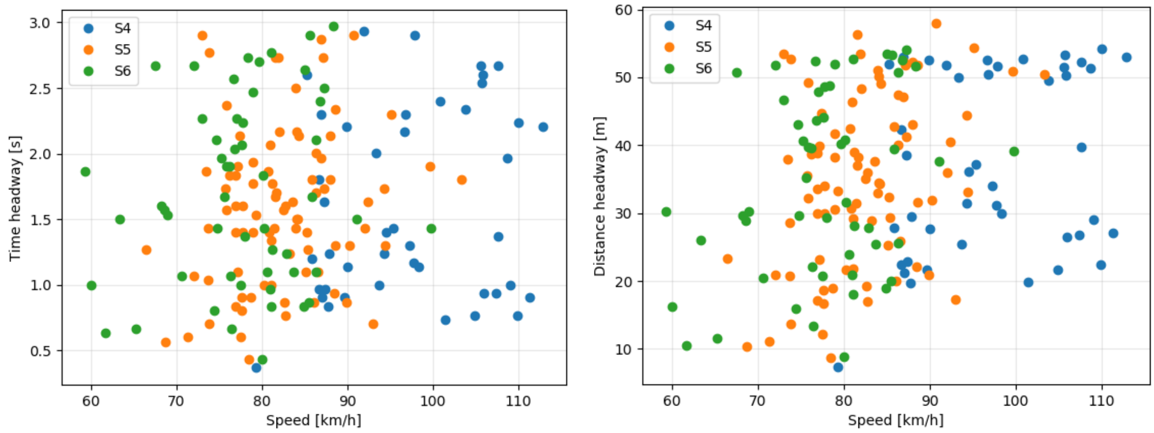

Figure E4. Relationship between speed and THW (left) and DHW (right) in Söderleden 2

Appendix F

Summary of statistical results for acceleration and deceleration

Table F1. Summary of statistical results for vehicles accelerating

Road environment	Gates	Max [m/s²]	Min [m/s²]	Median [m/s²]	Mean [m/s²]	σ [m/s²]	CV
Bifrostgatan	B1a	1.48	0.16	0.78	0.78	0.36	0.46
	B1b	0.84	0.13	0.37	0.37	0.21	0.54
	B1c	1.04	0.04	0.36	0.36	0.28	0.73
	B2a	0.54	0.06	0.29	0.29	0.18	0.61
	B2b	0.34	0.23	0.30	0.30	0.04	0.13
	B2c	5.80	0.17	1.31	1.31	1.73	0.99
Jolengatan	J1a	10.73	0.04	0.59	2.76	3.60	1.30
	J1b	0.51	0.05	0.24	0.25	0.13	0.51
	J1c	1.25	0.13	0.42	0.51	0.34	0.67
	J2a	-	-	-	0.07	-	-
	J2b	0.27	0.05	0.12	0.13	0.09	0.64
	J2c	7.44	0.21	3.37	3.83	2.37	0.62
Söderleden 1	S1a	10.50	0.25	0.82	2.52	3.24	1.29
	S1b	1.14	0.06	0.25	0.39	0.30	0.77
	S1c	1.85	0.12	0.81	0.82	0.44	0.54
	S2a	13.63	<0.01	0.87	3.81	4.20	1.10
	S2b	1.04	<0.01	0.26	0.29	0.20	0.69
	S2c	1.52	0.01	0.62	0.69	0.38	0.55
	S3a	15.71	0.38	1.19	4.94	5.30	1.07
	S3b	0.77	0.10	0.31	0.37	0.18	0.48
	S3c	1.72	0.27	0.78	0.84	0.42	0.50
Söderleden 2	S4a	4.47	0.48	1.91	2.19	1.99	0.91
	S4b	0.76	0.16	0.35	0.40	0.20	0.50
	S4c	12.81	0.16	5.49	5.54	3.81	0.69
	S5a	1.11	0.03	0.28	0.29	0.32	1.10
	S5b	0.71	0.05	0.28	0.30	0.17	0.56
	S5c	9.49	0.10	0.70	1.94	2.53	1.31
	S6a	1.80	0.16	0.24	0.54	0.61	1.11
	S6b	1.45	0.14	0.27	0.38	0.35	0.92
	S6c	10.56	0.01	0.98	2.28	2.99	1.31

Table F2. Summary of statistical results for vehicles braking

Road environment	Gates	Max [m/s^2]	Min [m/s^2]	Median [m/s^2]	Mean [m/s^2]	σ [m/s^2]	CV
Bifrostgatan	B1a	-	-	-	0.19	-	-
	B1b	0.33	0.10	0.10	0.18	0.13	0.75
	B1c	1.88	0.24	0.37	0.57	0.51	0.90
	B2a	3.34	0.03	0.76	0.91	0.76	0.83
	B2b	1.54	0.21	0.48	0.57	0.37	0.64
	B2c	1.04	0.05	0.49	0.49	0.25	0.52
Jolengatan	J1a	0.12	0.05	0.11	0.09	0.04	0.44
	J1b	0.66	0.06	0.24	0.25	0.18	0.72
	J1c	8.82	0.06	3.93	3.96	3.35	0.85
	J2a	15.3	0.38	7.25	7.44	3.92	0.53
	J2b	1.00	0.10	0.30	0.33	0.19	0.57
	J2c	0.88	0.18	0.27	0.34	0.18	0.53
Söderleden 1	S1a	-	-	-	0.08	-	-
	S1b	0.47	0.03	0.19	0.22	0.14	0.62
	S1c	1.83	0.05	0.50	0.61	0.56	0.92
	S2a	0.32	<0.01	0.06	0.08	0.09	1.05
	S2b	0.62	0.05	0.19	0.22	0.13	0.61
	S2c	5.77	0.10	1.00	1.21	1.11	0.92
	S3a	0.10	0.08	0.09	0.09	0.01	0.12
	S3b	0.79	0.08	0.28	0.30	0.21	0.69
	S3c	12.71	0.30	6.04	6.07	4.19	0.69
Söderleden 2	S4a	16.27	0.42	2.62	5.34	5.12	0.96
	S4b	1.03	0.05	0.41	0.43	0.23	0.55
	S4c	1.16	0.37	0.65	0.69	0.25	0.36
	S5a	12.22	0.04	3.91	4.45	3.31	0.74
	S5b	0.94	0.01	0.35	0.38	0.20	0.52
	S5c	1.68	0.08	0.63	0.64	0.38	0.59
	S6a	13.72	0.25	5.20	5.11	4.09	0.80
	S6b	0.96	0.04	0.36	0.42	0.23	0.55
	S6c	1.20	0.12	0.58	0.64	0.28	0.44

Appendix G

Simulation results considering default parameters

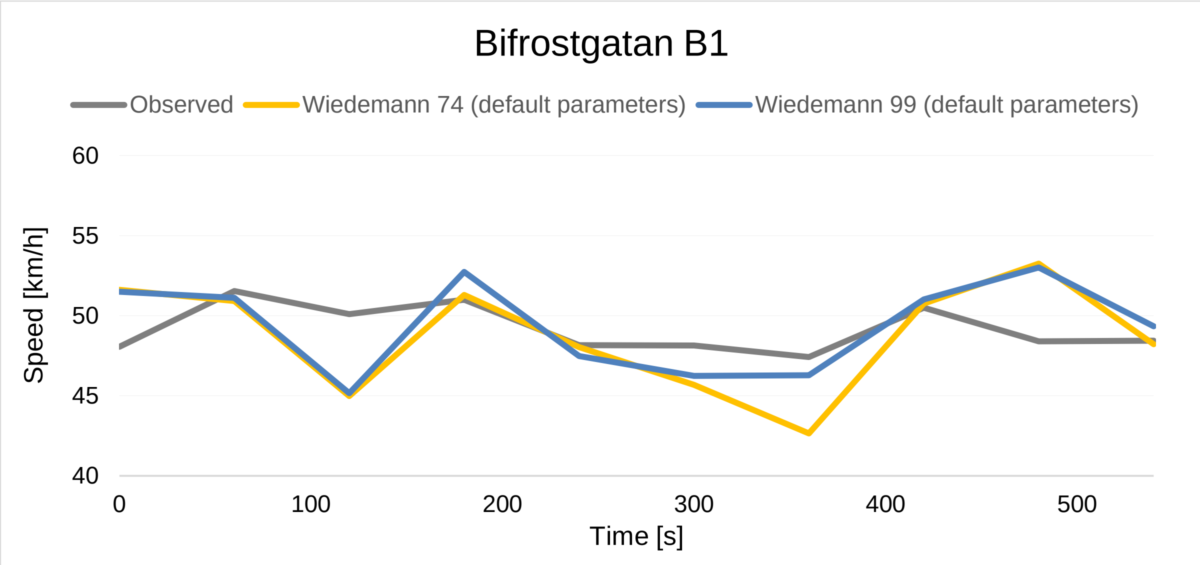

Figure G1. Speed output from the simulation results considering default parameters for car-following behaviour for both Wiedemann 74 and 99 in Bifrostgatan lane B1

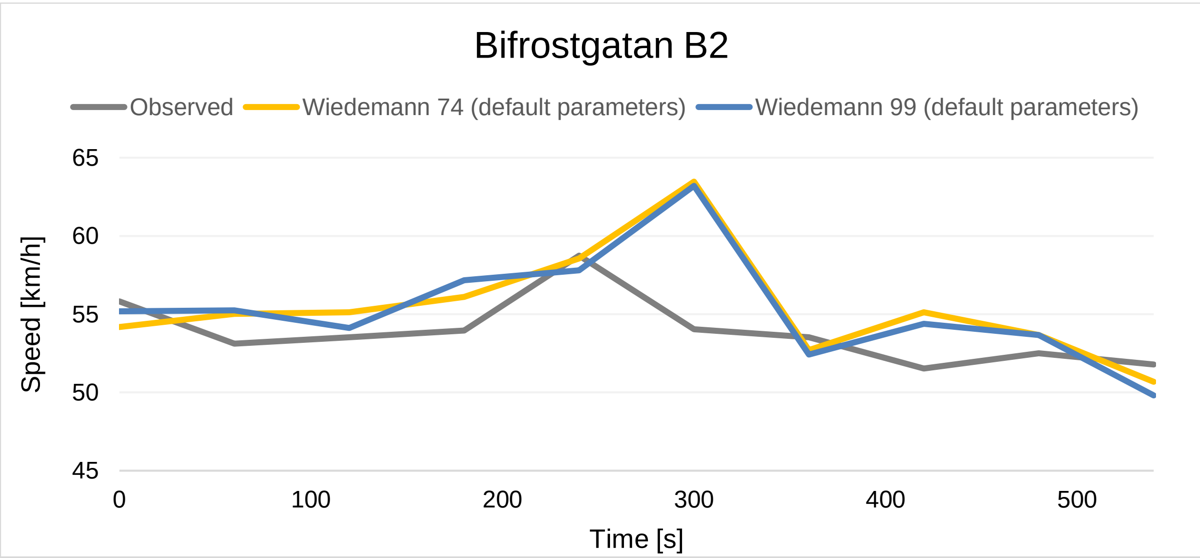

Figure G2. Speed output from the simulation results considering default parameters for car-following behaviour for both Wiedemann 74 and 99 in Bifrostgatan lane B2