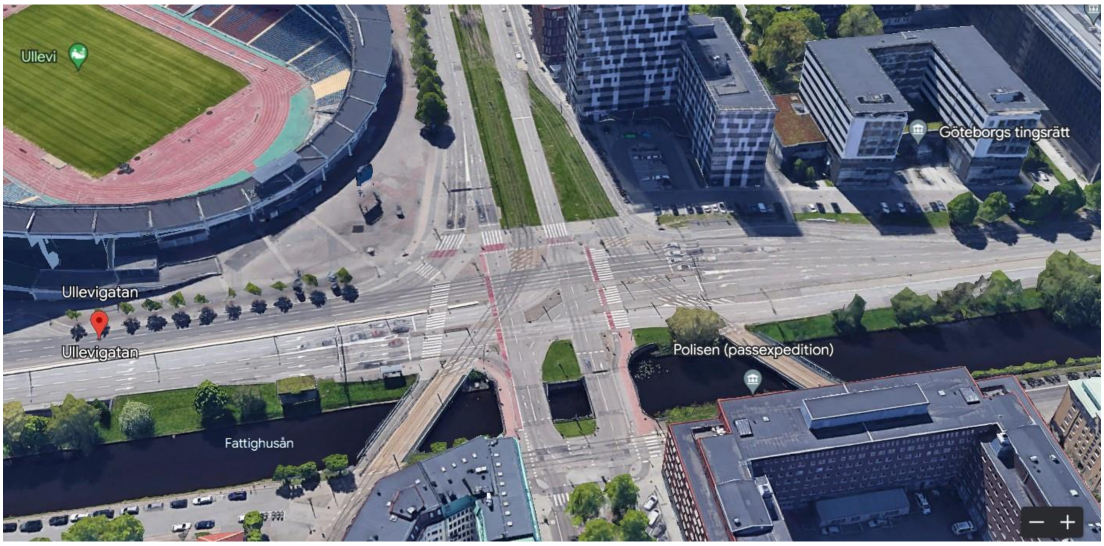

Signalized intersection simulation and traffic signal control for a complex intersection in Gothenburg

Analysis of signal control system in Ullevigatan – Skånegatan intersection using PTV Vissim

Master thesis in Infrastructure and Environmental Engineering

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Supervisor: Jiaming Wu, Chalmers University of Technology and Lei Chen, RISE
Examiner: Jiaming Wu, Chalmers University of Technology, Division of Urban Mobility

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Cover: Aerial view of Ullevigatan – Skånegatan intersection from Google
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Abstract

Signalized intersections play a key role in regulating effective traffic flow and reducing traffic congestion. This master's thesis focuses on the analysis of the signal controller at one of the most complex intersections in Gothenburg, the Ullevigatan-Skånegatan intersection. The intersection model was created using PTV Vissim traffic simulation software. Three scenarios were created and simulated in Vissim. The first one is the model with the current signal control plan at the intersection, which is the actuated signal control using the LHOVRA concept. The second one is the model with an actuated signal controller by vehicle actuated programming (VAP). The third model is the fixed-time signal controller model. These three models were simulated, and the results were analyzed. The analysis was done by evaluating performance measures such as queue delay, queue length, and vehicle travel time. This analysis provides a deep understanding of the performance at the intersection. These simulation results identified the potential area for signal optimization time improvement. This research provides the effects of different signal controller methods, such as actuated signal controllers and fixed-time signal controllers. The analysis explores whether the implementation of an actuated signal controller with VAP has the potential to improve overall efficiency at the intersections as well as reduce delays.

Keywords: Signalized intersection, PTV Vissim, actuated signals, traffic signal controller.

Preface

I would like to express my sincere gratitude to my master's thesis supervisor, Jiaming Wu at Chalmers University, for his great support throughout the thesis period and his expert knowledge. I would also like to express my thanks to Lei Chen, my supervisor from RISE, who gave assistance for my thesis.

The thesis is the result of my deep passion for transportation engineering, and during the work, I have learned valuable information that I can apply in my career.

Finally, I would like to extend my heartfelt appreciation to my family and friends who supported me during the entire thesis period. Their constant encouragement, along with my effort, resulted in this thesis's outcome.

Gothenburg, June 2023
Arya Muraleedharan

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1 Introduction

Traffic congestion is the main challenge faced by urban cities across the globe, which in turn affects transportation efficiency, the environment, and the quality of life for the people. Gothenburg city is continuously growing from a small city to a large city, accommodating more residents, more workers, and more immigrants. The traffic system should be effective to avoid congestion problems in traffic networks. Signalized intersection plays a major role in regulating an effective traffic flow and thereby reducing traffic congestion in traffic networks (Hellberg et al., 2014). The signalized intersection is the most complex location on any highway, as there are always conflicts. The conflicts occur because the vehicles are moving in different directions and all need to occupy the same space at the same time. Along with this, pedestrians also require the same space for crossing the road. An intersection contains two or more roads with traffic flow in each lane, due to which the chances of traffic congestion are higher at intersections (Mathew et al., 2006).

The objective of this study is to develop an extensive understanding of one of the complex intersections in Gothenburg city and the traffic flows through the intersection, and to propose an optimal traffic signal control system in order to avoid delays and improve the overall efficiency and performance of the traffic network in the intersection. To achieve this, the first stage of the thesis involves data collection from the intersection, including traffic volume, signal phasing, signal timing.

In this project, two different signal control methods are studied and compared, along with the current signal phase, to evaluate the current signal controller at the intersection, improve the signal system, and thereby reduce congestion. All these signal plans are accomplished by using the PTV Vissim traffic simulation software. The simulation model recreated the complex traffic network observed at the intersection, which led to the evaluation of the current signal phase along with two signal control systems, which are fixed-time signal control and actuated signal control methods. By running each simulation scenario, which leads to the evaluation of the effectiveness of each signal control method in terms of queue delay, travel time, queue length, and overall performance of the intersection. The results will give a complete idea about the advantages and disadvantages of each signal control method, and thereby identifying the most efficient and suitable signal control method for the intersection.

1.1 Background

Figure 1.1: Ullevigatan – Skånegatan Intersection (Google Earth)

Ullevigatan – Skånegatan Intersection is in the north-eastern part of Gothenburg city, and the intersection is very complex. The aerial view of the intersection is shown in Figure 1.1. This intersection is in centrum area and has a continuous flow of heavy traffic with a large number of private and public transport. The complexity is mainly due to public transport, especially trams. The roads linked to the intersection are named Ullevigatan, Skånegatan, Stampgatan, and Folkungagatan. The heavy traffic at the intersection is due to the regular flow of private cars and public transport.

Before constructing the model, two complex intersections in Gothenburg were visited. The first intersection was between Ullevigatan-Skånegatan and the second one was between Ullevigatan-Nya Allen Road. During the visit, observed the site's characteristics. Then, I drew both intersections on A3 paper and criticized the problems related to each intersection. Finally, due to the time limit to do both intersection modelling, proceeded with the Ullevigatan – Skånegatan Intersection, which is a very complex intersection in Gothenburg city.

The Ullevigatan road is heading towards another complex intersection, which is also a high traffic area. The heavy traffic results in traffic congestion in some lanes. The trams passing through the intersection include Central station – Ullevi Norra, Central station – Ullevi Södra, Ullevi Södra – Central station, Ullevi Södra – Ullevi Norra, Ullevi Norra – Ullevi Södra and Ullevi Norra – Central station. There are two bus stops near the intersection, Ullevi Norra A and B points.

1.3 Aim and objectives

Ullevigatan – Skånegatan Intersection in Gothenburg is challenging due to its complex network, high traffic volume and multiple conflicting movements. The main objective of this thesis are as follows.

- To investigate the traffic signal control system in Ullevigatan – Skånegatan Intersection in Gothenburg
- Analyse the problems faced at the intersection due to signal controller.
- To perform the simulation using PTV Vissim for different signal control methods.
- Recommend effective signal controller to improve the capacity of the intersection.

1.4 Method

The first step was the literature review which was performed through different Journal papers, books and websites related to traffic planning and traffic management. The traffic simulation software PTV Vissim (Academic) 2023 (SP06) was used to analyse the intersection and also to set up the new signal control plans. Microsoft excel was used for major calculations and result analysis. AutoCAD 2019 was also used to create the intersection layout.

The traffic survey and data collection were done by manual inspection at the intersection. The data collected includes the traffic flow, geometric layout of intersection, signal timing and signal phasing during the field visit. This information was used in Vissim to simulate the models.

Three models were created. Firstly, a model for the current signal plan was created and then the second model with new signal control system using Vehicle Actuated Program (VAP) method was developed. Finally, a fixed signal control method was generated by calculating the green signal time through the Signal time design method developed by Highway Capacity Manual (HCM 2010). There are three scenarios made for carrying out the study and as follows below.

Scenario 1: Vissim model with current signal plan in the intersection using VAP method.

Scenario 2: Vissim model with Vehicle Actuated Programming (VAP) signal methods.

Scenario 3: Vissim model with fixed signal time method.

The three scenarios were simulated, and the result obtained from each examined. By analysing, the effectiveness of each signal control method was carried out.

1.5 Limitations

The limitations that were encountered during the thesis study and analysis are mentioned as follows:

- No pedestrian movement considered; only vehicular traffic considered.
- Manual counting has been performed only during the peak hours 08.00 to 09.00 on weekdays. There is no other data available other than the observed data which includes signal time and signal phase.
- The manual vehicle count was used in PTV Vissim for creating the models. Manual counting has limitations and rounds off.
- Model representing the current signal plan at the intersection was created using VAP concept and the current existing signal control method use LHOVRA concepts.
- The green signal time design calculation, the East bound right, and West bound right directions vehicle movement not considered because the flow is less and also the signal time is same as East bound In and West bound in which included in the design.
- The first scenario considered having the model with current signal timing in the intersection modelled in Vissim. But the data was not available, and the signal timing assigned is only by observing manually. Thus, the signal time value is not accurate.
- The notations used in Vissim model, East bound left out (EBLO) and north bound out (NBO) is the same traffic lanes.

2 Literature Review

This chapter includes an overview of signalized intersections, signal control methods, especially vehicle-actuated signal controllers, the Swedish signal control concept LHOVRA and also the research gaps and difficulties in the existing study.

2.1 Signalized intersections

The signalized intersection, or traffic signal controller interaction, is where traffic movements are regulated using the traffic signals. The traffic signals consist of green, yellow, and red signals, which give an indication for the vehicles and pedestrians movements. The signals have a significant time plan to assign green time to provide the right of way for the traffic. These intersections play an important role in managing vehicle movement without any conflict, ensuring safe crossing of roads for pedestrians, and enhancing the overall efficiency of the transportation network (Pande et al., 2016). The road users in the traffic network include passenger cars, heavy goods vehicle (HGVs), large goods vehicles (LGVs), bicycles, pedestrians, public transportation including, buses and trams, emergency vehicles, transit vehicles and motorcycles(Eom et al., 2020).

Traffic signals are traffic control devices, that are operated electrically and used to control conflicts between opposing vehicle movements as well as pedestrian movements (Slinn et al., 2005). Signals can communicate what to do in the intersections and what not to do by the traffic users in the intersection. The traffic signal is to assign the right of way for the conflicting movements of traffic and provide time for vehicles in each lane to pass through the intersection without any congestion. Traffic signals can increase the safety and efficiency of both vehicles and pedestrians, thereby reducing accidents. Despite this, signals are not considered a complete solution for traffic congestion, and the main objective of traffic engineers is to design the intersection with the most efficient and safe traffic flow with a proper traffic control system (Azdot ,(n.d)).

A properly designed traffic signal has many advantages, such as the ability to provide efficient movement of vehicles as well as people, reduce accidents and their frequency, provide efficient accessibility for pedestrians. According to Fhwa, "the traffic signal timing plan is the key that assigns the required time based on the travel demand at the intersection and keeps the cycle length to a minimum green time". The signal controller works as the time setting device for the specific intersection(Fhwa, 2008).

The three main concepts that describe the traffic signal are the cycle, cycle length, and phase. The cycle is the complete sequence of all the phases. Cycle length is the duration of one complete cycle. The phase is the time interval during which a specific group of vehicle traffic movements are permitted or restricted at the signalized intersection. The signal control cycle has different phases, with each phase representing a combination of permitted movements for multiple lanes receiving the right of way simultaneously (HCM, 2000).

2.2 Signal controller

The signal controller is a device designed to alternate service between conflicting traffic. These devices need the assignment of green signal time from one movement to another. With the help of external information about user demands, such as requests for service, the signal controllers can adjust their operations. Traffic signals operate in three ways: which are pre-timed, actuated mode, and a combination of both. Depending on the number of traffic movements detected, the actuated control is characterized as a fully actuated or semi-actuated signal controller (Fhwa, 2008). Figure 2.1 shows the different types of signal controllers used in traffic intersections.

Figure 2.1: Different types of signal controllers (Fhwa, 2008)

2.2.1 Fully actuated signal control

Fully actuated signal control systems are fully adaptive to local traffic as they analyze the information from the detectors located at all the approaches. This system offers the most flexibility at intersections. Semi-actuated traffic signal controllers analyze the detection only in some lanes. This is because they receive partial demand information and only adapt operations based on this partial demand information. The best use of the fully actuated control is at isolated intersections, as there are varying traffic demands and patterns during the day (Urbanik et al., 2015).

The fully actuated control system has many advantages. Firstly, as the system is highly responsive to changes in traffic demand and patterns, it reduces delays relative to pre-timed control. In addition to that, the cycle time can be efficiently allocated on a cycle-by-cycle basis based on the detection information. Also, they are adaptable to short-term fluctuations in traffic flow and are effective at multiple phase intersections. Finally, when there is no call for the service, it allows the phases to be skipped. This allows the controllers to reallocate the unused time to a subsequent phase.

The cost for both the initial set-up and the maintenance is the major disadvantage of fully actuated control. The high cost is due to the amount of detection required. Also, there are chances for a higher percentage of vehicles to stop since the green time is not held for upstream traffic. Another disadvantage is that, if the traffic patterns are regular, the extra benefit obtained from the addition of local actuation is minimal or can be zero (Fhwa, 2008).

2.2.2 Pretimed control

Pre-time controllers, or fixed signal time controllers, are those controllers that do not use any detection to adapt their operations. In some special cases, modern pre-timed traffic signals are being used. This system is less costly to build as it doesn't incur any expense associated with detection. The pre-timed control consists of a fixed series of intervals that are fixed in signal duration (Fhwa, 2008).

Based on historic data at the intersection, the signal timing values were calculated, and these values are programmed into the pre-timed controllers. The pre-timed signal control has many advantages. For example, since both the start and end of green are predictable, it can be used for efficient coordination with adjacent pre-timed signals. Also, as this system does not require detectors, its operations are immune to problems that arise due to the failure of detectors. But on the other hand, fixed signal time control becomes inefficient at isolated intersections where traffic arrivals are very low. Pre-timed control is ideally suited to closely spaced intersections, mostly found in downtown areas. Also, this system is a great option for those intersections where a maximum of three phases are required (Urbanik et al., 2015).

The actuated signal controller has detectors on all the approach lanes. When a detector detects the vehicle, the information is transferred to the controller, and the controller will give the service needed for the road users. The current signal stage will reach its minimum green time if they do not have more vehicles, and then it will change to the next stage to give the right of way for the vehicles.

Detectors are placed on the lanes to communicate with the controller, and they should be properly numbered. The detector numbering depends on the phase numbering, or the type of signal controller used.

The maximum green time should be set for the actuated signals to determine the green signal splits for the intersection. If the maximum green time is set too high, then the high demand lanes would start to affect the operations on the other approach lanes. The minimum green time is the amount of green time required for the vehicle to clear the signalized intersections, it should be enough for the vehicle to pass the intersection, otherwise it will affect the efficiency of the intersection (Sinowatcher, (n.d.)).

2.2.3 Semi-Actuated Control

There are many advantages to the semi-actuated control system. The primary advantage is that they can be used effectively in a coordinated signal system. Also, they can reduce the delay caused by major road movements during periods of light traffic. The major road through movements refers to the movements that are associated with the non-actuated phases. A semi-actuated signal controller has detectors in some of the approaching lanes only. On the other hand, the major disadvantage of this system is that the continuous demands associated with one minor movement can result in excessive delay to the major road-through movements if the time parameters are not set appropriately for maximum green and passage time. Another drawback is the need for detectors on the minor approaches, which results in installation as well as maintenance cost. The operation of a semi-actuated system requires more training when compared to the pre-timed control system (Fhwa, 2008).

2.2.4 Detector

The Detector is the device used to inform the signal controller about the demand from the user. Detectors are placed on the roads, and their function is to call the signal controller. The controller utilizes the information from the detector and will display the appropriate signal.
The objective of the detector includes identifying the presence of vehicles on a signal phase and extending the signal phase upon the occurrence of a traffic queue (Fhwa, 2008).

2.2.5 Ring and Barrier Concept

The ring and barrier concept is mainly used to define how the signal controller organizes the phases, so that compatible phases will come together and there is no conflict.

Ring: A ring shows the sequence of conflicting phases, which means the phases in both rings operate simultaneously.

Barrier: This is the point where the phases in both rings must end simultaneously (Urbanik et al., 2015).

2.2.6 LHOVRA technique

In Sweden, most of the traffic signals are actuated by signal control using the LHOVRA strategy. LHOVRA is an actuated signal control method used at the signalized intersections developed by the Vägverket (now Trafikverket). When it was developed, there was one method called the "time gap" method, which is based on the vehicles that are passing through one or more detectors within a certain time gap. This time, gap was observed and used to calculate the green time (Grumert et al., 2021). Now the Swedish LHOVRA technique can be considered a further development of the older signal control functions. LHOVRA is a collection of different functions that can be used for assigning variable red times, variable amber times, and also variable past-end green times (Archer, J.,2005). The detector for LHOVRA functions and their locations are shown in Figure 2.2. The LHOVRA acronym stands for the following functions: "L: truck and bus priority, H : priority for main road, O : incident reduction, V : variable amber time, R : variable red time and A : all red turning" (Al-Mudhaffar, A., 2006).

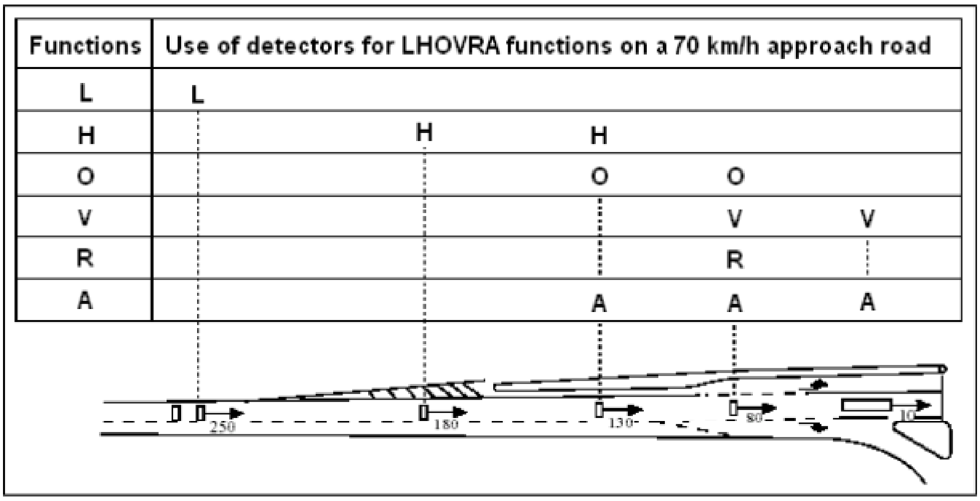

Figure 2.2: Detector for LHOVRA functions and their locations (Al-Mudhaffar, 2006)

2.3 Performance Measures

The parameters used for evaluating the effectiveness of the designed model are generally termed as the performance measures in traffic engineering. This includes different parameters; the most considered parameters are queueing and delay.

Queue length is the length of the vehicles that are waiting in the traffic queue at the signalized intersection. This is being measured to analyze the congestion level at the intersection. Queue delay describes the delay in time taken by vehicles to wait in traffic queue at an intersection. Travel time is the time taken by the vehicle to pass the intersection (Pande & Wolshon, 2016).

2.4 Research gaps and difficulties

There are some research gaps and difficulties in the study of signalized intersection simulation and traffic signal control in Ullevigatan – Skånegatan intersection, which will motivate future research. Some of the research gaps and difficulties are as follows:

The existing study includes only vehicle traffic and hasn't addressed non-motorized modes of transportation such as pedestrians and cyclists. The intersection has more than 10 pedestrian crossings and more cyclists. Investigating the non-motorized modes and their impact on the performance of the signalized intersection could be another research area. The existing study does not consider the environmental and sustainable factors that influence signalized intersection control methods. Strategies that optimize traffic flow with low emissions and energy consumption in a sustainable way could be another relevant research gap.

The lack of consideration of the latest technology which is connected and automated vehicles (CAVs) can be another one. There may be a research gap in evaluating the effect of CAVs on signalized intersection operations and traffic signal control methods. The combination of CAVs in the simulation and signal control at the intersection could be another interesting research area.

In future research, the struggles dealt in the existing studies can be addressed. This issue includes mainly the lack of data availability. The main challenge is obtaining accurate data, which includes signal timings, traffic volumes in each lane, etc. Data availability and reliability could be a difficulty faced by the researchers. Another one is with the intersection geometry and the traffic patterns. The complex intersection has different traffic patterns in different directions, which will make it challenging to create the simulation models and design an effective signal controller. The signalized intersection signal controller involves different goals, such as reducing congestion, minimizing queue delays, and ensuring the safety of people through sustainable transportation. It will be difficult to incorporate all these different objectives into modelling and signal control strategies, and it may have limitations in the existing studies. Future research that fills these knowledge gaps and overcomes these difficulties will increase the overall understanding of signalized intersections and traffic signal control strategies in complex intersections.

3 Methodology

This chapter includes the methods used to achieve the objective of the thesis, which was to create a signalized intersection simulation model and traffic signal control for a complex intersection in Gothenburg. The methodology includes data collection methods, PTV Vissim modelling, and signal time design for fixed signal control.

3.1 Problem formulation

The site is a very complex intersection, and during the field visit, observed problems associated with the signal controller at the intersection. The layout for the intersection is created in AutoCAD and shown in Figure 3.1.

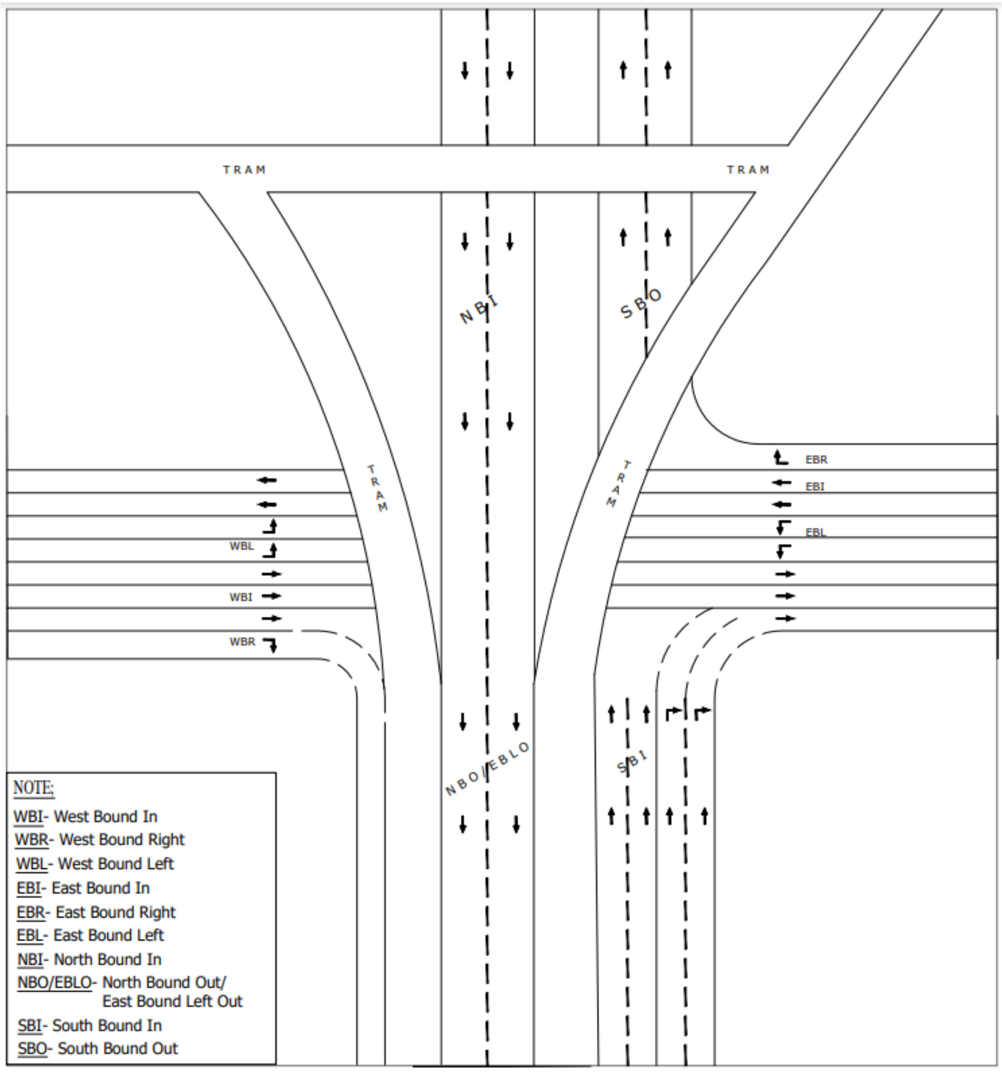

Figure 3.1: Layout of the Ullevigatan – Skånegatan Intersection (AutoCAD)

At the intersection, actuated signal control with the LHOVRA concept is being used. Whenever the tram arrives, the current signal phase, which is active will be completed, giving the right of way to the tram. There is no priority for the vehicles approaching from southbound in (SBI) and west bound left (WBL). The signal in the east bound left out EBLO (or NBO) is linked with the tram signal from Central station to Ullevi Södra, and this is one of the reasons for the congestion. Also, sometimes it is noticed that congestion is generated in the north bound out (NBO) road segment during the right of way to the tram from Central station to Ullevi Södra and Ullevi Södra to Central station. At this point, the signal at EBL is also green, which leads to a vehicle queue and thereby blocks access to the vehicles through WBI, even if WBI has a green signal. This congestion is shown in Figures 3.2 and 3.3. The same issue is occurring at SBO since there is no priority for WBL, which results in a long waiting time. When WBL vehicles get a green signal after a long time, they enter the SBO roadway and at the same time, if a tram comes from Ullevi Norra to Central Station or vice versa, congestion is observed, which will block the access of EBI vehicles and the tram from Ullevi Norra to Ullevi Södra as can be seen in Figures 3.4 and 3.5. Apart from that, the WBI signals have issues at signal timing, which results in long queues and long waiting times, as shown in Figure 3.6.

Figure 3.2: Traffic congestion in the NBO/EBLO direction

Figure 3.3: Traffic congestion in the EBLO/NBO direction due to tram

Figure 3.4: Traffic congestion in SBO direction

Figure 3.5: Traffic congestion in SBO direction

Figure 3.6: Traffic congestion in WBI direction

3.2 Data Collection

Multiple visits at various times were carried out to get enough data to analyze the intersection. The data collected manually is explained as follows:

The number of vehicles passing through the intersection during peak hours was counted manually and entered in the traffic survey chart. The peak hour considered was on a weekday from 8.00 am to 9. 00 am. The counts for public transportation (tram and bus) were obtained from the Västtrafik application corresponding to this same peak time. The estimated traffic count is shown in Table 3.1.

Table 3.1: Traffic count in each direction through manual counting

Time	Vehicle count in each direction								
	WBI	WBL	WBR	EBI	EBL	EBR	NBI	SBI	SBR
8.00	67	12	2	55	39	8	16	9	19
8.05	62	14	0	47	42	6	14	8	25
8.10	60	10	1	63	51	7	15	11	23
8.15	57	14	4	50	40	7	15	7	11
8.20	55	12	0	48	47	6	12	12	16
8.25	62	8	0	51	44	5	13	10	20
8.30	50	10	2	57	39	7	10	11	17
8.35	47	12	5	44	34	4	14	9	11
8.40	40	9	3	36	27	5	11	8	22
8.45	35	10	4	47	34	1	14	4	9
8.50	30	7	0	30	35	4	12	10	7
8.55	27	8	4	34	37	3	9	9	6
9.00	21	5	3	29	30	5	8	7	8
	613	131	28	591	499	68	163	115	194

Tram and bus details obtained from the Västtrafik application are shown in Table 3.2.

Table 3.2: Tram and bus details obtained from Västtrafik application.

Notation	Name	Tram	Bus
C-S	Central Station - Ullevi Södra	10	
C-N	Central Station - Ullevi Norra	13	14
N-S	Ullevi Norra - Ullevi Södra	14	
N-C	Ullevi Norra - Central Station	10	12
S-N	Ullevi Södra - Ullevi Norra	13	
S-C	Ullevi Södra – Central Station	15	

The vehicle count added to the Vissim model is shown in Table 3.3.

Table 3.3: The assigned vehicle counts in the Vissim model for simulation

Lane	WBI	WBL	WBR	EBI	EBL	EBR	NBI	SBI	SBR
Vehicle number	620	150	30	600	500	75	180	120	200

3.3 Modelling PTV vissim

PTV Vissim is a traffic simulation software that recreates the traffic patterns of all road users. This software is used to evaluate the efficiency of the traffic system. (PTV Vissim, (n.d)). Figure 3.7 shows the window for the intersection in Vissim software.

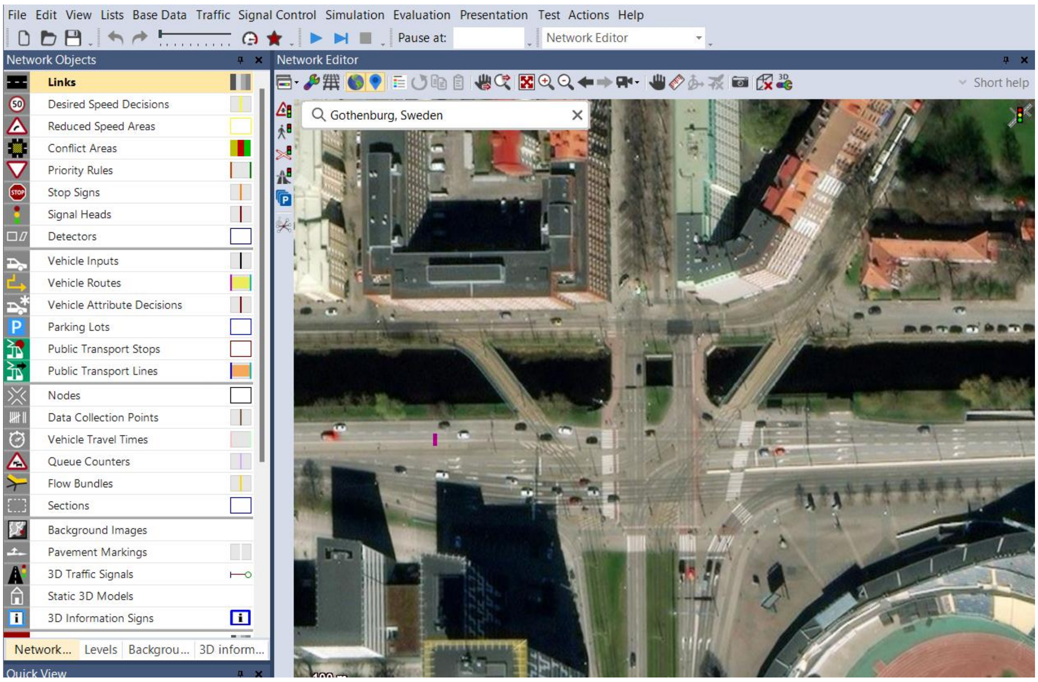

Figure 3.7: Ullevigatan – Skånegatan Intersection in PTV Vissim

The steps involved in creating the Vissim model are explained below.

3.3.1 Link

Firstly, each link was created at the intersection. Each link can have one or more lanes. The link properties in Vissim are shown in Figure 3.8. Table 3.4 displays the lanes at each direction of the intersection.

Table 3.4: The lane numbers in each direction of roads

	WBI	WBL	WBR	EBI	EBL	EBR	NB	SB	SBR
Lanes	3	2	1	2	2	1	2	2	2

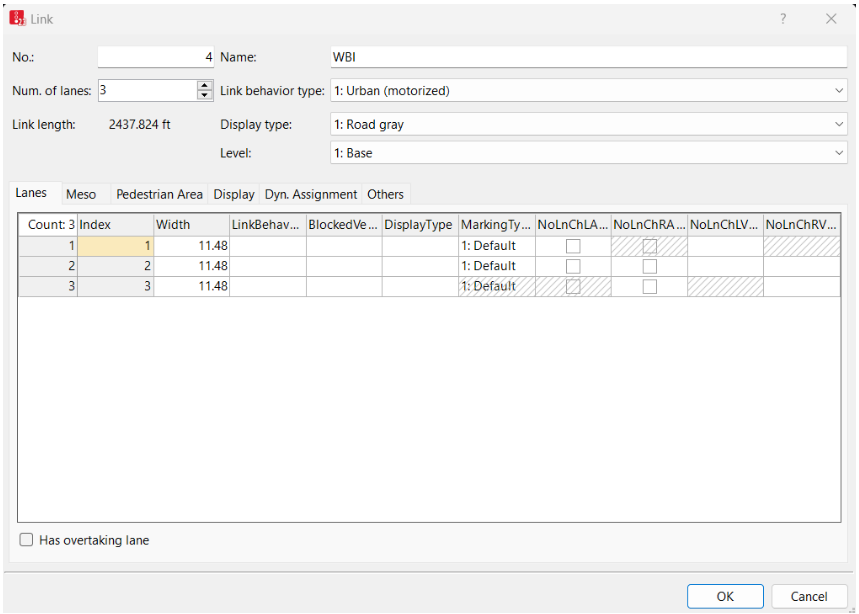

Figure 3.8: Link properties in Vissim

3.3.2 Connector

Connectors are used to connect two different links at the intersection. The connector properties in Vissim are shown in Figure 3.9, which shows the link with three lanes that is on the Ullevigatan westbound In (WBI) road. The link behaviour type is assigned as urban(motorized) and the display type is road gray based on the Ullevigatan- Skånegatan intersection. The behaviour and the display type have different options. The other link behaviour type options include Right-side rule(motorized), footpath, and cycle track, according to the site characteristics.

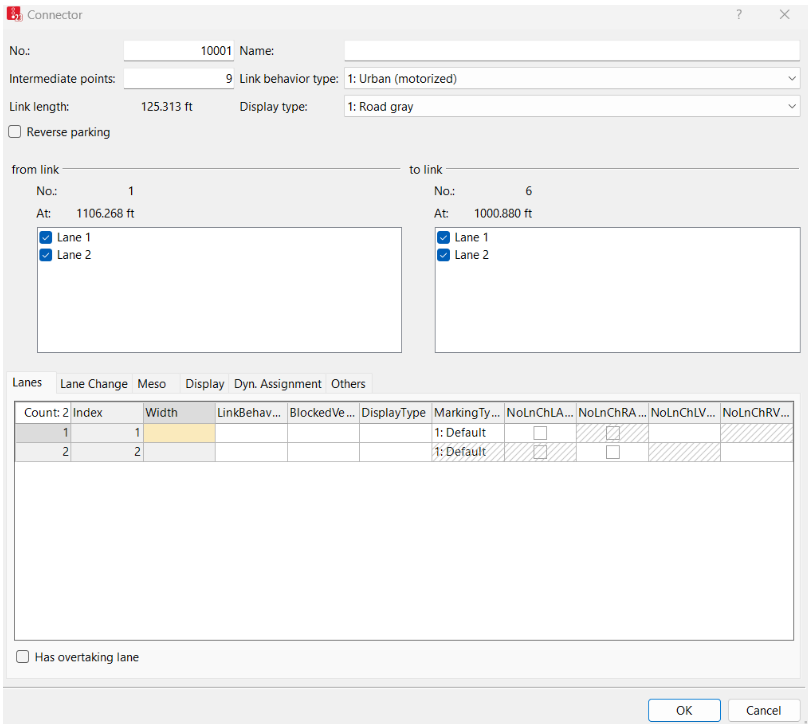

Figure 3.9: Connector properties example in Vissim

The connector tab displays link-to-link connections. Figure 3.9 shows the connection between link 1 and link 6 with both lanes. There is also an option to create curved and smooth connectors using spline.

3.3.3 Vehicle inputs and vehicle composition

The vehicle input function is used to add the vehicle volume per hour. The traffic estimations from Table 3.3 were assigned to the Vissim file. The collected traffic volume is added to the Vissim, as shown in Figure 3.10.

Vehicle Inputs / Vehicle volumes by time interval

Count: 15	No	Name	Link	Volume(0-MAX)	VehComp(0-MAX)
1	1	EBI	7: EBI	600.0	2
2	3	WBI	4: WBI	620.0	3
3	5	NBI	9: NBI	180.0	5
4	8	SBI	6: SBI	120.0	8
5	9	WBL	1: WBL	150.0	9
6	10	WBR	2: WBR	30.0	10
7	12	EBR	3: EBR	75.0	12
8	13	SBR	8: SBR	200.0	13
9	14	EBL	15: EBL	500.0	4
10	15	Centralstn-Ullevi Sodra	17	10.0	19
11	16	Centralstn-Ullevi Norra	17	13.0	20
12	17	Ullevi Norra - Ullevi sodra	10	14.0	16
13	18	Ullevi Norra - Central stn	10	13.0	21
14	19	Ullevi sodra -Ullevi Norra	22	13.0	15
15	20	Ullevi sodra -Central stn	13	15.0	17

Figure 3.10: Vehicle input in Vissim for model creation

Vehicle composition function is to assign different types of vehicles into the model which include Cars, Bus, Tram, Heavy vehicles etc. Then, the desired vehicle type, desired speed distribution and relative flow were added. The static function vehicle route was assigned to each tram line which has more than one direction in a link.

3.3.4 Conflict Areas

The conflict area can be described as the area in which two links or connectors in the Vissim model overlap each other. The conflict can be avoided at the crossing or merge areas, by setting up the conflict areas in Vissim. There are four ways to assign the conflict areas: passive (vehicles do not see each other and “drive over” each other), 2 waits for 1 (Link 2 waits for Link 1), 1 waits for 2 (Link 1 waits for Link 2), and undetermined (vehicles will see each other but remain in the same sequence) (Chepuri et al., 2018).

3.3.5 Detectors

Detectors were placed in the model, and the location of each detector is shown in Figure 3.11.

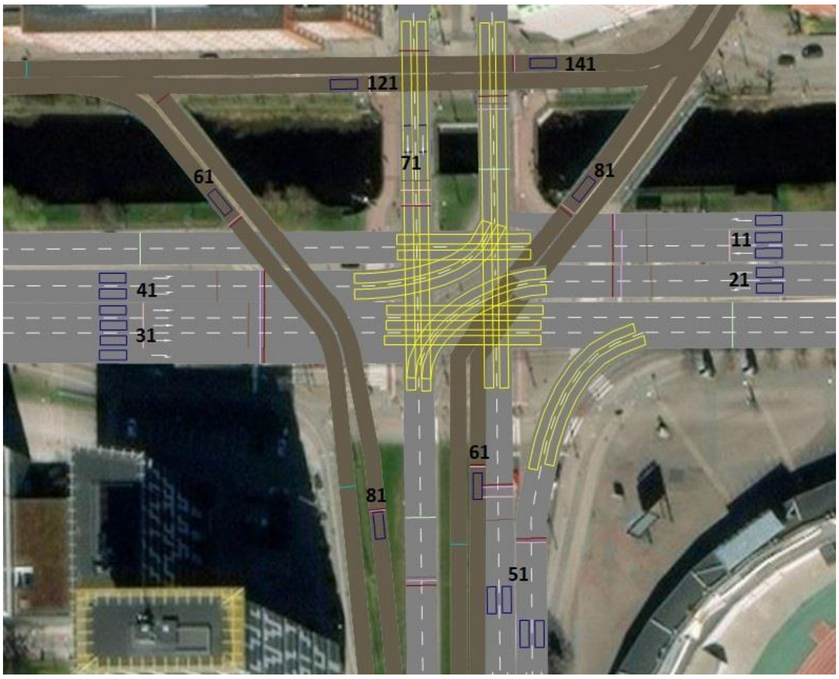

Figure 3.11: Detector locations in the Vissim model

The names of each detector placed in the Vissim model are shown in Table 3.5. The detectors are placed in each direction.

Table 3.5: Detector names placed in each direction.

Directions	EBI	WBI	EBL	WBL	SBI	NBI	Tram
Detector	11	31	21	41	51	71	61 and 81

3.4 Vehicle actuated programming (VAP)

Vehicle actuated programming (VAP) is a feature in PTV Vissim software to execute signal control strategies based on vehicle detection and actuation. They allow Vissim to simulate programmable, actuated signal control. The control logic (*.VAP) was created using the VisVAP tool by using the programming language. VisVAP (Visual VAP) is the tool used for defining the logic behind the VAP signal controller and expressing it through a flow chart (PTV Vissim user manual, 2018). The Interstage (*.pua), which contains the VAP signal data, was also created. The interstage definition file (.PUA) defines the signal groups, intergreen, each signal stage and the interstage. This file is created manually and exported to the VISSIM file.

The logic files (*.pua and *.vap) are then imported to the Vissim model in the signal control menu. The signal controller window in Vissim is as shown in Figure 3.12. The .vap and .pua file created shown in Appendices 1 and 2.

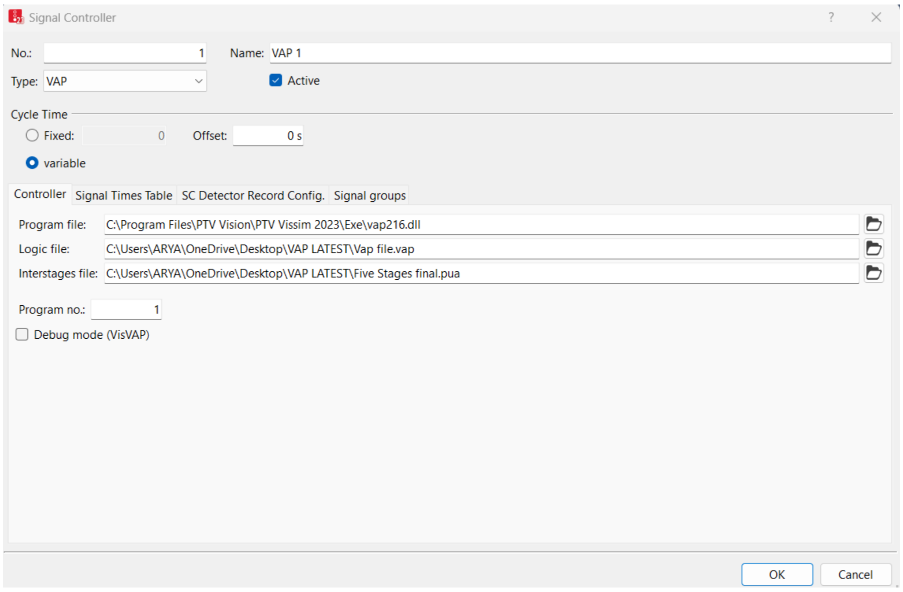

Figure 3.12: Signal controller properties in Vissim

3.4.1 Signal groups

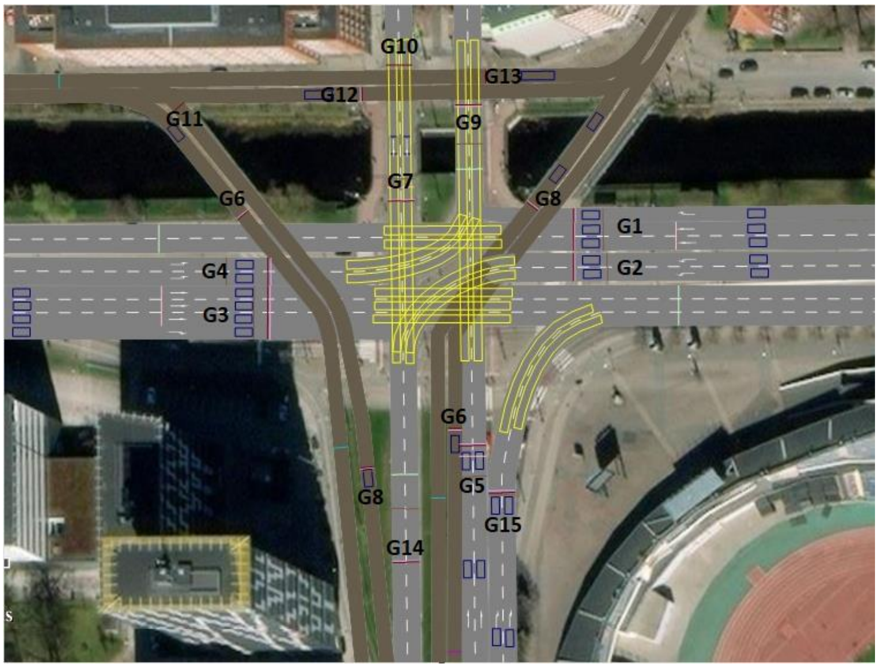

Figure 3.13: Signal head locations and their names

15 groups of signals were added, and each signal head can be seen in Figure 3.13 in the Vissim model. Signal stages for scenarios 1 and 2 are shown in Figure 3.14.

	Scenario 1	Scenario 2
Stage 1	G1 G2 G14	G1 G3 G9 G10 G11 G14
Stage 2	G5 G7 G9 G11 G14 G15	G2 G4 G9 G11 G14 G15
Stage 3	G2 G4 G14 G15	G5 G7 G9 G10 G11 G14 G15
Stage 4	G1 G3 G9 G10 G11 G14 G15	G6 G7 G8 G15
Stage 5	G6 G7 G8 G15	G1 G3 G12 G13 G14
Stage 6	G12 G13 G14	

Figure 3.14: Green signal stages for scenarios 1 and 2

3.4.2 Minimum Green Time

The Minimum green time and minimum amber time assigned for each direction in scenario 1 are seen in Table 3.6, and scenario 2 is shown in Table 3.7.

Table 3.6: Minimum green and amber time assigned for scenario 1

Signal group	Minimum green time	Minimum amber time
1	25	3
2	15	3
3	25	3
4	15	3
5	15	3
6	15	3
7	15	3
8	15	3
9	10	3
10	10	3
11	15	3
12	15	3
13	15	3
14	15	3
15	15	3

Table 3.7: Minimum green and amber time assigned for scenario 2

Signal group	Minimum green time	Minimum amber time
1	20	5
2	20	5
3	20	5
4	20	5
5	15	5
6	15	5
7	15	5
8	15	5
9	15	5
10	15	5
11	15	5
12	15	5
13	15	5
14	15	5
15	15	5

The maximum green time was assigned as 40 seconds for all directions in scenario 1. In scenario 2, the maximum time for signal G2 assigned was 60 seconds and for signal G4, it was 30 seconds, other directions were the same with 40 seconds. The logic files (*.pua and *.vap) that were imported into the Vissim model are shown in Appendices 1 and 2, including the VAP flow chart and interstage file elements.

3.5 Fundamental diagram

The fundamental diagram is the key aspect in traffic flow theory that describes the relationship between speed, traffic flow, and density. The fundamental diagram shows the graphical representation of traffic behaviour in the road network. The three variables included in the diagram are flow(Q), speed(V) and density(K) (Mathew et al., 2016).

Traffic Volume, Q = number/time (veh/hr)

Speed, V = distance/time (km/hr)

Density, K = number/distance (veh/km)

$$\text{Traffic Volume (Q)} = \text{Speed (V)} * \text{Density (K)} \tag{3.1}$$

Equation 3.1 represents the relationship between these three variables (Jiaming, 2022).

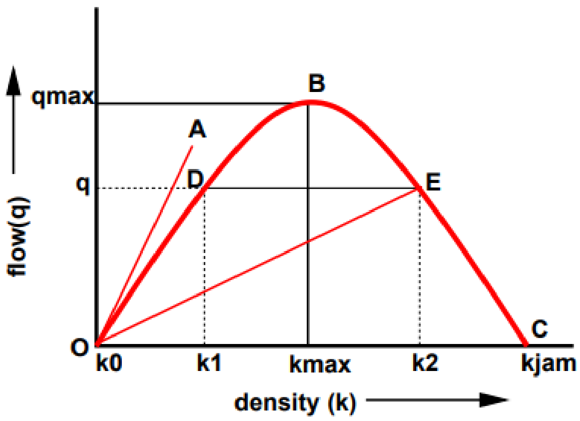

Figure 3.15: Fundamental diagram, flow density relationship (Mathew et al., 2006)

$$k_{op} = \frac{k_j}{2} \tag{3.2}$$

The number of vehicles in the road network increases gradually, and then the traffic flow and density increase. When the traffic flow is high, there is one point where the vehicles cannot move anywhere. This is referred to jam density (k_j) or maximum density. This relationship is described in Figure 3.15 and in Equation 3.2 (Jiaming, 2022). The point O represents that there is no flow and no density. The point B represents the maximum flow and density. The point C represents jam density, or maximum density. At the maximum flow rate, the density is between the jam density and zero density.

3.6 Key parameters for fixed signal timing plan

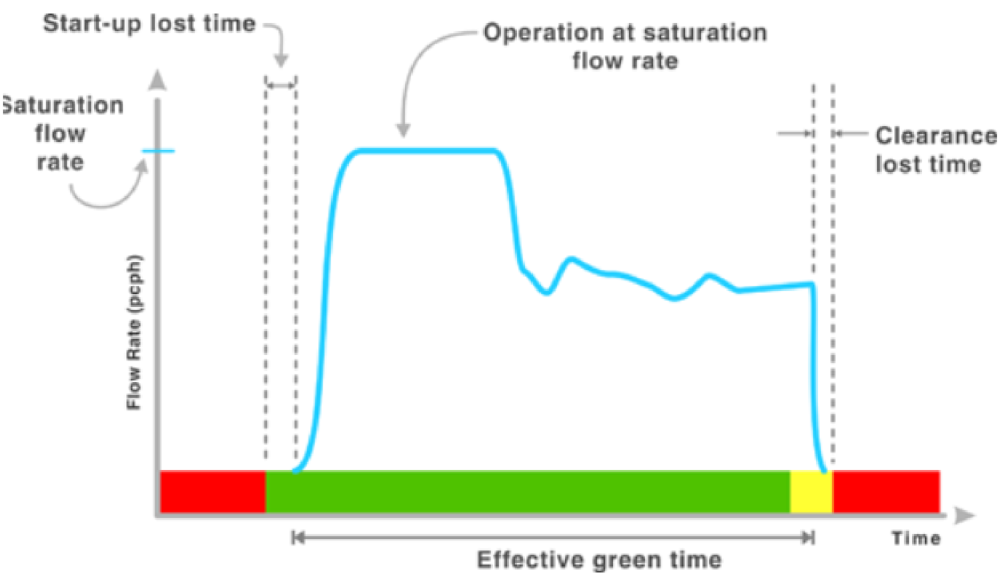

Figure 3.16: Signalized intersection movements and parameters(Fhwa, 2008)

The key parameters used for the signal timing design are headway, saturation flow rate, lost time, and effective times (Jiaming, 2022). These parameters are explained below.

3.6.1 Headway

Headway is the time interval between two consecutive vehicles passing through a specific point, measured in seconds. The headway is a key parameter for signal time calculation (Urbanik et al., 2015).

3.6.2 Saturation Headway

The average headway between vehicles occurs after the fourth vehicle in the queue and continuous until the last vehicle in the initial queue clears the intersection (Fhwa, 2008).

3.6.3 Saturation flow rate

Saturation flow rate is the maximum volume of vehicles that can pass through an intersection from a given lane or group of lanes, or the number of vehicles that can pass through the intersection in an hour if the green signal works continuously (FHWA, 2009). Equation 3.3 shows the relationship between saturation flow rate and saturation headway. From the Highway Capacity Manual 2010, the maximum saturation flow rate was assumed to be 1900 passenger cars per hour per lane when there was no data from the field.

$$s = \frac{3600}{h} \tag{3.3}$$

S – saturation flow rate in veh/h

h = saturation headway in s/veh, and

3600 = number of seconds per hour

Normally, headway can be as small as 2 seconds.

3.6.4 Lost time and effective times

Lost time is the time that is not effectively used by any movement at the intersection. It is the combination of startup lost time and clearance lost time (Jiaming, 2022). As Equation 3.4 describes, the total lost time is the sum of start-up lost time and clearance lost time.

Total lost times = start-up lost time + clearance lost time (3.4)

3.6.5 Start-up lost time.

The t_{sl} is the lost time at the beginning of green signal phase before the traffic in the intersection starts moving. From figure 3.16, the first three vehicles need more headway, and then the sum of the first three vehicle headways is defined as the startup lost time. Startup lost time will normally be 2 to 5 seconds in practice (Jiaming, 2022).

3.6.6 Clearance lost time.

The time t_{cl} in seconds that is not used by the intersection effectively is called clearance lost time. (Fhwa, 2008)

3.6.7 Total lost time

The sum of startup lost time and clearance lost time is called total lost time denoted with t_L. Equation 3.5 is the total lost time.

Total lost time = $t_L = t_{sl} + t_{cl}$ (3.5)

t_{sl}=Start-up lost time in seconds

t_{cl}= Clearnce lost time in seconds

3.6.8 Effective green times

The green time in which the given traffic movement or set of traffic movements can be expected to move It is equal to the cycle length minus the effective red time (Jiaming, 2022). This effective green time can be calculated by using Equation 3.6.

$$g = G + Y + AR - t_L \quad (3.6)$$

G = Displayed green time for traffic movement in seconds,

Y= Displayed yellow time for traffic movement in seconds,

AR = Displayed all-red time in seconds.

t_L = Total lost time for a movement during a cycle in seconds

3.6.9 Effective red times

It is the red signal duration effectively utilized by the vehicles in the signalized intersection (Jiaming, 2022). The effective red time (r) can be described as Equation 3.7.

$$r = R + t_L \quad (3.7)$$

R is the displayed red time for a traffic movement in seconds and $t_L$is the total lost time.

3.6.10 Capacity

The capacity is the maximum number of vehicles that can pass through the intersection (Jiaming, 2022). Equation 3.8 is for the capacity.

$$c = s \times \frac{g}{C} \quad (3.8)$$

c = capacity,

s = saturation flow rate of the lane group in vehicles per hour

g = effective green time for the movement in seconds

and C = cycle length in seconds.

3.6.11 Cycle length

The cycle length (C) is the total duration of the complete cycle of the signal changes at the signalized intersection. Equation 3.9 shows the relation between cycle length, effective green time, and effective red time.

$$r + g = C \quad (3.9$$

3.7 Traffic signal time design for an intersection under fixed time control

1.Signal phasing

The signal phasing or staging used for the signal time design for scenario 3 is shown in Figure 3.17.

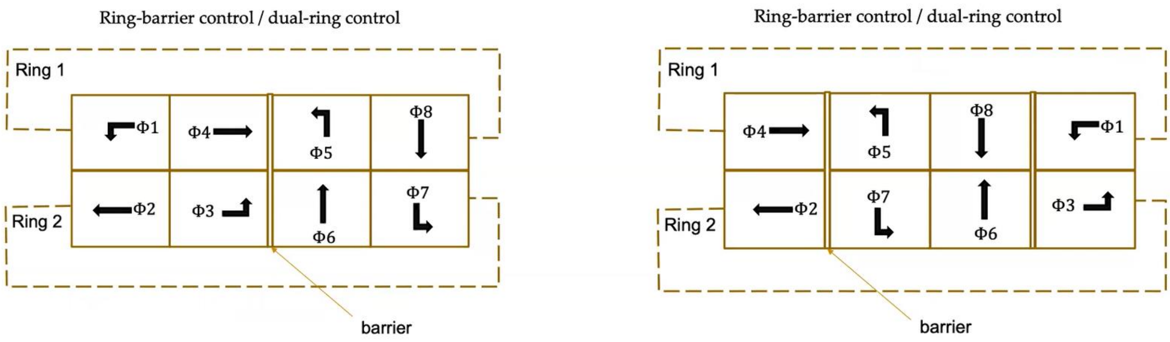

Figure3.17: Signal phasing (Jiaming, 2022)

2. Establish analysis lane groups.

Movement groups are the same as lane groups if there are no shared lanes. Figure 3.18 shows an example for lane groups.

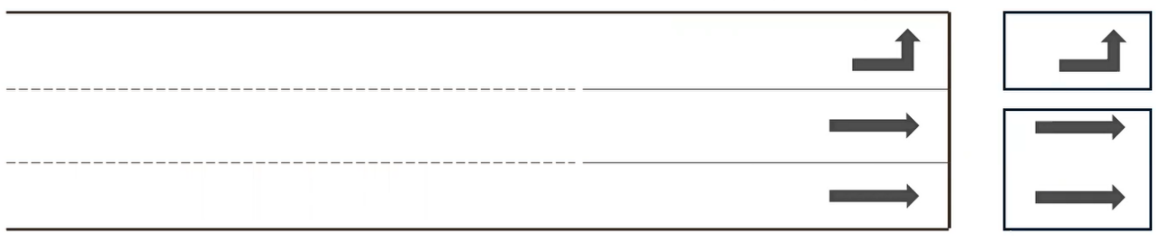

Figure 3.18: Lane groups (Jiaming, 2022)

3. Calculate the analysis flow rates and the adjusted saturation flow rates.

The traffic volume arriving at an intersection in one hour must be converted into an analysis flow rate that accounts for the peak 15-minute traffic flow.

4. Determine critical lane groups and total lost time.

The critical lane group is the one which has highest v/s (Arrival rate divided by saturation flow rate)

The sum of the flow ratios for the critical lane groups (Y_c) can be used to calculate a signal cycle length (Jiaming, 2022)

$$Y_c = \sum_{i=1}^{n} (\frac{v}{s})_{ci} \quad (3.10)$$

$(\frac{v}{s})_{ci}$- Flow ratio for critical lane group i

n- Number of critical lanes

5. Calculate the cycle length

$$C_{min} = \frac{L \times X_c}{X_c - Y_c} \tag{3.11}$$

C_{min} – Minimum cycle length in seconds

L – Total lost time for the cycle in seconds

X_c- Critical ratio for the intercection

6. Allocate green time.

3.8 Simulation of models

Next step done was the simulation run in Vissim, which has a one step or continuous simulation option.

Simulation results obtained and evaluated the three main performance measures, in which vehicle travel time, queue length and queue delay which will evaluate the efficiency of the signal control system.

Vehicle travel time

The travel time is the average time taken for one vehicle to pass the intersection (PTV Vissim 2011).

Queue length

The Vissim simulation provides maximum queue length and the average queue length. It is the length of the queue that vehicles need to wait in traffic, measured in meters (PTV Vissim 2011).

Queue delay

The delay is the time taken by the vehicles to pass the intersection, measured in seconds (PTV Vissim 2011). Queue counters are used to estimate the queue length in Vissim.

4 Results

4.1 Queue Delay

The total time in seconds taken by the vehicles in a traffic queue if the queue conditions are met (HCM, 2010). The average queue delay for each scenario is shown in Table 4.1.

Table 4.1: Average queue delay value comparison for all scenarios (PTV VISSIM 2023)

Directions	Average Queue delay (Seconds)		
	Scenario 1	Scenario 2	Scenario 3
WBL	49.16	3.38	3.10
WBI	21.67	10.65	18.23
WBR	1.62	10.96	18.97
SBI	84.45	4.62	4.74
SBR	1.23	7.06	7.22
EBL	26.99	13.68	13.05
EBI	13.34	9.80	15.77
EBR	7.83	3.43	7.43
NBI	42.49	16.94	22.35
Tram C-S	8.25	2.42	17.98
Tram C-N	0.80	3.15	9.43
Tram N-C	1.73	0.25	3.65
Tram N-S	3.30	2.15	0.73
Tram S-N	1.40	1.79	6.33
Tram S-C	4.73	7.80	15.80
EBLO	42.24	33.13	37.33
SBO	71.62	30.67	35.01

The average queue delay for scenario 1 is shown in Figure 4.1. The SBI, EBLO, and SBO have higher queue delays.

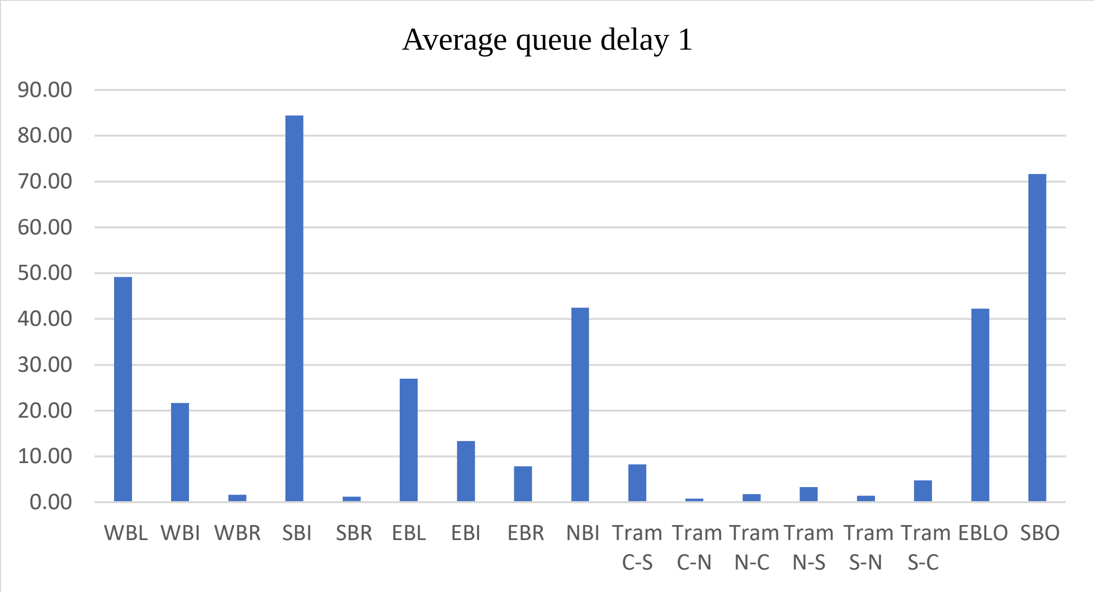

Figure 4.1: Average queue delay for scenario 1

The average queue delay for scenario 2 is shown in Figure 4.2.

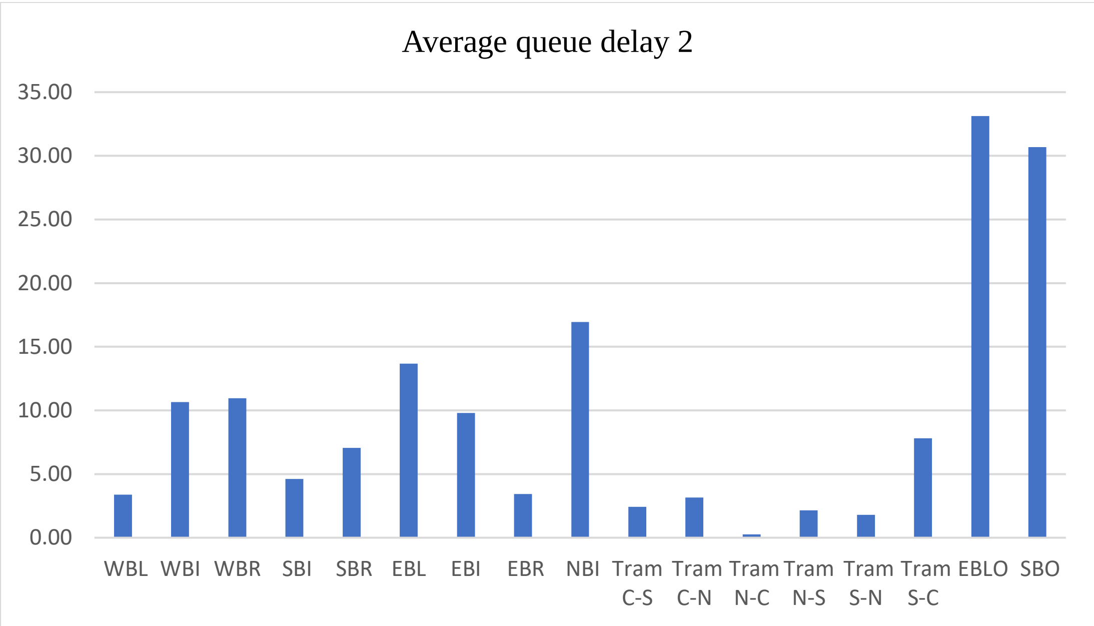

Figure 4.2: Average queue delay for scenario 2

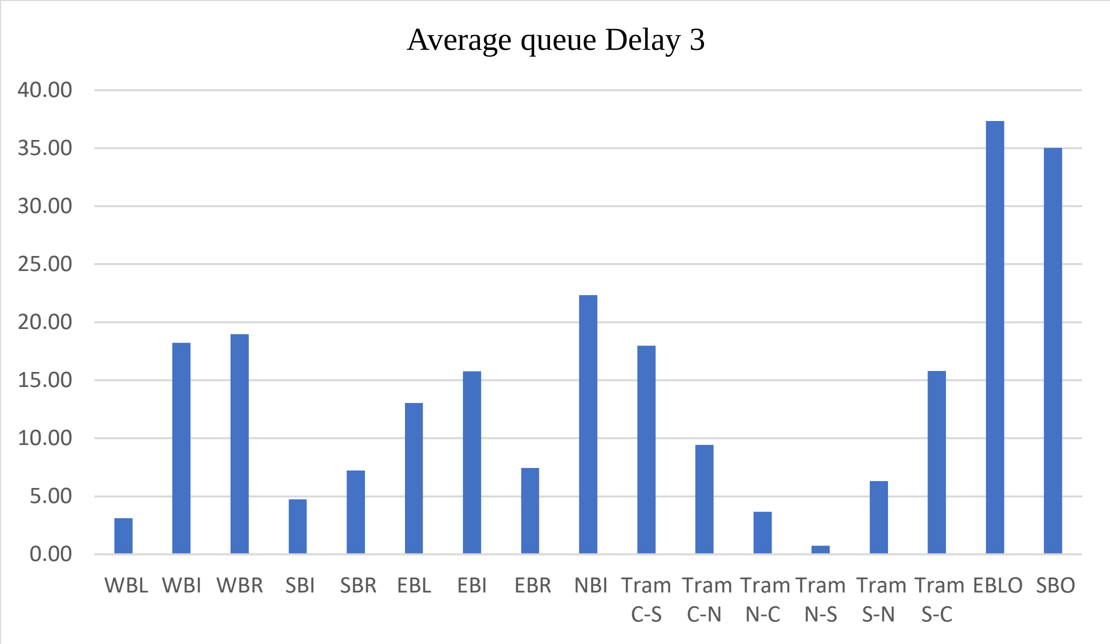

Figure 4.3: Average queue delay for scenario 3

The average queue delay for scenario 3 is shown in Figure 4.3.

The comparison of the average queue delay for the three scenarios is shown in Figure 4.4.

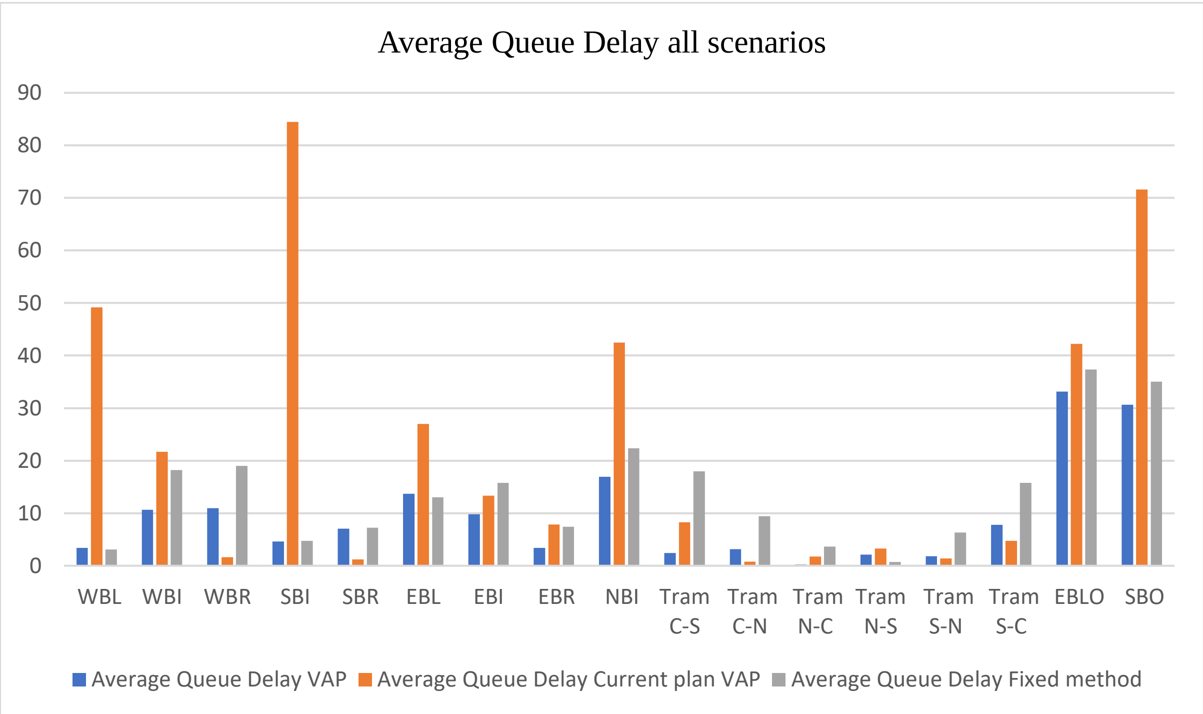

Figure 4.4: Average queue delay comparison graph for all scenarios

4.2 Queue Length

Queue lengths can be determined with queue counters at any point in the Vissim network and can be evaluated for any time interval. Queue lengths are measured in terms of units of length and not in terms of the number of vehicles (HCM, 2010). The average queue length for each scenario can be seen in Table 4.2.

Table 4.2: Average queue length values of all scenarios (PTV VISSIM 2023)

Directions	Queue Length in meters		
	Scenario 1	Scenario 2	Scenario 3
WBL	8.67	3.47	4.37
WBI	13.07	8.73	13.27
WBR	1.59	0.38	0.54
SBI	6.49	4.44	4.92
SBR	0.49	1.15	1.32
EBL	8.60	10.45	12.38
EBI	7.83	10.11	17.48
EBR	1.83	2.61	3.80
NBI	7.45	4.14	9.06
Tram C-S	0.38	1.18	2.82
Tram C-N	0.17	0.61	2.66
Tram N-C	1.70	1.94	2.99
Tram N-S	0.42	0.38	0.35
Tram S-N	3.85	1.46	4.08
Tram S-C	1.47	0.21	1.12
EBLO	1.32	0.43	0.58
SBO	3.72	0.24	0.02

The average queue length for scenario one is shown in Figure 4.5.

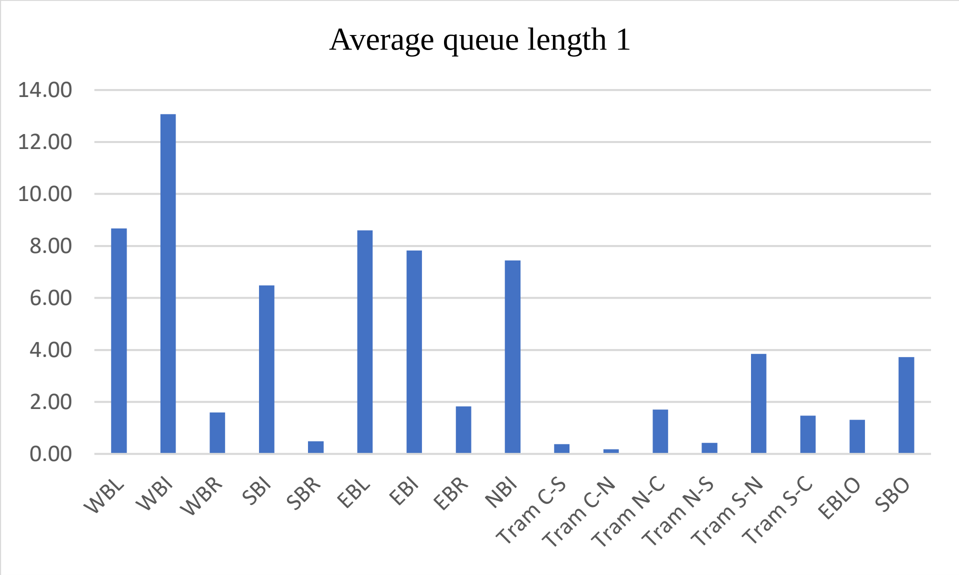

Figure 4.5: Average queue length for scenario 1

The average queue length for scenario 2 is shown in Figure 4.6.

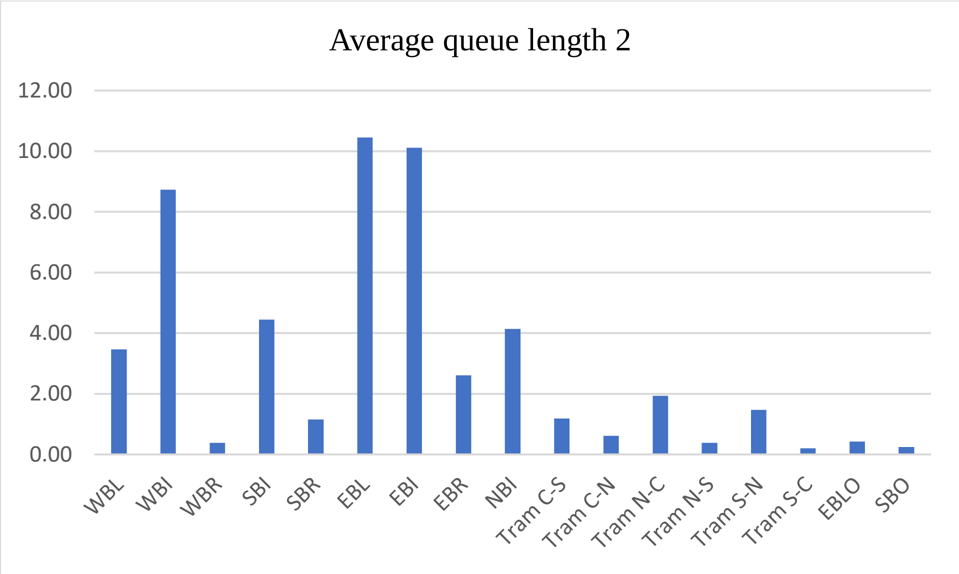

Figure 4.6: Average queue length for scenario 2

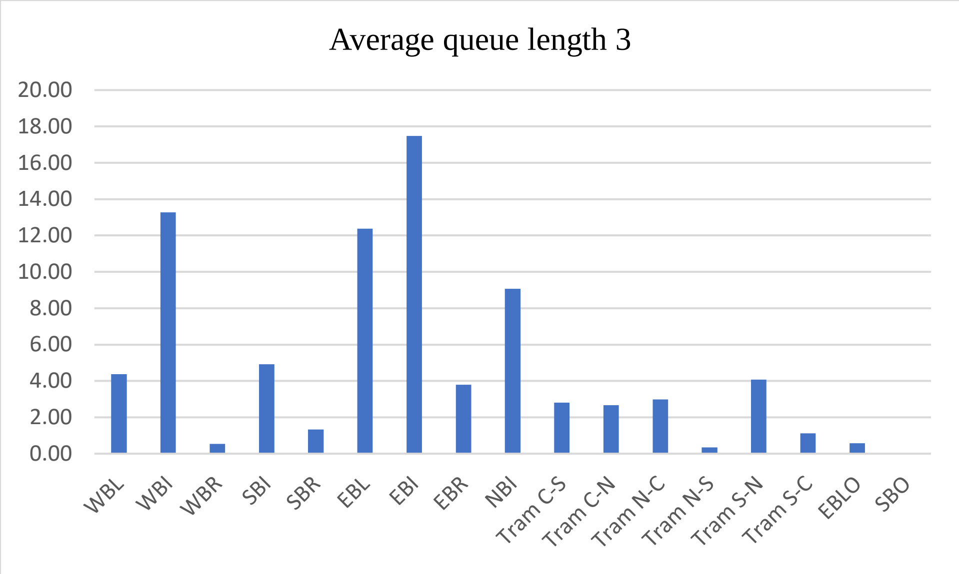

Figure 4.7: Average queue length for scenario 3

The average queue length for scenario 3 is shown in Figure 4.7.

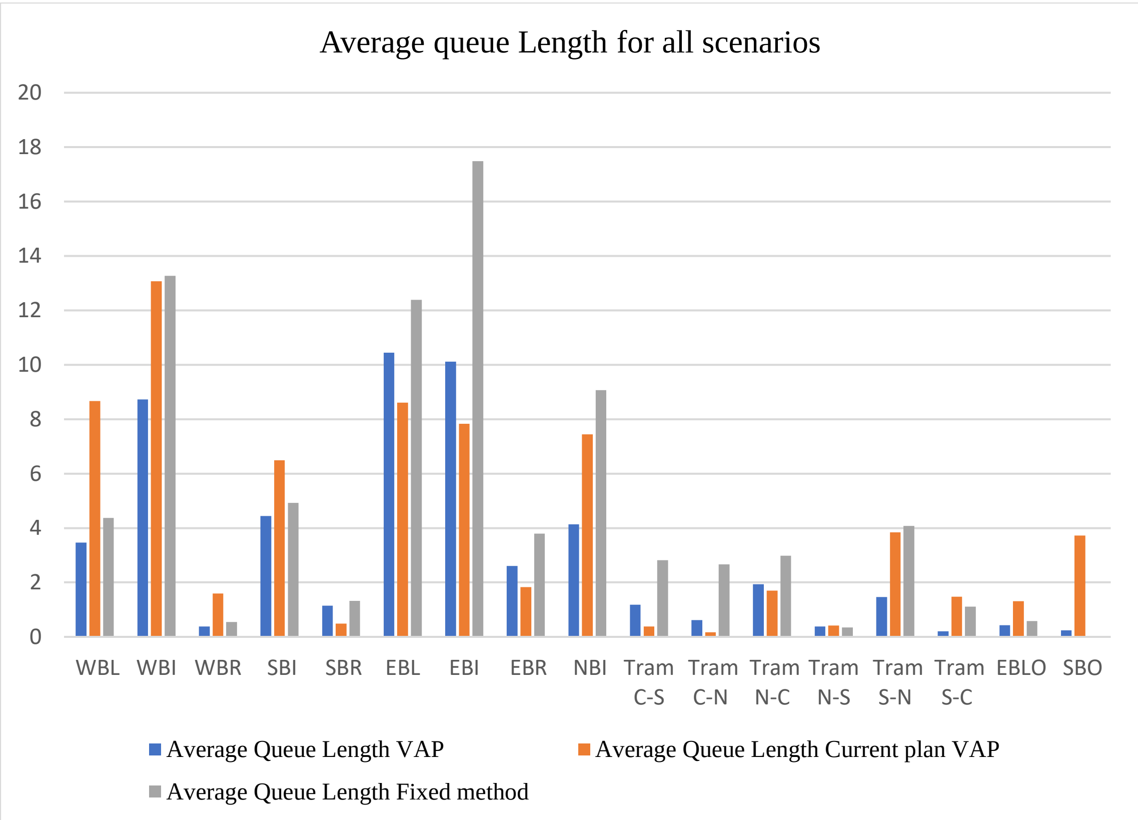

Figure 4.8: Comparison of the average queue length of all scenarios

The comparison of average queue length for the three scenarios is presented in Figure 4.8

4.3 Vehicle travel time

The vehicle travel time for each scenario is shown in Figure 4.3.

Table 4.3: Vehicle travel time values for all scenarios (PTV VISSIM 2023)

Directions	Vehicle travel time		
	Scenario 1	Scenario 2	Scenario 3
WB	66.90	53.14	51.1
EB	64.64	49.88	50.8
NB	64.06	36.84	43.9
SB	109.78	41.08	51.8

The vehicle travel time in each direction in scenario 1 can be seen in Figure 4.9.

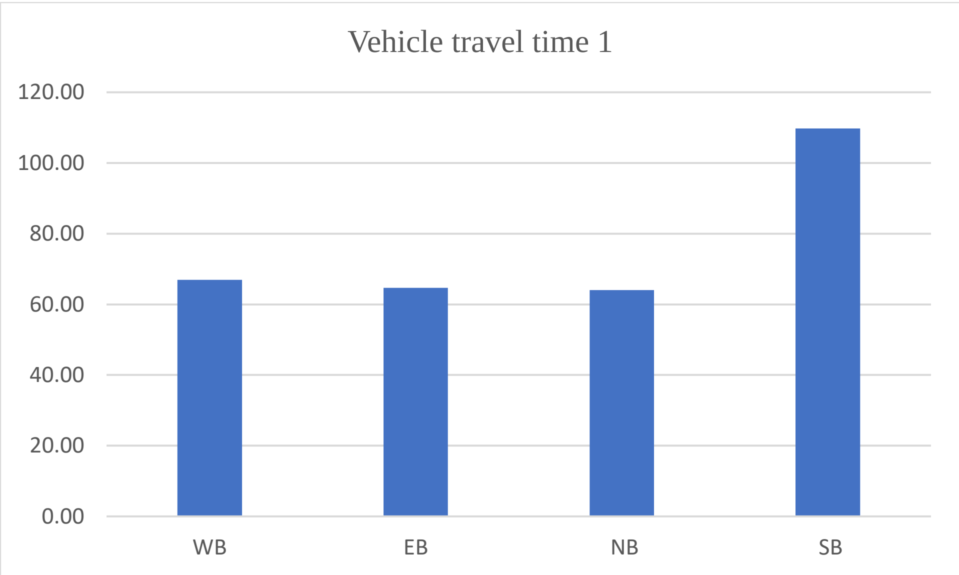

Figure 4.9: Vehicle travel time for scenario 1

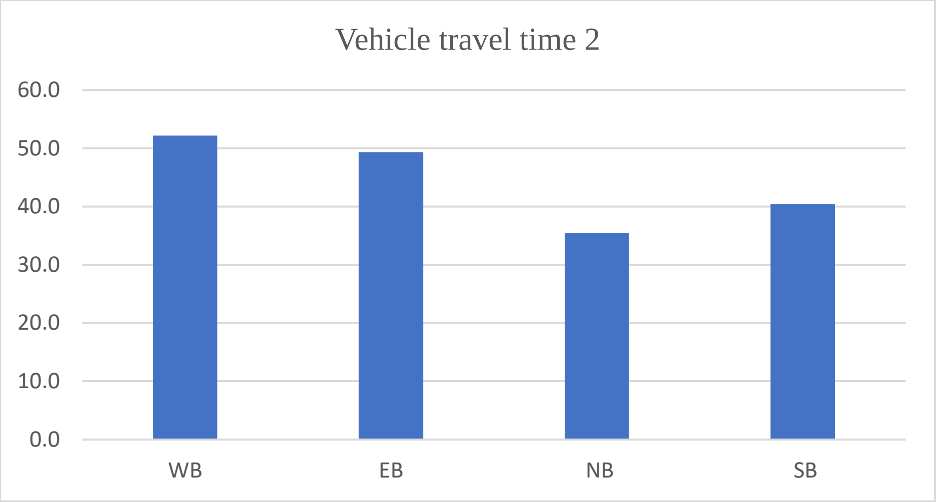

Figure 4.10: Vehicle travel time for scenario 2

The vehicle travel time taken in each direction in scenario 2 can be seen in Figure 4.10, and for scenario 3 seen in Figure 4.11.

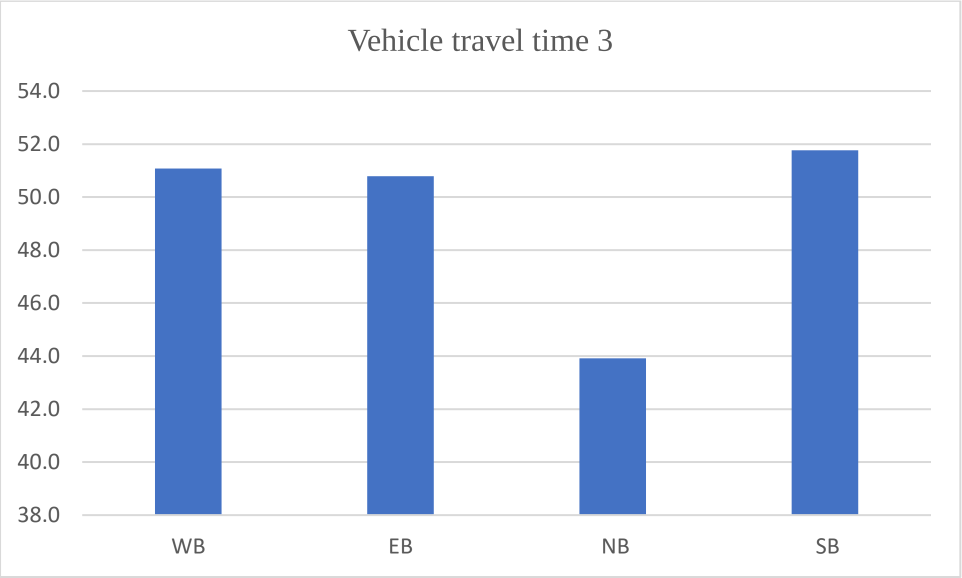

Figure 4.11: Vehicle travel time for scenario 3

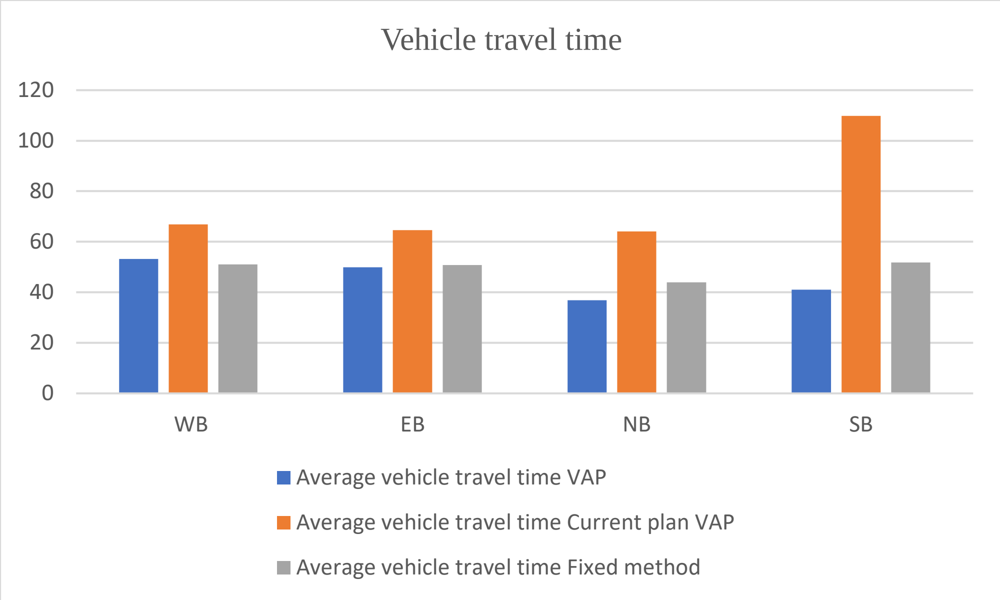

Figure 4.12: Vehicle travel time comparison for scenarios

The comparison of vehicle travel time for the three scenarios is shown in Figure 4.12. The results obtained for each parameter based on time interval is shown in Appendix 4.

4.4 Fundamental diagram

In order to check the level of congestion in EBLO/NBO,the fundamental diagram was used.

Figure 4.13: Distance measurement for checking the level of congestion.

The distance is measured from the google map. The distance from A to B (L) is 100 metre and the distance between B and C (l) is 55.38m. Jam density was assumed to be 125 veh/km.

k_{op} = Optimal traffic density in which the traffic density at which maximum flow occurs.

L = The considered length of roadway

k_j= Maximum traffic density at which vehicles

l = Congested roadway segment / queue length

$$k_{op} = \frac{k_j}{2} \tag{4.1}$$

k_{op} was obtained as 62.5 km/h using the Equation 4.1.

$$k_{op} \text{ x L } \leq k_j \text{ x l} \tag{4.2}$$

The product of the length of the roadway segment and optimal traffic density should be less than or equal to the product of queue lengths and jam density, as shown in Equation 4.2. This equation can be described as follows: the total number of vehicles that can be accommodated optimally in the road segment should not exceed the total number of vehicles that can be accommodated in the jam density (Ryus et al., 2011).

According to Equation 4.2, If the left side value is greater (the total number of vehicles that can accommodate optimally) than the right-side value (the total number of vehicles that can accommodate in the jam density), then there is congestion.

k_{op} x L = 62.5 x 100

= 6250

k_j x l = 125 x 55.38

= 6923

Thus, k_{op} x L $\leq$ k_j x l which means the congestion in this road segment is not severe, and if it still exists, it can be avoided by the signal time optimization (Ryus et al., 2011).

4.5 Signal phasing for the fixed signal control method

The intersection does not have shared lanes. So considered the protected phase which contains their own phase and their own signal.

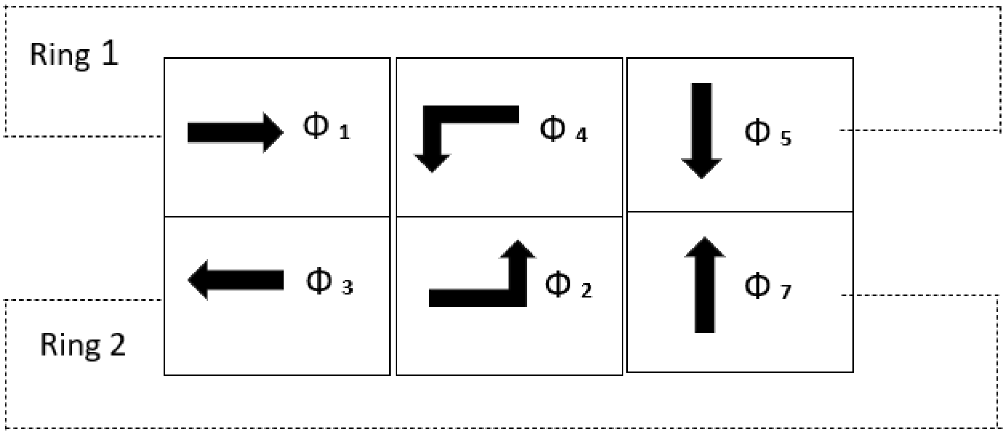

Figure 4.14: Signal phasing for scenario 3

The signalized intersection has three stages. The saturation flow rates and arriving traffic flow rates are as follows: (T: through, L: left-turning). We further assume 2 seconds start-up lost time and 2s clearance lost time.

The saturation flow rate for each direction is shown in Table 4.4.

Table 4.4: The saturation flow rate for each direction

Stage 1	Stage 2	Stage 3
EB T: 1800 veh/h	EBL: 1800veh/h	SB T: 1800 veh/h
WB T: 1800 veh/h	WBL: 1800veh/h	NB T: 1800 veh/h

Arrival flow rate of the vehicles in each direction can be seen in Table 4.5.

Table 4.5: The arrival rate of vehicles in each direction

Stage 1	Stage 2	Stage 3
EB T: 600 veh/h	EBL: 500 veh/h	SB T: 350 veh/h
WB T: 620 veh/h	WBL: 150veh/h	NB T: 180 veh/h

Critical lane groups

Identify the critical lane group in each phase. The flow ratio was calculated and shown in the Appendix 3. Table 4.6 shows the flow ratio and critical lane grouping for each stage in each direction.

Table 4.6: Flow ratio and critical lane grouping

	Directions	Flow ratio	Critical lane group
Stage 1	EB T	0.33	
	WB T	0.34	WB T
Stage 2	EB L	0.27	EB L
	WB L	0.08	
Stage 3	SB T	0.16	SB T
	NB T	0.1	

The sum of flow ratios of the critical lane group was obtained as 0.808 using Equation 3.10. For each stage, total lost time was assumed to be 4 seconds, and the total lost time for 3 stages was 12 seconds.

Minimum cycle length calculated as $117.39\ s$. By rounding up to 5s, the minimum cycle length is then 120s.The calculated effective green and red signals as well as displayed green time shown in Table 4.7.

Table 4.7: Calculated values for green and red signal time

	Effective green time (seconds)	Displayed green time	Effective red time	Displayed red time
Stage 1	46.38	45.38	73.62	69.62
Stage 2	36.40	35.4	83.6	79.6
Stage 3	26.15	25.15	93.85	89.85

The calculated display green time added in Vissim model to simulate the scenario 3. The detailed calculation is shown in Appendix 3.

5 Discussion of results

The simulation results were analyzed for the three scenarios, and the queue delay was the first parameter that was analyzed. The first scenario has the highest queue delay compared to the other two scenarios. The queue delay was mainly observed in the SBI, NBI, WBL, SBO, and EBLO directions. This is because there is no priority for SBI and WBL, resulting in more waiting time. The signal timing plan for these directions indicates that there may be congestion due to the reduced time allocation. In scenario 2, there is less queue delay compared to scenario 1. It has queue delays in NBI and EBLO, but those are within a considerable range. Scenario 3, which is the fixed-time signal method, can also be used for better signal improvement at the intersection, which has less queue delay compared to scenario 1.

The second parameter analyzed was the queue length. The largest queue length for scenario 1 is in the WBL, WBI, and SBI directions because there is no priority for these lanes. But in the second scenario, the VAP program has generated a queue by considering this main issue and reducing the queue length to a limit. Then in scenario 3, the queue length generated is more than the queue length in scenario 2, mainly in WBI, WBL, and SBI, but it is better than scenario 1 in terms of queue length.

The final parameter analysed was the vehicle travel time. In scenario 1, vehicles travel time is longer for WB and SB directions. Scenario 3 takes more travel time in the EB direction. There is a slight decrease in travel time for the NB direction in scenarios 2 and 3.

In scenario 2, the minimum green time for the signal groups 1 to 4 is 20 seconds, and 5 to 15 is 15 seconds. The minimum green time for the SBO and NBI is 10 s in scenario 1, which is not enough for the directions. This lack of time is creating congestion in the area. When the signal is green for SBI and WBL, the vehicles will start entering the section. In the same instance, if a tram comes, the minimum time of 10 seconds is not sufficient for the vehicles to pass and clear the tramway. This results in congestion in the area. There is also a change in signal phasing in scenario 2 when compared with scenario 1. This change in signal phasing also reduced congestion issues to a minimum.

The congestion level in the NBO road segment was also analyzed using the fundamental diagram. The results show there is not severe congestion, and the present congestion can be avoided by signal time optimization. This was solved by changing the signal phase.

Also, when the tram approaches from central station to Ullevi Södra, signal group 14 is off, which is associated with the tram signal. The signal group 2, which is for EBL, is on at the same time, resulting in the entry of a vehicle in Section NBO. This will cause congestion and a long queue, which will affect the movement of traffic in WBI even if they have a green signal. This problem was solved by adding signal group G14 along with signal group 2 in the same stage. The signals G2 and G14 will be off at the same time if a tram arrives. This prevents the entry of vehicles from EBL to NBO until the tramway is cleared.

In scenario 2, the minimum amber time is 5 seconds. This is because in scenario 1, the amber time of 3 seconds is not enough for vehicles to completely clear the intersection before the conflicting situation. This will increase the possibility of collisions. Also, the insufficient amber time will decrease the overall efficiency of the intersection. The 5 second amber time is perfect, and it shows the vehicle can clear the intersection within the time limit.

When the detectors detect the tram, according to scenario 1, the current running stage will complete its cycle, and after that, only the tram gets its signal. But in scenario 2, when the detector detects the tram, the current running stage will reach its minimum green time, and consequently, the green signal for the tram will be active. Public transportation has priority. Thereby reducing the queue delay for the trams.

Scenario 3, the fixed-time signal control, has a stage only for trams. There will be a queue delay in scenario 2 because it has no detection, and the tram needs to reach the signal stage for them.

6 Conclusion and Recommendations

The signalized intersection plays a major role in the transportation network. The signal controller at the intersection will decide the capacity and efficiency of the intersection. The objectives of the study were achieved, which were to evaluate the effectiveness of the signal control system at the intersection and reduce congestion. The PTV Vissim software was used to create the three different scenarios and simulations. Key performance measures such as queue delay, queue length, and vehicle travel time were evaluated.

The overall results were analysed. It shows that scenario 1 has more queue length and queue delay than scenario 2. The ranking of signal controllers goes like this: the actuated signal controller with VAP goes first, and the second one is the fixed-time signal controller. The real signal controller using the LHOVRA concept shows more queue length and queue delay in WBL, WBI, and SBI. The other two signal control systems can be used to improve of the signal controller in the intersection and thereby increase the overall capacity of the intersection.

Scenario 3, which is the fixed signal time controller, has the lowest initial and maintenance costs. It does not have detectors. The actuated signal controller needs the detectors, and thereby, maintenance of the detectors is needed. On the other hand, the actuated signal controller reduces the amount of queue delay through the detectors. A fixed-time signal controller is a cost-effective alternative for improving the intersection.

The study also examined the performance of different signal controllers, such as fixed-time signal controllers and actuated signal controllers using VAP. The analysis implies that the implementation of an actuated signal controller with VAP could improve the overall efficiency of the intersection and reduce congestion through green signal optimization based on traffic demand in each direction.

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Appendix 1

***.pua and *.vap files for scenario 1**

$SIGNAL_GROUPS

$

G1	1
G2	2
G3	3
G4	4
G5	5
G6	6
G7	7
G8	8
G9	9
G10	10
G11	11
G12	12
G13	13
G14	14
G15	15

$IGM

$

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15
G1	-127	-127	-127	5	5	5	5	5	-127	-127	-127	5	5	-127	-127
G2	-127	-127	5	-127	5	5	5	5	5	5	5	5	5	-127	-127
G3	-127	5	-127	5	5	5	5	5	-127	-127	-127	5	5	-127	-127
G4	5	-127	5	-127	5	5	5	5	5	5	5	5	5	-127	-127
G5	5	5	5	5	-127	5	-127	5	-127	5	-127	5	5	-127	-127
G6	5	5	5	5	5	-127	-127	-127	5	5	5	5	5	5	-127
G7	5	5	5	5	-127	-127	-127	-127	-127	5	-127	5	5	-127	-127

G8	5	5	5	5	5	- 127	-127	-127	5	5	5	5	5	5	-127
G9	-127	5	-127	5	-127	5	-127	5	-127	-127	-127	5	5	-127	-127
G10	-127	5	-127	5	5	5	5	5	-127	-127	-127	5	5	-127	-127
G11	-127	5	-127	5	-127	5	-127	5	-127	-127	-127	5	5	-127	-127
G12	5	5	5	5	5	5	5	5	5	5	5	-127	-127	-127	5
G13	5	5	5	5	5	5	5	5	5	5	5	-127	-127	-127	5
G14	-127	-127	-127	-127	-127	5	-127	5	-127	-127	-127	-127	-127	-127	-127
G15	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	5	5	-127	-127

$STAGES

$

stage_1 G1 G2 G14

red G3 G4 G5 G6 G7 G8 G9 G10 G11 G12 G13 G15

stage_2 G5 G7 G9 G11 G14 G15

red G1 G2 G3 G4 G6 G8 G10 G12 G13

stage_3 G2 G4 G14 G15

red G1 G3 G5 G6 G7 G8 G9 G10 G11 G12 G13

stage_4 G1 G3 G9 G10 G11 G14 G15

red G2 G4 G5 G6 G7 G8 G12 G13

stage_5 G6 G7 G8 G15

red G1 G2 G3 G4 G5 G9 G10 G11 G12 G13 G14

stage_6 G12 G13 G14

red G1 G2 G3 G4 G5 G6 G7 G8 G9 G10 G11 G15

```
$STARTING_STAGE
$
stage_1

$INTERSTAGE
INTERSTAGE_number :     1
length [second]    :    12
from stage    :    1
to stage    :    2
$
G1    -127    0
G2    -127    0
G5     5    127
G7     5    127
G9     5    127
G11    5    127
G15    5    127

$INTERSTAGE
INTERSTAGE_number :     2
length [second]    :    12
from stage    :    1
to stage    :    3
$
G1    -127    0
G4     5    127
G15    5    127

$INTERSTAGE
INTERSTAGE_number :     3
```

length [second] : 12

from stage : 1

to stage : 4

$

G2 -127 0

G3 5 127

G9 5 127

G10 5 127

G11 5 127

G15 5 127

$INTERSTAGE

INTERSTAGE_number : 4

length [second] : 12

from stage : 1

to stage : 5

$

G1 -127 0

G2 -127 5

G6 5 127

G7 5 127

G8 5 127

G14 -127 0

G15 5 127

$INTERSTAGE

INTERSTAGE_number : 5

length [second] : 12

from stage : 1

to stage : 6

```
$
G1      -127     0
G2      -127     0
G12      5      127
G13      5      127


$INTERSTAGE
INTERSTAGE_number :       6
length [second]     :       12
from stage       :       2
to stage         :       3
$
G2       5     127
G4       5     127
G5      -127      0
G7      -127      0
G9      -127      0
G11      -127      0


$INTERSTAGE
INTERSTAGE_number :       7
length [second]     :       12
from stage       :       2
to stage      :       4
$
G1       5     127
G3       5     127
```

G5 -127 0

G7 -127 0

G10 5 127

$INTERSTAGE

INTERSTAGE_number : 8

length [second] : 12

from stage : 2

to stage : 5

$

G5 -127 0

G6 5 127

G8 5 127

G9 -127 0

G11 -127 0

G14 -127 0

$INTERSTAGE

INTERSTAGE_number : 9

length [second] : 12

from stage : 2

to stage : 6

$

G5 -127 0

G7 -127 0

G9 -127 0

G11 -127 0

G12 5 127

G13 5 127

G15 -127 0

$INTERSTAGE

INTERSTAGE_number : 10

length [second] : 12

from stage : 2

to stage : 1

$

G1 5 127

G2 5 127

G5 -127 0

G7 -127 0

G9 -127 0

G11 -127 0

G15 -127 0

$INTERSTAGE

INTERSTAGE_number : 11

length [second] : 12

from stage : 3

to stage : 4

$

G1 5 127

G2 -127 0

G3 5 127

G4 -127 0

G9 5 127

G10 5 127

G11 5 127

$INTERSTAGE

INTERSTAGE_number :   12

length [second]   :   12

from stage   :   3

to stage   :   5

$

G2   -127   0

G4   -127   0

G6   5   127

G7   5   127

G8   5   127

G14   -127   0

$INTERSTAGE

INTERSTAGE_number :   13

length [second]   :   12

from stage   :   3

to stage   :   6

$

G2   -127   0

G4   -127   0

G12   5   127

G13   5   127

G15   -127   0

$INTERSTAGE

INTERSTAGE_number :   14

length [second]   :   12

from stage   :   3

to stage   :   1

$
G1 5 127
G4 -127 0
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 15
length [second] : 12
from stage : 3
to stage : 2
$
G2 -127 0
G4 -127 0
G5 5 127
G7 5 127
G9 5 127
G11 5 127

$INTERSTAGE
INTERSTAGE_number : 16
length [second] : 12
from stage : 4
to stage : 5
$
G1 -127 0
G3 -127 0
G6 5 127
G7 5 127
G8 5 127
G9 -127 0

G10 -127 0

G11 -127 0

G14 -127 0

$INTERSTAGE

INTERSTAGE_number : 17

length [second] : 12

from stage : 4

to stage : 6

$

G1 -127 0

G3 -127 0

G9 -127 0

G10 -127 0

G11 -127 0

G12 5 127

G13 5 127

G15 -127 0

$INTERSTAGE

INTERSTAGE_number : 18

length [second] : 12

from stage : 4

to stage : 1

$

G2 5 127

G3 -127 0

G9 -127 0

G10 -127 0

G11 -127 0

G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 19
length [second] : 12
from stage : 4
to stage : 2
$
G1 -127 0
G3 -127 0
G5 5 127
G7 5 127
G10 -127 0

$INTERSTAGE
INTERSTAGE_number : 20
length [second] : 12
from stage : 4
to stage : 3
$
G1 -127 0
G2 5 127
G3 -127 0
G4 5 127
G9 -127 0
G10 -127 0
G11 -127 0

$INTERSTAGE
INTERSTAGE_number : 21

length [second] : 12

from stage : 5

to stage : 6

$

G6 -127 0

G7 -127 0

G8 -127 0

G12 5 127

G13 5 127

G14 5 127

G15 -127 0

$INTERSTAGE

INTERSTAGE_number : 22

length [second] : 12

from stage : 5

to stage : 1

$

G1 5 127

G2 5 127

G6 -127 0

G7 -127 0

G8 -127 0

G14 5 127

G15 -127 0

$INTERSTAGE

INTERSTAGE_number : 23

length [second] : 12

from stage : 5

to stage : 2

$

G5 5 127

G6 -127 0

G8 -127 0

G9 5 127

G11 5 127

G14 5 127

$INTERSTAGE

INTERSTAGE_number : 24

length [second] : 12

from stage : 5

to stage : 3

$

G2 5 127

G4 5 127

G6 -127 0

G7 -127 0

G8 -127 0

G14 5 127

$INTERSTAGE

INTERSTAGE_number : 25

length [second] : 12

from stage : 5

to stage : 4

$

G1 5 127

G3 5 127

G6 -127 0

G7 -127 0

G8 -127 0

G9 5 127

G10 5 127

G11 5 127

G14 5 127

$INTERSTAGE

INTERSTAGE_number : 26

length [second] : 12

from stage : 6

to stage : 1

$

G1 5 127

G2 5 127

G12 -127 0

G13 -127 0

$INTERSTAGE

INTERSTAGE_number : 27

length [second] : 12

from stage : 6

to stage : 2

$

G5 5 127

G7 5 127

G9 5 127

G11 5 127

G12 -127 0

G13 -127 0

G15 5 127

$INTERSTAGE

INTERSTAGE_number : 28

length [second] : 12

from stage : 6

to stage : 3

$

G2 5 127

G4 5 127

G12 -127 0

G13 -127 0

G15 5 127

$INTERSTAGE

INTERSTAGE_number : 29

length [second] : 12

from stage : 6

to stage : 4

$

G1 5 127

G3 5 127

G9 5 127

G10 5 127

G11 5 127

G12 -127 0

G13 -127 0

G15 5 127

$INTERSTAGE

INTERSTAGE_number : 30

length [second] : 12

from stage : 6

to stage : 5

$

G6 5 127

G7 5 127

G8 5 127

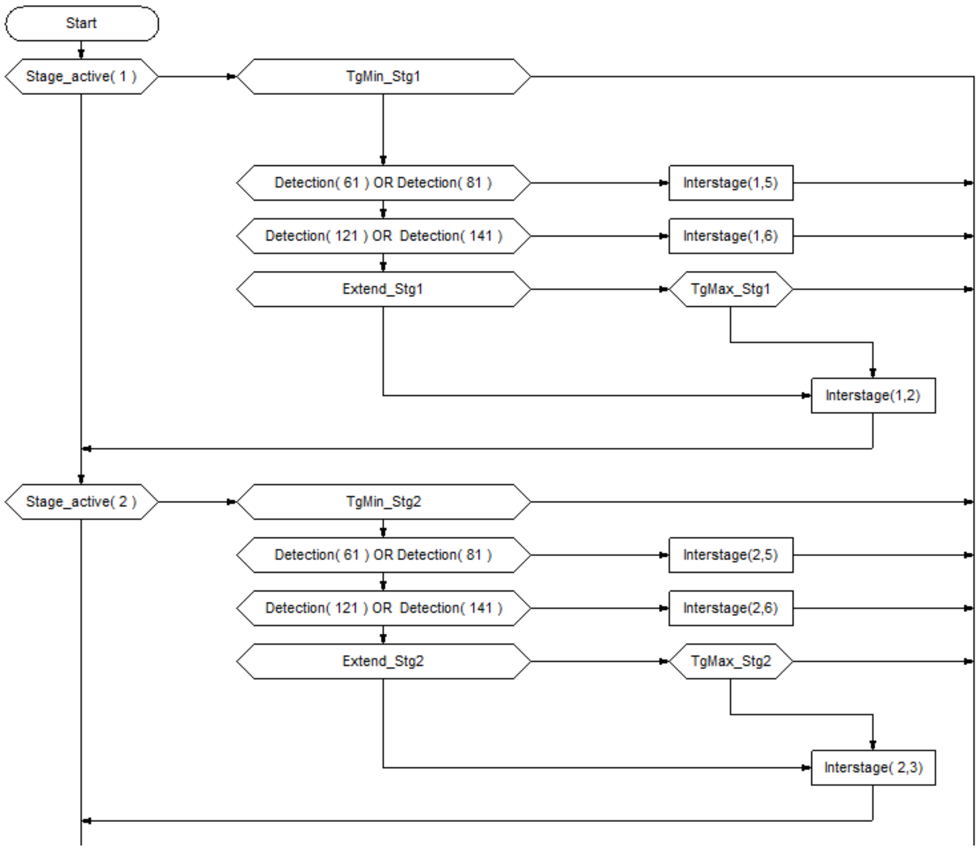
G12 -127 0

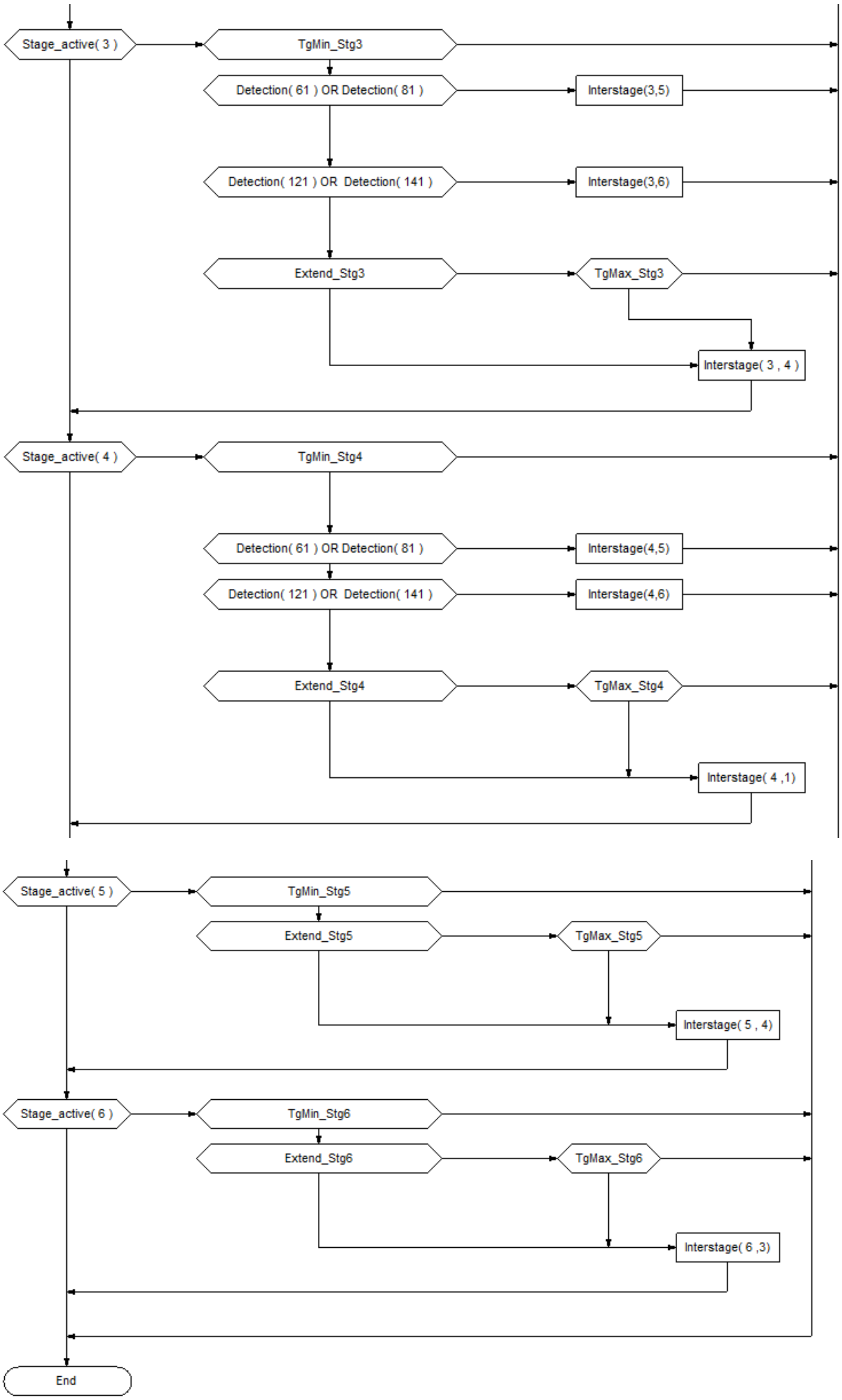
G13 -127 0

G14 -127 0

G15 5 127

$END




Stage_active(3)
TgMin_Stg3
Detection(61) OR Detection(81)
Interstage(3,5)
Detection(121) OR Detection(141)
Interstage(3,6)
Extend_Stg3
TgMax_Stg3
Interstage(3 , 4)
Stage_active(4)
TgMin_Stg4
Detection(61) OR Detection(81)
Interstage(4,5)
Detection(121) OR Detection(141)
Interstage(4,6)
Extend_Stg4
TgMax_Stg4
Interstage(4 ,1)
Stage_active(5)
TgMin_Stg5
Extend_Stg5
TgMax_Stg5
Interstage(5 , 4)
Stage_active(6)
TgMin_Stg6
Extend_Stg6
TgMax_Stg6
Interstage(6 ,3)
End

Parameters	**Gen**	**Comment**
MAX_GAP	**3**	Max gap time for extending stage
TgMax_Stg1	**40**	Max green time for each stage

Expressions	Contents
Extend_Stg1	(Headway(11) <= MAX_GAP) OR (Headway(21) <= MAX_GAP)
Extend_Stg2	(Headway(51) <= MAX_GAP) OR (Headway(71) <= MAX_GAP)
Extend_Stg3	(Headway(21) <= MAX_GAP) OR (Headway(41) <= MAX_GAP)
Extend_Stg4	(Headway(11) <= MAX_GAP) OR (Headway(31) <= MAX_GAP)
Extend_Stg5	(Headway(61) <= MAX_GAP) OR (Headway(81) <= MAX_GAP)
Extend_Stg6	(Headway(121) <= MAX_GAP) OR (Headway(141) <= MAX_GAP)
TgMin_Stg1	(T_green(1) <= T_green_min(1)) & (T_green(2) <= T_green_min(2))
TgMin_Stg2	(T_green(5) <= T_green_min(5)) & (T_green(7) <= T_green_min(7))
TgMin_Stg3	(T_green(2) <= T_green_min(2)) & (T_green(4) <=T_green_min(4))
TgMin_Stg4	(T_green(1) <= T_green_min(1)) & (T_green(3) <= T_green_min(3))
TgMin_Stg5	(T_green(6) <= T_green_min(6)) & (T_green(8) <=T_green_min(8))
TgMin_Stg6	(T_green(12) <= T_green_min(12)) & (T_green(13) <=T_green_min(13))
TgMax_Stg1	(T_green(1) <= 40) & (T_green(2) <= 40)
TgMax_Stg2	(T_green(5) <= 40) & (T_green(7) <= 40)
TgMax_Stg3	(T_green(2) <= 40) & (T_green(4) <= 40)
TgMax_Stg4	(T_green(1) <= 40) & (T_green(3) <= 40)
TgMax_Stg5	(T_green(6) <= 40) & (T_green(8) <= 40)
TgMax_Stg6	(T_green(12) <= 40) & (T_green(13) <= 40)

Appendix 2

***.pua and *.vap files for scenario 2**

$SIGNAL_GROUPS

$

G1	1
G2	2
G3	3
G4	4
G5	5
G6	6
G7	7
G8	8
G9	9
G10	10
G11	11
G12	12
G13	13
G14	14
G15	15

$IGM

$

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15
G1	-127	5	-127	5	5	5	5	5	-127	-127	-127	-127	-127	-127	5
G2	5	-127	5	-127	5	5	5	5	-127	5	-127	5	5	-127	-127
G3	-127	5	-127	5	5	5	5	5	-127	-127	-127	-127	-127	-127	5
G4	5	-127	5	-127	5	5	5	5	-127	5	-127	5	5	-127	-127
G5	5	5	5	5	-127	5	-127	5	-127	-127	-127	5	5	-127	-127
G6	5	5	5	5	5	-127	-127	-127	5	5	5	5	5	5	-127
G7	5	5	5	5	-127	-127	-127	-127	-127	-127	-127	5	5	-127	-127
G8	5	5	5	5	5	-127	-127	-127	5	5	5	5	5	5	-127
G9	-127	-127	-127	-127	-127	5	-127	-127	-127	-127	-127	5	5	-127	-127
G10	-127	5	-127	5	-127	5	-127	5	-127	-127	-127	5	5	-127	-127
G11	-127	-127	-127	-127	-127	5	-127	5	-127	-127	-127	5	5	-127	-127
G12	-127	5	-127	5	5	5	5	5	5	5	5	-127	-127	5	5
G13	-127	5	-127	5	5	5	5	5	5	5	5	-127	-127	5	5
G14	-127	-127	-127	-127	-127	5	-127	5	-127	-127	-127	-127	-127	-127	127
G15	5	-127	5	-127	-127	-127	-127	-127	-127	-127	-127	5	5	-127	-127

$STAGES

$

stage_1 G1 G3 G9 G10 G11 G14

red G2 G4 G5 G6 G7 G8 G12 G13 G15
stage_2 G2 G4 G9 G11 G14 G15
red G1 G3 G5 G6 G7 G8 G10 G12 G13
stage_3 G5 G7 G9 G10 G11 G14 G15
red G1 G2 G3 G4 G6 G8 G12 G13
stage_4 G6 G7 G8 G15
red G1 G2 G3 G4 G5 G9 G10 G11 G12 G13 G14
stage_5 G1 G3 G12 G13 G14
red G2 G4 G5 G6 G7 G8 G9 G10 G11 G15

$STARTING_STAGE
$
stage_1

$INTERSTAGE
INTERSTAGE_number : 1
length [second] : 18
from stage : 1
to stage : 2
$
G1 -127 0
G2 5 127
G3 -127 0
G4 5 127
G10 -127 0
G15 5 127

$INTERSTAGE
INTERSTAGE_number : 2
length [second] : 18
from stage : 1
to stage : 3
$
G1 -127 0
G5 5 127
G3 -127 0
G7 5 127
G15 5 127

$INTERSTAGE
INTERSTAGE_number : 3
length [second] : 18

from stage : 1
to stage : 4
$
G1 -127 0
G3 -127 0
G6 5 127
G7 5 127
G8 5 127
G9 -127 0
G10 -127 0
G11 -127 0
G14 -127 0
G15 5 127

$INTERSTAGE
INTERSTAGE_number : 4
length [second] : 18
from stage : 1
to stage : 5
$
G9 -127 0
G10 -127 0
G11 -127 0
G12 5 127
G13 5 127

$INTERSTAGE
INTERSTAGE_number : 5
length [second] : 18
from stage : 2
to stage : 3
$
G2 -127 0
G4 -127 0
G5 5 127
G7 5 127
G10 5 127

$INTERSTAGE
INTERSTAGE_number : 6
length [second] : 18
from stage : 2

to stage : 4
$
G2 -127 0
G4 -127 0
G6 5 127
G7 5 127
G8 5 127
G9 -127 0
G11 -127 0
G14 -127 0

$INTERSTAGE
INTERSTAGE_number : 7
length [second] : 18
from stage : 2
to stage : 5
$
G1 5 127
G3 5 127
G2 -127 0
G4 -127 0
G9 -127 0
G11 -127 0
G12 5 127
G13 5 127
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 8
length [second] : 18
from stage : 2
to stage : 1
$
G1 5 127
G2 -127 0
G3 5 127
G4 -127 0
G10 5 127
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 9
length [second] : 18

from stage : 3
to stage : 4
$
G5 -127 0
G6 5 127
G8 5 127
G9 -127 0
G10 -127 0
G11 -127 0
G14 -127 0

$INTERSTAGE
INTERSTAGE_number : 10
length [second] : 18
from stage : 3
to stage : 5
$
G1 5 127
G3 5 127
G5 -127 0
G7 -127 0
G9 -127 0
G10 -127 0
G11 -127 0
G12 5 127
G13 5 127
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 11
length [second] : 18
from stage : 3
to stage : 1
$
G1 5 127
G3 5 127
G5 -127 0
G7 -127 0
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 12
length [second] : 18
from stage : 3

to stage : 2
$
G2 5 127
G4 5 127
G5 -127 0
G7 -127 0
G10 -127 0

$INTERSTAGE
INTERSTAGE_number : 13
length [second] : 18
from stage : 4
to stage : 5
$
G1 5 127
G3 5 127
G6 -127 0
G8 -127 0
G7 -127 0
G12 5 127
G13 5 127
G14 5 127
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 14
length [second] : 18
from stage : 4
to stage : 1
$
G1 5 127
G3 5 127
G6 -127 0
G7 -127 0
G8 -127 0
G9 5 127
G10 5 127
G11 5 127
G14 5 127
G15 -127 0

$INTERSTAGE
INTERSTAGE_number : 15
length [second] : 18

from stage : 4
to stage : 2
$
G2 5 127
G4 5 127
G9 5 127
G11 5 127
G6 -127 0
G7 -127 0
G8 -127 0
G14 5 127

$INTERSTAGE
INTERSTAGE_number : 16
length [second] : 18
from stage : 4
to stage : 3
$
G5 5 127
G6 -127 0
G8 -127 0
G9 5 127
G10 5 127
G11 5 127
G14 5 127

$INTERSTAGE
INTERSTAGE_number : 17
length [second] : 18
from stage : 5
to stage : 1
$
G9 5 127
G10 5 127
G11 5 127
G12 -127 0
G13 -127 0

$INTERSTAGE
INTERSTAGE_number : 18
length [second] : 18
from stage : 5

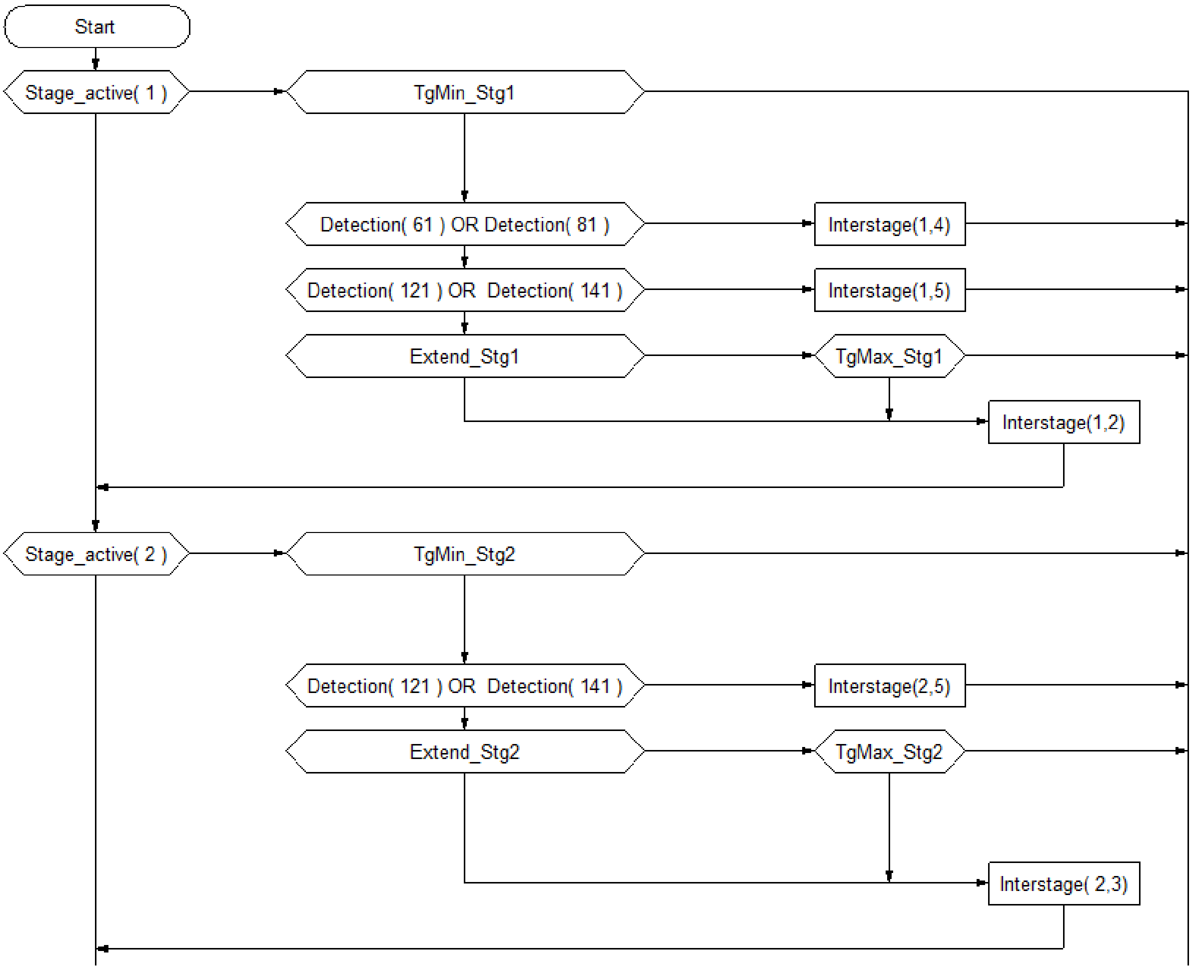
to stage : 2
$
G1 -127 0
G3 -127 0
G2 5 127
G4 5 127
G9 5 127
G11 5 127
G12 -127 0
G13 -127 0
G15 5 127

$INTERSTAGE
INTERSTAGE_number : 19
length [second] : 18
from stage : 5
to stage : 3
$
G1 -127 0
G3 -127 0
G5 5 127
G7 5 127
G9 5 127
G10 5 127
G11 5 127
G12 -127 0
G13 -127 0

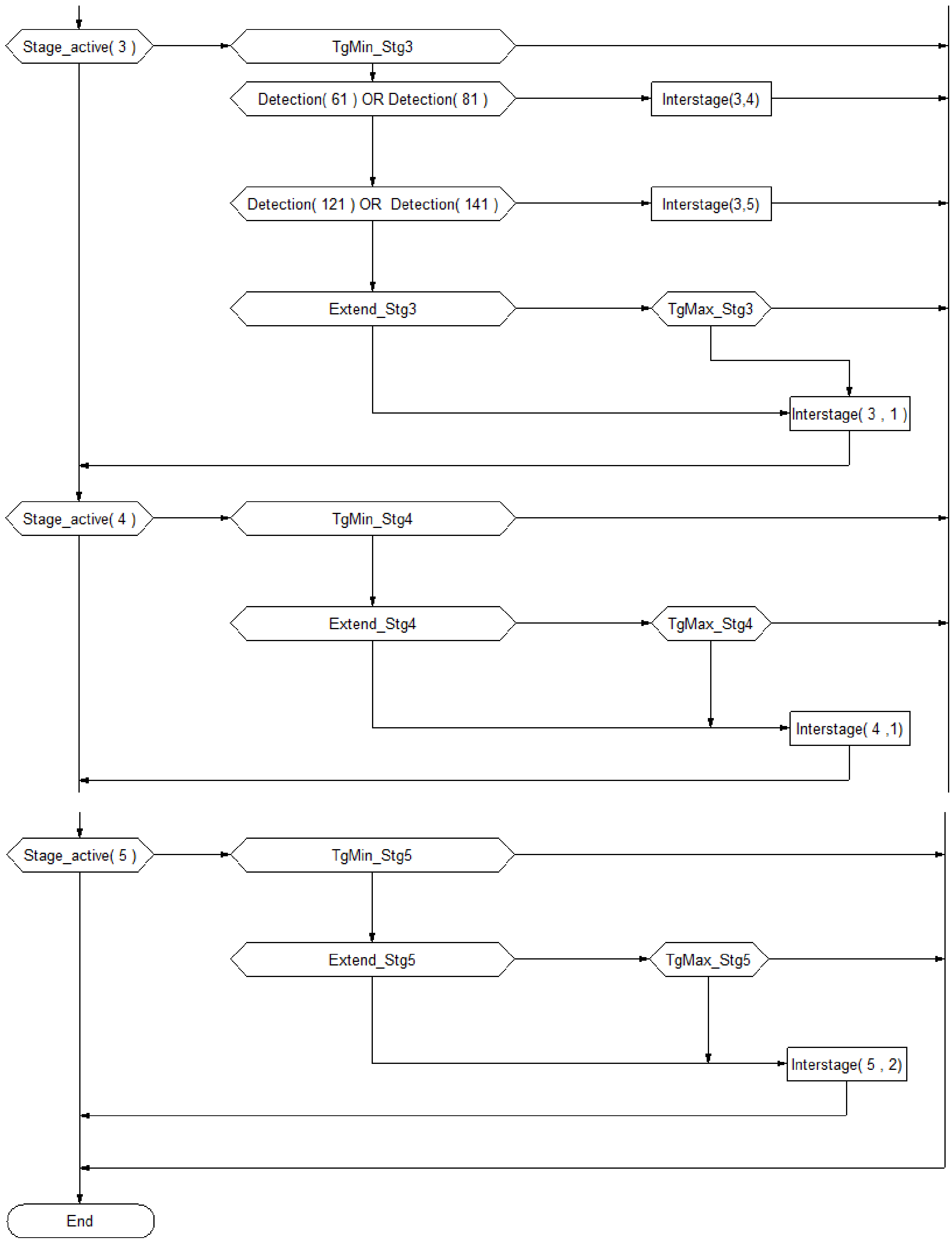
$INTERSTAGE
INTERSTAGE_number : 20
length [second] : 18
from stage : 5
to stage : 4
$
G1 -127 0
G3 -127 0
G6 5 127
G7 5 127
G8 5 127
G12 -127 0
G13 -127 0
G14 -127 0

G15 5 127

$END



Start
Stage_active(1)
TgMin_Stg1
Detection(61) OR Detection(81)
Interstage(1,4)
Detection(121) OR Detection(141)
Interstage(1,5)
Extend_Stg1
TgMax_Stg1
Interstage(1,2)
Stage_active(2)
TgMin_Stg2
Detection(121) OR Detection(141)
Interstage(2,5)
Extend_Stg2
TgMax_Stg2
Interstage(2,3)


Stage_active(3)
TgMin_Stg3
Detection(61) OR Detection(81)
Interstage(3,4)
Detection(121) OR Detection(141)
Interstage(3,5)
Extend_Stg3
TgMax_Stg3
Interstage(3 , 1)
Stage_active(4)
TgMin_Stg4
Extend_Stg4
TgMax_Stg4
Interstage(4 ,1)
Stage_active(5)
TgMin_Stg5
Extend_Stg5
TgMax_Stg5
Interstage(5 , 2)
End

Parameters	Gen	Comment
MAX_GAP	3	Max gap time for extending stage
TgMax_Stg1		Max green time for each stage

Expressions	Contents
Extend_Stg1	(Headway(11) <= MAX_GAP) OR (Headway(31) <= MAX_GAP)
Extend_Stg2	(Headway(21) <= MAX_GAP) OR (Headway(41) <= MAX_GAP)
Extend_Stg3	(Headway(51) <= MAX_GAP) OR (Headway(71) <= MAX_GAP)
Extend_Stg4	(Headway(61) <= MAX_GAP) OR (Headway(81) <= MAX_GAP)
Extend_Stg5	(Headway(121) <= MAX_GAP) OR (Headway(141) <= MAX_GAP)
TgMin_Stg1	(T_green(1) <= T_green_min(1)) & (T_green(3) <= T_green_min(3))
TgMin_Stg2	(T_green(2) <= T_green_min(2)) & (T_green(4) <= T_green_min(4))
TgMin_Stg3	(T_green(5) <= T_green_min(5)) & (T_green(7) <= T_green_min(7))
TgMin_Stg4	(T_green(6) <= T_green_min(6)) & (T_green(8) <=T_green_min(8))
TgMin_Stg5	(T_green(12) <= T_green_min(12)) & (T_green(13) <=T_green_min(13))
TgMax_Stg1	(T_green(1) <= 40) & (T_green(3) <= 40)
TgMax_Stg2	(T_green(2) <= 60) & (T_green(4) <= 30)
TgMax_Stg3	(T_green(5) <= 40) & (T_green(7) <= 40)
TgMax_Stg4	(T_green(6) <= 40) & (T_green(8) <= 40)
TgMax_Stg5	(T_green(12) <= 40) & (T_green(13) <= 40)

Appendix 3

Signal phasing for fixed signal control method

Critical lane groups

Identify the critical lane group in each phase.The flow ratio was calculated using the equation X and shown in appendix X

Stage 1:

Flow ratio for EB T and WB T are.

$$\text{EB T: } \frac{600}{1800} = 0.333\ ;\ \text{ WB T: } \frac{620}{1800} = 0.344$$

WB T is thus the critical lane group.

Stage 2:

Flow ratio for EB L and WB L are

$$\text{EB L: } \frac{500}{1800} = 0.27\ ;\ \text{ WB L: } \frac{150}{1800} = 0.08$$

EB L is thus the critical lane group.

Stage 3:

Flow ratio for SB T and NB T are.

$$\text{SB T: } \frac{350}{1800} = 0.16\ ;\ \text{ NB T: } \frac{180}{1800} = 0.1$$

SB T is thus the critical lane group.

Flow ratio

The sum of the flow ratios for the critical lane groups is shown below.

$$Y_c = \sum_{i=1}^{n} (\frac{v}{s})_{ci} = 0.344 + 0.27 + 0.194 = 0.808$$

Total lost time

For each stage, the total lost time

$$t_L = t_{sl} + t_{cl} = 4s$$

Therefore, the total lost time for a cycle is 12s (since there are 3 stages).

Minimum cycle length

The minimum cycle length can be calculated as follows, where $X_c = 0.9$

$$C_{min} = \frac{L \times X_c}{X_c - Y_c} = \frac{12 \times 0.9}{0.9 - 0.808} = 117.39\ s$$

The optimal cycle length can be calculated as follows.

$$C_{opt} = \frac{1.5L + 5}{1 - Y_c} = \frac{1.5 \times 12 + 5}{1 - 0.808} = 119.79\ s$$

By rounding up to 5s, the minimum cycle length is then 120s. Since the cycle length has changed slightly compared to Q3, we need to recalculate X_c using again the following equation.

$$C_{min} = \frac{L \times X_c}{X_c - Y_c}$$

$$120 = \frac{12X_c}{X_c - 0.808}$$

$$X_c = 0.89$$

Effective green time

The effective green times are.

Stage 1:

$$g_1 = \left(\frac{v}{s}\right)_{c1}\left(\frac{C}{X_c}\right) = 0.344 \times \frac{120}{0.89} = \mathbf{46.38s}$$

Stage 2:

$$g_2 = \left(\frac{v}{s}\right)_{c2}\left(\frac{C}{X_c}\right) = 0.27 \times \frac{120}{0.89} = \mathbf{36.40s}$$

Stage 3:

$$g_2 = \left(\frac{v}{s}\right)_{c2}\left(\frac{C}{X_c}\right) = 0.194 \times \frac{120}{0.89} = \mathbf{26.15}s$$

Effective green times

$$g = G + Y + AR - t_L$$

g = Effective green time for a traffic movement in seconds,

G = Displayed green time for atraffic movement in seconds,

Y= Displayed yellow time for a traffic movement in seconds (Assuming as 3s)

AR = Displayed all-red time in seconds. (Assuming as 2s)

t_L = Total lost time for a movement during a cycle in seconds

Displayed green time.

Stage 1

$$g_1 = G + Y + AR - t_L$$

$$46.38 = G + 3 + 2 - 4$$

Displayed green time for a traffic movement in seconds G_1 = 45.38s

Stage 2

$$g_2 = G + Y + AR - t_L$$

$$36.40 = G + 3 + 2 - 4$$

Displayed green time for a traffic movement in seconds G_2 = 35.4s

Stage 3

$$g_3 = G + Y + AR - t_L$$

$$26.15 = G + 3 + 2 - 4$$

Displayed green time for a traffic movement in seconds G_3 = 25.15s

$r + g = C$

g = Effective green time for a traffic movement in seconds,

C =cycle length in seconds.

Effective red times

$$r = R + t_L$$

r =effective red time for a traffic movement in seconds,

R = displayed red time for a traffic movement in seconds,

t_L= total lost time for a movement during a cycle in seconds

Stage 1

$$r_1 + g_1 = C$$

Effective red time

$$r_1 = 120 – 46.38$$

$$= 73.62s$$

$$r1 = R + t_L$$

Displayed red time for a traffic movement in seconds.

$$R_1 = 73.62 - 4$$

$$= 69.62s$$

Stage 2

$$r_2 + g_2 = C$$

Effective red time $r_2 = 120 – 36.40$

$$= 83.6s$$

$$r_2 = R + t_L$$

Displayed red time for a traffic movement in seconds.

$$R_2 = 83.6 - 4$$

$$= 79.6s$$

Stage 3

$$r_3 + g_3 = C$$

Effective red time $r_3 = 120 – 26.15$

$$= 93.85s$$

$$r_3 = R + t_L$$

Displayed red time for a traffic movement in seconds.

$$R_3 = 93.85 - 4$$

$$= 89.85s$$

Appendix 4

Vissim results

Average queue delay

			Queue delay		
Sim run	**Time interval**	**Data collection measurement**	**Scenario 1**	**Scenario 2**	**Scenario3**
Average	300-600	1: WBL	107.76	3.05	0.00
Average	300-600	2: WBI	14.65	13.55	17.93
Average	300-600	3: WBR	1.30	0.00	36.30
Average	300-600	4: SBI	3.10	0.03	9.02
Average	300-600	5: SBR	2.40	6.92	3.02
Average	300-600	6: EBL	72.72	31.41	14.17
Average	300-600	7: EBI	10.72	9.58	13.72
Average	300-600	8: EBR	0.25	0.00	0.13
Average	300-600	9: NBI	31.35	24.13	26.92
Average	300-600	10: Tram C-S	1.80	4.65	44.15
Average	300-600	11: Tram C-N	0.70	0.40	0.85
Average	300-600	12: Tram N-C	0.21	0.10	0.12
Average	300-600	13: Tram N-S	2.20	0.00	1.00
Average	300-600	14: Tram S-N	0.00	2.10	2.00
Average	300-600	15: Tram S-C	0.00	0.00	0.00
Average	300-600	16: EBLO	86.95	46.72	41.12
Average	300-600	17: SBO	101.82	26.70	33.67
Average	600-900	1: WBL	70.64	0.73	6.19
Average	600-900	2: WBI	32.32	11.24	19.76
Average	600-900	3: WBR	0.60	0.00	0.00
Average	600-900	4: SBI	118.13	19.08	0.08
Average	600-900	5: SBR	3.19	10.68	7.31
Average	600-900	6: EBL	18.68	1.78	21.66
Average	600-900	7: EBI	13.27	4.45	16.37
Average	600-900	8: EBR	1.83	0.00	14.62
Average	600-900	9: NBI	57.19	14.57	19.95
Average	600-900	10: Tram C-S	14.80	0.00	0.00
Average	600-900	11: Tram C-N	0.00	1.55	2.48
Average	600-900	12: Tram N-C	0.60	0.10	0.30
Average	600-900	13: Tram N-S	0.00	0.00	0.00
Average	600-900	14: Tram S-N	0.00	0.00	0.00
Average	600-900	15: Tram S-C	0.00	0.00	0.00
Average	600-900	16: EBLO	44.27	32.13	44.43
Average	600-900	17: SBO	135.67	39.52	36.15
Average	900-1200	1: WBL	23.89	0.70	3.91
Average	900-1200	2: WBI	16.34	21.09	18.63
Average	900-1200	3: WBR	0.40	0.00	48.70
Average	900-1200	4: SBI	37.18	0.12	0.11
Average	900-1200	5: SBR	0.15	4.08	5.73

Average	900-1200	6: EBL	33.19	14.76	12.82
Average	900-1200	7: EBI	4.50	19.93	13.09
Average	900-1200	8: EBR	0.00	0.00	2.40
Average	900-1200	9: NBI	32.36	23.96	31.38
Average	900-1200	10: Tram C-S	2.95	1.10	1.30
Average	900-1200	11: Tram C-N	0.40	0.70	0.00
Average	900-1200	12: Tram N-C	0.00	0.00	0.00
Average	900-1200	13: Tram N-S	1.60	0.00	0.00
Average	900-1200	14: Tram S-N	0.00	0.00	0.00
Average	900-1200	15: Tram S-C	1.90	1.40	1.50
Average	900-1200	16: EBLO	33.35	39.76	42.35
Average	900-1200	17: SBO	35.59	24.80	36.01
Average	1200-1500	1: WBL	93.07	15.30	1.01
Average	1200-1500	2: WBI	22.75	3.46	17.19
Average	1200-1500	3: WBR	1.86	0.50	0.90
Average	1200-1500	4: SBI	116.81	6.19	19.53
Average	1200-1500	5: SBR	1.43	7.39	9.52
Average	1200-1500	6: EBL	16.34	34.63	7.72
Average	1200-1500	7: EBI	9.24	4.01	24.06
Average	1200-1500	8: EBR	11.81	2.88	0.07
Average	1200-1500	9: NBI	42.86	10.77	19.45
Average	1200-1500	10: Tram C-S	0.00	1.20	1.20
Average	1200-1500	11: Tram C-N	0.80	0.10	0.50
Average	1200-1500	12: Tram N-C	0.32	0.1	0.18
Average	1200-1500	13: Tram N-S	0.00	0.00	0.00
Average	1200-1500	14: Tram S-N	1.25	1.25	1.25
Average	1200-1500	15: Tram S-C	1.90	1.50	1.70
Average	1200-1500	16: EBLO	50.69	54.64	37.85
Average	1200-1500	17: SBO	95.39	49.89	40.45
Average	1500-1800	1: WBL	24.57	3.89	1.79
Average	1500-1800	2: WBI	19.19	13.33	18.13
Average	1500-1800	3: WBR	0.90	0.00	0.00
Average	1500-1800	4: SBI	18.85	1.89	5.18
Average	1500-1800	5: SBR	1.14	8.16	7.51
Average	1500-1800	6: EBL	7.36	30.61	14.45
Average	1500-1800	7: EBI	10.97	11.87	15.56
Average	1500-1800	8: EBR	0.00	4.86	11.70
Average	1500-1800	9: NBI	39.11	8.02	18.67
Average	1500-1800	10: Tram C-S	5.44	1.70	16.10
Average	1500-1800	11: Tram C-N	1.10	0.94	2.84
Average	1500-1800	12: Tram N-C	0.00	0.30	0.30
Average	1500-1800	13: Tram N-S	0.00	0.00	0.00
Average	1500-1800	14: Tram S-N	0.00	0.00	0.00
Average	1500-1800	15: Tram S-C	0.85	0.40	0.20
Average	1500-1800	16: EBLO	21.98	43.53	34.98
Average	1500-1800	17: SBO	58.46	37.18	32.11

Average	1800-2100	1: WBL	39.78	0.00	0.00
Average	1800-2100	2: WBI	28.37	12.71	18.27
Average	1800-2100	3: WBR	14.06	15.58	9.92
Average	1800-2100	4: SBI	98.63	0.45	1.82
Average	1800-2100	5: SBR	0.09	7.69	15.51
Average	1800-2100	6: EBL	38.84	14.31	18.44
Average	1800-2100	7: EBI	24.41	13.36	19.97
Average	1800-2100	8: EBR	18.13	0.00	0.08
Average	1800-2100	9: NBI	51.61	21.52	24.20
Average	1800-2100	10: Tram C-S	0.68	0.72	0.94
Average	1800-2100	11: Tram C-N	0.70	0.88	1.79
Average	1800-2100	12: Tram N-C	0.45	0.30	0.00
Average	1800-2100	13: Tram N-S	0.69	0.94	1.25
Average	1800-2100	14: Tram S-N	0.00	0.00	0.00
Average	1800-2100	15: Tram S-C	2.00	1.50	1.90
Average	1800-2100	16: EBLO	49.58	30.63	33.49
Average	1800-2100	17: SBO	116.11	23.19	38.54
Average	2100-2400	1: WBL	27.94	0.52	2.78
Average	2100-2400	2: WBI	32.03	6.75	20.17
Average	2100-2400	3: WBR	2.38	7.30	19.63
Average	2100-2400	4: SBI	220.73	0.07	0.00
Average	2100-2400	5: SBR	3.70	5.19	5.59
Average	2100-2400	6: EBL	16.95	0.87	10.81
Average	2100-2400	7: EBI	24.38	7.46	6.48
Average	2100-2400	8: EBR	14.51	3.99	9.90
Average	2100-2400	9: NBI	144.50	13.06	33.46
Average	2100-2400	10: Tram C-S	22.10	10.90	18.45
Average	2100-2400	11: Tram C-N	0.00	0.00	0.00
Average	2100-2400	12: Tram N-C	10.60	0.40	0.40
Average	2100-2400	13: Tram N-S	0.00	0.00	0.00
Average	2100-2400	14: Tram S-N	1.50	1.30	1.30
Average	2100-2400	15: Tram S-C	1.11	0.97	2.45
Average	2100-2400	16: EBLO	92.39	15.19	40.53
Average	2100-2400	17: SBO	99.40	18.83	27.58
Average	2400-2700	1: WBL	42.23	0.00	0.00
Average	2400-2700	2: WBI	32.42	11.01	24.52
Average	2400-2700	3: WBR	0.30	34.30	32.28
Average	2400-2700	4: SBI	57.82	5.91	2.85
Average	2400-2700	5: SBR	5.88	7.74	3.96
Average	2400-2700	6: EBL	6.35	4.57	16.06
Average	2400-2700	7: EBI	14.88	10.05	19.64
Average	2400-2700	8: EBR	5.50	0.00	13.63
Average	2400-2700	9: NBI	74.81	36.07	24.38
Average	2400-2700	10: Tram C-S	0.00	1.20	1.20
Average	2400-2700	11: Tram C-N	0.76	0.84	1.24
Average	2400-2700	12: Tram N-C	0.20	0.25	17.40

Average	2400-2700	13: Tram N-S	0.55	0.63	0.97
Average	2400-2700	14: Tram S-N	0.40	0.10	0.85
Average	2400-2700	15: Tram S-C	0.00	0.00	0.00
Average	2400-2700	16: EBLO	36.47	33.59	35.64
Average	2400-2700	17: SBO	97.24	37.98	38.92
Average	2700-3000	1: WBL	25.71	0.41	0.97
Average	2700-3000	2: WBI	21.24	4.90	20.34
Average	2700-3000	3: WBR	0.60	17.95	28.70
Average	2700-3000	4: SBI	23.56	0.02	7.70
Average	2700-3000	5: SBR	2.03	6.83	2.84
Average	2700-3000	6: EBL	6.77	7.96	5.32
Average	2700-3000	7: EBI	22.51	10.18	14.30
Average	2700-3000	8: EBR	4.65	0.10	0.20
Average	2700-3000	9: NBI	45.38	37.70	18.07
Average	2700-3000	10: Tram C-S	2.60	3.15	4.22
Average	2700-3000	11: Tram C-N	1.20	5.55	14.15
Average	2700-3000	12: Tram N-C	0.56	0.30	0.30
Average	2700-3000	13: Tram N-S	1.90	1.20	1.50
Average	2700-3000	14: Tram S-N	1.50	1.40	0.00
Average	2700-3000	15: Tram S-C	0.00	0.00	0.00
Average	2700-3000	16: EBLO	32.42	38.18	37.53
Average	2700-3000	17: SBO	38.51	27.42	33.02
Average	3000-3300	1: WBL	148.68	30.99	10.83
Average	3000-3300	2: WBI	11.43	11.32	16.65
Average	3000-3300	3: WBR	0.00	0.00	7.27
Average	3000-3300	4: SBI	34.57	25.18	1.53
Average	3000-3300	5: SBR	1.79	7.50	12.23
Average	3000-3300	6: EBL	155.64	31.89	14.94
Average	3000-3300	7: EBI	7.42	2.34	6.97
Average	3000-3300	8: EBR	1.26	17.03	15.28
Average	3000-3300	9: NBI	20.22	6.65	14.72
Average	3000-3300	10: Tram C-S	8.20	3.20	5.70
Average	3000-3300	11: Tram C-N	0.90	0.25	10.40
Average	3000-3300	12: Tram N-C	0.50	0.58	0.10
Average	3000-3300	13: Tram N-S	0.00	0.00	0.00
Average	3000-3300	14: Tram S-N	5.20	4.70	21.70
Average	3000-3300	15: Tram S-C	0.00	0.00	0.00
Average	3000-3300	16: EBLO	110.01	44.96	35.49
Average	3000-3300	17: SBO	109.51	70.72	35.01

Average queue length

			Queue length		
Sim run	**Time interval**	**Data collection measurement**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Average	300-600	1: WBL	12.86	6.44	2.46
Average	300-600	2: WBI	7.38	10.25	15.18
Average	300-600	3: WBR	0.35	0.11	1.02
Average	300-600	4: SBI	19.35	8.44	6.77
Average	300-600	5: SBR	0.28	1.00	0.52
Average	300-600	6: EBL	32.45	21.89	13.67
Average	300-600	7: EBI	9.88	12.96	19.22
Average	300-600	8: EBR	0.47	0.11	5.54
Average	300-600	9: NBI	7.54	5.96	9.58
Average	300-600	10: Tram S-N	2.45	5.63	0.36
Average	300-600	11: Tram S-C	5.39	3.52	4.45
Average	300-600	12: Tram C- S	0.79	6.67	11.62
Average	300-600	14: Tram C-N	3.52	1.23	2.70
Average	300-600	15: Tram N-C	15.43	4.84	8.54
Average	300-600	16: Tram N-S	6.26	4.79	7.78
Average	300-600	17: EBLO	7.49	1.10	0.05
Average	300-600	18: SBO	3.27	0.68	0.29
Average	600-900	1: WBL	10.92	4.83	8.33
Average	600-900	2: WBI	17.52	9.68	14.18
Average	600-900	3: WBR	0.02	0.01	0.02
Average	600-900	4: SBI	13.57	5.05	4.41
Average	600-900	5: SBR	0.81	2.90	1.65
Average	600-900	6: EBL	10.43	4.79	17.26
Average	600-900	7: EBI	13.85	8.65	16.00
Average	600-900	8: EBR	1.07	0.73	1.92
Average	600-900	9: NBI	8.56	4.49	9.52
Average	600-900	10: Tram S-N	0.01	0.00	0.02
Average	600-900	11: Tram S-C	0.02	0.02	0.42
Average	600-900	12: Tram C- S	4.60	0.42	1.76
Average	600-900	14: Tram C-N	0.00	0.00	0.00
Average	600-900	15: Tram N-C	0.52	0.49	5.00
Average	600-900	16: Tram N-S	0.00	0.00	0.00
Average	600-900	17: EBLO	1.08	0.00	0.31
Average	600-900	18: SBO	13.01	0.43	0.00
Average	900-1200	1: WBL	7.46	1.48	5.90
Average	900-1200	2: WBI	8.14	15.10	16.28
Average	900-1200	3: WBR	0.01	0.00	0.01
Average	900-1200	4: SBI	9.47	4.47	2.78
Average	900-1200	5: SBR	0.19	0.33	0.85
Average	900-1200	6: EBL	13.49	11.27	11.14

Average	900-1200	7: EBI	7.06	21.04	22.58
Average	900-1200	8: EBR	0.62	1.45	2.27
Average	900-1200	9: NBI	6.36	9.60	12.38
Average	900-1200	10: Tram S-N	0.52	1.00	0.75
Average	900-1200	11: Tram S-C	3.18	2.93	6.10
Average	900-1200	12: Tram C- S	0.00	6.62	9.78
Average	900-1200	14: Tram C-N	0.00	2.42	0.00
Average	900-1200	15: Tram N-C	0.00	0.00	0.00
Average	900-1200	16: Tram N-S	0.42	0.00	0.00
Average	900-1200	17: EBLO	0.31	0.79	0.12
Average	900-1200	18: SBO	1.40	0.58	0.00
Average	1200-1500	1: WBL	11.30	8.98	5.83
Average	1200-1500	2: WBI	12.03	6.87	12.62
Average	1200-1500	3: WBR	0.00	0.00	0.00
Average	1200-1500	4: SBI	15.64	8.09	7.75
Average	1200-1500	5: SBR	0.19	1.34	1.98
Average	1200-1500	6: EBL	8.21	17.25	10.47
Average	1200-1500	7: EBI	9.65	8.20	22.13
Average	1200-1500	8: EBR	5.10	3.89	3.99
Average	1200-1500	9: NBI	4.73	3.14	7.29
Average	1200-1500	10: Tram S-N	2.16	4.32	7.22
Average	1200-1500	11: Tram S-C	2.07	2.56	12.01
Average	1200-1500	12: Tram C- S	0.00	5.08	7.62
Average	1200-1500	14: Tram C-N	0.00	0.00	0.00
Average	1200-1500	15: Tram N-C	0.00	0.00	0.00
Average	1200-1500	16: Tram N-S	0.00	0.00	0.00
Average	1200-1500	17: EBLO	1.82	0.37	0.03
Average	1200-1500	18: SBO	6.99	0.00	0.00
Average	1500-1800	1: WBL	1.66	7.42	2.75
Average	1500-1800	2: WBI	9.14	8.50	13.38
Average	1500-1800	3: WBR	0.89	0.00	0.89
Average	1500-1800	4: SBI	5.83	7.36	5.64
Average	1500-1800	5: SBR	0.17	0.86	1.24
Average	1500-1800	6: EBL	5.73	19.46	12.29
Average	1500-1800	7: EBI	16.29	13.46	23.54
Average	1500-1800	8: EBR	3.24	2.71	5.17
Average	1500-1800	9: NBI	7.61	3.41	10.22
Average	1500-1800	10: Tram S-N	0.00	0.00	0.00
Average	1500-1800	11: Tram S-C	0.00	0.00	0.00
Average	1500-1800	12: Tram C- S	0.00	1.91	4.87
Average	1500-1800	14: Tram C-N	1.93	0.00	0.00
Average	1500-1800	15: Tram N-C	3.28	3.91	2.95
Average	1500-1800	16: Tram N-S	0.00	0.00	0.00
Average	1500-1800	17: EBLO	0.00	0.30	0.84
Average	1500-1800	18: SBO	3.49	0.00	0.00
Average	1800-2100	1: WBL	4.92	1.02	1.39

Average	1800-2100	2: WBI	13.39	10.63	14.32
Average	1800-2100	3: WBR	2.33	1.35	0.11
Average	1800-2100	4: SBI	13.74	3.67	6.64
Average	1800-2100	5: SBR	0.02	1.49	2.74
Average	1800-2100	6: EBL	22.40	12.05	16.10
Average	1800-2100	7: EBI	20.40	16.96	18.75
Average	1800-2100	8: EBR	4.14	2.86	1.54
Average	1800-2100	9: NBI	13.93	8.66	10.58
Average	1800-2100	10: Tram S-N	0.00	0.00	0.00
Average	1800-2100	11: Tram S-C	0.85	0.85	6.22
Average	1800-2100	12: Tram C- S	0.00	0.00	0.00
Average	1800-2100	14: Tram C-N	0.52	0.00	0.00
Average	1800-2100	15: Tram N-C	4.01	2.51	0.00
Average	1800-2100	16: Tram N-S	0.00	0.00	0.00
Average	1800-2100	17: EBLO	0.69	1.18	2.14
Average	1800-2100	18: SBO	11.01	0.29	0.00
Average	2100-2400	1: WBL	3.69	3.00	3.25
Average	2100-2400	2: WBI	13.35	6.85	16.22
Average	2100-2400	3: WBR	1.52	0.55	2.66
Average	2100-2400	4: SBI	20.19	2.56	2.50
Average	2100-2400	5: SBR	1.08	0.59	1.79
Average	2100-2400	6: EBL	7.47	4.41	9.40
Average	2100-2400	7: EBI	17.18	6.93	15.67
Average	2100-2400	8: EBR	3.82	2.59	7.71
Average	2100-2400	9: NBI	45.71	1.29	11.00
Average	2100-2400	10: Tram S-N	2.15	2.15	2.15
Average	2100-2400	11: Tram S-C	0.00	0.00	0.00
Average	2100-2400	12: Tram C- S	2.88	0.00	0.00
Average	2100-2400	14: Tram C-N	0.00	0.00	0.00
Average	2100-2400	15: Tram N-C	11.34	5.80	17.02
Average	2100-2400	16: Tram N-S	0.00	0.00	0.00
Average	2100-2400	17: EBLO	4.91	0.00	0.28
Average	2100-2400	18: SBO	7.43	0.29	0.00
Average	2400-2700	1: WBL	2.54	1.53	3.33
Average	2400-2700	2: WBI	13.55	9.93	13.28
Average	2400-2700	3: WBR	0.71	0.02	0.14
Average	2400-2700	4: SBI	12.16	7.92	8.48
Average	2400-2700	5: SBR	0.46	1.07	0.54
Average	2400-2700	6: EBL	5.86	7.38	15.27
Average	2400-2700	7: EBI	11.34	9.00	13.44
Average	2400-2700	8: EBR	1.70	1.28	1.51
Average	2400-2700	9: NBI	19.74	3.84	9.26
Average	2400-2700	10: Tram S-N	3.57	2.17	9.80
Average	2400-2700	11: Tram S-C	0.00	0.00	0.00
Average	2400-2700	12: Tram C- S	0.00	10.69	1.96
Average	2400-2700	14: Tram C-N	0.00	0.00	0.00

Average	2400-2700	15: Tram N-C	1.19	3.28	12.32
Average	2400-2700	16: Tram N-S	0.00	0.00	0.00
Average	2400-2700	17: EBLO	0.01	0.75	0.46
Average	2400-2700	18: SBO	6.24	1.76	0.00
Average	2700-3000	1: WBL	4.05	4.22	4.55
Average	2700-3000	2: WBI	9.96	6.73	13.17
Average	2700-3000	3: WBR	0.05	0.03	0.03
Average	2700-3000	4: SBI	2.97	2.70	4.69
Average	2700-3000	5: SBR	0.19	1.34	0.14
Average	2700-3000	6: EBL	6.95	7.77	8.02
Average	2700-3000	7: EBI	15.56	8.55	14.32
Average	2700-3000	8: EBR	2.38	4.10	5.81
Average	2700-3000	9: NBI	19.74	5.32	10.40
Average	2700-3000	10: Tram S-N	1.90	2.40	0.00
Average	2700-3000	11: Tram S-C	0.00	0.00	0.00
Average	2700-3000	12: Tram C- S	2.10	0.00	0.00
Average	2700-3000	14: Tram C-N	0.66	3.66	4.18
Average	2700-3000	15: Tram N-C	0.00	1.98	0.79
Average	2700-3000	16: Tram N-S	0.00	0.00	0.00
Average	2700-3000	17: EBLO	0.00	0.00	1.15
Average	2700-3000	18: SBO	3.27	0.28	0.00
Average	3000-3300	1: WBL	13.08	11.22	6.83
Average	3000-3300	2: WBI	6.05	9.55	10.76
Average	3000-3300	3: WBR	0.00	0.00	0.02
Average	3000-3300	4: SBI	25.92	11.51	5.60
Average	3000-3300	5: SBR	0.25	1.53	2.88
Average	3000-3300	6: EBL	65.50	23.16	16.48
Average	3000-3300	7: EBI	8.25	7.74	10.61
Average	3000-3300	8: EBR	0.62	2.49	1.46
Average	3000-3300	9: NBI	6.75	2.41	8.00
Average	3000-3300	10: Tram S-N	2.54	2.28	11.11
Average	3000-3300	11: Tram S-C	0.00	0.00	0.00
Average	3000-3300	12: Tram C- S	3.28	0.00	0.00
Average	3000-3300	14: Tram C-N	0.00	0.00	0.00
Average	3000-3300	15: Tram N-C	3.35	0.00	2.36
Average	3000-3300	16: Tram N-S	0.00	0.00	0.00
Average	3000-3300	17: EBLO	6.42	0.40	0.65
Average	3000-3300	18: SBO	2.73	0.00	0.00

Vehicle travel time

			Vehicle travel time		
Sim run	Time interval	Data collection measurement	Scenario 1	Scenario 2	Scenario 3
Average	300-600	1: WB	60.25	53.14	66.24
Average	300-600	2: EB	60.65	49.73	64.27
Average	300-600	3: NB	63.14	51.17	66.74
Average	300-600	4: SB	47.88	29.85	53.98
Average	600-900	1: WB	75.50	51.41	67.56
Average	600-900	2: EB	64.52	43.37	69.29
Average	600-900	3: NB	79.66	35.88	54.49
Average	600-900	4: SB	195.69	37.92	47.38
Average	900-1200	1: WB	61.69	64.09	61.13
Average	900-1200	2: EB	52.85	60.81	64.29
Average	900-1200	3: NB	58.86	39.01	51.27
Average	900-1200	4: SB	72.97	44.01	40.79
Average	1200-1500	1: WB	67.73	41.87	66.39
Average	1200-1500	2: EB	57.69	41.31	77.94
Average	1200-1500	3: NB	57.00	32.75	56.00
Average	1200-1500	4: SB	149.18	56.17	79.32
Average	1500-1800	1: WB	67.30	56.98	66.21
Average	1500-1800	2: EB	59.92	51.17	65.92
Average	1500-1800	3: NB	51.89	28.69	55.28
Average	1500-1800	4: SB	77.89	41.69	51.35
Average	1800-2100	1: WB	73.55	53.89	67.41
Average	1800-2100	2: EB	76.49	55.81	69.56
Average	1800-2100	3: NB	87.89	35.67	39.00
Average	1800-2100	4: SB	167.42	37.07	70.46
Average	2100-2400	1: WB	78.48	47.84	71.47
Average	2100-2400	2: EB	77.69	46.89	56.48
Average	2100-2400	3: NB	128.72	12.30	57.83
Average	2100-2400	4: SB	407.30	39.74	52.57
Average	2400-2700	1: WB	79.19	51.04	76.36
Average	2400-2700	2: EB	67.88	42.15	71.69
Average	2400-2700	3: NB	57.43	38.87	59.01
Average	2400-2700	4: SB	146.91	36.85	54.30
Average	2700-3000	1: WB	70.50	51.42	69.09
Average	2700-3000	2: EB	72.07	53.77	64.36
Average	2700-3000	3: NB	53.48	43.34	58.99
Average	2700-3000	4: SB	71.86	35.65	62.87
Average	3000-3300	1: WB	55.74	49.68	64.08
Average	3000-3300	2: EB	56.30	39.09	58.24
Average	3000-3300	3: NB	58.57	28.42	57.57
Average	3000-3300	4: SB	58.82	50.03	54.81