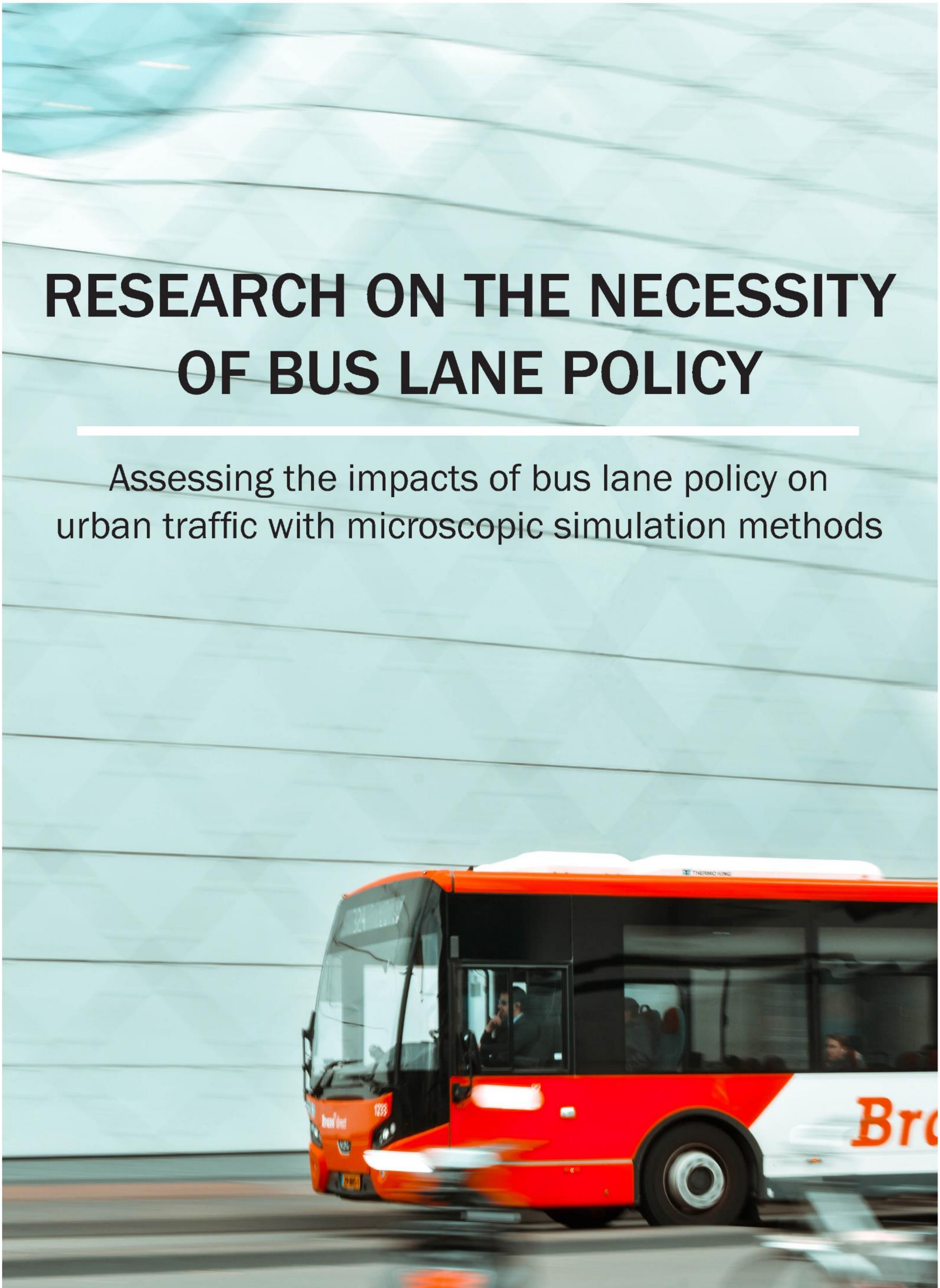
RESEARCH ON THE NECESSITY OF BUS LANE POLICY

Assessing the impacts of bus lane policy on urban traffic with microscopic simulation methods



Haoke Ji | 2020 - 2021

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RESEARCH ON THE NECESSITY OF BUS LANE POLICY

Assessing the impacts of bus lane policy on urban traffic with microscopic simulation methods

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Master Thesis

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PREFACE

Dear reader,

I am glad you could take some time to read my thesis which represents my final result as a master student from Construction Management and Engineering at Eindhoven University of Technology. In the past two years, from a stranger to this country at the beginning to gradually got to know people and find what I want to do, it was growth filled with excitement and challenges. Through the way of doing this research, it is truly a process to think about the relation between people and cities, and this is where my interest lies. Innovative technologies are always there but they can only make values when they are actually used by smart cities.

This work would not have been done without help from many people. First, I wish to thank my supervisors, Dr. Dujuan Yang and Ir. Miloš Viktorović not only for their critical feedback and assistance on the thesis but also for their sincere concerns and encouragements as friends. Without them, this work would not be achieved in any way. Besides, I also want to thank Dr. Seheon Kim from the Urban Planning group who helped me to extract valuable data. Moreover, I would like to thank my CME fellows and friends, Hua Du, Jianli Zhai, Siddharth Panjwani, Xiuxian Huang, and Xingyu Piao, for their comments on the thesis. The insights and experience from these people added considerable value to the work. Last, I want to explicitly express my gratitude to the people I love, my family and my girlfriend Kexin, their strong support stimulates me to accomplish this. Thank you!

This year is an unusual year which is full of unexpected things. We experience together, suffer together, overcome together, and grow together, which I will never forget in my life. But one thing without doubt is that I am really lucky to meet so many kindhearted and sincere people to help me get over all the troubles, such as this master thesis.

Finally, I hope you could get some inspirations from this work. Enjoy!

Eindhoven, September 2020

Haoke Ji

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TABLE OF CONTENTS

SUMMARY

To alleviate the increasing pressure brought by road transport on urban traffic system, development of the public transport has been emphasized a lot in many places. Especially the development of bus priority has become the guiding ideology of urban transportation development (Ye & Ma, 2013). Among different bus priority measures implemented around the world, the dedicated bus lane is one of the most effective, convenient and cost-efficient approaches to realize the bus priority by providing buses with road rights, especially an exclusive lane, over private traffic. Although the bus lane system succeeds in significantly improving the performance of bus services, enhancing public transit attractiveness and further encouraging transport participants to switch from passenger cars to public transport, the concern about the overemphasis on the public transport and its excessive occupation of road resources has been rising in recent years (Anderson & Geroliminis, 2020; Princeton & Cohen, 2011; Xie et al., 2012). Therefore, an appropriate discussion on the opening degree of the bus lane, namely the balance between private and public transport, has been performed in this research with the main research question:

How to evaluate the bus lane policy based on data from different sources through simulation methodology?

In this regard, an evaluation of the bus lane policies was defined as the research objective and the research goals were summarized as: establishing an integrated framework coupling several models; evaluating the bus lane policy alternatives from multiple perspectives; finding a more competitive scenario that improves the private traffic performance while maintains the current bus service performance.

In order to identify appropriate simulation tools, a thorough literature review has been performed regarding three different types of simulation models: traffic flow simulation, vehicle emission simulation, and air quality simulation. Not only the state-of-the-art of each simulation theory was reviewed but also the experiences from other studies about the integration of simulation models were summarized. Most microscopic traffic flow models were usually coupled with instantaneous emission models, but the trend changed when the air quality simulation was included in the integration that researchers preferred to use average-speed emission models and near-source dispersion models but no preference was shown in terms of traffic flow simulation. Based on the exploration on the existing studies and the research goals, selection standards of simulation models have been determined: firstly, the simulation tools should be open-source and can provide the necessary functions to achieve an accurate simulation; secondly, the selected tools could reflect the characteristics of the study case; finally, the correlation between selected models should be significant and reliable so that they can be integrated. Thus, research gaps regarding lack of diversity in bus lane policies; insufficient adoption of data; limited expansion based on instantaneous emission models; and lack of framework analysis have been identified.

With a strong theoretical basis and clear guidelines, an open-source architecture that couples three models: a microscopic traffic simulator (SUMO), a Dutch instantaneous emission model (VERSIT+) and a pollutant concentration simulator (GRAL) was presented as the principle research methodology. The integrated modelling framework was set up based on data from both external data sources and internal simulated results. The former one included multiple sources for each simulation model: network configuration, traffic demand (of public and private transport) for traffic simulation, emission class and emission factor of Dutch vehicles for vehicle emission simulation, and meteorological parameters (wind speed and wind direction) and infrastructure design parameters (roadside buildings and vegetations) for air quality modelling. The latter one acted as the key components to link three models that *total driven mileage* imported information of traffic modelling to vehicle emission modelling, and *emission source intensity* used outputs of traffic and vehicle emission modelling to generate input for air quality modelling. As the main contribution of this research, the integration system successfully connected three simulation models from different fields based on a reliable data flow through microscopic simulation methodology.

After mapping out the appropriate simulation flow, a case area was selected to study the current bus lane policy and its influence on urban traffic, vehicle emissions, and roadside air quality. As a critical urban

arterial in the Eindhoven urban area, the Veldmaarschalk Montgomerylaan street and its neighbouring blocks which account for around 2.2 square kilometres were chosen. The road connected the city centre with the Woensel area and bore a traffic volume of thousands of passenger cars per day. There were seven bus lines (i.e., line 2, 3, 9, 322, 400, 405, 406) and five bus stops on the road, and hundreds of bus trips passed through the road every day. The traffic situations in this small area have been simulated from 06:30 to 19:00 on a typical weekday, covering peak and daytime off-peak hours. At the same time vehicle emissions were calculated on those streets where vehicles passed, and the air quality computation was performed at two road segments (street canyons) and one intersection on the Veldmaarschalk Montgomerylaan street. Generally speaking, under the current bus lane policy, the traffic flow did not fluctuate much before evening peak but experienced a dramatic increase around 18 o'clock, which brought the corresponding lowest average speed. Although the computed vehicle emissions could not show the variation in time series, the simulated emission results have indicated that the Veldmaarschalk Montgomerylaan street suffered more vehicle pollution than other roads. Furthermore, the roadside air quality of the Veldmaarschalk Montgomerylaan street was represented by the distribution of pollutant CO concentrations and implied that the air quality in the intersection area was better than that of the two street canyons and the closer to the city centre, the more polluted the streets would be. Moreover, the simulation results based on the current bus lane policy have been validated by actual situations from the perspectives of bus operating deviation time and monitored air quality. With the successful adoption of the integrated modelling framework, the baseline scenario in the selected modelling domain with high spatial resolution under the current bus lane policy has been set up.

Different traffic management scenarios have been distinguished and compared with the introduction of the dynamic bus lane (DBL) and adaptive traffic light (ATL) strategies to discuss the necessity of the current bus lane policy. Both strategies were developed from the traffic simulation perspective and were implemented through modifying parameters in SUMO. The first strategy, dynamic bus lane, was designed to change the accessibility of the dedicated bus lane to passenger cars by allowing them to drive on the lanes during specific periods of a day. It was therefore able to change the route choices of passenger car drivers. Moreover, the second strategy, adaptive traffic light, aimed to improve the efficiency of vehicles to pass through the intersections by considering the traffic volume in different directions. The DBL strategy has explored the potential of road capacity while the ATL system was used as a compensation measure to mitigate the impact of additional vehicles on buses. The simulation results of the baseline scenario, as well as other five designed scenarios were then reviewed and compared from two perspectives: (a) traffic situations and (b) vehicle emission and air quality situations: the traffic situations about the *traffic volume* and *average speed* in time series of the whole road network, and also the private and public transport performance on the Veldmaarschalk Montgomerylaan road have been extracted and investigated under each scenario. Furthermore, the vehicle emissions and air quality in selected modelling domains on the Veldmaarschalk Montgomerylaan road were presented as supplementary evidence. For the selected urban road network, the scenario which allowed private traffic to access the bus lane during off-peak hours and employed the adaptive traffic light system was the most feasible schema which found a balanced resource allocation point between public and private transport and improved the traffic flow performance and air quality. The findings of the research also proved that the dedicated bus lane policy was not suitable for every area. By repeating the established simulation flow under different traffic management scenarios, it has also been proved that the integrated framework permitted the prediction of changes in urban traffic, vehicle emissions, and air quality.

To summarize, this thesis started with a daily phenomenon of inefficient use of bus lanes and attempted to debate the necessity of completely separating buses and cars under the current bus lane policy. This goal was achieved by setting up an evaluation framework based on the microscopic simulation methodology, and review and comparison of alternative bus lane policies. With the findings of the thesis, it can be conclusively stated that before implementing public transport priority measures (the dedicated bus lane), a careful analysis must be carried out.

ABSTRACT

The impact of public transport priority measures, especially the dedicated bus lane, on urban traffic is an increasing topic of interest. This paper contributed to discuss the necessity of the dedicated bus lane on an urban arterial. In order to comprehensively evaluate the current bus lane policy, three different perspectives, namely traffic flow, vehicle emission, and air quality, were identified. Correspondingly, three microscopic simulators (SUMO, VERSIT+, and GRAL) were chosen. Based on the reliable data flow and efficient data preparation, an integrated modelling framework was introduced which can generate various measurement indices such as traffic volume comparison, bus deviation time, street vehicle emissions, and pollutant concentration distributions. Afterwards, an urban road in Eindhoven, the Netherlands, that includes the dedicated bus lane was selected to set up the baseline scenario. Bus trips and car trips were simulated from 06:30 to 19:00 on a typical weekday, as well as the corresponding vehicle emissions and air quality. Furthermore, by changing the accessibility of the bus lane to private vehicles and setting up the adaptive traffic lights, in total five possible bus lane policy alternatives were created and analyzed. By comparing the performance from different perspectives under each scenario, a significant improvement regarding the traffic performance and matching vehicle emissions and air quality in the modelling domain was found when the bus lane was set as a dynamic bus lane and the adaptive traffic light system was employed.

Keywords: Dynamic bus lane, Adaptive traffic light, Microscopic simulation methodology, SUMO, Urban traffic, Vehicle emission, Air quality

LIST OF ABBREVIATIONS

ALBATROSS	A Learning BAsed TRansportation Oriented Simulation System
BAA	Bus Advance Area
BC	Black Carbon
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
CTM	Chemical Transport Model
DBL	Dynamic Bus Lane
DPF	Diesel Particulate Filter
DT	Dwell Time
DUE	Dynamic User Equilibrium
HOF	Half Open Particulate Filter
LPG	Liquefied Petroleum Gas
OSM	Open Street Map
PCA	Postal Code Area
QT	Queuing Time
SUE	Stochastic User Equilibrium
TAZ	Traffic Analysis Zone
TBST	Total Bus Stop Time
TCP	Transmission Control Protocol
TraCI	Traffic Control Interface
VGI	Volunteered Geographic Information
VIT	Vehicle-Induced Turbulence
VKT	Vehicle Kilometres Travelled
VOC	Volatile Organic Compound

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

- 1.1 Background
- 1.2 Research Question
- 1.3 Research Guide

1.1 BACKGROUND

With the worldwide deepening of urbanization, road transport in urban areas is facing increasing pressure, which has caused not only the traffic congestions but also brought an adverse impact on the environment.

Due to these reasons, public transport has been emphasized a lot with the expectation to alleviate and reverse both adverse trends. Among the public transport planning measures, the development of bus priority has become the guiding ideology of urban transportation development (Ye & Ma, 2013). A considerable number of different bus priority schemes have been implemented in many urban areas around the world to enhance bus attractiveness and improve its competitiveness over private traffic (Shalaby, 1999). Basically, these traffic management measures, including bus gates, transit malls, dedicated bus lanes, priority signals, and etc., aim to offer priority treatment to the movement of public transport, especially buses through the road network. (Alam et al., 2014; Ben-Dor et al., 2018; KIM, 2003).

Among these schemas, the dedicated bus lane is one of the most effective, convenient and cost-efficient approaches to realise the bus priority (KIM, 2003; Ye & Ma, 2013). By providing buses with road rights, especially a dedicated lane, over private traffic, the bus lane system can significantly improve the performance of bus services and enhance transit attractiveness while encouraging transport participants to switch from passenger cars to public transport. Consequently, the performance of the region traffic system can be improved by reducing travel times, improving traffic efficiency, relieving urban congestions, and reducing vehicle emissions (Ben-Dor et al., 2018; Y. Chen et al., 2016; Xu et al., 2013).

However, every coin has two sides and so does the public transport system. Many researchers have pointed out that the excessive investment of road resources in public transport can cause a series of problems. Princeton & Cohen (2011) found in their case that the operation of dedicated bus lane on an urban motorway could not achieve its goal, i.e., reducing travel times for taxis and buses, which was caused by the fact that these vehicles still entered in pre-existing congestions on the dedicated lane. Xie et al., (2012) argued that dedicated bus lanes have certain limitations because the lane reduction limits the available capacity for the general traffic and turned to the dynamic lane allocation strategy which was called bus lanes with intermittent priorities (BLIPs) to improve bus transit. Anderson & Geroliminis (2020) stressed that complete separation of buses and cars may not be necessary particularly when the frequency of buses is not high and mixed traffic operation can work reasonably well until the road becomes congested.

In other words, circumstances exist where buses would take up too much road space but underutilize it in some regions of low bus frequencies, which is also seen in the study area on the bus lane of Veldmaarschalk Montgomerylaan road in Eindhoven. Therefore, an appropriate discussion on the opening degree of the bus lane, namely the balance between private and public transport, is conducted in this research, aiming to provide buses with the benefits of the current bus lane policy while reducing its intrusion on private traffic resources. Moreover, the research goals can be summarized as:

- Establish an integrated framework coupling several models;
- Evaluate the bus lane policy alternatives from multiple perspectives;
- Find a more competitive scenario that improves the private traffic performance while maintains the current bus service performance.

Based on the discussion above, the research object is defined as the evaluation on the bus lane policies, while the impact of these traffic management schemas on the traffic performance as well as the ambient environment will be measured and compared. In addition, to mitigate the deteriorating effect by introducing additional vehicles in the bus lane, one public transport priority measure, priority signal, will be adopted as a compensation measure.

1.2 Research Question

The balance between public transport and private traffic, especially the overemphasis on the priority of public transport, has attracted a lot of interests, which brings the main research question in this research:

> *How to evaluate the bus lane policy based on data from different sources through simulation methodology?*

Following sub questions are proposed to answer the main question::

1. *From what perspectives can the impact of the bus lane policy be evaluated? What simulators are present in the market that are suitable for the research?*
2. *How to establish an integrated framework based on the selected simulation models?*
3. *What available data sources are suitable to be used, and how can the data be prepared?*
4. *What is the situation under the current bus lane policy in the simulation environment?*
5. *Is there any suitable alternative policy can be established in the microscopic simulation, and what are the impacts of these alternatives compared with the current bus lane policy?*

Content-wise, the study will be constructed by answering these questions. Namely, the literature review can answer the first sub-question to lay the theoretical foundation and indicate the proper simulation tools. Next, aiming at the second question, the methodology chapter gives the description of the general approach of the research and focuses on explaining the way of coupling simulation models based on the integrated modelling framework. For the third sub-question, the process of data preparation will be discussed thoroughly to find suitable data sources. Afterwards, to answer the fourth question, the established framework will be put into practice to set up the baseline scenario after designating the study area. The fifth question can only be answered by conducting a scenario analysis which considers five additional traffic management scenarios to predict the changes in traffic flow, vehicle emissions, and air quality. Finally, the concluding chapter will be given to answer the main research question by summarizing all the sub-questions.

By fulfilling the questions, the main contributions of the paper include:

- An integrated framework for coupling microscopic traffic model, vehicle emission model, and air quality model is generated. It identifies multiple external data sources for each simulator and includes equations for computing *total driven mileage* (including *vehicle count* and *street length*) and *emission source intensity* (consists of *average emission rate* and *emission modulation factors*). The framework connects three models to simulate different traffic behaviours in the network and corresponding vehicle emissions and air quality.
- For a small urban traffic network, different traffic scenarios (based on the combination of the dynamic bus lane and adaptive traffic light strategies) are distinguished and compared. The traffic situations about the traffic volume and average speed with time series in the whole study area and also the private and public transport performance on the Veldmaarschalk Montgomerylaan road are extracted and investigated under each scenario. Furthermore, the air quality in selected modelling domains on the Veldmaarschalk Montgomerylaan road is presented as supplementary evidence.

1.3 Reading Guide

The remainder of the thesis is organised as follows: Chapter 2 (literature review) starts from the methodology perspective to describe the state-of-the-art traffic flow modelling, vehicle emission modelling, and a necessary extension, air quality modelling. In addition, the current research progress of the integration of the simulation models is discussed and the research gaps are summarized. In order to clarify the key components of the thesis, Chapter 3 (methodology) illustrates the general approach of the thesis and explains the integrated framework which couples all simulation models and generates various measurement indices. Chapter 4 (data preparation) points out the appropriate external data sources for each simulation model. By designating a study area, Chapter 5 (case study) explains the detailed process of implementing the integrated framework and generating simulation results to set up the baseline scenario. With the successful implementation of the framework, five additional scenarios are simulated in Chapter 6 (scenario analysis) based on the dynamic bus lane and adaptive traffic light strategies. Lastly, the conclusions and discussions are presented in Chapter 7. The flow chart below indicates the research process.

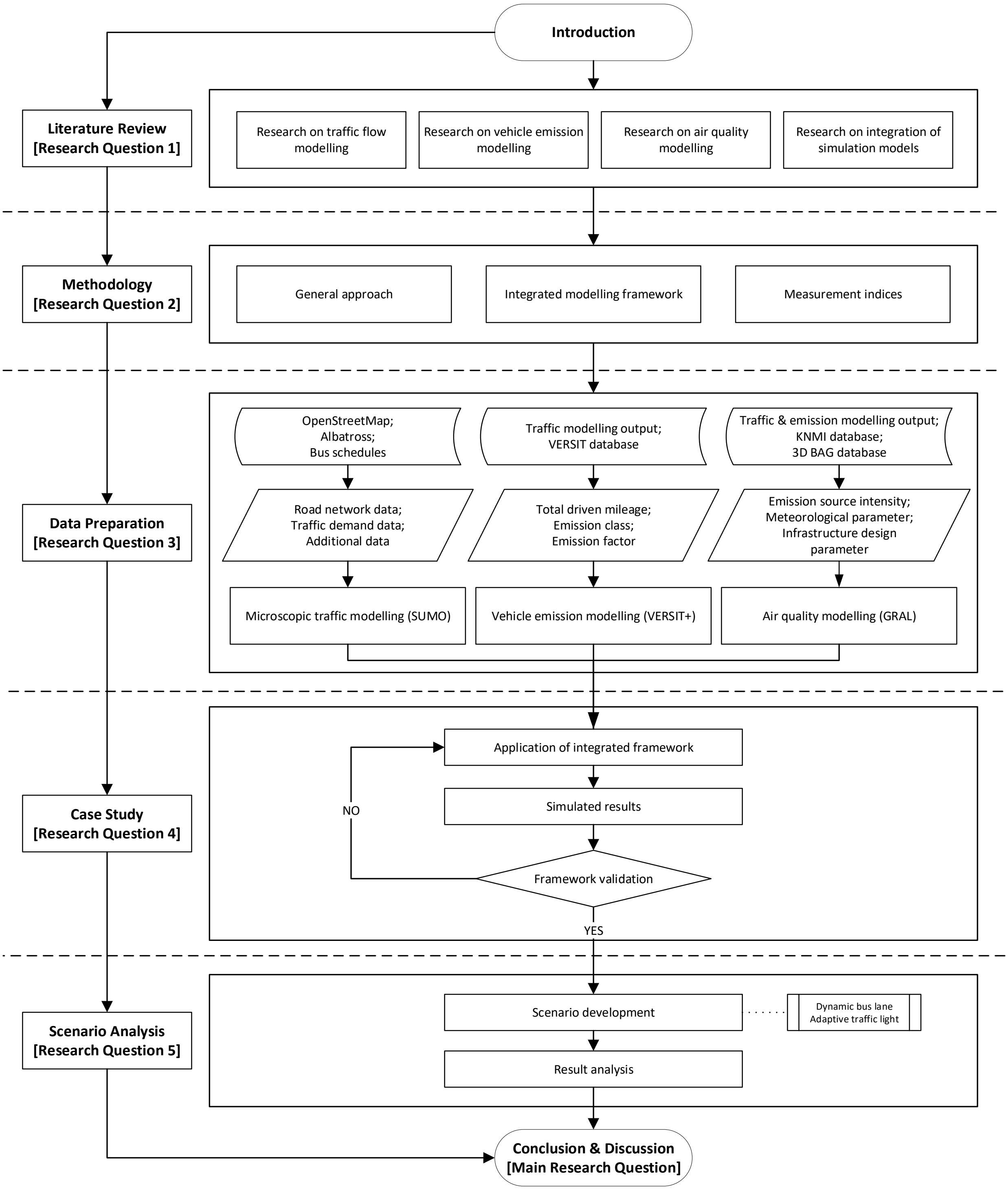

Figure 1 *The research process.*

Chapter 2 Literature Review

This chapter introduces the state-of-the-art of modelling traffic flow, vehicle emission and air quality separately and the integration of these simulation models. Section 2.1 paves the background for traffic modelling theories, including classification of traffic simulation models, the introduction of two microscopic modelling tools (VISSIM and SUMO) and the fundamental theories for traffic modelling. Next, section 2.2 elaborates the detail of vehicle emission models and emphasizes on the HBEFA and VERSIT+ model. The theory of another crucial expansion, air quality modelling, is introduced in section 2.3 with a brief introduction on its classification and one open-source model, GRAL. After establishing the basic concepts of traffic, emission and air quality modelling, section 2.4 first gives a review of relevant research on coupling traffic and emission simulation models; and then includes the air quality modelling into the integration framework; followed by emphasizing the importance of introducing external data sources (meteorological data and infrastructure design parameters) based on the experience from other projects. Next, section 2.5 summarizes the research gaps based on the discussions above. Lastly, a conclusion part is given to discuss the findings from the literature research.

2.1 TRAFFIC FLOW MODELLING

2.1.1 Classification of Traffic Modelling

Based on the level of detail, traffic modelling can be categorized as microscopic, mesoscopic, and macroscopic (Jamshidnejad et al., 2017) (see Table 1).

***Table 1** Characteristics of different traffic models (adapted from Pinto et al., 2020).*

Category	Level of detail	Representation of traffic	Traffic flow variables	Examples
Macroscopic	Low	Traffic flow	Aggregated	METANET, NFD
Mesoscopic	Medium	Driver-vehicle entity	Aggregated	DTA Lite, VISUM
Microscopic	High	Driver-vehicle entity	Individual	SUMO, VISSIM

When the traffic simulation can present more details and take into the consideration of the behaviour of each individual vehicle in the simulated network, it is classified as microscopic traffic model (see examples in Chen et al., 2016; Lopez et al., 2018; Ma et al., 2014; Osorio & Nanduri, 2015; Samaras et al., 2018; Ye & Ma, 2013). In microscopic models, each driver-vehicle entity is treated and simulated explicitly, and each retains all attributes of simulated movement (e.g., vehicle trajectories, speed profile) modelled by the system.

On the other hand, traffic flows can be modelled macroscopically from an aggregated point of view based on a hydrodynamic analogy by regarding traffic flows as a particular fluid process whose state is characterized by aggregate macroscopic variables: density, volume, and speed (Barceló, 2010). The macroscopic traffic models usually depict the average behaviour of the traffic flow without describing the dynamics of individual vehicle in the traffic network (see examples in Bandeira et al., 2011; Nejadkoorki et al., 2008; Sider et al., 2013; Zegeye et al., 2013). This kind of models, contrary to microscopic simulations, usually show the spatial and temporal evolution of the aggregated traffic flow through a given road network. With this regard, the traffic flow is considered as fluid, which means vehicles are usually neglected at the individual level and for variables such as counts (Pinto et al., 2020). Due to the low level of detail, macroscopic simulations have low flexibility but a computational advantage in terms of the running speed.

Furthermore, efforts are made to choose and combine some characteristics of the above two models, and thus the level of detail for a mesoscopic traffic model is less than a microscopic model and greater than a macroscopic model (see examples in Borrego et al., 2004; Jamshidnejad et al., 2017; Lin et al., 2011; Zhou et al., 2015). In this kind of models, vehicles can either be grouped (into platoons) or either emulated individually and their behaviour rules in both situations are specified in the form of probability distribution functions of the flow/capacity relationship (Pinto et al., 2020). The mesoscopic traffic analysis is designed to focus more on the constitutes of traffic streams. It seeks to explain the spatial and temporal behaviour of vehicles based on the traffic flow dispersion theory.

Due to different level of detail contained by each kind of model, Zegeye et al., (2013) pointed that one thing that needs to be thought twice before choosing among traffic simulation models is the trade-off between simulation speeds and the accuracy of estimated traffic states (or traffic phenomena).

However, three main advantages were proposed by Krajzewicz et al., (2016) of using microscopic simulation methods over macroscopic ones when benchmarking environmental measures by simulation methods: first, microscopic simulations contain greater detail of road layout and infrastructure unit representations; second, microscopic models have the possibility of distinguishing different types of vehicles. Combined with lane restrictions, it allows regulating the priority of specific vehicle types; the third and probably the most important advantage is the availability of acceleration and speed profiles of simulated vehicles for all simulation steps within microscopic simulations. Therefore, traffic flow modelling using microscopic approach can include and generate more information which can act as the input for other simulation models.

In the field of traffic planning, great value and potential of microscopic traffic simulation have been seen in traffic safety analysis (see reference by Archer & Young, 2010; So et al., 2015) and public transport priority studies. It is noteworthy that evaluating public transport priority studies by microscopic traffic simulation increasingly attracted the attention of academia in recent years. That is, modelling the impact of public transport on other traffic participants or the other way around to evaluate public transport priority measures. Papageorgiou et al., (2009) assessed many dedicated bus lane priority scenarios via the microscopic simulation model (VISSIM) in terms of the effect on the traffic network considering congestion and travel times; Zyryanov & Mironchuk (2012) adopted AIMSUN simulation tool intending to know the advantages and limitations of intermittent bus lanes at different volume of background traffic and bus signal priority; Y. Chen et al., (2016) took the Beijing southwest third ring expressway, for example and built the microscopic simulation model by Paramics to evaluate the performance of bus lanes on this specific transport infrastructure.

2.1.2 Microscopic Traffic Simulation Tools

Microscopic traffic simulation models have been known since the 1950s (Lighthill, F.R.S., & Whitham, 1955), which has been developed as a tool accepted by both academia and commercial users so far. Many microscopic simulation models have been built up at varying levels of complexity and network size, and most of them can support the different transportation modes, including road vehicles, bicycles, public transport, pedestrians, and more. In this section, two chosen microscopic simulation tools, VISSIM and SUMO, are discussed as follows:

VISSIM

VISSIM is a microscopic, discrete, behaviour-based multi-purpose traffic simulation to analyze and optimize motorway traffic as well as urban traffic operations. It generates trajectories for each vehicle within a specified link, the sequence of links or sub-network and therefore offers the possibility of estimating traffic flows from a microscopic perspective.

VISSIM has a long history since it was developed based on a psycho-physical car-following model presented by Wiedemann (1974). The basic idea of the Wiedemann model is the assumption that a driver can be in one of four driving modes: free driving, approaching, following and braking (Fellendorf & Vortisch, 2001). Since then, it has been improved and expanded step by step and is deployed in over 2,500 cities worldwide and has already become the standard for traffic simulation in many countries (PTV Group, n.d.-b). Nowadays, about one-third of the users are within consultancies and industry, one-third within public agencies, and the remaining third is applied at academic institutions for teaching and research (Fellendorf & Vortisch, 2010).

In the VISSIM simulation, the position of each vehicle usually is recalculated and recorded every 0.1-1s. The system can be used to investigate private and public transport as well as pedestrian trajectories. In addition, it can also estimate vehicles transit under the effects of traffic restrictions like traffic lights, traffic composition and public transport stops (Quaassdorff et al., 2016). Prominent examples developed by other researchers, using VISSIM include corridor studies on the influence of access traffic on the operational efficiencies of public transport lanes and the main road (Ye & Ma, 2013); studies on truck platooning on other vehicles in terms of traffic efficiency and safety (Kuijpers, 2017); analysis on the energy efficiency of electric vehicles considering the impact of external variables (Donkers, 2019).

VISSIM does include several characteristics which make it the most popular microscopic traffic simulation tool (PTV Group, n.d.-a): first of all, it can give a realistic and detailed overview of the traffic status with the possibilities to define multiple what-if scenarios; secondly, due to its timely upgrades, it is now flexible and can be seamlessly coupled with other PTV Traffic Suite (for example VISUM) and also other external applications; thirdly, it has been adopted in practice and proved as valid by many academic researchers and commercial users. Besides, it can also provide animation capabilities in 3D simulation to show the simulated results more vividly (Choa, Milam, & Stanek, 2003).

SUMO

As a simulation informatic tool, Simulation of Urban MObility (Eclipse SUMO) is a free, open-source, highly portable, microscopic road traffic simulation package designed to handle large road networks since 2001 (German Aerospace Center (DLR), 2019c, 2019h). Since the creation, SUMO has evolved into a full-featured package of traffic modelling utilities, including a road network importer capable of reading different source formats, demand generation and routing utilities, which use a wide variety of input sources (traffic networks, origin-destination matrices, traffic counts, traffic light plans, and more) (Krajzewicz et al., 2012).

SUMO offers various features such as microscopic traffic simulation; multimodal simulation (including road vehicles, public transport, pedestrians); automatic generation of time schedules of traffic lights; evaluation of eco-aware routing based on pollutant emission and investigations of autonomous route choice on the overall network (Behrisch et al., 2011).

Moreover, with an extension called Traffic Control Interface (TraCI), SUMO as a network simulator can act as a server which is interlinked by a client (German Aerospace Center (DLR), 2020f). It permits us to control the behaviour of the simulated object, such as pedestrians, vehicles, traffic lights, and etc. during the simulation period, and consequently to better understand the influence of any changes on traffic patterns. More details on the application of TraCI can be found in the scenario analysis chapter.

Because of the versatility of SUMO, it has been used for answering a large variety of research questions that fall into these topics: vehicular communication, route choice and dynamic navigation, traffic light algorithms, evaluation of surveillance systems (Krajzewicz et al., 2012). For example, testing and optimizing the effectiveness of environmental zones or traffic light control algorithms in a simulation before being deployed in the real world (German Aerospace Center (DLR), 2019c); providing a simulation framework which makes it possible to investigate the impacts on V2X communication strategies and reroute vehicles over bus lanes using V2X communication (Bieker & Krajzewicz, 2011).

Morenz (2007) pointed out that the main drawback of SUMO is the lack of model flexibility, i.e., it is not possible to dynamically adapt the traffic flows in a simulation at that time. However, two advantages are identified: first, it is an open-source software and available under the GNU general public license (GPL), giving the full access to the source code and allowing for compensating the missing features; second, all input and output files in SUMO are in a well-documented XML format, making the data human-readable and allowing for the possibility of reproducing by other programs.

2.1.3 Traffic Modelling Fundamentals

After having the basic idea of traffic simulation models, the fundamental theories of these models have to be explained thoroughly since the traffic simulation will be the foundation of the whole research. Two categories of fundamental core models, namely the driving behaviour model and the demand generation model, are presented as follows:

2.1.3.1 Driving Behaviour Models

Driving behaviour models capture drivers' tactical manoeuvring decisions in different traffic conditions (Toledo, 2007). These models adopt mathematical tools to depict the vehicles' trajectories in a two-dimension way and are therefore essential to traffic simulation methods. The driving behaviour model can be categorized as the acceleration model and lane-changing model which explain vehicles' longitudinal movement and lateral movement through the road network, respectively.

Acceleration Model

According to Toledo (2007), acceleration models can be briefly defined as car-following models and general acceleration models. The difference between them is if the simulated vehicles are closely following their leaders (the car in front). The primary principle in the acceleration model is to prevent vehicle collisions: the car driver would keep a safety gap with the vehicle ahead, and his/her speed is therefore determined by the vehicle in front.

Lane-changing Model

Similar to the acceleration model, the lane-changing model also uses the collision-free principle that lane changes only occur if the gap on the aimed lane is big enough for the vehicle to safely swap lanes (Morenz, 2007). The lane-changing model usually consists of two steps: the lane-selection process, i.e., the decision to consider a lane change and the lane choice, and the decision to execute the lane change

(Toledo, 2007). Drivers are assumed only to make lane changes when driving in another lane can bring advantages (i.e., the front vehicle is too slow, and the speed limit is not yet reached).

2.1.3.2 Demand Generation Models

With the concept of modelling the trajectory of one vehicle, it is time to consider further modelling route choices made by a group of vehicles within a specific geographic scale. In this section, two fundamental traffic demand generation models are introduced:

Origin-Destination Matrix Model

Origin-destination (O/D) matrices are usually used in modelling large-scale areas, which gives the information about the number of vehicles that leave an “origin” traffic analysis zone (TAZ) for travelling to a “destination” TAZ (Krajzewicz et al., 2016). O/D matrices are often built based on the four-step modelling approach (McNally, 2008). In brief, this approach starts with the estimated number of daily trips based on statistics to compute the participants’ routes using specific algorithms given their trip purposes and traffic model choice. The result is then a collection of predicted route choices made by traffic participants in a specific area, including the origin TAZ, destination TAZ, and transportation mode within a predefined amount of time.

Agent-based Model

Another approach for modelling the traffic demand is called the agent-based or activity-based demand model. Different from modelling the aggregate population for each TAZ in O/D matrix model, in the agent-based model, every agent is modelled individually being described by a set of attributes and keeps a record of its trip including necessary information of behaviours, such as lane changing or gap acceptance (Krajzewicz et al., 2016; Nagy & Simon, 2018). The traffic participants are characterized by their gender, age, income, car ownership, driving license holding, employment status, and more, which promises the model to be intrinsically sensitive to a large number of factors. To summarize, agent-based models give insights of individual agents’ behaviour and how the agents interact with each other considering different built environment conditions.

2.2 Vehicle Emission Modelling

2.2.1 Classification of Vehicle Emission Modelling

Vehicle emission models are mostly developed based on laboratory and on-road measurements. These model generally takes into account four types of inputs (Huang & Ma, 2009):

- Vehicle technology specifications such as vehicle type, length and fuel type (gasoline or diesel), and etc.;
- Vehicle status such as vehicle age;
- Vehicle operating conditions, such as engine speed, physical speed, acceleration and others;
- External environment conditions, such as temperature and road geometric conditions.

They are designed to provide the estimate of vehicle emissions in a traffic network based on the operating conditions of vehicles (Zegeye et al., 2013). Regardless of the specific implementation adopted by different models, they all aim to provide appropriate Emission Factors (EFs), i.e., empirical functional relations between vehicle emissions and the activity that causes them, for further calculations (Franco et al., 2013).

Similar to traffic flow models, vehicle emission models can also be categorized based on the used modelling approaches. Smit et al., (2010) proposed a detailed classification framework according to the incorporated driving behaviour as well as the required input variables: (a) average-speed models, where EFs are a function of the mean travelling speed, including COPERT, MOBILE, EMFAC, and etc.; (b) traffic-situation models, where EFs are determined by description of a particular traffic situations (e.g., ‘stop-and-go-driving’, ‘free-flow motorway driving’), including HBEFA, ARTEMIS, and etc.; (c) traffic-variable model, where EFs are defined by traffic flow variables such as average speed, traffic density, queue length and signal settings, including TEE, Matzoros, and etc.; (d) cycle-variable models, where EFs are a function of various driving cycle variables (e.g., idle time, average speed, positive kinetic energy) at high resolution (seconds to minutes), including MEASURE, VERSIT+, and etc.; (e) modal models, where EFs are produced via engine or vehicle operating models at the highest resolution (one to several seconds), including PHEM, CMEM, and etc. In summary, these models range from those which only require average travelling speed or use particular traffic situations (i.e., qualitative description of driving conditions) to predict emissions, to those which ask for various driving cycle variables at high resolution, like instantaneous data on speed, acceleration and road gradient, to generate detailed emission data based on complex driving profile.

Therefore, one simplified categorization scheme is introduced by Csikós & Varga (2012) and Fontes et al., (2015) (see Table 2). The former group of researchers came up with the idea of separating emission models into macroscopic and microscopic models, and the latter group divided emission models into instantaneous and average-speed models. These two classifications on emission models are similar because microscopic models use detailed traffic data (e.g., speed, acceleration or vehicle trajectories) to estimate instantaneous emission rates of individual vehicles (e.g., PHEM, CMEM, VERSIT+). In contrast macroscopic models (COPERT, MOBILE, HBEFA) adopt aggregated traffic variables (trip-based average speed or a description of the traffic situation) for a large-scale estimation during a given period.

Table 2 *Characteristics of different vehicle emission models.*

Category	Input	Examples
Average-speed	Aggregated traffic variables	COPERT, MOBILE, HBEFA
Instantaneous	Vehicle operating conditions	PHEM, CMEM, VERSIT+

Average-speed models are more coarse than instantaneous models and compared with the instantaneous emission models, they are easier to be used and allow for faster emission computations. Zegeye et al., (2013) explained that because the input for instantaneous models is the operating condition of individual vehicles, the computation time required is proportional to the number of vehicles. However, speaking of the average-speed model, the situation has changed, and their input is the average operating conditions of a group of vehicles. Hence, the computation time required by the average-speed model is much less. However, one drawback of average-speed models is that they cannot capture the vehicle emission caused by the speed variation of the traffic because they only take the average velocity as inputs (Zegeye et al., 2013) while this is the main strength of instantaneous models over average-speed models.

2.2.2 Vehicle Emission Modelling Tools

In order to fully consider different types of vehicle emission models, two different tools are discussed in this section. As pointed by the review research of Smit et al., (2010), five emission models are validated by researchers frequently, namely MOBILE, COPERT, HBEFA, EMFAC and ARTEMIS, among which, HBEFA has been proven to be able to cooperate with SUMO reasonably (Krajzewicz et al., 2014), and it is therefore chosen to be discussed. VERSIT+, contrary to HBEFA, is an instantaneous emission model which will be elaborated as well.

HBEFA

The Handbook of Emission Factors for Road Transport (HBEFA) is a database application that provides emission factors for all relevant vehicle categories in road transport (passenger cars, light-duty vehicle, high-duty vehicles, urban buses, coaches and motorcycles) (Notter et al., 2019). The first version (HBEFA 1.1) was published in December 1995, an update (HBEFA 1.2) followed in January 1999. Version HBEFA 2.1 was available in February 2004, HBEFA 3.1 followed in Jan. 2010, HBEFA 3.2 dates from July 2014, HBEFA 3.3 was released in April 2017. The current version HBEFA 4.1 dates from August 2019 (iNFRAS, 2019). It was initially developed on behalf of the Environmental Protection Agencies of Germany, Switzerland and Austria. Afterwards, other countries (Sweden, Norway and France), as well as the JRC (Joint Research Centre of the European Commission) also came to support the development of HBEFA (Sun et al., 2014).

HBEFA provides emission factors, i.e., the specific emission in g/km for all current vehicle categories, each divided into different size classes and for a wide variety of traffic situations (Sun et al., 2014).

HBEFA is mostly meant for use at finer geographical scales (down to street levels), needs a more-in-depth knowledge of traffic details and is mostly used in the DACH-NL-S European countries (Germany, Austria, Switzerland, Netherlands and Sweden) (Franco et al., 2012).

HBEFA usually estimates traffic emissions in three large blocks, namely hot emissions, cold-start and warming-up effects and evaporation emissions (Franco et al., 2012). Total emission is calculated as the combination of vehicle fleet and activity data selected by the user and emission factors calculated by the model. Several examples are found in the literature research process where HBEFA has been widely used for various purposes. Sun et al., (2014) succeed in adapting HBEFA to the local traffic situations in China and have developed a bottom-up emission model for urban transport for several Chinese cities, which facilitates a reliable estimation of fuel consumption and CO_2 emissions of urban road transport. Kickhöfer (2016) described a tool which calculates warm and cold start exhaust emissions for private cars and freight vehicles by linking the MATSim simulation output to the detailed HBEFA database. Samaras et al., (2018) used the HBEFA model to reproduce the results as a validation part for their research.

The HBEFA method has gradually earned popularity among the academia. There must be several reasons behind it: one of the advantages of HBEFA is that it is particularly suitable for city traffic simulation as it provides emission factors for different road types (such as expressways, trunk roads or branch roads) and different levels of traffic situations (such as free-flow or stop-and-go traffic) as well as for different vehicle categories and sizes (Sun et al., 2014). Secondly, HBEFA itself is adaptable for different situations, like the successful case implemented in China mentioned above, it can be partly customized and is applicable for various simulation situations. Furthermore, HBEFA is not only an emission factors database but also a toolbox for calculating vehicle emissions at various geographical levels.

VERSIT+

To predict traffic emissions in the Netherlands, the Netherlands Organisation for Applied Scientific Research (TNO) has developed VERSIT based on vehicle type, velocity and acceleration from 1987 (Smit et al., 2007). The model initially predicted vehicle emissions as a function of propulsion energy using Euro test emissions data (Van Helden, 1994). Due to the need for greater predictive accuracy and versatility, Smit, Smokers, & Schoen (2005) has designed VERSIT + LD model (VERSIT + light-duty) which aims to imitate traffic stream emissions for light-duty vehicles in any particular traffic situation. Since then, VERSIT+ has been refined continuously, and it is capable of providing vehicle emission prediction for other types of vehicles (Geilenkirchen et al., 2020).

The VERSIT+ model includes two main parts: VERSIT class (emission class) and emission factors. The first component describes the vehicle categories based on several factors such as vehicle type, fuel type, environment-class, and more In total, more than 200 VERSIT classes have been defined in the VERSIT+ model (Klein et al., 2019); the second part is the most important result of this model that since 2005, TNO uses the VERSIT+ emission model to calculate the emission factors per VERSIT class and road type for NOx, NO_2, PM_{10}, $PM_{2.5}$, VOC (HC), NH_3 and CO (Geilenkirchen et al., 2020).

With VERSIT+, emission factors can be calculated for different transport situations and scale levels. The following formula is used to determine the emission factors per vehicle class and road type:

$$Emission\ Factor = BASw + BASw * (AGEw - 1) + PERCc * BASc * AGEc \qquad [2-1]$$

Where

BASw - emissions per vehicle kilometre travelled for a hot engine, excluding the effect of ageing;

AGEw - the effect of ageing on “hot driving”, depending on the year of use;

PERCc - the average number of cold starts per kilometre travelled;

BASc - total extra emissions caused by driving with a cold engine;

AGEc - the effect of ageing on the extra emissions caused by "cold start", depending on the year of use.

Similar to the HBEFA model, these parameters all represent effects of different emission factors, BASw quantifies the hot engine basic emission factors, BASc and PERCc represent the production of cold-start emissions, AGEw and AGEc serve as the impact of vehicle ageing.

Additionally, from 2014 on almost all emission factors for road vehicles are determined in on-road testing and monitoring conducted by TNO. The analysis of the measurement data determines if systematic effects, for cold start and other conditions are found, and need to be corrected for (Geilenkirchen et al., 2020), which ensures the validity and accuracy of the adopted emission factors.

Several projects are found that they did the vehicle emission forecast with the help of VERSIT+. Madireddy et al., (2011) deployed VERSIT+ in an integrated model to calculate the instantaneous CO_2 and NO_x emission of each vehicle and measure the effects of two traffic management measures in the chosen area of Antwerp, Belgium. Quaassdorff et al., (2016) combined VERSIT+ with VISSIM to evaluate the exhaust pollution, specifically NO_x and PM_{10}, from traffic flows based on twelve different scenarios in a high-density urban area of Madrid, Spain. The calculated results, especially emission factors, were compared to those obtained with COPERT (mesoscale model previously evaluated for the Madrid area). Their results indicate that the emission factors calculated by VERSIT+ and COPERT are in a reasonable agreement that VERSIT+ emissions range between -6% and 31% compared to COPERT results, and present a mean normalized bias error of 14% (taking COPERT as a reference).

In conclusion, VERSIT+ model is based on data that includes a large number of emission measures covering a range of distinctive speed-time profiles and uses a large sample of Dutch vehicles that reflect the actual fleet composition (Smit et al., 2007). The large test sample used by VERSIT+ model happens to be the most significant advantage over other models (Trachet et al., 2010), which considers the complex driving behaviour of modern Dutch vehicles. According to the way it works, it can be expected that speed-based emissions can be precisely predicted while the emissions that depend strongly on engine dynamics can most probably not be forecasted accurately.

2.3 AIR QUALITY MODELLING

As increasing attention is paid to the public's health, air pollution, especially in the domain of road transport, has been emphasized more and more by academia with the aim of explaining the impact on transportation participants. However, air quality modelling is a complex science and the models can be very computationally intensive (Forehead & Huynh, 2018). It is therefore not sufficient to understand the vehicle-induced emissions and the related air pollution problem in urban areas with two models introduced in the previous sections.

For this purpose, there is a growing trend to link the air quality model with the traffic and emission models. Traffic simulation models, vehicle emission models and air quality models that are initially developed and evolved separately are now applied in one framework, to first characterize the traffic flows, and then to quantify the emission amounts, and finally to evaluate the air quality in the ambient area by the distribution of pollutant concentrations. Air quality models, mainly dispersion models, aim at using mathematical equations to simulate the dispersion process of the pollutants emitted by stationary (such as power plants, oil refineries, industrial facilities, and factories) and mobile pollution sources (such as cars, buses, planes, trucks, and trains). Consequently, it can describe the atmospheric transport process and chemical and physical transformation processes, and calculate pollutants concentrations and deposition fluxes between the point(s) of emissions and the receptor location(s) at various locations and times (Fallah Shorshani et al., 2015; Holmes & Morawska, 2006).

Within the scope of this study, the research object is limited to the air pollution caused by road traffic consisting of motor vehicles, which accounts for a signigicant part of mobile pollution sources. The addition of the air quality model, therefore, could help to understand the distribution of traffic pollutant concentrations in the urban environment to characterize the nature of risk to other traffic participants (mainly pedestrians and cyclists) and residents in the chosen area (Misra et al., 2013).

The major input data for the air quality model is usually spatially-distributed and temporally-resolved emissions provided by the emission model, meteorological inputs (i.e., wind, turbulence, pressure, temperature, relative humidity, solar radiation, cloud cover), and background concentrations, source emissions, physiographic data (i.e., building configuration, street geometry), and more It is also useful to have input data from the traffic model for dispersion models that account for vehicle-induced turbulence (VIT) (Lim et al., 2005). As for the output, the air quality model usually generates concentrations and atmospheric deposition fluxes along the model trajectories or near sources at specified receptor locations to visualize certain pollutant dispersion process (see Figure 2).

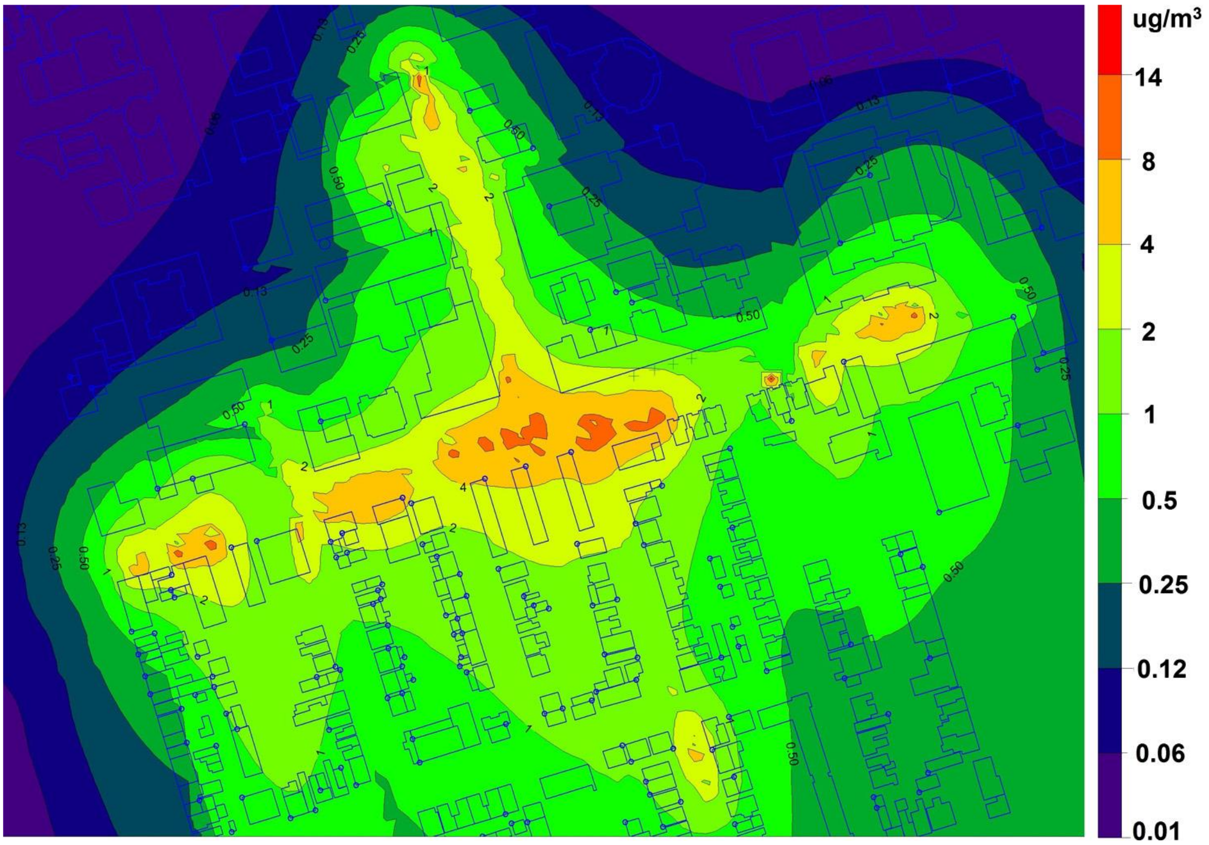

Figure 2 *Example output from air quality models - NOx concentration map (Retrieved from Misra et al., 2013).*

2.3.1 Classification of Air Quality Modelling

Similar to traffic flow and vehicle emission modelling, in order to better clarify the differences between air quality models, and the development of air quality models, several classification theories can be found in the literature:

One popular scheme proposed by Zannetti (1990) was to classify the air quality models based on their scales, and they can be categorized as near-field (<1 km), short-range (<10 km), intermediate transport (10-100 km), long-range (>100 km), and global effects. The scale has also been simplified by (Tiwary & Colls, 2010) as macroscale (measured in more than 100 kilometres and days), mesoscale (measured in 10-100 km and hours), and microscale (measured in less than 1 km and minutes).

According to adopted computational approaches, Holmes & Morawska (2006) proposed another mainstream classification that categorizes most air quality models into Box models, Gaussian models, Lagrangian/Eulerian models, Computational Fluid Dynamics models and models which include aerosol dynamics. Based on previous works, Fallah Shorshani et al., (2015) gave a refined classification approach which has only three categories: Chemical Transport Models (CTM), Near-source dispersion models and CFD models. However, this framework overlaps with the former one a lot: CTM models compose of Lagrangian models, Eulerian models and part of Plume-in-Grid models, Near-source dispersion models composed of part of Plume-in-Grid models, Gaussian models and Street-canyon models and CFD models are more independent in both two classification frameworks. See the summary in Table 3.

***Table 3** Characteristics of different air quality models (adapted from Fallah Shorshani et al., 2015).*

Category	Inputs	Solution methods	Application domain	Examples
Chemical Transport Models (CTM)	meteorological data, initial and boundary concentrations, emissions, physiographic data	Lagrangian models; Eulerian models; Part of Plume-in-Grid models	urban to global (from 1 km to several hundred km)	VADIS, QUIC, Micro-Swift-Spray, GRAL
Near-source Dispersion Models	local meteorological data, background concentrations, source emissions, physiographic data	Gaussian models; Street-canyon models; Part of Plume-in-Grid models	local impacts (up to 50 km)	AERMOD, CALPUFF, URBAIR, STACKS
Computational Fluid Dynamics (CFD)	emissions, physiographic data, initial and boundary conditions for meteorology and concentrations	Direct Numerical Simulation (DNS); Large-Eddy Simulation (LES); Reynolds-Average Navier-Stokes (RANS)	complex environment, local scale (up to 10 km)	PHOENICS, Fluidity, ENVI-met

Another method to classify pollutant concentration models is using the employed deterministic methods, and according to this, models can be defined as mathematics-based, statistic-based, and physics-based modelling (Khare & Sharma, 2002).

In this research, the classification proposed by Fallah Shorshani et al., (2015) is chosen. Near-source dispersion models use the parameterization approach to represent the transport and dispersion of pollutants from one or a selected number of sources (Fallah Shorshani et al., 2015). This type of models are composed of Gaussian models which consist of plume and puff approaches. Plume approaches assume steady-state conditions while puff approaches simulate instantaneous releases in a changing environment and are computationally more demanding (Forehead & Huynh, 2018). Usually, a combination of plume and puff methods could give a more accurate result (Fallah Shorshani et al., 2015).

Computational Fluid Dynamics (CFD) models had emerged since the 1990s when the continuous increase of hardware capabilities and the optimization of numerical methods occurred. As an accurate tool for simulating fluid flow, chemical species dispersion and reaction and heat transfer, and offering the possibility to generate unstructured meshes on the local scale, CFD models are appropriate for small scale urban areas because of its sophisticated process (Vardoulakis et al., 2003). Moreover, there has been an increasing popularity of CFD models such as PHOENICS and FLUIDITY over the conventional Gaussian-type dispersion models recently (Forehead & Huynh, 2018). The reason is that a CFD emission model can show more details like eddies generated by cross-streets and increased concentrations of pollutants in the lower leeward sides of street canyons (Mumovic et al., 2006).

The last type of air quality models, Chemical Transport Models (CTM), mainly contains Lagrangian models and Eulerian models. In short, they can reflect changes in concentration caused by mean fluid velocity, wind turbulence, and molecular diffusion (Holmes & Morawska, 2006). With the consideration of homogeneous properties volume (air pollutant concentrations, meteorological variables), CTM models study the flow of those variables through a 3D gridded mesh, i.e., grid cells (Fallah Shorshani et al., 2015). In this category, a specific model has to be introduced, i.e., the GRAL simulation model.

2.3.2 GRAL

The Graz Lagrangian model (GRAL) which was initially developed in 1999 by the Institute for Internal Combustion Engines and Thermodynamics of TU Graz, has been used extensively in regulatory assessments and scientific studies (TU Graz, 2020). The model was developed with an initial aim of dealing with the meteorological conditions in the inner-Alpine basins of Austria.

Over the years of development, the functions of GRAL have been extended dramatically and the current version of the model is able to compute the results such as:

- dispersion of chemically non-reactive pollutants;
- dry and wet (only in transient mode) deposition and sedimentation;
- dispersion from road tunnel portals;
- dispersion over the full range of wind speeds without any lower threshold, and for all stability conditions;
- dispersion in built-up areas, including building downwash effects;
- dispersion of stack emissions, taking temperature and exit velocity into account;
- dispersion in complex terrain, allowing for the effects of buildings;
- decay rates (e.g., bacteria die off, radioactive decay)
- flow and dispersion within vegetation layers.

All in all, the main function of the GRAL dispersion model is still calculating the distribution of particle concentrations in the defined modelling area. In most cases, particle concentrations are computed by using equations below:

$$C = \sum_{i=1}^{R} \frac{m_{p,i}}{dV \cdot T_{ges}} dt \qquad [2-2]$$

Where

m_p is the mass of one particle defined by the total emissions per time unit within the model domain divided by the total number of released particles per time unit;

R is the total number of integration steps;

dV is the volume of one cell.

The total number of released particles per time unit is defined by:

$$N = \frac{T_{ges} \cdot dn}{dt} \qquad [2-3]$$

Where

dn/dt is the user-specified released particles per second;

T_{ges} is the averaging time for the concentration computation defined by the user (usually 1800 s or 3600 s).

Based on equation [2-3], GRAL is able to provide two options for time series computation: steady-state (standard) mode and transient mode. More details can be referred to the GRAL documentation (Öttl, 2020).

In brief, GRAL is an open microscale Lagrangian particle model with a Graphic User Interface (GUI) available in both Linux and Windows systems. It can be employed in both flat and complex terrain as well as the built-up area. The scale of the model ranges from streets (e.g., street canyons) to city-scale which may up to several dozens of kilometres. Moreover, at all scales the effects of buildings, vegetation and topography (e.g., cold air drainage flows) on dispersion can be considered by GRAL.

It should be noted that one drawback of the GRAL model is it is not possible to include chemical reactions (TU Graz, 2020). The conversion of NO to NO_2 for example, cannot be computed under the default settings.

2.4 Integration of Simulation Models

2.4.1 Integration of Traffic and Vehicle Emission Models

With the purpose of calculating the road-side exhaust pollution, vehicle emission prediction would be a multiple-step process. Usually, vehicle emission models could provide applicable Emission Factors (EFs) which can express the mass of pollutant emitted per unit distance ($g \cdot km^{-1}$), time ($g \cdot s^{-1}$) or mass of fuel burned ($g \cdot kg^{-1}$). After generating EFs from the first step, detailed emission prediction from traffic is estimated by multiplying EFs with corresponding activity data which follows the units like vehicle kilometres travelled (VKT) or total time spent in particular driving conditions (e.g., idling) (Smit et al., 2010).

However, based on the level of detail of the emission prediction approaches, the required output from the traffic simulation varies a lot: on one hand, for average-speed based models, traffic flow attributes like vehicle population, mileage, speed, ambient temperature, road grade, and more are required for a specific area/region. On the other hand, Cen et al., (2016) argued that modelling vehicle emissions from the instantaneous perspective is an elaborated process, as it entails not only traffic flow characteristics, but also vehicle parameters (e.g., weight, drag coefficient) and the corresponding emission standards of the technology (such as EURO III, IV, and V). Therefore, average-speed vehicle emission models are in principle used with macroscopic traffic flow models, and instantaneous emission models are usually coupled with microscopic traffic flow models (Zegeye et al., 2013)

Table 4 listed the most relevant studies coupling traffic flow with vehicle emission modelling. As the table indicates, most researchers combined microscopic traffic flow modelling tools and instantaneous emission modelling tools to investigate the environmental influence brought by traffic flow in the case studies (see examples in Abou-Senna & Radwan, 2013; Csikós & Varga, 2012; Hirschmann et al., 2010; Madireddy et al., 2011). Only a few studies were conducted using the integrated toolbox built based on macroscopic or mesoscopic traffic modelling and average-speed based emission modelling.

***Table 4** Review of relevant studies on the integration of traffic flow and vehicle emission models.*

Reference	Traffic Flow Models			Vehicle Emission Models		Metrics	Country
	Macroscopic	Mesoscopic	Microscopic	Instantaneous	Average-speed		
Abou-Senna et al., (2013)			VISSIM	MOVES		CO, CO_2, NO_x, $PM_{2.5}$, PM_{10}	USA
Ahn (1998)			INTEGRATION	Non-linear multiple regression models[1], neural network models		CO, HC, NO_x	USA
Bartin et al., (2007)			Paramics		Mobile 6.2	CO, HC, NO_x, PM_{10}	USA
Chen et al., (2007)			VISSIM	CMEM		CO, HC, NO_x	China
Csikós et al., (2015)	NFD			VERSIT+micro		CO	Hungary
Csikós et al., (2012)			VISSIM	VERSIT+micro		CO, CO_2, PM_{10}, NO_x	Hungary
Fontes et al., (2015)			VISSIM	VSP	EMEP/ EEA	CO, HC, NO_x, PM	Portugal
Hirschmann et al., (2010)			VISSIM	PHEM		CO, HC, NO, NO_2, PM, PN	Austria
Hülsmann et al., (2011)			MATSim		HBEFA	NO_x	Germany
Int Panis et al., (2006)			DRACULA	Non-linear multiple regression[2]		CO_2, NO_x, PM, VOC	Belgium
Jamshidnejad et al., (2017)	S-model			VT-micro		CO, HC, NO_x	Netherlands
Krajzewicz et al., (2016)			SUMO	PHEMlight	HBEFA	NO_x	Germany
Lin et al., (2011)		DynusT[3]		MOVES		$CO_{2\text{-eq}}$	USA
Madireddy et al., (2011)			Paramics	VERSIT+		CO_2, NO_x	Belgium
Quaassdorff et al., (2016)			VISSIM	VERSIT+micro		NO_x, PM_{10}	Spain
Samaras et al., (2018)			AIMSUN	AVL CRUISE		CO_2	Italy
Sider et al., (2013)	VISUM			MOVES		NO_x	Canada
Tomàs Vergès, (2013)			SUMO		HBEFA	NO_2, PM_{10}	Germany
Zegeye et al., (2013)	METANET				VT-macro	CO, HC, NO_x	Netherlands
Zhao et al., (2013)			Paramics	MOVES		CO, NO_x	USA
Zhou et al., (2015)		DTA Lite		MOVES Lite		CO, CO_2, HC, NO_x	USA

Among these popular microscopic traffic simulation models, each traffic simulation model has advanced features. As pointed by Kokkinogenis et al., (2011), VISSIM has developed parameters and function flexibility, Paramics adapts to use all the distributed machine resource available, AIMSUN provides different forms for the extension, SUMO has a flexible architecture. In addition, Hülsmann et al., (2011) added that MATSim is originally agent-oriented and consists of an iterative loop, Int Panis et al., (2006) illustrated that DRACULA can represent individual vehicle movements through a network and record and update individual drivers' experiences and perceptions of the network. Furthermore, Ratrout & Rahman, (2009) explained that INTEGRATION is potentially useful for Intelligent Transportation System (ITS).

Apart from using formulated and developed traffic simulation models, another option adopted by some researchers is gathering the traffic flow data directly from the reality or test data (e.g., local driving cycle tests including accurate GPS data), like the work done by Alam et al., (2014); N. Ligterink et al., (2009); Perugu (2019); Rodríguez et al., (2016); Ryu et al., (2015); Sun et al., (2014). These studies are not listed in the table above.

Similar to the situation happened in traffic flow modelling, most analyzed studies tend to use instantaneous emission simulation models, like CMEM model by Amirjamshidi et al., (2013); K. Chen

[1] The non-linear multiple regression models in this research were established by the author based on the Oak Ridge National Laboratory raw data.
[2] This instantaneous emission model was developed based on actual measurements with several instrumented vehicles driving in real urban traffic situations (Int Panis et al., 2006).
[3] DynusT (Dynamic Urban Systems in Transportation) is a simulation-based DTA model system.

& Yu (2007); Misra et al., (2013); VERSIT+ model by Csikós et al., (2015); Madireddy et al., (2011); Quaassdorff et al., (2016); MOVES model by Abou-Senna & Radwan (2013); Lin et al., (2011); Sider et al., (2013); Zhao & Sadeka (2013); Zhou et al., (2015). The fact that most popular models are categorized as instantaneous models is not a coincidence. Kousoulidou (2011) explained this phenomenon as EFs derived from instantaneous data allow for the simulation of vehicle emission for any driving pattern and vehicle configuration. Osorio & Nanduri (2015) pointed out the potential reason could be that this integration usually considers the following factors:

(i) detailed vehicle-to-vehicle and vehicle-to-supply interaction;
(ii) instantaneous speed and acceleration information;
(iii) vehicle-specific attributes (e.g., vehicle type, age).

Based on the discussion above, microscopic traffic simulation models coupled with instantaneous vehicle emission models are able to provide the highest-resolution approach. However, every coin has two sides, coupled microscopic traffic-emission models show their disadvantages in the complexity and computational efficiency. Due to this, their use is mostly limited to what-if analysis, i.e., to evaluate the performance of a pre-determined small set of transportation schemes, rather than to perform optimization (Osorio & Nanduri, 2015).

Nevertheless, many examples of coupling microscopic traffic flow models and instantaneous emission models were proposed by previous work (see an integration framework example introduced by Ma et al., (2014) in Figure 3).

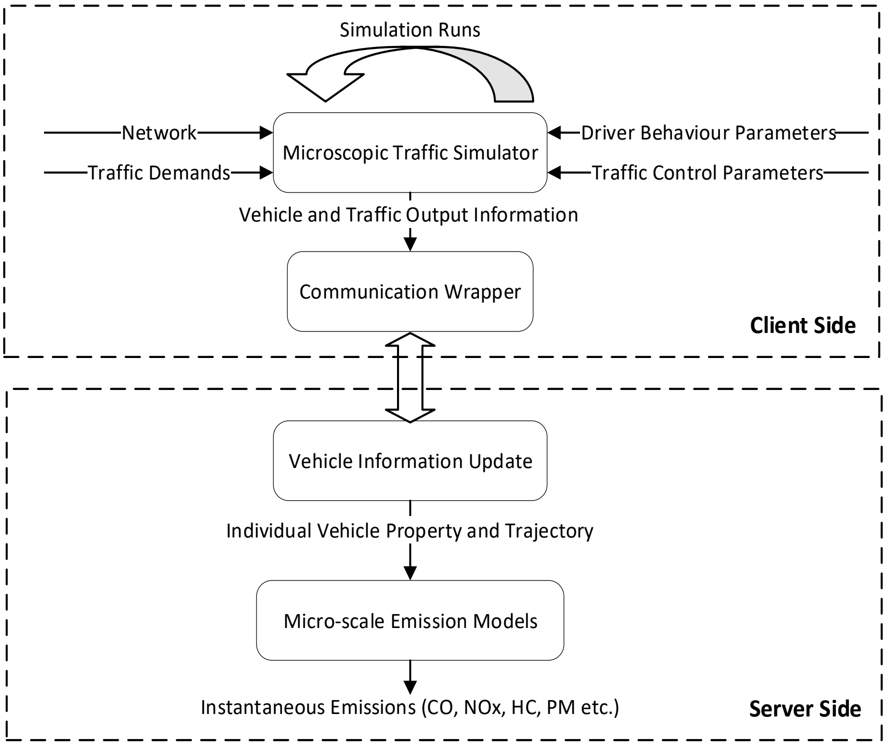

Figure 3 *An integration framework example proposed by Ma et al., (2014).*

Comparing different integration frameworks, the emphasis of different methodological frameworks varies depending on their research objects: some highlighted the importance of traffic demand generation part, e.g., Krajzewicz et al., (2016); some pointed out the need of complete data for accurate estimation, validation as well as adjustment, e.g., Yang et al., (2020); some extended the framework to include air quality model, e.g., Dias et al., (2014); Forehead & Huynh, (2018). Considering the research goals, air quality model will also be involved as a further adoption to imitate the pollutant dispersion process and evaluate the impact of roadside pollutions influenced by different bus lane scenarios on potential victims.

2.4.2 Integration of Traffic, Vehicle Emission and Air Quality Models

If the air quality model is considered, the literature on the integration of the three models shows a different situation. Table 5 lists a number of studies which discussed the integrated framework of traffic, emission and air quality models. From the analyzed studies, researchers tend to use macroscopic and microscopic traffic models than mesoscopic models (only two studies used mesoscale models). Similarly, this situation also applies to the vehicle emission and air quality models that average-speed emission models and near-source dispersion models attracted more attention from the academia (11 out of 14 and 8 out of 14 respectively).

Possible reasons are: for emission modelling average-speed based models require less accurate information than instantaneous models, which makes the emission prediction more feasible when there is not too much input data; for air quality modelling, near-source dispersion models (mainly Gaussian models) have more practical use cases and longer development history (Johnson et al., 1973) compared to CFD models (Baskaran & Kashef, 1996); for situations in both modelling theories, although models that can provide a high-resolution description of emission prediction or pollution dispersion like instantaneous emission models and CFD models, they do require higher computational resources which set limitations for application both in academia and industry.

Table 5 *Review of relevant studies on the integration of traffic flow, vehicle emission and air quality models.*

Reference	Traffic Flow Models			Emission Models		Air Quality Models			Metrics	Country
	Macroscopic	Mesoscopic	Microscopic	Instantaneous	Average-speed	Near-source dispersion	CFD	CTM		
Amirjamshidi et al., (2013)			Paramics	CMEM		Gaussian plume model			CO, HC, NO_x	Canada
Bandeira et al., (2011)	TRANUS				TREM		TAPM		CO, PM_{10}	Portugal
Borrego et al., (2003)		VISUM			TREM			VADIS	CO	Portugal
Csikós et al., (2015)	METANET				COPERT	Gaussian Plume Model			CO, HC, NO_x	Hungary
Dias et al., (2014)			VISSIM		TREM	URBAIR			CO	Portugal
Ghermandi et al., (2019)			Direct field measurement		Tier 3			Micro-Swift-Spray	NO_x	Italy
Gulliver et al., (2005)	SATURN system				SATURN system	ADMS-Urban			CO, PM_{10}, NO_x	UK
Hatzopoulo et al., (2010)			TASHA		Mobile6.2C	CALPUFF			NO_x	Canada
Ježek et al., (2018)			Direct field measurement		EMISENS	Simplified Gaussian Model			Black Carbon (BC), NO_x	Slovenia
Landolsi et al., (2017)	CTM/DNTM				COPERT	Line Gaussian Dispersion Model			CO, NO_x	Tunisia
Misra et al., (2013)			Paramics	CMEM		AERMOD		QUIC	CO, NO_x	Canada
Mumovic et al., (2006)	SATURN system				EFT 2e		PHOENICS		CO	UK
Woodward et al., (2019)			VISSIM	Non-linear multiple regression[4]			Fluidity		NO_x	UK
Yang et al., (2020)		Smart City Model			COPERT		ENVI-met		NO_x	China

Such a need exists and requires efforts to be made to integrate traffic data into emission models to improve air quality modelling results using better traffic flow representations (Pinto et al., 2020). Ideally, the traffic data flow starts from external databases to generate travel demands (usually in the form of road network contains travel demands at each link) as input for the traffic simulation model, the travel activity data (the accuracy depends on the type of simulation models) is then fed to the emission prediction model which includes its own emission factors database as an important part of the calculation. The calculated mobile source emission is now able to be imported into the pollutant dispersion model

[4] The regression equations were developed by Int Panis et al., (2006).

which can simulate the diffusion process of vehicle emissions, calculate the specific concentration of pollutant and visualize the impact of road transport on the ambient air quality.

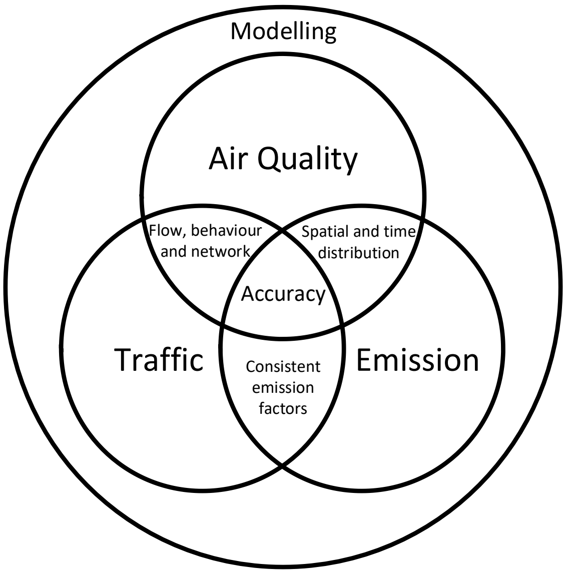

Figure 4 *Relations between traffic, emission and air quality modelling (retrieved from Pinto et al., 2020).*

Figure 4 describes the relations between the three modelling theories. As mentioned earlier, the most difficult decision to be made when choosing a modelling tool is the trade-off between the estimation accuracy and the level of detail in model inputs. Higher simulation accuracy normally means a higher level of detail in model inputs, which requires more resources to collect and prepare the input data. Nevertheless, highly accurate models are complex but are supposed to describe reality more accurately, whereas simpler models are usually used in real-time applications such as proactive traffic management (Madireddy et al., 2011). Therefore, descriptive and predictive accuracy must be weighed against the need for fast simulations.

Another note from the literature is that there is no such thing as the best or perfect traffic-emission-air quality integration model that is suitable for every case. The integration framework has to be adapted to aggregate research object, research goal, scientific treatment, adopted approaches, available data, and the content and the way to present the final results to decision-makers. In conclusion, the integration of these models should aim to help understand the relationship between the sources of pollutant emissions (road transport in this study) and their impacts on the ambient air quality.

2.4.3 Influence of External Data

It is noted by Huang & Ma (2009) that of the four types of input data in vehicle emission modelling, vehicle operating conditions are in principle the most crucial inputs while external environment conditions can be introduced as secondary important inputs. The former data is usually retrieved from simulated traffic models and the external data means the information obtained from exogenous databases. Similar situations also apply to traffic flow modelling and air quality modelling. Two types of exogenous parameters often considered by such simulation studies are introduced in this section.

Influence of Meteorological Data

Meteorological data in the domain of air pollution usually refers to air temperature, humidity, wind direction, and wind speed (Tiwary & Colls, 2010), which has been considered in many emission and air quality modelling tools. For instance, Johnson et al., (1973) proposed a relatively simple near-source dispersion model for calculating urban carbon monoxide (CO) concentrations as a function of local wind direction and speed and the distribution of traffic; when using the dispersion modelling tool, AERMOD, Misra et al., (2013) also adopted meteorological data comprising surface and upper-air data for the study period and hypothetical weather station location from external sources; Alam et al., (2014) suggest using additional inputs of meteorology including temperature (°F) and relative humidity (%) for accurate emission rate estimations (g/h) in MOVES; some studies, like the research accomplished by

Amirjamshidi et al., (2013), even extended the integration framework further by employing professional meteorological model (e.g., AERMET) to obtain wind rose patterns for the investigated period.

Examples of using meteorological data for emission and air quality modelling can be seen in many studies. Possible reasons are: the deeper understanding of pollution dispersion theories; the increase in accuracy demands of simulation tools, which makes the further applications possible; the internal compatibility of including calculations that account for meteorology in most emission and air quality models (Forehead & Huynh, 2018). However, it is noted that meteorological data such as wind velocity and direction, temperature, relative humidity, and more, require rigorous validation before being used in pollution dispersion models (Pinto et al., 2020; Tiwary & Colls, 2010).

Influence of Infrastructure Design Data

Infrastructure design factors vary significantly in terms of research topics. In the domain of traffic-emission-air quality modelling, it comprises factors like land use, transportation infrastructure, ambient building geometry, and more.

A number of studies have highlighted the substantial influence infrastructure design factors can have on traffic-emission-dispersion modelling. Misra et al., (2013) argued that emission prediction models should require data such as geographic terrain of the network that may influence vehicle power demand and thus vehicle emissions; another important factor is the traffic control measure which can change the road design, like bus priority lanes, traffic light, traffic limit, and more. These controls will limit the vehicle's driving trajectory and driving speed and therefore affect vehicles' hot emissions (Alam et al., 2014; Int Panis et al., 2006; Krajzewicz et al., 2005; Rehimi & Landolsi, 2013; Sentoff et al., 2015; Wyatt et al., 2014). One factor influencing the pollutant dispersion process considered by many researchers is the height of surrounding buildings in a street canyon. The work done by Aristodemou et al., (2018) showed clearly how the building height affects the surrounding air flows and dispersion patterns (see Figure 5).

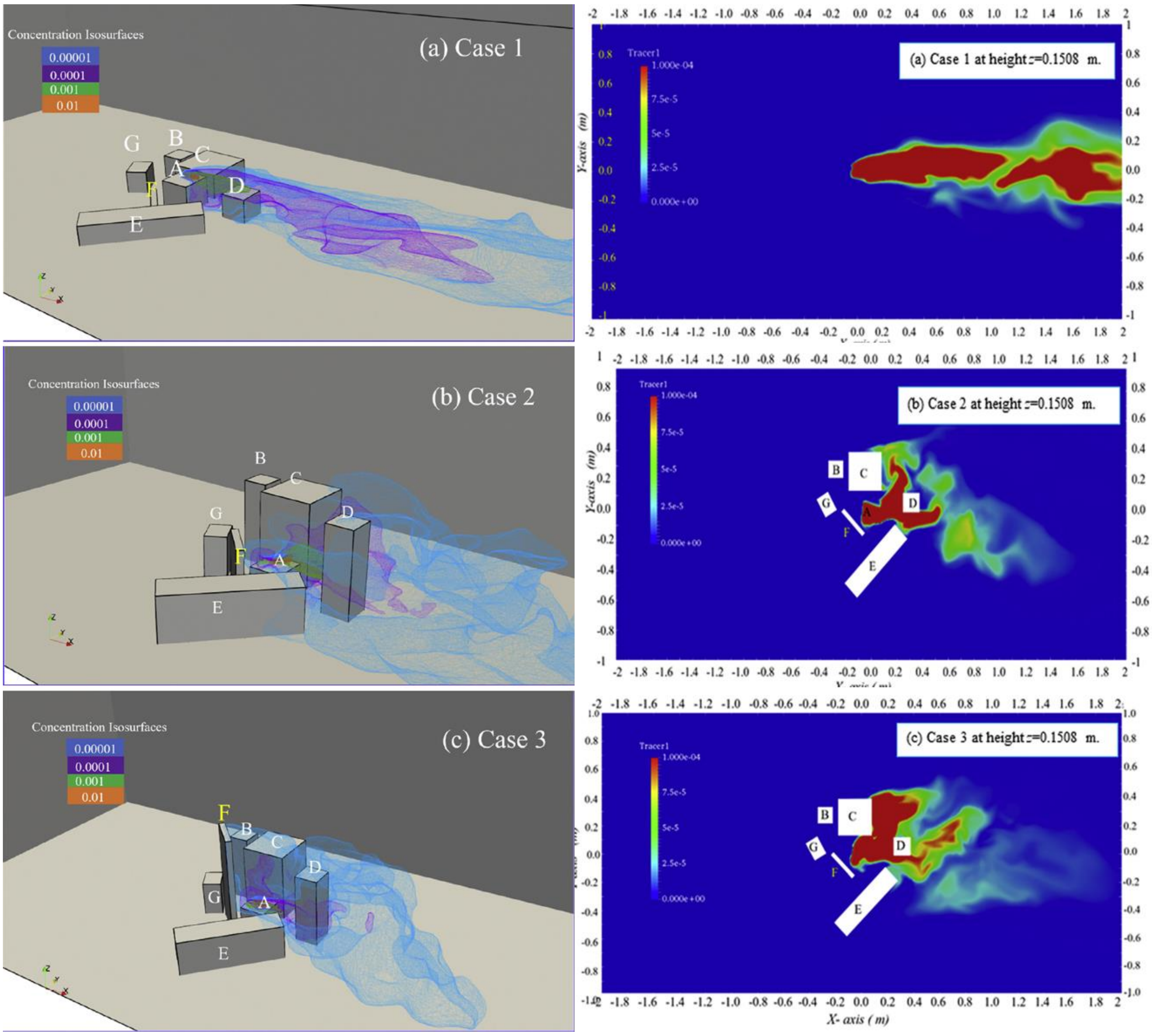

Figure 5 The impact of building height on turbulent air flows and pollutant dispersion within a neighbourhood: Left column, the iso-surfaces in concentration simulation for Cases 1, 2 and 3, showing how the presence of tall buildings affects pollution dispersion within a local neighbourhood. Right column, concentration maps in the horizontal plane (x-y) view for Case 1, 2, and 3. The effect of the taller buildings is clearly seen.(retrieved from Aristodemou et al., 2018).

2.5 RESEARCH GAPS

After reviewing the current literature on the traffic flow, vehicle emission, and air quality modelling as well as the integration of models, several research gaps can be identified:

First of all, as an important practical application of traffic simulation, public transport priority measures have been investigated by many studies, especially those related to bus lane measures (Ben-Dor et al., 2018; KIM, 2003; Koryagin, 2015; Thamizh Arasan et al., 2010; Xu et al., 2013). However, most research listed here only considers the adoption of fixed bus lane policy, which provides room for exploring more alternatives.

Secondly, plenty of research has demonstrated the necessity and feasibility for using external data like infrastructure design factors and meteorological data in simulating traffic flows, vehicle emissions and pollutant dispersion process. However, most research on simulating dedicated bus lanes does not always consider external data sources as a valuable input like studies mentioned in section 2.4.2. Although the real traffic flow, emission production and pollution dispersion process can never be simulated as the same as the reality, valid external information would help increase the credibility of the research.

Thirdly, as illustrated in section 2.4.1 and 2.4.2, it can be observed that most analyzed cases are using instantaneous emission models in the integration of only traffic and emission models while the trend is changed to the opposite situation that nearly 80% of investigated research adopts average-speed based emission models when the air quality model is also included. Such a result can be firstly explained by the difficulties to transpose the information from the vehicle, used by the microscopic traffic models, to road links, required by the air quality models (Fontes et al., 2015). Secondly, another reason is that much additional work in the instantaneous emission modelling is required in order to accurately assess the environmental impacts of vehicle emissions. In addition, higher requirements for input data and computational resources would be another obstacle for using the instantaneous approach in such a framework. Nevertheless, the more accurate the input data for air quality models, the more credible the results can be used to assess the human health impacts. Therefore, using instantaneous emission models to link road traffic and air quality models, which has not been well addressed in the literature.

Lastly, all simulation models (traffic, vehicle emission, and air quality) have uncertainties (i.e., inevitable errors) that are reflected in the accuracy and results (Pinto et al., 2020), which essentially causes the accumulation of errors in the traffic-emission-air quality modelling framework. For instance, one of the critical issues in traffic modelling is the travel demand generation in the road network; when limitations and uncertainties exist in producing demand, the uncertainties in the travel activities are, therefore, propagated to emission rate in the emission modelling and further total amount of pollutants in air quality modelling. However, this chain reaction within the framework has not been discussed broadly in the literature.

2.6 CONCLUSION

As the characteristics of various traffic simulation approach summarized in section 2.1, macroscopic traffic modelling tends to use coarser and aggregated variables to describe the traffic flow in a larger scope while microscopic methods typically take the attributes of each individual unit into account for generating more accurate outputs. Considering the necessity of representing different vehicle types (at least passenger vehicles and buses), road configuration and most importantly, road restriction policies, microscopic traffic simulation is more suitable for simulating the traffic flows influenced by bus priority policies in a micro traffic network. Between the two discussed traffic simulation tools, SUMO, as an open-source tool, is less polished compared with the commercial software package VISSIM. However, its openness and compatibility also bring more potentials due to its decent cooperation with the TraCI controller. Efforts are expected to be made in this research to explore and discuss the potentials of this open-source traffic simulation tool.

The second section mainly elaborated the basic theories of vehicle emission modelling. It started with categorising most popular vehicle emission models into average-speed models and instantaneous models. The most apparent difference between two types of the model was the granularity of adopted variables that the instantaneous model uses detailed traffic activity data to estimate emission rates while the average-speed model uses aggregated traffic variables for a large-scale emission estimation during a given period. Logically, that the average-speed model consumes fewer computation resources since it only considers the average traffic characteristics of the whole flow, but the computation time required by the instantaneous model is proportional to the number of vehicles. However, speaking of specific emission modelling tools, the required computation resource was only one factor that determines the suitable tool.

On the other hand, the ability to accurately evaluate vehicle emissions in the study area was another important factor that needed to be considered. Although HBEFA has been included internally in SUMO since the creation of this traffic simulation tool (German Aerospace Center (DLR), 2019d), it mainly uses the traffic data measured in Germany, Austria, Switzerland, France, Sweden and Norway to generate the emission factor database, concerns exist that emission factors may vary from the actual traffic-induced emission rates happened in the Netherlands. In order to reduce the uncertainty of the integrated framework essentially, VERSIT+ is more suitable for the experiments carried in this research because this model was built based on a reliable database that covers more than 20,000 driving cycles and 3,200 different vehicles performed in the Netherlands in a period over twenty years (N. E. Ligterink & de Lange, 2009; Trachet et al., 2010).

Next, a necessary extension, air quality modelling, was introduced in section 2.3 as a response to the increasing emphasis on the public's health. As a sufficient tool to describe the atmosphere, dispersion and chemical and physical processes at various locations, three classical types of the air quality model, namely CTM model, near-source dispersion model and CFD models, were explained. Furthermore, the characteristics of one open-source dispersion model, GRAL, was also presented.

In terms of the integration of simulation models, Zegeye et al., (2013) argued that microscopic traffic flow models were usually coupled with instantaneous emission models. From the broad literature research, the same conclusion can be drawn from Table 4. Additionally, most researchers preferred to combine these two specific types of simulation approaches to investigate the environmental influence brought by traffic flows. However, when the air quality modelling was also included in the integration framework, researchers were fonder of using average-speed emission models and near-source dispersion models instead, but they do not show a preference for any branch traffic flow models (see Table 5). Reasons were summarized as follows: average-speed models require less computational resources; near-source dispersion models have provided more successful use cases. In this regard, the discussion on the remaining categories was not enough, namely the instantaneous emission model and CTM dispersion model. Thus, the exploration of the other models would be one sub-goal of this research. Besides, according to the wide adoption of external data in other projects, additional external information that relates to meteorological data and infrastructure design parameters was introduced.

In the end, the research gaps between the current literature and proposed research goals haven been concluded from various perspectives: lack of diversity in bus lane policies; insufficient adoption of data; limited expansion based on instantaneous emission models; and lack of framework analysis.

In conclusion, three types of simulation theories, including traffic flow modelling, emission modelling and air quality modelling, and their specific simulation tools were thoroughly discussed in this chapter, providing the theoretical support for the following chapters.

Chapter 3 Methodology

This chapter aims to illustrate the methodology, including the general approach for the whole thesis, the integrated modelling framework based on the selected simulation models and the calculation methods of measurement indices. Section 3.1 elaborates the research process composed of three main stages to clarify the general approach. Next, the main research contribution, the integrated modelling framework based on three simulation models as well as the data flow behind it, is illustrated in section 3.2. Lastly, the indicators for evaluating designed scenarios, including traffic efficiency index and vehicle emission index, are explained in section 3.3.

3.1 General Approach

This section presents the general approach proposed in this study, which involves three stages (see Figure 6). In the flow chart, blue boxes indicate the main steps implemented during the research process, and white boxes demonstrate the supplementary information about specific steps.

Figure 6 *General approach.*

Stage 1: Microscopic simulation modelling. The simulation flow framework, which consists of three different microscopic simulation models (SUMO, VERSIT+ and GRAL) is established at first. Data from external sources is imported into the simulation to keep it consistent with the microscale. Besides, the internally generated data is used to connect three models, which is explained in section 3.2.

Stage 2: Case study. A microscopic baseline road network based on a real case is simulated by applying the integrated framework. The simulated results include the fluctuations of traffic volume and vehicle speed with time, vehicle emissions per street as well as the distribution of pollutant concentrations in the modelling domains. Among the range of traffic-induced pollutants, CO is chosen as an example indicator since it typically originates from incomplete combustion of carbon fuels, such as that which occurs in car engines and power plants. The simulation result is then validated by comparisons with actual bus schedules and monitored air quality data, after which the model is adjusted.

Stage 3: Scenario analysis. After setting up the baseline simulation environment, we zoom into the bus lane on the main road, and model the impact of different traffic management schemas that are based on two strategies (dynamic bus lane and adaptive traffic light) on urban traffic flow and roadside air quality (in this case, refers to CO concentration). The microscopic simulation results in terms of the traffic situation, vehicle emission and air quality are used for evaluating the efficiency of various scenarios through indices like traffic volume, bus deviation time and street vehicle emissions. The explanations on the measurement indices can be found in section 3.3.

3.2 INTEGRATED MODELLING FRAMEWORK

As explained in the general approach, one of the main contributions of this research is an integrated modelling framework which connects three simulation models. Besides, the data flow behind the integrated system is also important since the framework is established based on external data sources and is connected by two important data links.

In this section, the integrated modelling framework is presented first, and the method of calculating two connection datasets are explained in the second part, while the data preparation process based on external data sources related to the baseline scenario will be introduced in the next chapter.

3.2.1 Integrated Framework

The integrated framework which couples microscopic traffic, vehicle emission and air quality modelling can be drawn (see Figure 7). It illustrates the procedure to link the selected simulation models and the main data input and output of each model.

Firstly, information related to the road network configuration, traffic demands, and additional data will be collected from different external data sources and used to set up the microscopic traffic simulation environment in SUMO. The outputs of this model, including road network and traffic volumes, are converted to total driven mileage per street (highlighted in orange in Figure 7). It is then used with the combination of emission class and emission factor from the VERSIT+ database as inputs for vehicle emission calculation to quantify the street vehicle emissions of the investigated road segments. At last, the GRAL model is applied based on the emission source intensity (generated from both traffic and vehicle emission modelling results and highlighted in orange in Figure 7) and external environmental data (infrastructure design parameters and meteorological parameters), the distribution of pollutant concentrations can be then computed to show the roadside air quality in the modelling domains.

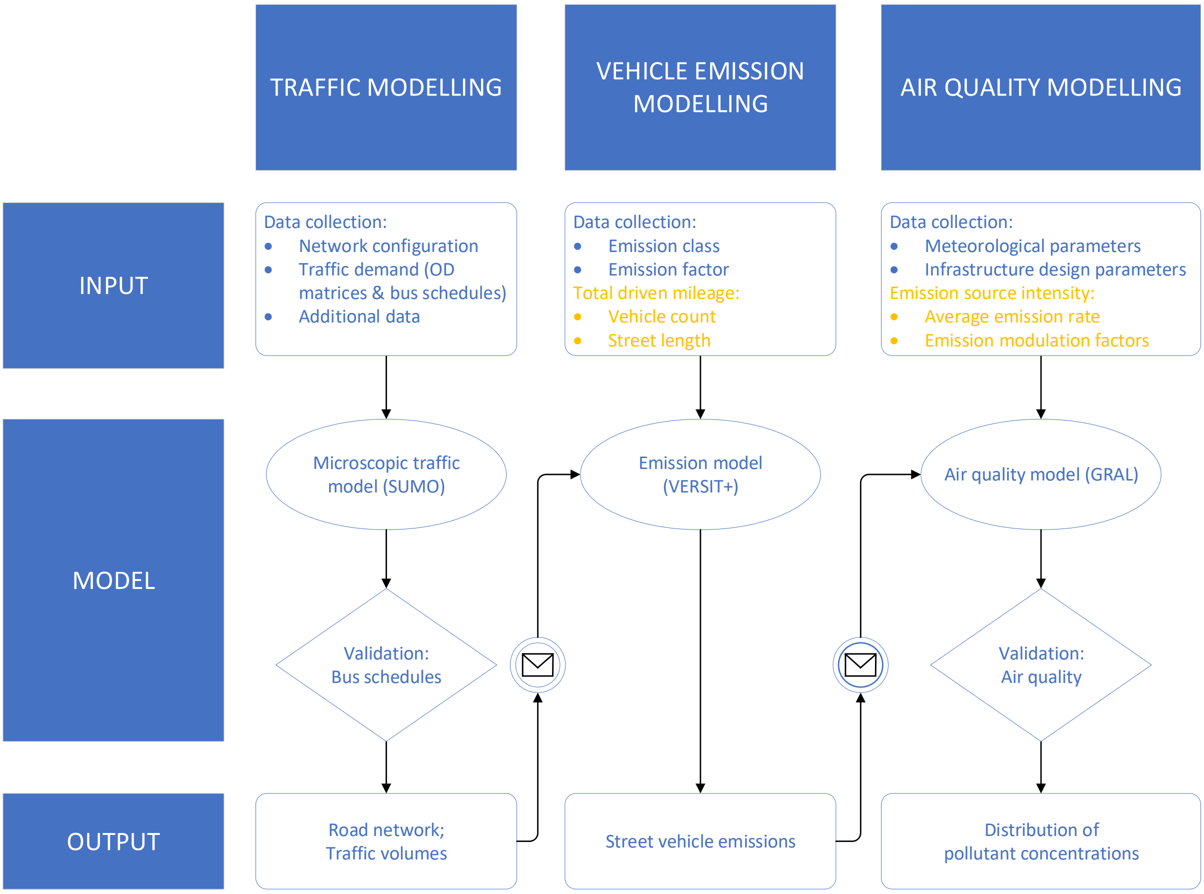

Figure 7 *The integrated framework based on the traffic, vehicle emission and air quality models (connection data is highlighted in orange).*

The established framework successfully integrates the traffic, vehicle emission and air quality models based on a reliable data flow, which explains how the integration framework can permit the prediction of urban air quality influenced by different traffic management scenarios. With the change in any parameters in the framework, it allows to create various scenarios, generate the corresponding simulation results, and therefore evaluate these scenarios based on various indices. Two validation parts that related to the baseline case will be illustrated after establishing the baseline scenario in section 5.5.

3.2.2 Data Links Between Simulation Models

As emphasized by the integrated framework, the key to link three different simulation models is the two mentioned internal datasets. To clarify this reasonable information flow, the methods of generating the internal data connections are explained as follows.

3.2.2.1 Linking Traffic and Vehicle Emission Models

In the vehicle emission modelling, to calculate the traffic-induced emissions per street, the output of traffic simulation, i.e., *total driven mileage* by passenger cars (vehicle kilometres travelled, VKT) on the investigated streets, is needed. However, the current SUMO does not have the ability to generate such output directly. Instead, two sub-datasets, *vehicle count* and *street length*, that can constitute the *total driven mileage* per street will be retrieved.

Vehicle Count

The first retrieved component is *vehicle count* which gives the number of passenger cars that have travelled through each street in the simulation period. An XML script is prepared as below. It will be invoked by SUMO during the traffic simulation to compute the number of passed vehicles in the designated simulation period.

```
<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/additional_file.xsd">
	<edgeData id="Measurement_whole_simulation_period" file="edge_output_car_06.30-19.00.xml"
begin="23400" end="68400" excludeEmpty="True" vTypes="car"/>
</additional>
```

Several attributes are defined in the counter: the attribute *excludeEmpty* is set TRUE to exclude those streets that were not used by any car during the simulation period. The attribute *vTypes* is specified in the detector to count only passenger cars. *Begin* and *end* are the attributes to specify the time to start and end writing (only the cars travelled in the interval are recorded).

After running the traffic simulation by SUMO, the computed information summary on a certain edge has values like *id*, *travelTime*, *density*, *occupancy*, *waitingTime*, *speed*, *departed*, *arrived*, *entered*, *left*, and etc. Noted that these values can only describe the situation by macroscopic mean values such as the mean vehicle speed, the mean density, and more. The detailed explanations to these values can be referred to the SUMO documentation (German Aerospace Center (DLR), 2020d). Next, another python script shown below will be invoked to convert SUMO output files (.xml) into editable data sheet files (.csv) with chosen attributes, *id*, *departed*, *arrived*, *entered*, and *left*.

```
# import the library
import csv
import sumolib

with open ('edge_vehicle count_06.30-19.00.csv','w',newline='') as csvfile:
        fieldnames = ['edge_id','edge_departed','edge_arrived','edge_entered','edge_left',]
        thewriter = csv.DictWriter(csvfile,fieldnames=fieldnames)
        thewriter.writeheader()
        # parse all edges in the edge data (meanData) file
        for interval in sumolib.output.parse("edge_output_car_06.30-19.00.xml", "interval"):
                for edge in interval.edge:
                        thewriter.writerow({'edge_id':edge.id,'edge_departed':edge.departed,'edge_arriv
                ed':edge.arrived,'edge_entered':edge.entered,'edge_left':edge.left})
```

Id indicates the specific street, *departed* and *arrived* gives the number of vehicles that launch or finish their routes on this street within the simulation period, *entered* and *left* store the information about the number of vehicles that have entered or left the street within the period. Based on SUMO's default settings, a vehicle begins its trip from the upstream end of the street when calculating *departed*, and arrives at the downstream end when calculating *arrived*. Besides, when a car is about *leaving* from this street it always starts its journey from the upstream end and, when it *enters* the street, it always reaches the downstream end (see Figure 8).

Figure 8 *The upstream end and downstream end of a street.*

Therefore, to avoid double counting on vehicle numbers, *vehicle count* is computed to use the value of *departed+entered* or *arrived+left*. Here, *vehicle count* chooses to use the sum of *departed* and *entered.*

Street Length

As the name indicates, this data extracts the length of the investigated streets. It represents the average distance travelled by vehicles on the street. Since cars are free to change lanes, turn around, park at roadsides (where traffic rules permit), they are probably to travel slightly different distance on the same road in real traffic conditions. But from a macroscopic perspective, the average mileage of a large number of cars on a normal road would be close to the street length since most cars would travel from the beginning to the end. It is therefore reasonable to use *street length* for the average mileage of the investigated streets in the calculation.

It is done by extracting the length information of all edges first and then matching the investigated streets with edges by their unique *Ids*. The python script below is invoked to convert the road network file (*.net.xml*) to retrievable edge length dataset (*.csv*) which contains only two types of information, *edge.id* and *edge.length*.

```
# import the library
import csv
import sumolib

with open('all_edges_length.csv', 'w') as csvfile:
        fieldnames = ['edge_id','edge_length',]
        thewriter = csv.DictWriter(csvfile,fieldnames=fieldnames)
        thewriter.writeheader()
        # parse all edges in the network data file
        net = sumolib.net.readNet("Network.net.xml", withInternal=True)
        edges = net.getEdges()
        for edge in edges:
                thewriter.writerow({'edge_id':edge.getID(), 'edge_length':edge.getLength()})
```

With the converted street information dataset, the length of investigated streets can then be retrieved and added to form the list with attributes including *edge.id*, *edge.vehicle_count*, and *edge.length*.

Thus, the *total driven mileage* travelled by all passenger cars on street *s* can be calculated using:

$$mileage^{s} = vehicle\ count^{s} \times length^{s} \qquad [3-1]$$

Where

> $mileage^{s}$ is the *total driven mileage* by all passenger cars on street *s* (in km);
>
> $vehicle\ count^{s}$ is the number of passenger cars that have travelled through street *s* in the simulation period;
>
> $length^{s}$ is the length of street *s* (in km).

Therefore, the calculation of *total driven mileage* succeeds in importing the information from traffic modelling into vehicle emission modelling with a proper scope.

3.2.2.2 Linking Traffic, Vehicle Emission and Air Quality Models

As road traffic has peak and off-peak periods of a day, the other important data link that includes air quality modelling into the framework is the traffic-induced *emission source intensity* with time series. As illustrated in the user manual of GRAL (Öttl & Kuntner, 2020), the intensity of emission sources is usually composed of *average emission rate* and *emission modulation factors*, reflecting fluctuations in emission rates. Thus, this data link will be derived by converting the outputs from both traffic modelling and emission modelling.

Average Emission Rate

To describe the time-related intensity of vehicle emissions on the street, the *average emission rate* on each street is calculated first. It needs the result of vehicle emission modelling, namely the *street vehicle emission* (explained in section 3.3.2) on a road segment over the simulation period. The average emission rate er_p^s of pollutant *p* on street *s* during the simulation period can be calculated by equation [3-2]:

$$er_p^s = emission_p^s \div duration \div length^s \qquad [3-2]$$

Where

> er_p^s is the average generation rate of pollutant *p* on street *s* (in kg/h/km);
>
> $emission_p^s$ is the total emission of pollutant *p* on street *s* (in kg);
>
> *duration* is the simulation duration (in hour);
>
> $length^s$ is the length of street *s* (in km).

It should be noted that one further modification based on the *average emission rate* is needed that the complete *average emission rate* of the whole street is generated by aggregating the rates of both opposite directions on the same road segment unless it is a one-way street.

Emission Modulation Factors

Based on the literature review of the pollutant dispersion simulator, the GRAL model is capable of providing the function of modulating the emission rate with time series to consider the fluctuation of pollutant concentrations through a day and therefore calculate the daily max and daily mean concentrations (Öttl & Kuntner, 2020).

Furthermore, proved by most literature on emission modelling and pollutant dispersion modelling (Pérez-Martínez et al., 2014; Zhang & Batterman, 2013; D. Zhao et al., 2018), it is reasonable to assume that the fluctuations in street emission rate are consistent with changes in traffic volume in this research. In other words, the deposition value of pollutants is proportional to the number of running vehicles in the network. Based on this assumption, the number of vehicles running at each moment will be recorded (this function is provided by SUMO) and used to calculate the diurnal modulation factors at each recorded moment.

One more assumption was made that when the average number of vehicles is running in the network, they will generate vehicle emissions at a rate of one unit. Then, the corresponding *emission modulation factor* at time *t* can be obtained by the following equation:

$$(modulation\ factor)_t = \frac{(number\ of\ vevhicles)_t}{average\ number\ of\ vehicles} \qquad [3-3]$$

Where

(modulation factor)$_t$ is the emission modulation factor at time *t*;

(number of vehicles)$_t$ is the number of vehicles at time *t*;

average number of vehicles is the average running vehicle number through the whole simulation period.

The calculated results of modulation factors for the baseline scenario can be found in the general settings for air quality modelling in section 5.4.1. In addition, since the seasonal changes in road traffic are not the focus of this project, they were therefore neglected.

In a summary, *average emission rate* is designed to import the information from vehicle emission modelling into air quality modelling while the influence of traffic modelling is represented by the *emission modulation factors*. With the help of these sub-datasets, it makes possible to define the intensity of street emission sources in the GRAL simulator as the *average emission rate* at first and then *emission modulation factors* can be used to simulate the fluctuation in the emission rate through a day.

3.3 MEASUREMENT INDICES

Next to the modelling framework, it is also necessary to clarify the indices used to evaluate the efficiency of redesigned traffic management scenarios. The first part explains the indicators used in comparing the traffic efficiency between scenarios and the second part gives a description on how to compare scenarios from the perspective of vehicle emissions.

3.3.1 Traffic Efficiency Index

Traffic volume comparison C_i (%) is designed with the purpose of comparing the traffic volume fluctuations of each designed scenario with the baseline scenario in a more straightforward way, especially for private traffic. It can be calculated by using equation [3-4]:

$$C_i^t = \frac{TV_i^t}{TV_b^t} - 1 \qquad [3-4]$$

Where

C_i^t is the comparison between the investigated scenario and the baseline scenario (in %);

TV_i is the traffic volume measured at time t in scenario i;

TV_b is the traffic volume measured at time t in the baseline scenario.

In addition to measuring the performance of private traffic, the stability of bus operation is another critical indicator in this research. Therefore, the *deviation time* based on the simulated departure time of buses from each stop and the scheduled time on the actual timetables is computed by equation [3-5]:

$$(Deviation\,Time)_i^n = (Simulated\,Time)_i^n - (Scheduled\,Time)_i^n \qquad [3-5]$$

Where

$(Deviation\ Time)_i^n$ is the deviation time of the bus trip n at bus stop i (in second);

$(Simulated\ Time)_i^n$ is the simulated time of the bus trip n at bus stop i (in second);

$(Scheduled\ Time)_i^n$ is the scheduled time of the bus trip n at bus stop i (in second).

In short, these two indicators are chosen to evaluate the traffic efficiency of different traffic scenarios from the perspectives of private traffic as well as public transport.

3.3.2 Vehicle Emission Index

As mentioned earlier, *street vehicle emission* represents the cumulative vehicle exhaust emissions over the simulation period. It is employed as the indicator to show the vehicle emission modelling results. It is noted that the discussion on the exhaust pollutants source is limited on private traffic since the Netherlands are committed to achieving zero-emission public transport by 2025, and all the investigated bus lines in the study area have already been switched to electric buses (Transdev, 2018).

It is reflected by the literature review that vehicle emission modelling based on the VERSIT+ model is essentially the combination of the vehicle activity information (vehicle kilometres travelled) from traffic modelling results and the emission factor data (gram/vehicle kilometres travelled) provided by the database, which would calculate the total vehicle emission (gram) for the designated period:

To measure the total *street vehicle emission*, the *weighted emission factor* of pollutant p should be calculated at first:

$$wef_p = \sum (Prop_{ij} \times ef_{pi}) \qquad [3-6]$$

Where

wef_p is the weighted emission factor of pollutant p (in g/km);

$Prop_{ij}$ is the proportion of the vehicle kilometres travelled by emission class i to the total kilometres by vehicle-fuel combination j (emission class will be explained in section 4.2.1 and the values of $Prop_{ij}$ can be found in Table 9);

ef_{pi} is the emission factor of pollutant p for emission class i (in g/km).

With the *weighted emission factor* of pollutant p and the *total driven mileage* (equation [3-1]) on street s, the *street vehicle emission* of pollutant p can be calculated using equation [3-7]:

$$emission_p^s = \sum (Prop_j \times wef_p \times mileage^s) \qquad [3-7]$$

Where

$emission_p^s$ is the total emission of pollutant p on street s (in g);

$Prop_j$ is the proportion of the vehicle kilometres travelled by vehicle-fuel combination j to the total kilometres by all passenger cars, the values can be found in Table 6;

$mileage^s$ is the *total driven mileage* by all passenger cars on street s (in km).

Table 6 *Number of vehicle kilometres by different vehicle-fuel combinations in 2018 (rounded to 0,1 million)(extracted from Geilenkirchen et al., 2020).*

VERSIT class	Vehicle	Fuel	Kilometres (million)	Proportion
LPAB	Passenger car	Petrol	73,912	68.5%
LPAD	Passenger car	Diesel	31,352	29.1%
LPAL	Passenger car	LPG	1,943	1.8%
LPAC	Passenger car	CNG	108	0.1%
LPAE	Passenger car	Electricity	589	0.5%
Total			107,903	100%

By these equations, the vehicle emission per street can be computed based on the vehicle activity data from traffic modelling as well as the emission factors from VERSIT+ model, which indicates that it is an appropriate indicator.

3.4 CONCLUSION

In conclusion, the methodology chapter explained both the general approach of the whole research process, and the detailed method of integrating simulation models and calculating measurement indices:

The research process was illustrated at first that it can be divided into three stages: microscopic simulation modelling, case study and scenario analysis. Microscopic simulation modelling is going to use three different simulation models to set up an integrated modelling framework. The established framework is then applied based on a real case to create the baseline scenario. The scenario analysis will be conducted in the end by comparing different traffic management schemas in terms of several indices.

The second section aimed to emphasize one main research contribution, the integrated modelling framework, and the data flow that supports it. The integrated simulation system started with the traffic modelling by SUMO which simulates the vehicle movement in the simulation road network. The results will then be combined with emission factors in the VERSIT+ model to calculate vehicle emissions per street. The air quality of the ambient environment will be represented by the pollutant concentration distribution which can be computed by the GRAL simulator using the output of the two previous models. Additionally, the data flow behind the simulation flow was depicted. The models were linked by two specific datasets: *total driven mileage* and *emission source intensity*. The continuity of the information flow internally proved the feasibility of reflecting the impact of traffic management scenarios by vehicle emissions and air quality in the ambient environment.

To evaluate the efficiency of designed scenarios, a quantitative analysis is necessary. Therefore, three indicators, including *traffic volume comparison*, *bus deviation time*, and *street vehicle emission*, were selected and discussed in the third part, which permits to assess the traffic management schemas from the perspectives of traffic efficiency and vehicle emissions.

In conclusion, this chapter depicted the road map for the research and emphasized the key components before the detailed explanations in the following chapters.

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Chapter 4 Data Preparation

This chapter explains the adopted data from external data sources for simulating traffic flows, vehicle emissions and air quality. Section 4.1 gives a description of collecting and preparing different types of data, including network data, traffic demand data and additional data, for the traffic simulator SUMO. Similarly, the preparation of data for vehicle emission modelling, including emission class and emission factor from the VERSIT+ model, is demonstrated in section 4.2. In section 4.3, the external environmental data composed of meteorological parameters and infrastructure design factors are prepared for air quality modelling based on the requirements of the open-source model GRAL.

4.1 DATA FOR TRAFFIC MODELLING

In order to simulate realistic traffic, a number of elements are needed. The most important ones are pointed as the following (Bieker et al., 2014; Lopez et al., 2018):

- Representation of road network (e.g., normal roads, bus lanes)
- Representation of traffic demand (e.g., OD matrices, bus schedules)
- Representation of additional elements (e.g., vehicle types, total bus stop time)

Following this structure, section 4.1.1 describes the OpenStreetMap database for the simulation network as well as two options of extracting the information; section 4.1.2 introduces the corresponding traffic demand data from two perspectives, namely private traffic and public transport. Lastly, two types of additional data for traffic simulation are proposed in section 4.1.3. The following sections will describe each part in detail.

4.1.1 Network Data

A SUMO network file is designed to describe the traffic-related part of a map, the roads and intersections the simulated vehicles run along or across (German Aerospace Center (DLR), 2019e). The simplest network can be constructed from *nodes* and *edges*. *Nodes*, also named *junctions* in SUMO-context, represent intersections, and *edges* mean roads or streets. An *edge* connects two *nodes* and represents one or several *lanes* going in the same direction. Noted that *edges* are unidirectional, which means one complete road normally consists of two edges in opposite directions. Besides, a more complete SUMO network can be imported from external data sources and contains information including:

- Every street (*edge*) as a collection of *lanes*, including the position, shape and speed limit of every *lane*;
- *Junctions* including their right of way regulation;
- Traffic light logics referenced by *junctions*;
- *Connections* between *lanes* at *junctions*.

According to the information described, a data model for a *network* is developed in Figure 9 to depict the object attributes and data structure. More descriptions on object attributes can be found in Appendix A.1.

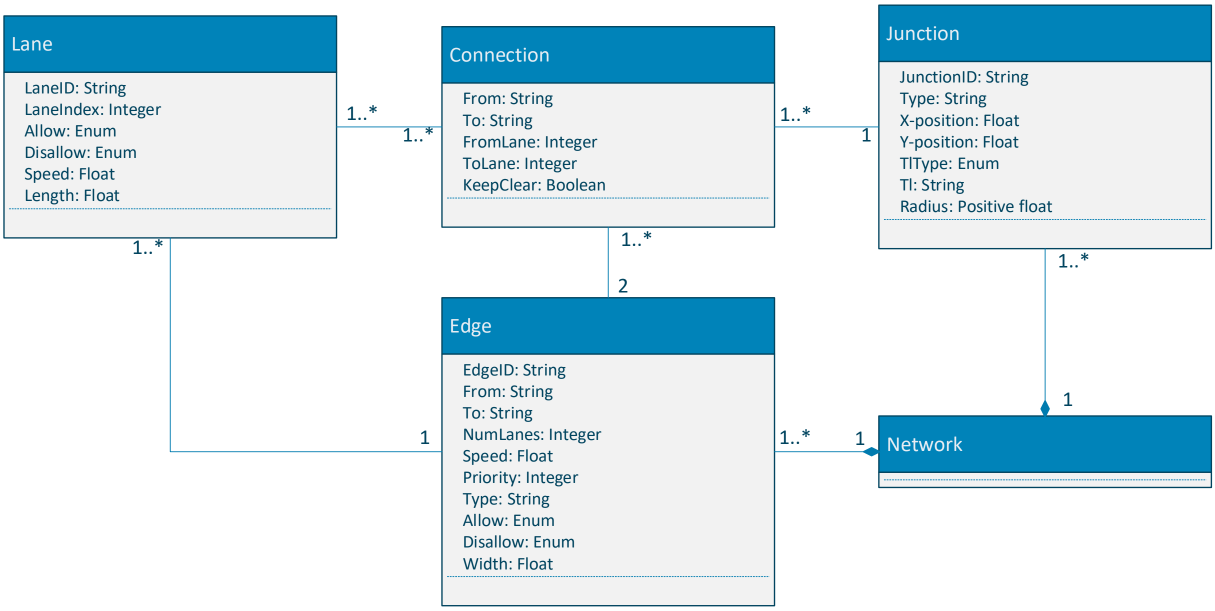

Figure 9 *Network data model.*

Compared with constructing the network by the NETEDIT application provided by SUMO packages, the option of extracting the road configuration information from an external network database is more accurate and convenient for this study. OpenStreetMap is such a compatible and open data source.

4.1.1.1 OpenStreetMap Database

OpenStreetMap (OSM) is a collaborative project to create an editable map of the world, licensed under the Open Data Commons Open Database License (ODbL) by the OpenStreetMap Foundation (OpenStreetMap Foundation, 2020) (see the OSM interface in Figure 10). This database starts with the aim of providing open and free geographical information and is now becoming a valuable example of volunteered geographic information (VGI) (Goodchild, 2007). The application of OSM has been validated in a number of previous studies including simulation of road terminal operations (Carboni & Deflorio, 2020), determination of electric vehicle charging strategies (Miranda & Syr, 2020) and most importantly, generation of realistic urban traffic flows (Stolfi & Alba, 2018). Hence both the openness and availability of OSM have proved that the use of this data source aligns with the aims of this research.

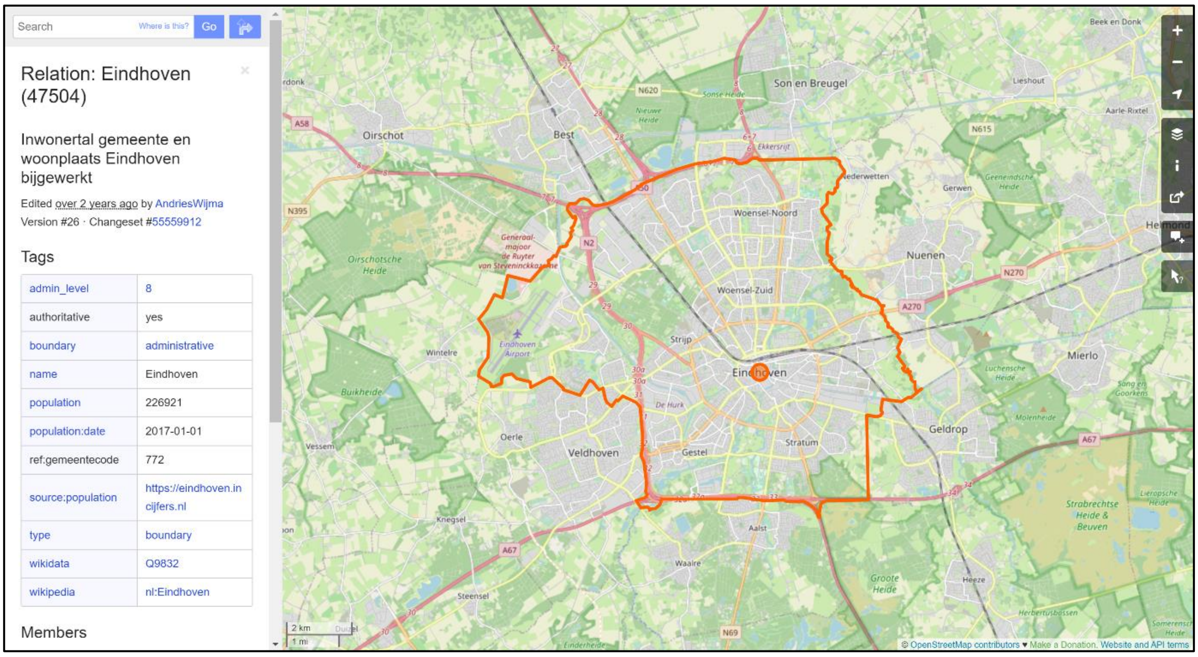

Figure 10 *Eindhoven city map in OSM.*

4.1.1.2 Network Import

As mentioned above, the road network data would be imported from the OpenStreetMap database for setting up the simulation environment. There are several ways to retrieve OSM data regarding different geographical scales, like using OSM WebWizard or directly exporting from the OSM website for microscopic scale, using the OSM API for a single city or even larger areas. Considering the scale of the study area, the first two options are discussed below:

OSM WebWizard

The first option would be extracting the OSM data by using the OSM WebWizard. By invoking the command line below, a web browser should open to show a map (see Figure 11).

```
python osmWebWizard.py
```

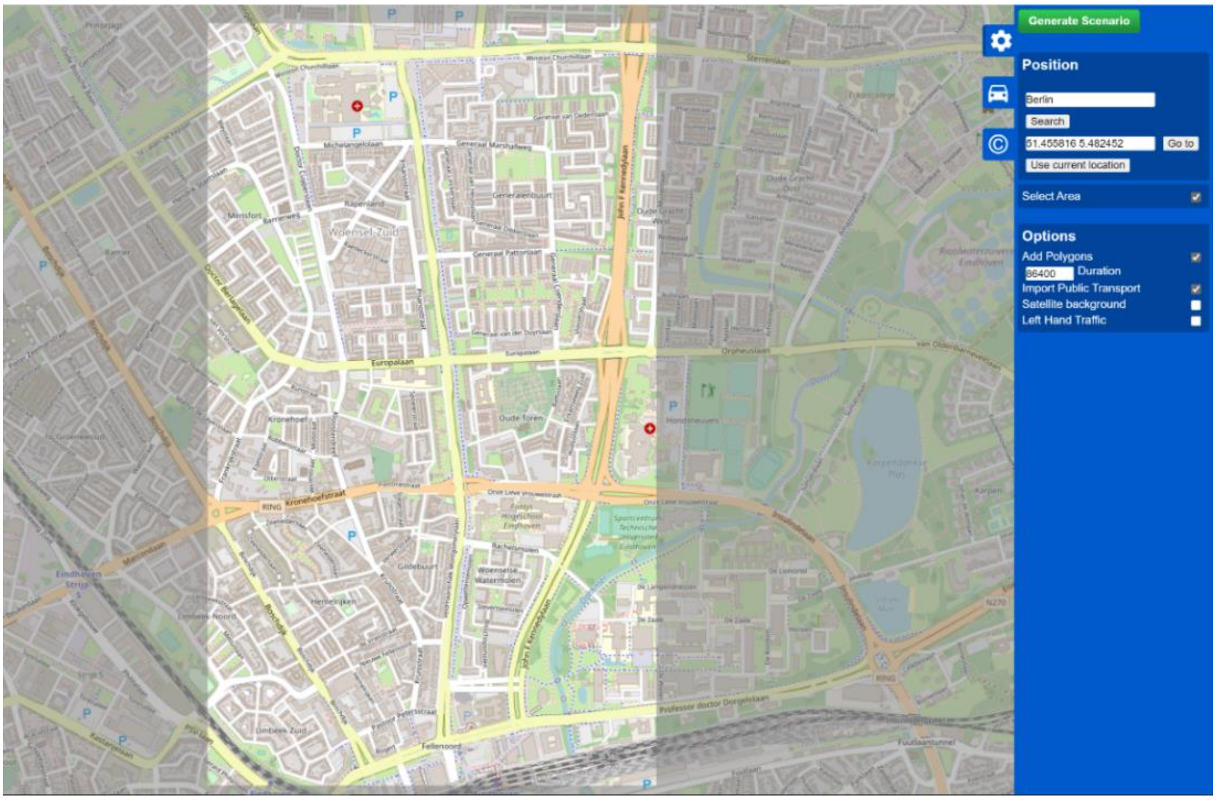

Figure 11 *The OSM WebWizard interface.*

The infrastructure imported by the OSM WebWizard into the SUMO simulation is controlled by different options. By default, all types of roads and rails will be imported (bicycle lanes, footpaths, railways, and etc.) when generating a scenario. Facilities related to public transport, like bus stops and train stations, are also possible to be imported with specific checkboxes.

OSM WebWizard can also generate traffic demands for different chosen transport modes. The demands are generated based on a certain probability distribution which is determined by two parameters (German Aerospace Center (DLR), 2020g): “Through Traffic Factor” and “Count”. The first parameter defines how many times it is more likely for an edge at the boundary of the area being chosen as an origin or a destination compared with an edge entirely located inside the area. A big value can bring out the result that many vehicles depart and arrive at the boundary, making a lot of through traffic. The second parameter specifies how many vehicles are generated per hour per lane-kilometre.

Although this method is very convenient for generating traffic scenarios, the demand of public transport, in this case, is generated based on “synthetic” schedules defined in OSM (German Aerospace Center (DLR), 2020g). Thus, the imported schedule cannot be manipulated and modified at will and therefore it cannot achieve situation analysis easily. The randomness of generating traffic demands brought by this method determines it is not suitable for this project.

OpenStreetMap

Another option to extract the road network information is exporting directly from the OpenStreetMap. As Figure 12 indicates, the website does provide the function to export the OSM file. Once the study area is selected, “Export” is available to download the information.

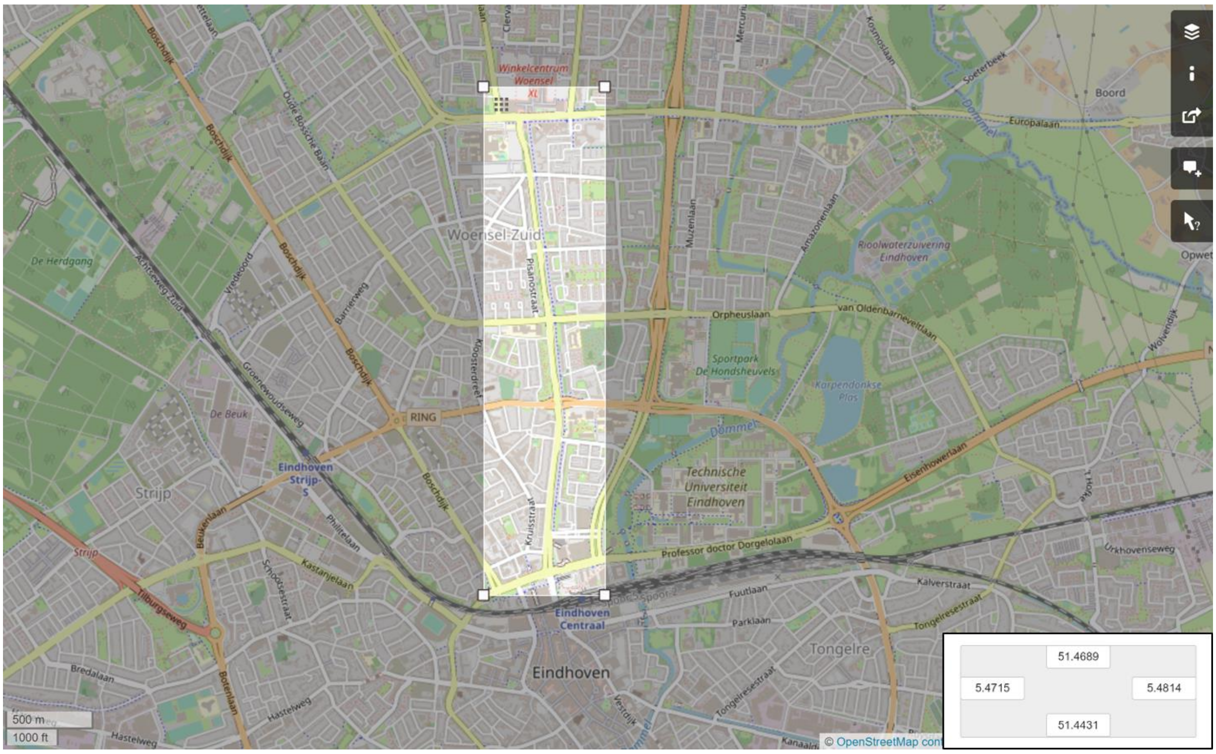

***Figure 12** The OpenStreetMap website interface.*

Once the OSM file is downloaded, it cannot be used by SUMO yet and NETCONVERT has to be conducted. Basically, NETCONVERT is a command-line application which enables to translate the information stored in the downloaded file (*.osm*) to the road network file (*.net.xml*) that can be imported to SUMO environment for the following steps.

NETCONVERT showed below will be invoked: the first line indicates the edge type definitions used in the network, including the types of default settings and edges in the urban area (See Appendix B.1, B.2 for the codes of *osmNetconvert.typ.xml* and *osmNetconvertUrbanDe.typ.xml*). The following line is called to import the original network stored in "*OpenStreetMap.osm.xml*" and store the SUMO-network into "*Network.net.xml*". The last line indicates adopting additional options like simplifying the network without changing topology, identifying roads that have additional acceleration/deceleration lanes and add those lanes, representing traffic lights at intersections, and more[5].

```
netconvert --type-files osmNetconvert.typ.xml, osmNetconvertUrbanDe.typ.xml
--osm-files OpenStreetMap.osm --output-file Network.net.xml
--geometry.remove --roundabouts.guess --ramps.guess --tls.guess-signals --tls.discard-simple --tls.join
```

The process of extracting the road network information directly from the OpenStreetMap is summarized in Figure 13.

[5] The detailed explanations on these options can be referred to the SUMO documentation (German Aerospace Center (DLR), 2020b).

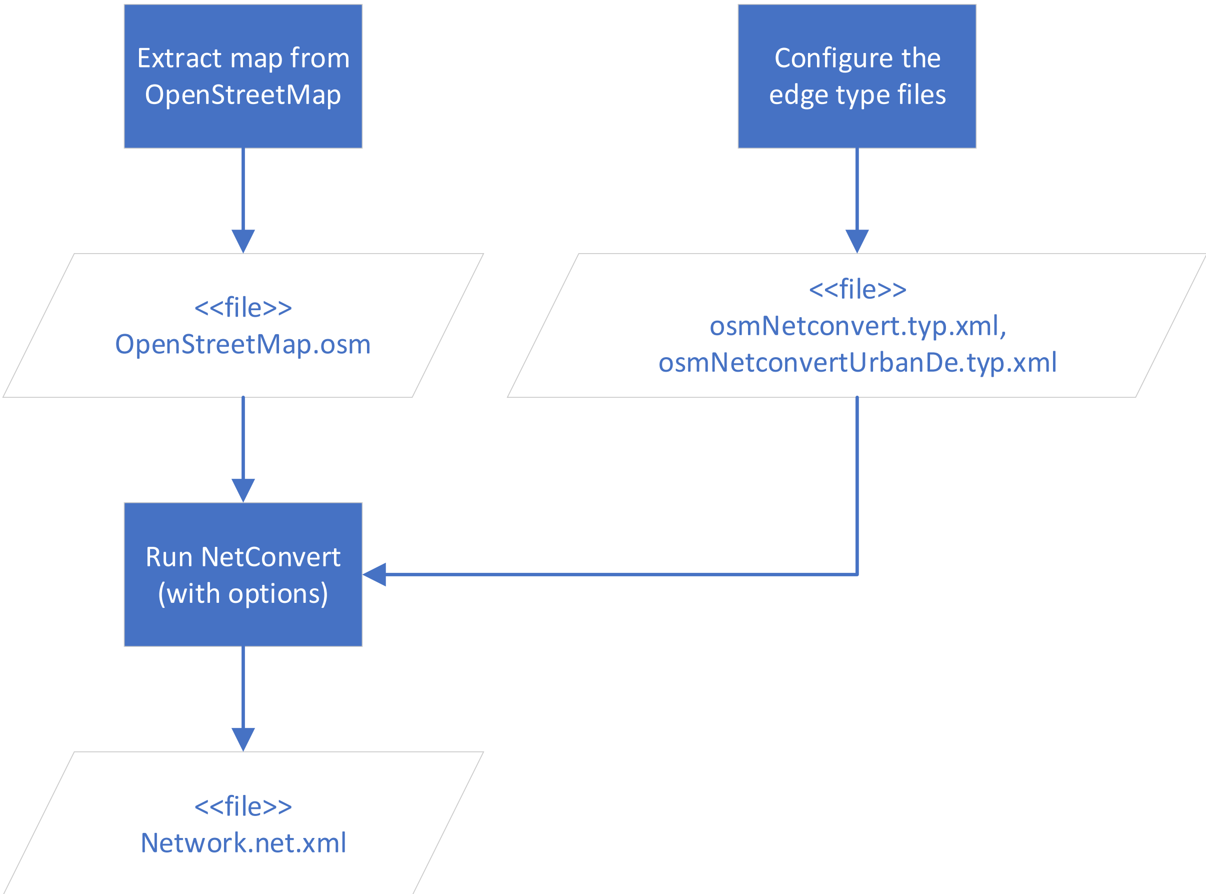

Figure 13 *The process of importing the network from OSM.*

4.1.2 Traffic Demand Data

After having obtained network data from the external database, the input of traffic demand for generating vehicle routes in the road network is also needed. The traffic demand data used here is acquired aiming for two types of traffic, private traffic and public transport (specifically refers to buses in this research). For the period that needs to be simulated, two data sources are accessed for the corresponding traffic flows.

4.1.2.1 Private Traffic Data

The basic idea of traffic simulation in SUMO is that each individual vehicle is associated with an explicit route and a specific departure time. At the scheduled time, the vehicle enters the network at the route origin, follows the designed route and exits the simulation once it reaches the destination. Thus, the traffic demand data containing information about trip origins and destinations plays an important role in modelling realistic traffic situations.

As for generating private traffic routes, there are several options available from the following data (German Aerospace Center (DLR), 2019b; Morenz, 2007):

- Using random data;
- Using trip data;
- Using origin/destination (OD) matrices;
- Using flow definitions and junction turning ratios;
- Using induction loop counts;
- Using detector data (observation points);
- Using populations statistics;
- Using data from other sources;

Random data allows creating routes based on random demands and will therefore bring unrealistic results. It would only be suitable for testing purposes (Morenz, 2007). Trip data contains information about the origin, destination and start time of each vehicle trip. If this data input wants to be adopted, the level of detail of vehicle's activity information needs to be high enough which is not easily available. Next one is the OD matrix which is essentially a generalization of trip data (Morenz, 2007). It contains the same information, but in a more generalised way, in other words, it is applied to trips by a number of vehicles but not to a single-vehicle trip compared with trip data. The combination of flow information and junction turning ratios makes it possible to describe vehicle movement in a probabilistic way, i.e., calculating the most likely movement of vehicles after a certain junction. Besides, Morenz (2007) states that it is also possible to generate traffic demand automatically if there is enough amount of induction loops in the road network. Similar to induction loop counts, detector data or observation points are commonly used by authorities to measure traffic, which is not always open to the public. As for the work on converting sociodemographic statics into traffic demand, not too much work on this topic has been found that only the program ACTIVITYGEN has been progressed in recent years (German Aerospace Center (DLR), 2019a). At last, some other types of input data are still possible to be found and used in the future.

In summary, each type of input data for generating private traffic routes has its own pros and cons. Some information input would simulate the most precise routes but cost too many resources to import, like using trip data; some may be hard to manipulate, like using flow definitions and junction turning ratios; some would bring unrealistic results but can be used to test the road network, like generating trips randomly; some may have too many preconditions to adopt, like induction loop counts. Considering the trade-off between the level of detail and required resources, the OD matrix, among all input data, would be the most feasible choice for this study to build a reasonable private traffic simulation.

OD Matrix Based on Albatross Output

As one of the outputs from the traditional 4-step transportation forecasting model, the origin and destination (O-D) matrix has been a typical way to describe the traffic demands in the given traffic analysis zones since decades ago (Lopez et al., 2018). It can describe the frequency of origins or destinations of trips by trip purpose. Normally, OD matrices are available from organizations like government traffic authorities, research institutes, traffic-oriented data companies, and more (German Aerospace Center (DLR), 2019b). In this study the OD matrix is generated using the output from Albatross (A Learning Based Transportation Oriented Simulation System) which was developed by the urban planning group at Eindhoven University of Technology (Arentze & Timmermans, 2000). Briefly, Albatross is a micro simulation system which predicts activity schedules including activity-trip information of individuals of every household based on decision rules incorporating various constraints (Kwak, 2011), and hence, it is capable of predicting transport demand of an area.

By using population synthesis and defining the study population as the households from Eindhoven Metropolitan Region (Wikipedia, 2020), the travel schedules could be generated as outputs of the Albatross system. However, it should be noted that the input data for Albatross is strictly limited to the specific household-based activity diary, MON 2009 (Projectteam MON & Rijkswaterstaat Dienst Verkeer en Scheepvaart, 2010) for training decision trees which governs agents' travel behaviours. In other words, the travel decisions made in the schedules can only reflect people's travel behaviours at that time which may have changed compared with nowadays. In addition, the unit of analysis, i.e., Traffic Analysis Zone (TAZ), in the Albatross system is set to 4-digit postal code area (PCA) due to privacy reasons, which brings the unit of the output OD matrix is also 4-digit PCA which is too coarse for running microscopic traffic simulation. The subsequent work to make up this gap is described in section 5.2.2.

To sum up, the adopted passenger car data model in the traffic simulation can be depicted as Figure 14 (more explanations on the attributes of this model can be found in Appendix A.2).

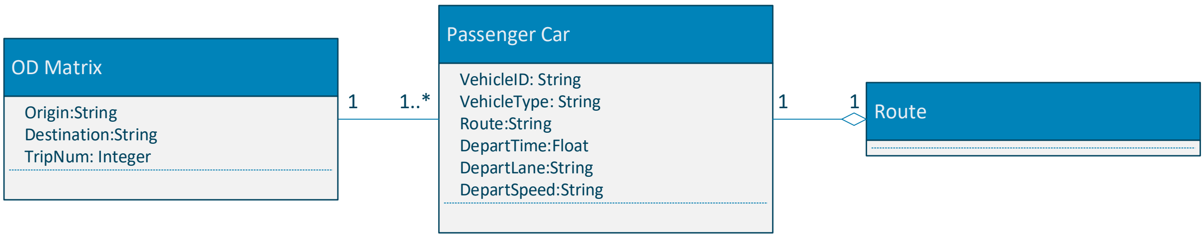

Figure 14 *Private traffic data model.*

As shown in the data model, predicting traffic demands based on the OD matrix makes it possible to reroute vehicles since it doesn't give the specific information about each vehicle but a generalization of traffic flows. Therefore, it enables to test different scenarios because new private traffic routes can be generated with the conduction of rerouting.

4.1.2.2 Public Transport Data

As for public transport, especially for buses, the routes are usually fixed and predefined. Every bus of a specific route follows the same path from the beginning to the end so that a series of bus stops can be served by the designed route. In addition to the designed route, the departure time of each bus trip is also predicted and fixed, which is given in the bus schedule for passengers.

Next to the planned bus routes, the existence of bus stops along the route becomes another big difference compared with private traffic. In most cases, passenger cars only stop because of traffic conditions like congestions, traffic lights, and more, however, in addition to the above situations, buses need to pick up or drop off passengers by stopping at bus stations temporarily. The time of serving passengers at each stop is influenced by many factors like the number of served passengers, the frequency of bus services at the stop, the number of buses can stop at a bus station at one time and so on. Thus there is a need to consider the total bus stop time (TBST) taken place at each stop in a reasonable traffic simulation (Arhin et al., 2016), which will be discussed later in section 4.1.3.2.

Therefore, in order to imitate vehicle movements during the simulation period close to real situations as much as possible, the demand data for generating public transport is essentially different from that used for private transport. For public transport, the demand will be set up from the perspective of the service provider, i.e., the bus operating company.

Once the study area is chosen, the bus schedules of bus lines in the area can be retrieved from the bus operating company (see an example in Table 7). Based on these timetables, the information about when a bus leaves a particular bus stop is available, which will be used as the main data source for developing public transport demand.

Table 7 *Part of bus Line 9b timetable.*

Bus stop name	Trip	2	4	6	8	10	12
Eindhoven, Station	from	6 36	7 06	7 33	8 03	8 33	9 06
Eindhoven, Fontys Rachelsmolen		6 39	7 09	7 36	8 06	8 36	9 09
Eindhoven, WoensXL/ZH Catharina		6 42	7 12	7 40	8 10	8 40	9 12
Eindhoven, Pieter Eijffuhuis		6 47	7 17	7 46	8 16	8 46	9 17
Eindhoven, Estafettelaan		6 49	7 19	7 48	8 18	8 48	9 19
Eindhoven, Boschdijk/Steenoven		6 53	7 23	7 52	8 22	8 52	9 23
Best, Wilhelminaplein		6 59	7 29	7 58	8 28	8 58	9 29
Best, Nazarethstraat		7 05	7 35	8 05	8 35	9 05	9 35
Best, Station	to	7 11	7 41	8 11	8 41	9 11	9 41

In addition, considering the available bus schedule information and several options for creating public transport provided by German Aerospace Center (DLR) (2020g), the *Flow* element will be chosen instead of using *Route* or *Trip* to construct the public transport route file. The reason is because that these two elements are not eligible to be implemented in a short time: *Route* requires to specify all intermediate *edges* the bus goes through in one trip, while *Trip* asks for the exact departure time of each trip.

Compared with them, the element *Flow* can create a bus flow which has a number of buses emitted from *FromEdge* to *ToEdge* with a specified interval time (*period*) but no need for indicating all passing streets. With the definition of the begin bus stop, end bus stop and intermediate bus stops, buses will, however, take the fastest path between *FromEdge* and *ToEdge* that visits all stops in their correct order (German Aerospace Center (DLR), 2020e), which may cause a situation where the simulated bus route are different from the actual prescribed route.

In conclusion, the public transport data model can be created as shown in Figure 15. The details of the object attributes can be found in Appendix A.3.

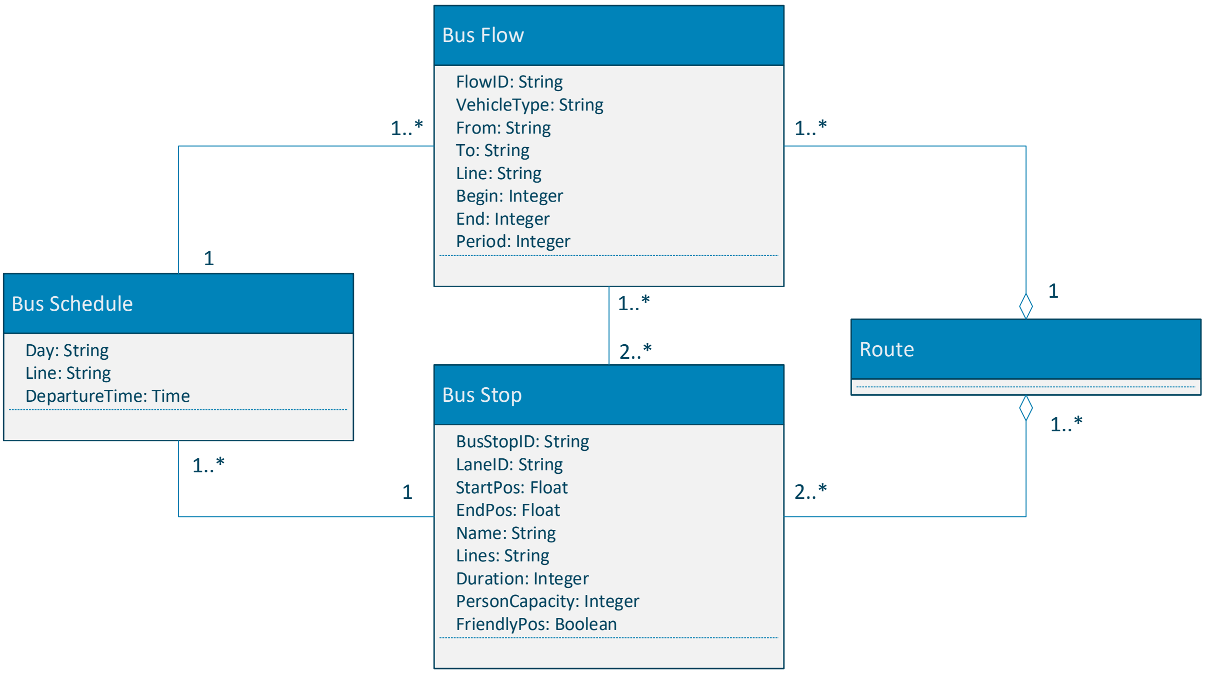

***Figure 15** Public transport data model.*

In this section, all the data related to the generation of traffic demand have been explained.

4.1.3 Additional Data

Two additional types of traffic-related data, *vehicle type* and *total bus stop time*, are needed to model traffic flows reasonably.

4.1.3.1 Vehicle Type

In addition to the vehicle attributes used above, vehicle type is another important information needed to be considered in traffic simulation. As the object diagram in Figure 16 indicates, it defines the attributes of vehicle performance (acceleration, deceleration), outer appearance (length), used driving behaviour models (car-following model, lane-changing model), classification on vehicle functions (vehicle class), and more.

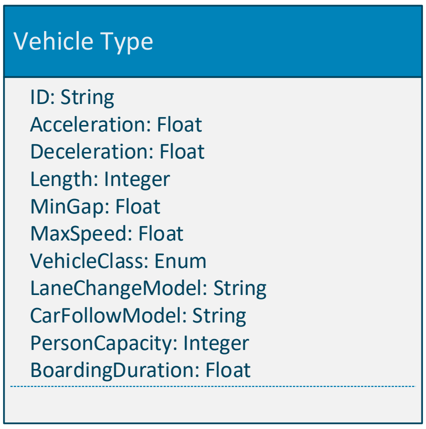

Figure 16 *Vehicle type object diagram.*

It should be noted that the *VehicleClass* is one child attribute of *VehicleType* object that they represent different contents in SUMO applications. *VehicleClass* is used to define an abstract vehicle class which is used in lane definitions (see attributes *Allow* and *Disallow* of object *Lane* in Figure 9) and allow or disallow the usage of lanes for certain vehicle types. This succeeds in giving different privileges to certain vehicles and thus setting up dedicated bus lanes in the simulation road network or prohibiting certain vehicles using the lane, like implementing Heavy Good Vehicle (HGV) bans which exists in urban areas. More explanations to the attributes of this object can be found in Appendix A.4.

Road transport includes all motorized vehicles that are licensed and travel on public roads. Road transport comprises, among other things, passenger cars, light-duty trucks, lorries, road tractors, buses, special purpose vehicles (such as fire trucks and garbage trucks) and powered two-, three- or four-wheelers such as motorcycles and mopeds (Geilenkirchen et al., 2020). As the trends shown in the line chart (see Figure 17 and more detailed background information can be found in Appendix A.4), the total amount of passenger cars climes to 8,677,911 by January 2020 which increases by 147,327 from the previous year, however, compared with the share in the year 2018 and 2019, the proportion of passenger cars keeps nearly unchanged and fluctuates around 74.15% of total road vehicles. Besides, the amount of buses shows a slightly different trend that it decreased by around 200 from 2018 to 2019 and increased by about 150 to 9,876 in 2020. In a word, private traffic is still booming up while the demand for public transport does not show a clear tendency. Considering the research goals in this study, the discussion on road transport is limited within passenger cars and buses which account for 74.23% of total road transport by January 2020.

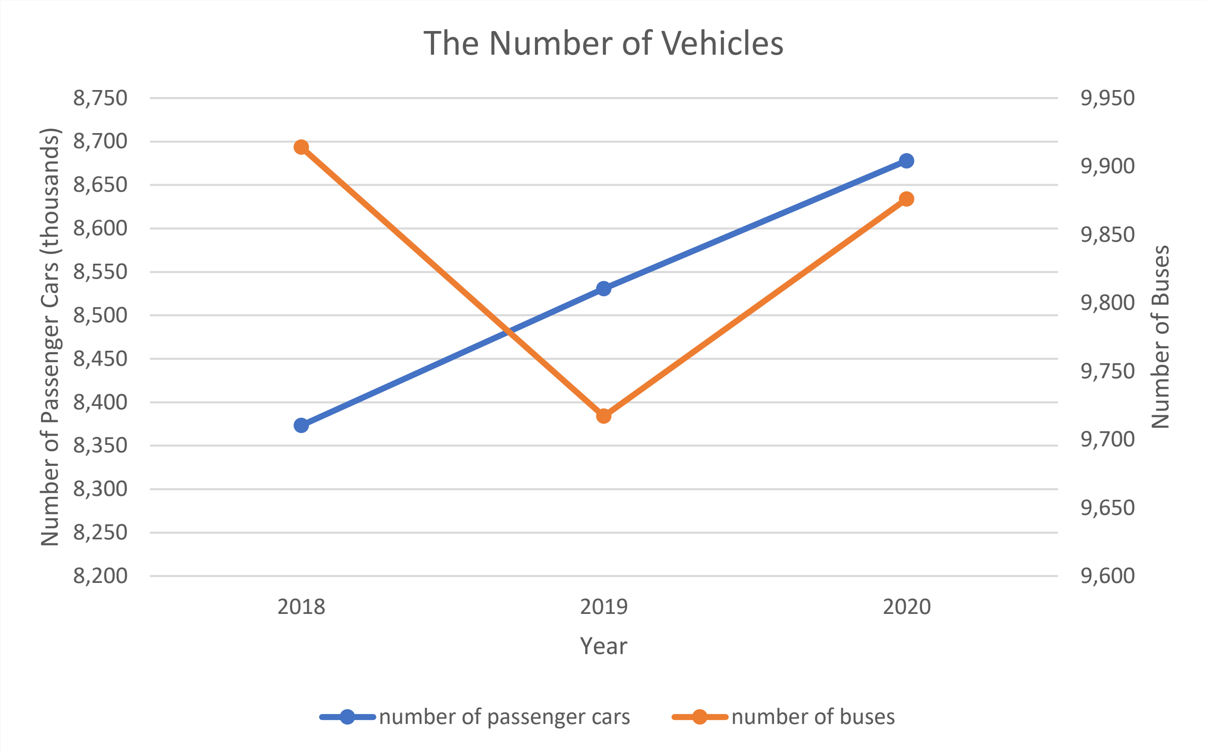

Figure 17 *The number of vehicles according to selected vehicle types in the last three years (CBS, 2020; CBS & RDW, 2020).*

By defining vehicle types in SUMO, it allows for modelling vehicles with different physical properties and driving behaviours. Table 8 lists simulated types in SUMO, i.e., passenger car type, and bus type.

Table 8 *Overview of the simulated vehicles types.*

Vehicle Type	Acceleration (m/s^2)	Deceleration (m/s^2)	Length (m)	Min Gap (m)	Max Speed (m/s)	Vehicle Class	Lane Change Model	Car Follow Model	Person Capacity	Boarding Duration (s)
passenger car	2.6	4.5	5.0	2.5	55.55	passenger	LC2013	Krauss	4	0.5
bus[6]	1.2	2.5	18.0	3.0	19.44	bus	LC2013	Krauss	130	2

4.1.3.2 Total Bus Stop Time

As mentioned before, public transport vehicles need to stop at each station along the scheduled route to let passengers enter or leave the vehicle. This time is specified as the value of attribute *Duration* of object *Bus Stop* (see Figure 15) while the academic term is Total Bus Stop Time (TBST) which was proposed by Arhin et al., (2016). It is used to elaborate on the time spent for serving passengers. As equation [4-1] indicates, the timing of buses at bus stops can be split into the time used during boarding and alighting of passengers and the time it takes a bus to efficiently park at a bus stop and the re-joining the traffic stream. The first type of time is defined by them as the dwell time (DT) and for the ease of explanation, the second type of time is defined as the queuing time (QT).

$$time^i_{total} = time^i_{dwell} + time^i_{queuing} \qquad [4-1]$$

Where

$time^i_{total}$ is the total bus stop time at bus stop *i*;

$time^i_{dwell}$ is the dwell time at bus stop *i*;

$time^i_{queuing}$ is the queuing time at bus stop *i*.

[6] The bus technical specifications are derived based on the most common type, SLFA-181 Electric, of Eindhoven urban buses (VDL Bus & Coach bv, 2019). See Appendix A.3 for details.

The dwell time is the section describing the period when the bus is actually interacting with the passengers between the opening and closing of the doors. It is the product of the *BoardingDuration* of one person defined in the *VehicleType* object multiplies the number of boarding passengers. Only when passengers are customers with special needs like travelling with wheelchairs, the dwell time will be extended accordingly. However, these situations won't happen very often which can be simply neglected.

To simplify the simulation, the dwell time for buses at the same bus stop in the traffic simulation is assumed to keep as a constant time. Considering the passenger capacities of different bus stops, usually the dwell time at busy bus stops is longer than less-occupied stops (see details in section 5.2.3).

The queuing time describes the period used to safely manoeuvring buses into a bus stop and re-entering the traffic stream. The queuing time is determined by the capacity of the bus stop and the number of preceding buses using the stop when the next bus arrives. Studying the behaviour of buses in the study area, relatively short queuing times can be found. The main reason is that most investigated bus stops are set on the dedicated bus lanes while the frequency of buses is rather low. In general, no more than three buses use a single stop at one time. Secondly, most of these stops are lane-based, i.e., there are no extra bus bays at the stops and the buses don't need to re-join the traffic flow when leaving the stops. On the other hand, Li et al., (2017) stated that the tactical manoeuvring (with other four activities) can be broadly regarded as activities reflecting driver's driving style, indicating that this specific operation type can be explained by general driving behaviour models (refer to Erdmann (2014) and Krauß (1998) for details). Thus, queuing time will not be considered in this research.

For the purpose of simulating buses close to the reality, the total bus stop time that buses spend at bus stops is estimated by neglecting the queuing time and the dwell time is set as the same for the same bus stop.

In summary, the preparation of three types of data for traffic simulation is described above. For detailed traffic simulation process on private and public transport can be found when setting up the baseline scenario in the next chapter.

4.2 Data For Vehicle Emission Modelling

In the current version (V1.5.0), SUMO does provide a vehicle attribute named as *EmissionClass* representing a specific emission class when defining *vehicle types* (German Aerospace Center (DLR), 2019d) and therefore is able to calculate the vehicle emissions within the given simulation period. As for the built-in emission models, they either do not include Dutch traffic situations (HBEFA was developed based on the fleet compositions in Germany, Austria, Switzerland, Sweden, Norway and France) or they are not open-source (PHEM developed by TU Graz), both models do not meet the requirements of this study. However, these emission models implicitly clue the way to calculate *street vehicle emissions*: by multiplying the *total driven mileage* (as explained in section 3.2.2.1) on roads per emission class by the corresponding emission factors (which consider road type, congestion level and other factors). The straightforward theory makes it possible to adopt other emission models, like VERSIT+ which was developed based on Dutch vehicle compositions and road types by the Netherlands Organisation for Applied Scientific Research (TNO).

Emission modelling of this research aims to calculate the total amount of pollutants produced by vehicles in the simulation road network to show the influence of the proposed traffic scenario on the environment. It is built based on the perspective of streets that, in other words, it calculates vehicle emissions per street. Besides, the discussion on the vehicle emission source is limited on private traffic as explained in section 3.3.2. The data preparation for vehicle emission modelling focuses on two parts: section 4.2.1 describes the distribution of Dutch vehicle emission class and the needed emission factor data is illustrated in section 4.2.2.

4.2.1 Emission Class

The first component is the Emission Class or called as VERSIT class in the VERSIT+ modelling approach. It categorises passenger cars into different classes according to factors like fuel type, environment class and weight class. Table 9 gives the data retrieved from an annually updated national emission calculation report by PBL Netherlands Environmental Assessment Agency (Geilenkirchen et al., 2020).

Table 9 *Emission class of passenger cars.*

Vehicle type	Fuel type	VERSIT class	Environment class	Weight class	Share in total kilometres of VERSIT class per vehicle-fuel combination in 2018 (rounded to 1%)[7]
Passenger car	Petrol	LPABEUR1	EURO-1	all	1%
		LPABEUR2	EURO-2	all	8%
		LPABEUR3	EURO-3	all	11%
		LPABEUR4	EURO-4	all	31%
		LPABEUR5	EURO-5	all	26%
		LPABEUR6	EURO-6	all	23%
		Sum			100%
	Diesel	LPADEUR1	EURO-1	all	0%
		LPADEUR2	EURO-2	all	1%
		LPADEUR3	EURO-3	all	7%
		LPADEUR3HOF	EURO-3 half open particulate filter	all	1%
		LPADEUR4	EURO-4	all	5%
		LPADEUR4DPF	EURO-4 closed particulate filter	all	11%
		LPADEUR4HOF	EURO-4 half open particulate filter	all	0%
		LPADEUR5	EURO-5	all	39%
		LPADEUA6	EURO-6A	all	35%
		Sum			99%
	LPG	LPALEUR1	EURO-1	all	1%
		LPALEUR2	EURO-2	all	8%
		LPALEUR3	EURO-3	all	25%
		LPALEUR4	EURO-4	all	35%
		LPALEUR5	EURO-5	all	21%
		LPALEUR6	EURO-6	all	4%
		LPALPR82MED	Pre-Euro	medium weight	1%
		LPALPR82ZWA	Pre-Euro	heavy	3%
		Sum			98%
	CNG	LPACEUR2	EURO-2	all	0%
		LPACEUR3	EURO-3	all	0%
		LPACEUR4	EURO-4	all	6%
		LPACEUR5	EURO-5	all	40%
		LPACEUR6	EURO-6	all	54%
		Sum			100%
	Electricity	LPAEZEEV	All	all	100%

The adopted VERSIT class can distinguish vehicle groups between various emission behaviours for the purpose of assessing real-world emissions of vehicles (Spreen et al., 2016). This detailed categorization method is coded taking account of the following vehicle properties:

- Gross vehicle weight (the maximum mass of the vehicle, further specified as the technically permissible maximum loaded mass);
- Fuel type (petrol, diesel, LPG, CNG, electricity, and etc.);
- Environment class (Euro class);
- Emission reduction technology (DPF, HOF, and etc.);

More detailed explanations regarding the letter coding rules of VERSIT classes can be found in Appendix A.5.

Although the combination of VERSIT categories can result in about 150 different emission classes for passenger cars in total, only 29 specific categories are chosen because the shares of other emission

[7] Data on the number of vehicle kilometres travelled in the Netherlands by different vehicle types are derived from Statistics Netherlands (CBS) and the shares of vehicle-kilometres per VERSIT class is processed by the Netherlands Vehicle Authority in the mobility chain (RDW).

classes in the corresponding vehicle-fuel combination group in total kilometres keep at a low level in the year 2018. The selected emission classes in Table 9 almost account for 100% of total kilometres in the corresponding vehicle-fuel group (the complete information regarding the shares in total kilometres of all VERSIT classes can be referred to the report by Geilenkirchen et al., (2020)).

4.2.2 Emission Factor

In addition to the emission class, the corresponding emission factor data is also retrieved. Except for a small (but increasing) number of electric vehicles, most road vehicles still use combustion engine for propulsion. Emissions from road transport can originate from several processes, including exhaust emissions due to combustion of motor fuels in engines, evaporation of motor fuels and coolants, wear of tyres, brakes and road surface, and leakage and consumption of motor oil (Geilenkirchen et al., 2020). During these processes, various substances are emitted via the exhaust gas and these pollutants include but not limited to carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x), particulate matter 10 micrometres or less (PM_{10}), elemental carbon[8] (EC), ammonia (NH_3), Nitrous oxide (N_2O) and carbon dioxide (CO_2).

These emission factors are updated annually by the Dutch GCN/GDN committee, a collaboration of the Dutch Ministry of Infrastructure and the Environment, PBL, TNO and RWS, under supervision of RIVM (Geilenkirchen et al., 2020). The factors take vehicle category, fuel type, road type, and etc. into account and can reflect almost all combinations of traffic situations in the real world. Noted that only emission factors for urban areas are considered since the simulated road network is located next to city centre. Part of emission factors for those cars powered by petrol is shown in Table 10 and the complete information of all VERSIT classes can be found in Appendix A.6.

***Table 10** Part of emission factors for passenger cars[a].*

VERSIT class	Vehicle category	Fuel type	Environment class	Manufacture year (s)	CO			NOx		
					RT1[b]	RT2	RT3	RT1	RT2	RT3
					grams/vehicle·km					
LPABEUR1	Passenger car	Petrol	Euro-1	1993-1996	10.033	4.575	1.655	0.724	0.475	0.250
LPABEUR2	Passenger car	Petrol	Euro-2	1995-2000	10.683	4.399	3.407	0.468	0.213	0.198
LPABEUR3	Passenger car	Petrol	Euro-3	2000-2004	6.647	3.291	1.885	0.300	0.300	0.300
LPABEUR4	Passenger car	Petrol	Euro-4	2003-2010	5.615	2.873	1.652	0.259	0.254	0.252
LPABEUR5	Passenger car	Petrol	Euro-5	2009-2014	4.492	2.299	1.322	0.043	0.020	0.012
LPABEUR6	Passenger car	Petrol	Euro-6	2014 and later	4.492	2.299	1.322	0.043	0.020	0.012

[a]The data is measured for the year 2018.
[b]RT1 = Urban areas; RT2 = Rural roads; RT3 = Motorways;

Further information about the current methodology for calculating emission factors for VERSIT classes and the background information and context that is needed for the correct understanding and interpretation of measurement results can be referred to Spreen et al., (2016).

With the retrieved emission class and emission factors from VERSIT+ model, all needed information and methodology for emission modelling are described and the results based on the baseline scenario is shown in the next chapter.

4.3 DATA FOR AIR QUALITY MODELLING

According to the user manual (Öttl & Kuntner, 2020), the distribution of pollutant concentrations is mainly affected by two parts: one input to the GRAL platform is the *emission source intensity* as explained in section 3.2.2.2; and the other important data source contains external environment information such as meteorological conditions and infrastructure design parameters.

This section aims to prepare the required external environment data for air quality modelling. These two data sources will be illustrated in the following sections:

[8] A specific part of the particulate matter in vehicle exhaust consists of elemental carbon, commonly known as soot, and is designated as EC (Stelwagen & Ligterink, 2015).

4.3.1 Meteorological Parameters

The meteorological data used by GRAL only selects the most influential factor on the spread of pollution: wind (Öttl & Kuntner, 2020), while the effects of other meteorological conditions are neglected. The retrieved wind information aims to describe the background wind information including the wind speed and corresponding direction in the study area.

The data was retrieved from KNMI Data Platform which provides open data on weather, climate and seismology like real-time weather observations, climatological records, satellite and weather radar and data on earthquakes (Royal Netherlands Meteorological Institute, 2020). Once the filters on time range (from 01-Jan-2019 to 31-Dec-2019) and geographic scope (Eindhoven city) are set, the matching data can be extracted from the data platform at a one-hour interval through the whole year 2019 and a total of 8,760 data points were retrieved.

Based on the extracted data, information about wind speed and wind direction during the simulation period (06:30 - 19:00) is further extracted into the final dataset. It is noted that the retrieved wind speed and direction numbers are using the average speed and direction measured in each one-hour interval (KNMI Data Centre, 2019). The prepared wind dataset contains 5,110 datapoints.

The distribution of wind speed and direction of prepared dataset is listed in Table 11. Figure 18 gives the mean wind rose which shows the general wind speed and direction for the simulation period in the simulation area. It indicates that most winds blow from the southwest direction and the speed ranges from 3 - 6 m/s.

***Table 11** Distribution of wind speed and wind direction of imported data.*

Direction	0 - 0.5 m/s [%]	0.5 - 1 m/s [%]	1 - 2 m/s [%]	2 - 3 m/s [%]	3 - 4 m/s [%]	4 - 6 m/s [%]	6 - 8 m/s [%]	> 8 m/s [%]	sum [%]
N	0.1	0.2	0.4	0.7	0.8	1.2	0.4	0.0	3.7
NNE	0.1	0.0	0.6	0.6	0.5	0.9	0.2	0.0	3.1
NE	0.1	0.1	0.5	0.7	0.6	1.7	0.4	0.0	4.0
ENE	0.0	0.1	0.6	1.0	1.3	1.4	0.2	0.0	4.6
E	0.0	0.0	0.8	0.9	1.1	0.7	0.1	0.0	3.7
ESE	0.0	0.2	0.8	1.5	1.1	1.1	0.0	0.0	4.8
SE	0.0	0.2	1.3	1.5	0.8	0.5	0.1	0.0	4.4
SSE	0.0	0.2	1.0	1.5	1.2	1.0	0.2	0.0	5.1
S	0.0	0.3	1.0	1.3	1.7	2.5	0.9	0.1	7.7
SSW	0.1	0.2	1.0	1.7	2.7	4.4	3.0	1.1	14.1
SW	0.0	0.2	0.8	1.1	2.0	4.4	3.3	2.2	13.9
WSW	0.0	0.2	0.6	1.3	1.6	3.4	1.8	0.6	9.7
W	0.0	0.1	0.9	1.1	1.4	2.2	0.7	0.4	6.8
WNW	0.0	0.1	0.7	1.1	1.4	1.4	0.2	0.1	5.0
NW	0.0	0.1	0.9	1.1	1.3	1.4	0.4	0.3	5.5
NNW	0.1	0.1	0.6	0.9	0.9	1.0	0.4	0.1	4.1
Sum [%]	0.5	2.3	12.5	18.0	20.4	29.2	12.3	4.9	100.0

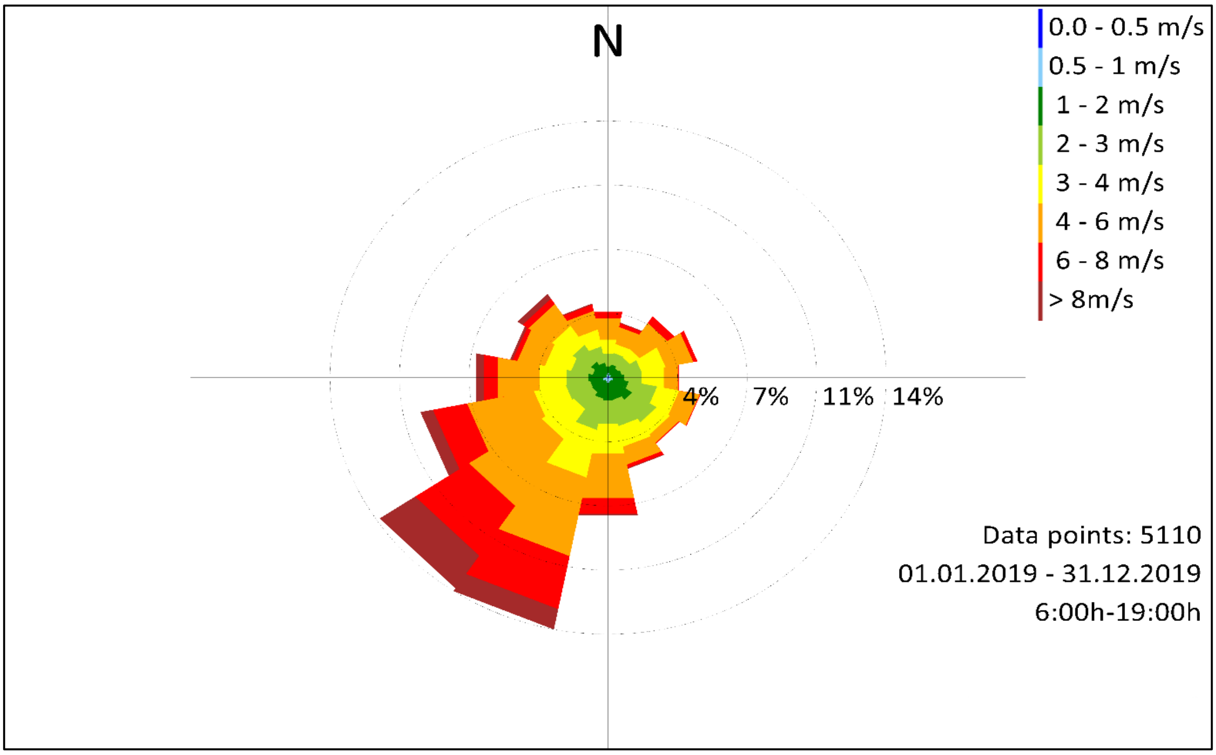

Figure 18 *Mean wind rose of Eindhoven area for 2019.*

4.3.2 Infrastructure Design Parameters

Another dataset related to the simulation environment is the parameters of infrastructure design. The width of the streets and the area of vegetations can be measured from the Google Map (Google, 2020) while the preparation for surrounding building objects (mainly about their contour and average height) is slightly more complicated.

Usually the Level of Detail of these abstract objects required by GRAL is LOD1 which is a coarse prismatic model that contains information about the building contour polygons and their heights (see Figure 19).

Figure 19 *The level of detail in CityGML 2.0 (Biljecki, Ledoux, & Stoter, 2016).*

The footprint of buildings in the simulation environment can be drawn referring to the georeferenced base map obtained from OpenStreetMap (OpenStreetMap Foundation, 2020) and the average height of buildings is retrieved from the 3D BAG database (Dukai, 2018). It should be noted that most buildings in the reality are not equipped with an absolute flat roof surface while the exact attribute chosen from the 3D BAG to represent the average building height is *roof-75* which means the roof surface is set at the 75th percentile of the z-coordinates of the point cloud of the building (see Figure 20). The reliability of this open database, the 3D BAG, has been validated by other projects like Building Ages in the Netherlands (Parallel, 2020).

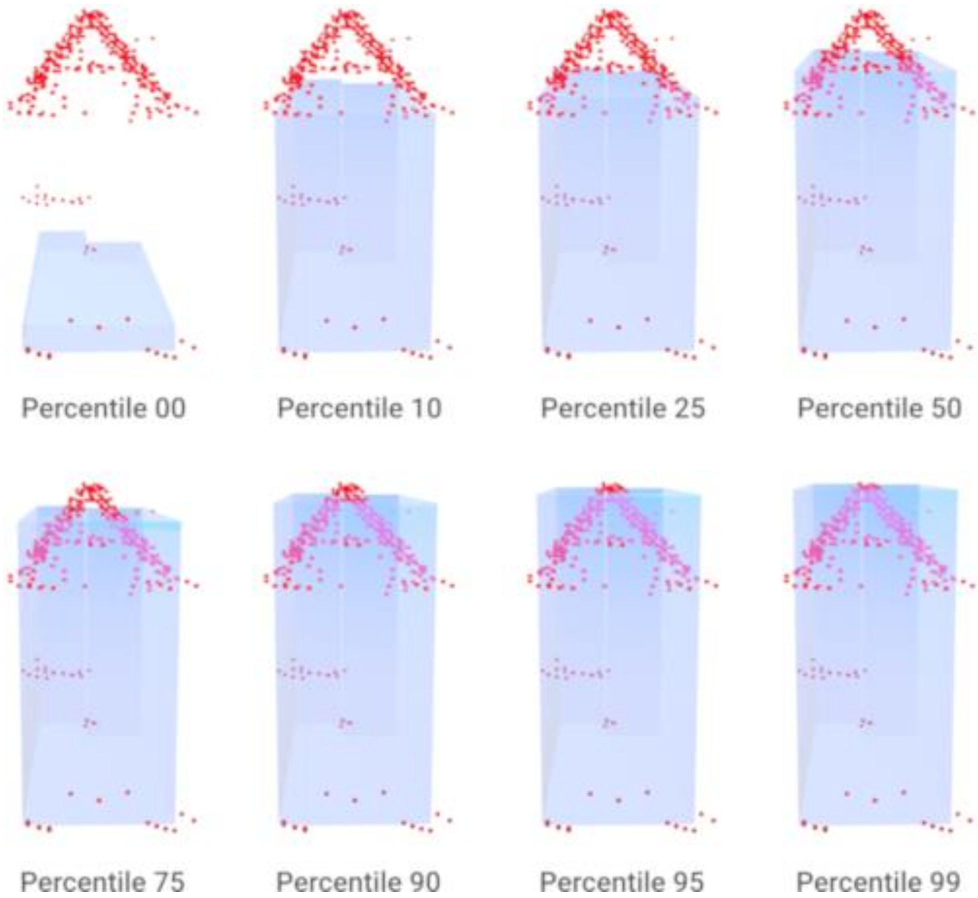

Figure 20 *Roof heights of different percentiles (Dukai, 2018).*

4.4 CONCLUSION

In this chapter, the reasons for choosing certain information as well as the data preparation process of each simulation model were described in detail:

In order to replicate the realistic traffic situations as much as possible, a microscopic traffic simulation model, SUMO, was chosen as the simulator to build the road network as well as public transport infrastructures (bus stops and bus lanes). OpenStreetMap was designated as the network data source which was able to be imported and edited. To perform reasonable traffic simulation, the traffic demand data for private traffic and public transport was of importance to make realistic vehicle trips. Thus, the private traffic flows would be generated based on the OD matrices from Albatross and the public transport was planned in align with bus schedules which can be retrieved from the bus operating company.

With the distribution of Dutch vehicle emission class and corresponding emission factors from the VERSIT+ model, emission modelling was made ready to compute the vehicle emissions per road segment.

To prepare for air quality modelling, the external environment parameters (meteorological parameters and infrastructure design parameters) were extracted from KNMI Data Platform and 3D BAG database respectively. With those credible data bases, the GRAL dispersion model is feasible and capable of simulating the distribution of pollutant concentrations and reflecting the impact of road traffic on ambient air quality.

In summary, not only the internally generated outputs by models would be used in the simulation flow but also open and valid external data sources have been designated for three simulators, which proves the integrity of the framework.

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CHAPTER 5 CASE STUDY

In this chapter, a specific simulation area is chosen to test the integrated simulation framework and set up the baseline scenario. Section 5.1 gives a brief introduction to the study area, the neighbourhoods around Veldmaarschalk Montgomerylaan road in Eindhoven. Detailed steps, including setting up the road network and generating routes for both private traffic and public transport, are elaborated in section 5.2. Next, based on adequate equations and sufficient data preparation, the calculated results of street vehicle emissions is described in section 5.3. The distribution of one specific pollutant in selected modelling domain is computed in section 5.4, giving the insights of air quality along the Veldmaarschalk Montgomerylaan road. Last but not least, the validation on the integrated framework is performed from the perspectives of traffic situation and air quality in section 5.5.

- 5.1 Background Introduction of Study Area
- 5.2 Traffic Simulation
- 5.3 Vehicle Emission Simulation
- 5.4 Air Quality Simulation
- 5.5 Framework Validation
- 5.6 Conclusion

5.1 BACKGROUND INTRODUCTION OF STUDY AREA

It is noted that microscopic traffic, emission and dispersion models are normally computationally demanding (Csikós et al., 2015; Ma et al., 2014; Osorio & Nanduri, 2015; Y. Zhao & Sadeka, 2013; Zhou et al., 2015), let alone integrating them in one framework. Common situations would occur that the simulation framework may suffer from the lack of computing power because of the increased size of the road network. Hence, the area of the study network is selected and limited to the computing capacity of personal computers. In specific, the neighbourhoods (buurtgrens in Dutch) around Veldmaarschalk Montgomerylaan street (Rapenland, Generalenbuurt, Kronehoef, Oude Toren, Gildebuurt and Woenselse Watermolen) account for around 2.2 square kilometres (Eindhoven Open Data, 2017) are chosen as the study area (see Figure 21).

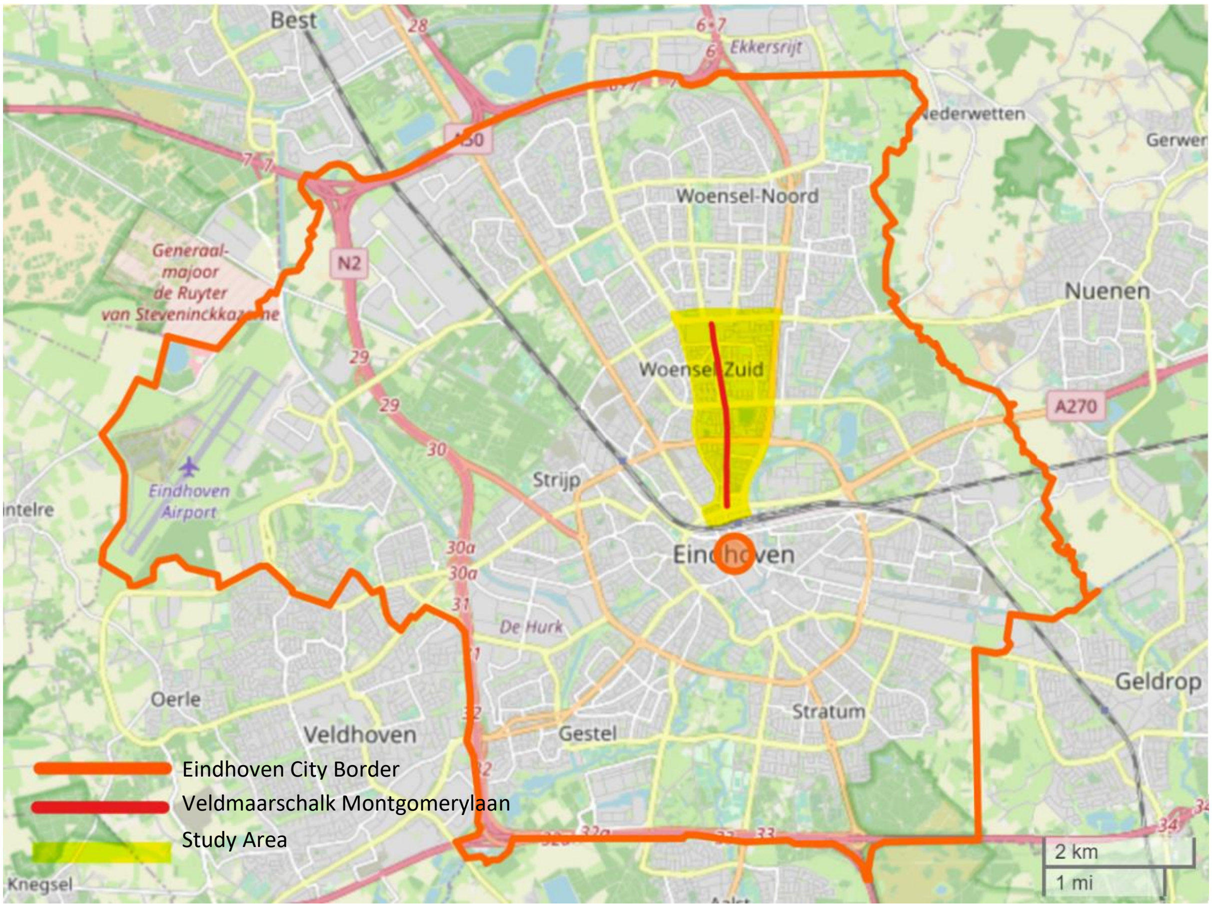

Figure 21 *Glance over the study area.*

The reason for setting up the simulation network in this area is explained as below: as shown in the bus line network map of Eindhoven area (see Figure 22), except for Eindhoven Centraal Station, WoensXL/ZH Catharina Station is another main bus station which connects people between Eindhoven centre area, Woensel area and further Best, Son en Breugel and Nuenen. In addition, a total of five bus lines (line 9, 322, 400, 405, 406) are planned to travel along the entire investigated road, Veldmaarschalk Montgomerylaan street, and another two lines (line 2, 3) also go through part of the road (including WoensXL/ZH Catharina Station), which means the discussion on the performance of dedicated bus lanes on this road is valuable and therefore brings more realistic meanings for this research.

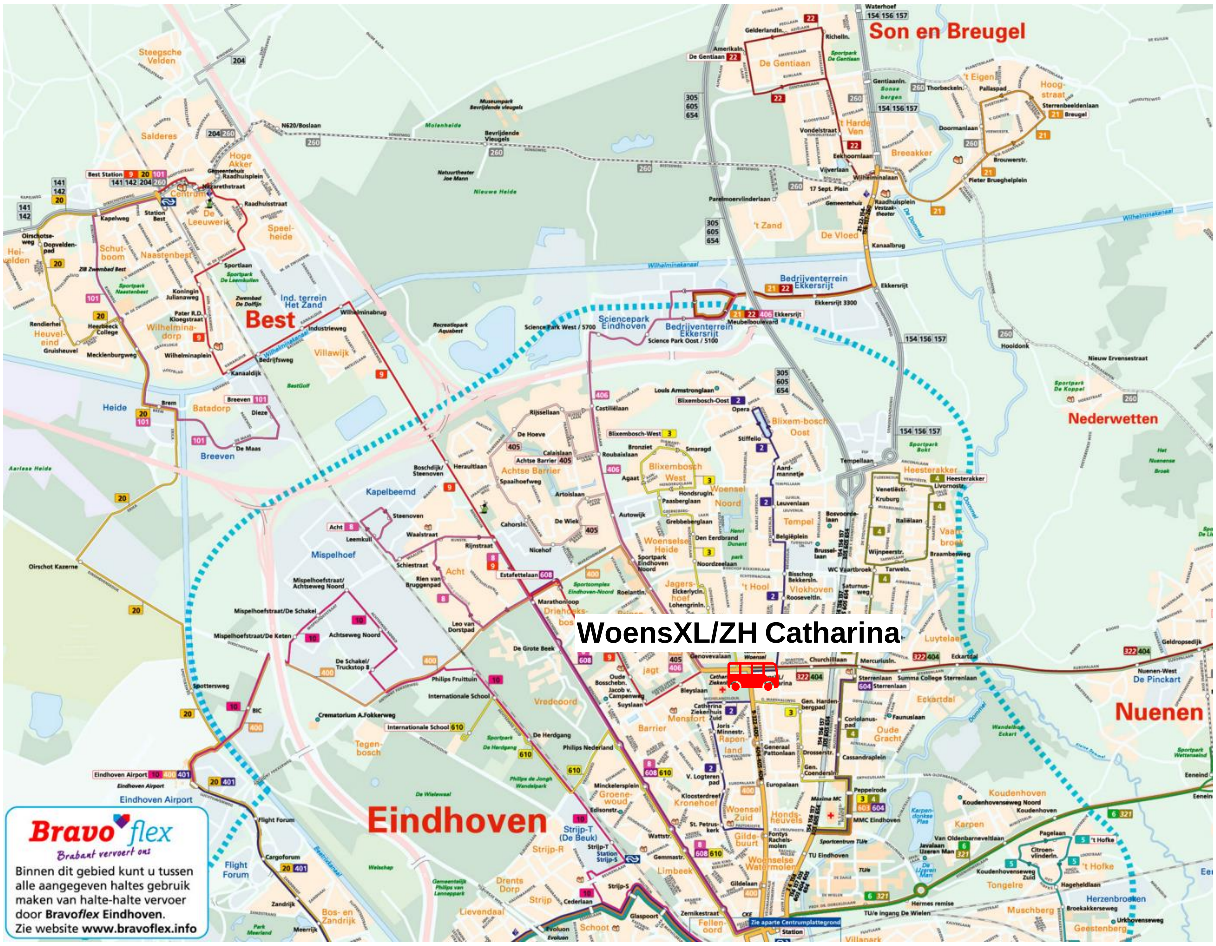

Figure 22 *Part of bus lines map in/around Eindhoven area (Bravo & Hermes, 2019b).*

In short, the consideration of making the research more realistic and a suitable field to test different traffic scenarios determines the choice of study area.

Characteristics of Veldmaarschalk Montgomerylaan

Veldmaarschalk Montgomerylaan is the main urban corridor between Eindhoven city centre and Woensel shopping area, with a total length of around 2.6 kilometres and 5 bus stops on the road (see Figure 23). It connects Winston Churchilllaan road in the north and Fellenoord road in the south. Most sections of this road are one lane for each direction and usually two or three lanes are set at crossroads for diverting turning vehicles.

Figure 23 *An overview of Veldmaarschalk Montgomerylaan: (a) bus stations on Veldmaarschalk Montgomerylaan; (b) the dedicated bus Lane; (c) WoensXL/ZH Catharina bus station.*

Additionally, the dedicated bus lanes begin from the south end of Veldmaarschalk Montgomerylaan, converge at the intersection of Vincent van Den Heuvellaan (see Figure 24-a) and extend to the north end (see Figure 24-b). It is estimated that about 25 buses use the bus lanes every hour.

Along the investigated road, the current configuration design of bus stops (see Figure 24-c) and dedicated bus lanes is quite straightforward. Two bus lanes are separated from the general traffic by green verge to be set on one side of the road and bus stops are located next to bus lanes meaning that the waiting buses may block the road[9].

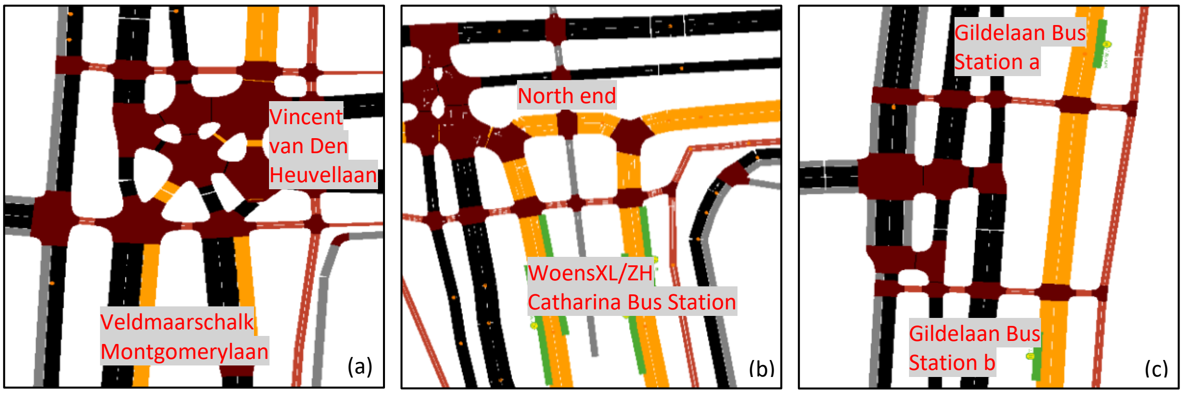

Figure 24 *The simulated dedicated bus lanes (in orange) and bus stops (in green) in NETEDIT application: (a) the convergence of bus lanes at the intersection of Vincent van Den Heuvellaan and Veldmaarschalk Montgomerylaan; (b) the north end of Veldmaarschalk Montgomerylaan and WoensXL/ZH Catharina bus station; (c) Gildelaan bus station a & b.*

[9] Line 400 bus goes through the entire road but only stops at WoensXL/ZH Catharina bus station.

5.2 TRAFFIC SIMULATION

Based on the study area, traffic simulation using the SUMO package is described below. Section 5.2.1 explains the modification to the imported road network to represent the realistic layout of the streets. Section 5.2.2 illustrates the adjustments on the preliminary OD matrices and the generation of routes travelled by private traffic within the road network. Since public transport is regarded as a special form of general traffic, the last section describes the process of generating bus routes based on those differences that distinguish public transport from private traffic.

5.2.1 Network Setup

The road network is important for modelling the journeys of private and public transport in several ways. First of all, it represents the available infrastructure of the environment, especially the public transport facilities related to the research goals. Besides, the network for urban areas can be very complex and it is therefore vital to replicate it in the simulation accurately.

As explained in chapter 4, the information from the OpenStreetMap database is extracted and imported to SUMO. The converted network is not yet complete, and more steps are needed to finalise the imported road network.

To make the network complete, additional modifications have to be made in NETEDIT application based on the converted road network, including cleaning redundant elements, configuring the connections between lanes, editing traffic lights at intersections, and adding further traffic elements such as bus stops based on the bus route map (Bravo & Hermes, 2019b). It is of worth to note that each traffic light in the editing application can be configured individually in terms of light phases; if there is no data about the traffic light sequence available (which is the case in this study), traffic light phases can be generated automatically by using *tls.guess-signals, --tls.discard-simple, --tls.join* options during the importing process based on the priority of edges, making the output closely resemble the real traffic light sequence. Besides, the traffic light plan is also the tool which will be used in the scenario analysis chapter for setting up different scenarios.

The finalised road network is shown in Figure 25 by road types which are defined according to the development of a hierarchy of roads, with primary road at the highest level and tertiary roads at the lowest (see Table 12). Two dedicated active transport lanes are also specified as supplements.

Table 12 *Defined road types.*

Road type	Colour	Priority	Speed Limit (km/h)	Speed Limit (m/s)
Primary road	(magenta)	4	50	13.89
Secondary road	(cyan)	3	50	13.89
Tertiary road	(green)	2	30	8.33
Cycleway	(orange)	1	20	5.56
Footpath	(red)	1	5	1.39

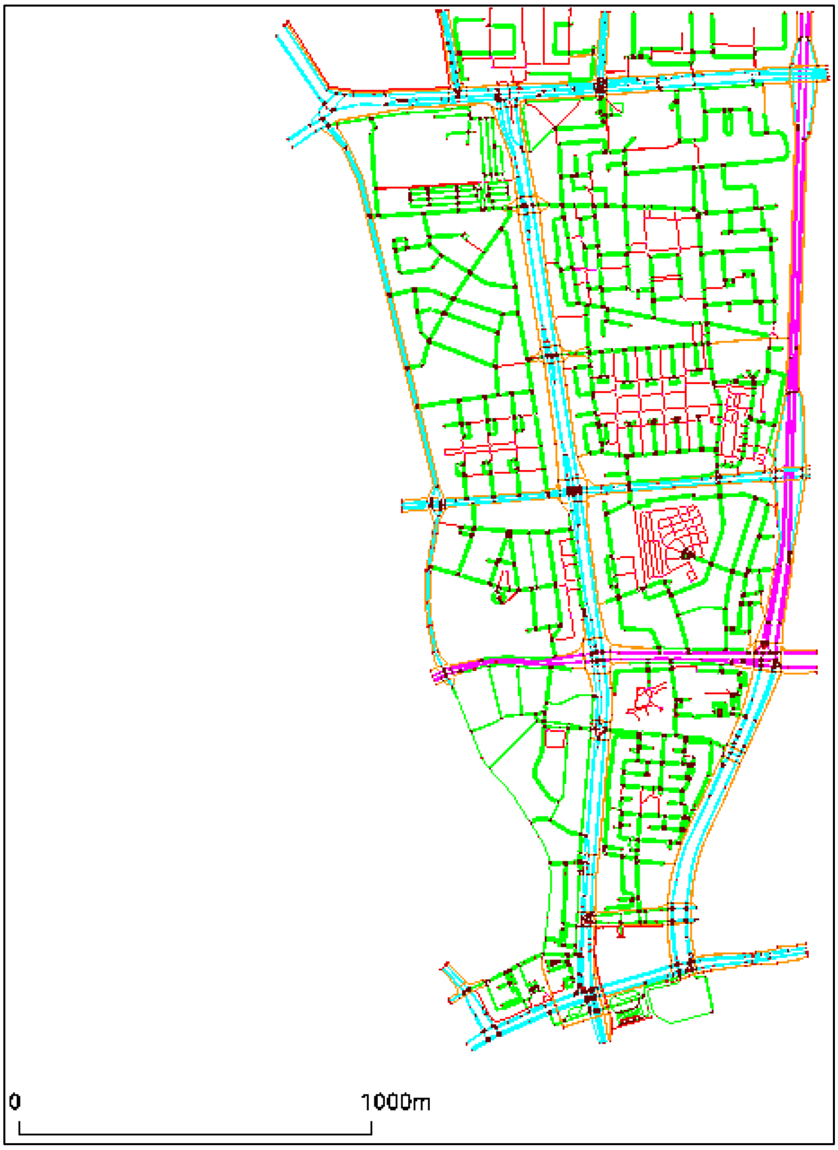

***Figure 25** The modified road network classified by road type.*

5.2.2 Private Traffic Simulation

After establishing the usable simulation network, private traffic trips and further their routes can be generated with the help of efficient driving behaviour models and corresponding traffic demand data sources. Two parts of constructing the traffic simulation are described below.

5.2.2.1 OD Matrices Generation

Preliminary OD Matrices

Before generating the OD matrices based on Albatross activity diary, several filters for selecting trips have to be clarified: firstly, selecting proper transport mode. Currently four transport modes are used in the Albatross system: *slow* (walk and bike), *car driver*, *car passenger*, *public transport*. In order to accurately present the number of passenger cars running in the network, only the transport mode of the *car driver* is selected while the trips by *car passenger* will cause double calculation on the number of vehicles.

Secondly, selecting trips taken place during the corresponding simulation periods. As Figure 26 indicates, the traffic congestion level fluctuates through working days and the most congested traffic happened during Tuesday afternoon and the lightest traffic can be seen on Friday morning. Considering this specific situation in Eindhoven city, Monday is chosen for simulation because the traffic congestion level on this day is considerably "average", which can show the effect of proposed traffic scenarios fairly.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
12:00 AM	4%	0%	0%	0%	0%	0%	3%
	0%	0%	0%	0%	0%	0%	0%
02:00 AM	0%	0%	0%	0%	0%	0%	0%
	0%	0%	2%	1%	0%	0%	0%
04:00 AM	0%	1%	2%	2%	2%	1%	0%
	0%	1%	1%	1%	1%	2%	0%
06:00 AM	0%	11%	10%	9%	9%	7%	0%
	0%	29%	28%	24%	26%	18%	1%
08:00 AM	0%	44%	45%	37%	43%	30%	4%
	4%	23%	22%	20%	23%	19%	9%
10:00 AM	6%	17%	18%	18%	18%	22%	14%
	10%	20%	18%	18%	19%	26%	18%
12:00 PM	13%	21%	20%	22%	21%	28%	20%
	17%	22%	21%	22%	22%	30%	20%
02:00 PM	18%	24%	23%	23%	24%	34%	21%
	14%	26%	27%	28%	29%	38%	18%
04:00 PM	14%	35%	42%	40%	42%	42%	16%
	13%	43%	55%	44%	52%	42%	13%
06:00 PM	10%	19%	25%	21%	25%	24%	11%
	10%	11%	13%	12%	13%	15%	10%
08:00 PM	7%	9%	9%	9%	9%	12%	8%
	4%	6%	7%	7%	8%	9%	7%
10:00 PM	4%	5%	7%	6%	6%	7%	7%
	1%	2%	4%	2%	4%	6%	7%

Figure 26 *Weekly traffic congestion by time of day in Eindhoven (TomTom, 2020).*

According to the guidelines of the Royal Dutch Touring Club ANWB (ANWB, 2020), morning and evening peak hours in the Netherlands usually refer to 06:30 – 09:30 and 15:30 – 19:00, which is consistent with Figure 26. Based on this situation, a weekday can be split into 5 periods: 00:00 – 06:29; 06:30 – 09:30; 09:31 – 15:29; 15:30 – 19:00; 19:01 – 23:59 and categorised as Table 13 shows.

Table 13 *The definitions of time period.*

Time period	00:00 – 06:29	06:30 – 09:30	09:31 – 15:29	15:30 – 19:00	19:01 – 23:59
Category	night off-peak hours	morning peak hours	daytime off-peak hours	evening peak hours	evening off-peak hours

However, not the whole day will be simulated but only two peak-hour periods and daytime off-peak hours are chosen for simulation, since most commuting takes place during these periods in a day (ANWB, 2020). It is performed by firstly manifesting *Day* value as 0 (0 to 6: Monday to Sunday) in the household data and then setting *LeaveTime*, i.e., trip leave time as three periods: 06:30 – 09:30; 09:31 – 15:29; 15:30 – 19:00. The reason why these periods are not merged into one long period will be explained in section 5.2.2.2.

Lastly, selecting trips that depart from and arrive in the designated PCAs. Considering only the traffic generated within the study area is not much realistic, but generally the traffic also occurs from or to outside the simulated road network. Therefore, the designated PCAs include the study area (in yellow): part of 5612 PCA and the whole 5623 PCA, and the surrounding areas (in green) like Woensel area and city centre (see Figure 27). A total of six complete 4-digit PCAs (5611, 5612, 5622, 5623, 5625, 5631) are defined as origins and destinations of the OD matrix.

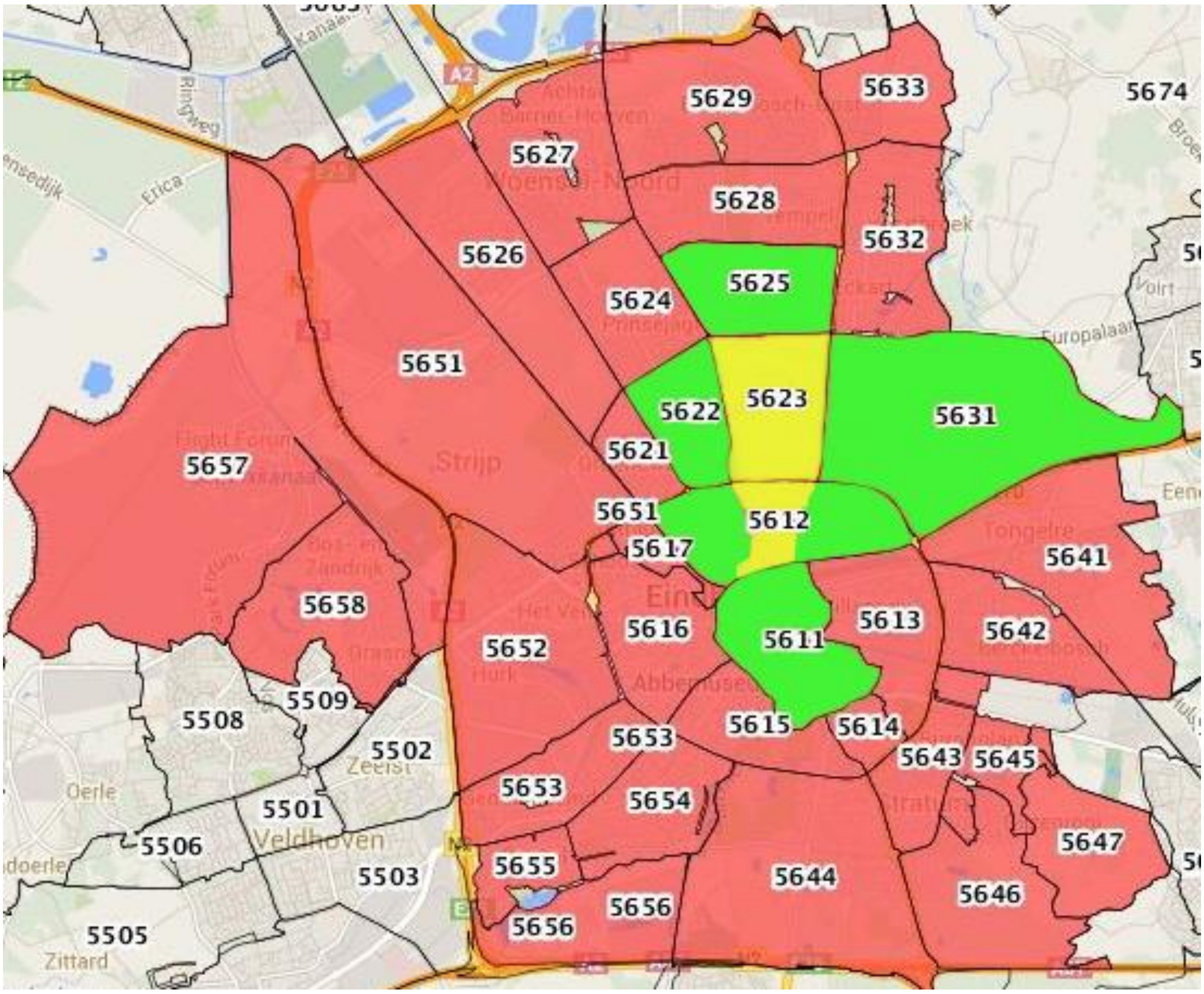

Figure 27 *The map of 4-digit postal code areas in Eindhoven (study PCAs in yellow and supplementary PCAs in green).*

With the implementation of the above filters, only those trips that travelled as a *car driver* and happened during morning peak, daytime off-peak and evening peak hours with the origin and destination in the designated PCAs (5611, 5612, 5622, 5623, 5625, 5631) are selected. After having the complete activity-trip diary and proper filters, a script written in R (see *Generate_OD.R* in Appendix B.3) is invoked to generate three OD matrices.

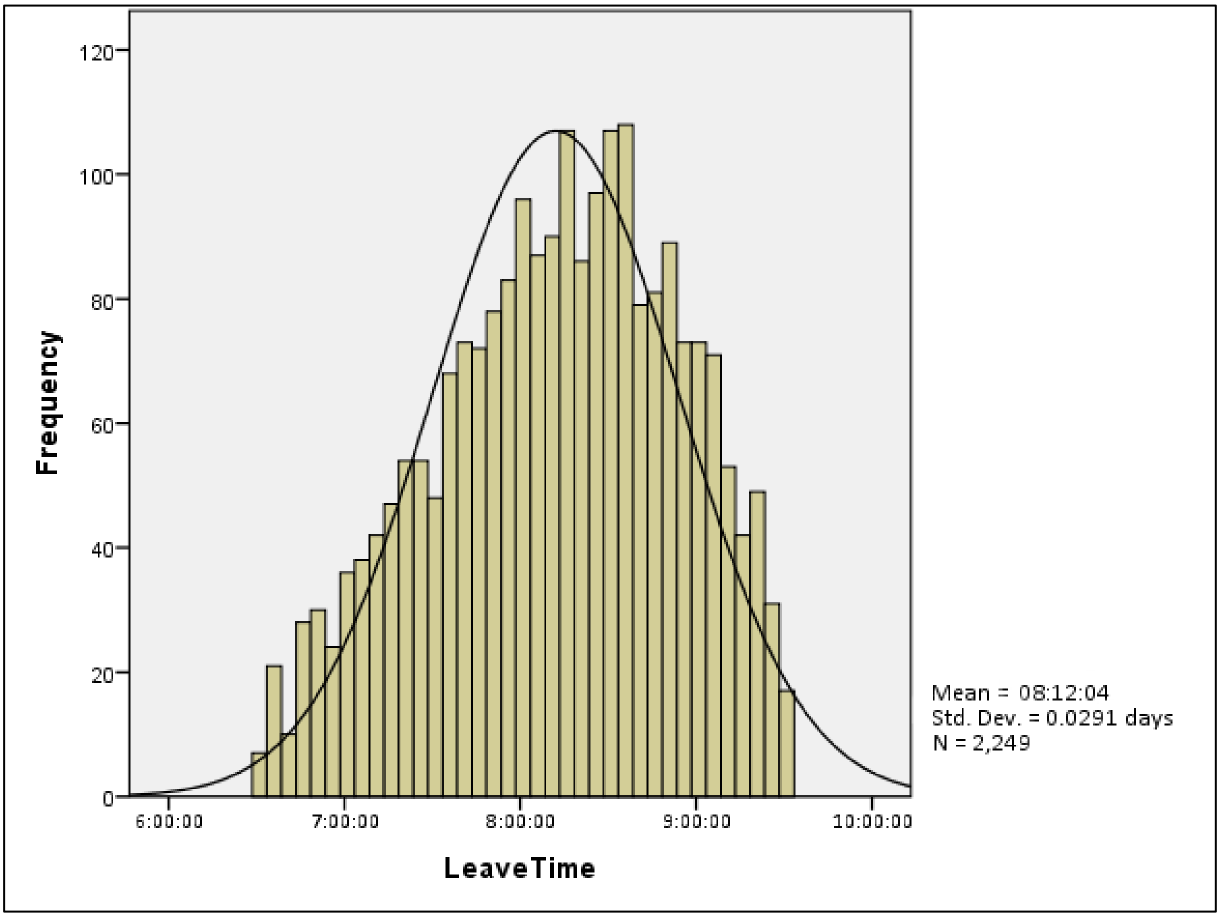

Figure 28 *The histograms of trips happened during morning peak hours (06:30 - 09:30) by LeaveTime.*

Figure 28 gives the distribution of trips happened during morning peak hours by their leave time, which is consistent with the congestion level fluctuating through a typical workday shown in Figure 26. The histograms of trips happened during daytime off-peak hours (09:31 - 15:29) and evening peak hours (15:30 – 19:00) help to prove the validity of the traffic demand (the graphs can be found in Appendix A.2).

The preliminary OD matrices are generated based on the activity-trip data and are shown in Table 14, Table 15 and Table 16. The *frequency* of each OD pair represents the number of trips happened during the corresponding periods. The OD pairs that have the same PCA (mainly supplementary PCAs, i.e., 5611, 5622, 5625 and 5631) for both origin and destination are neglected since those vehicles won't pass through the study area if the drivers take the shortest path for route decisions.

Table 14 *The preliminary OD matrix during morning peak hours (06:30 - 09:30).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	5612	73	5622	5611	53	5625	5611	93
5611	5622	38	5622	5612	77	5625	5612	100
5611	5623	63	5622	5623	33	5625	5622	11
5611	5625	30	5622	5625	12	5625	5623	35
5611	5631	25	5622	5631	9	5625	5631	11
5612	5611	91	5623	5611	59	5631	5611	15
5612	5612	609	5623	5612	58	5631	5612	31
5612	5622	17	5623	5622	35	5631	5622	24
5612	5623	38	5623	5623	499	5631	5623	21
5612	5625	25	5623	5625	22	5631	5625	11
5612	5631	16	5623	5631	15	All	All	2249

Table 15 *The preliminary OD matrix during daytime off-peak hours (09:31 - 15:29).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	5612	147	5622	5611	102	5625	5611	139
5611	5622	89	5622	5612	65	5625	5612	87
5611	5623	97	5622	5623	43	5625	5622	24
5611	5625	122	5622	5625	25	5625	5623	42
5611	5631	48	5622	5631	23	5625	5631	25
5612	5611	139	5623	5611	105	5631	5611	51
5612	5612	1358	5623	5612	77	5631	5612	67
5612	5622	67	5623	5622	57	5631	5622	24
5612	5623	64	5623	5623	999	5631	5623	29
5612	5625	99	5623	5625	39	5631	5625	21
5612	5631	58	5623	5631	29	All	All	4361

Table 16 *The preliminary OD matrix during evening peak hours (15:30 - 19:00).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	5612	179	5622	5611	101	5625	5611	128
5611	5622	111	5622	5612	47	5625	5612	94
5611	5623	118	5622	5623	54	5625	5622	21
5611	5625	174	5622	5625	24	5625	5623	55
5611	5631	73	5622	5631	22	5625	5631	34
5612	5611	143	5623	5611	109	5631	5611	58
5612	5612	1266	5623	5612	83	5631	5612	61
5612	5622	83	5623	5622	36	5631	5622	21
5612	5623	99	5623	5623	926	5631	5623	43
5612	5625	144	5623	5625	69	5631	5625	32
5612	5631	85	5623	5631	53	All	All	4546

Traffic Analysis Zones (TAZs) Redefinition

As seen in the three preliminary OD matrices, the unit of TAZs in the generated OD matrices was inherited from Albatross. The unit is defined as 4-digit postal code area (PCA) which is too coarse for a microscopic traffic simulation application. In SUMO, the unit of TAZs is usually defined as *edge(s)* to point out specific street(s). Therefore, the study unit, i.e., Traffic Analysis Zone has to be redefined to have finer granularity for the traffic simulation.

When zooming the function map to the study area and the surrounding neighbourhoods (shown in Figure 29), it is clear the most occupied and therefore most important function is residential. Next to many dwellings, buildings with special functions like office buildings, educational buildings, hospitals, and more, also account for a large proportion of the area. Besides, a large number of retail and leisure facilities are located around both ends of Veldmaarschalk Montgomerylaan street, namely the city centre and Woensel shopping area. Besides, a large area of nature landscape located to the east side of the study area, giving a different function for residents.

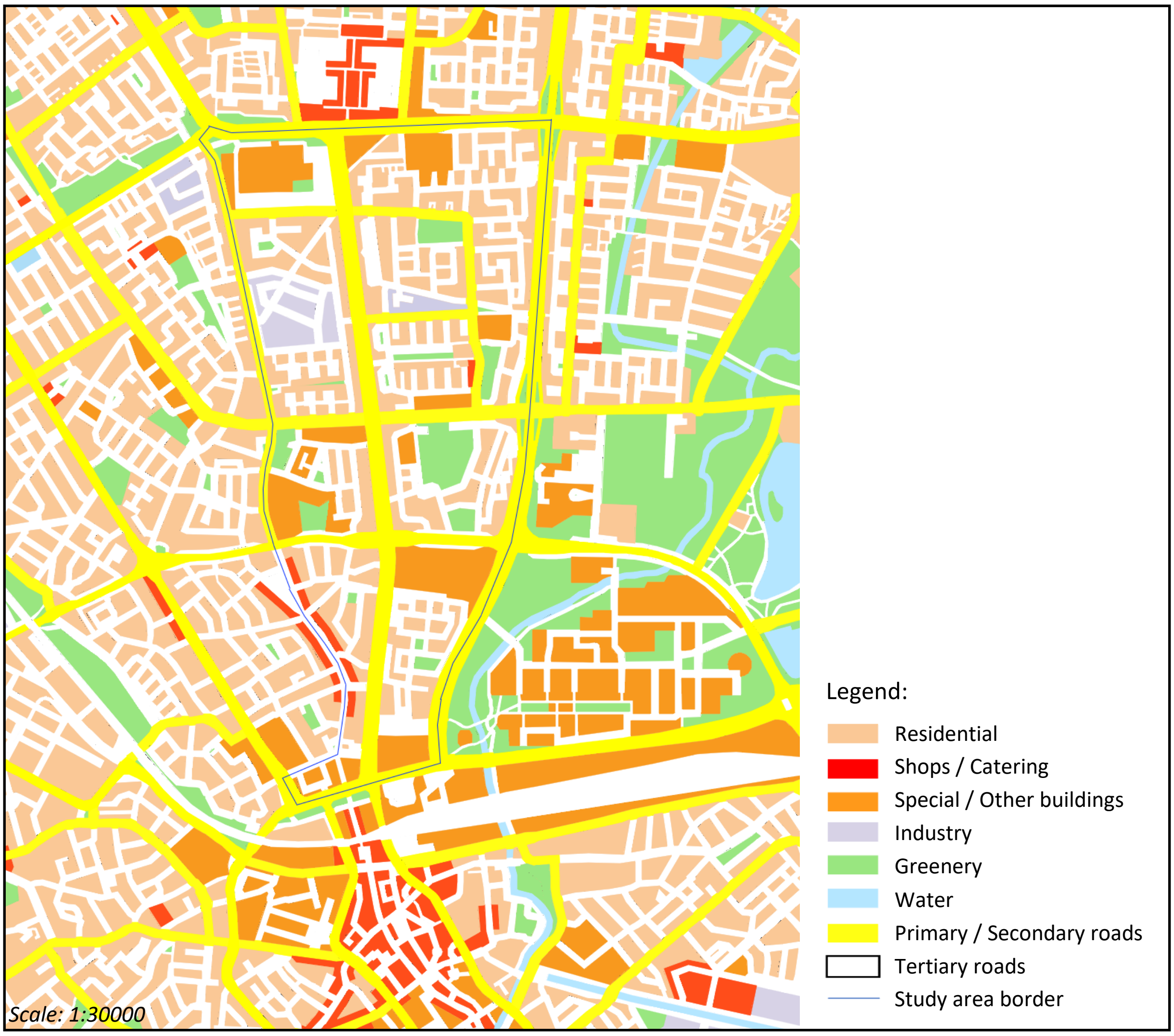

Figure 29 *Function map of the study area.*

What came to light from this function map is that the location lays at the intersections of multiple functions, like residential, business, retail, leisure, industrial, and more. Thus, the trips travelled through or within the study area can be triggered for various purposes. However, from the description on trips' activity types or trip purposes (see Table 17), it can be found most trips were made towards homes or workplaces as destinations, which shows that the vast majority of trips is made by commuters between their homes and workplaces. It is in line with the characteristics of the study area. In other words, most areas, as communities, provide residence for commuters.

***Table 17** Distribution of trips by activity type during each simulation period[10].*

Morning peak hours (06:30 – 09:30)			Daytime off-peak hours (09:31 – 15:29)			Evening peak hours (15:30 - 19:00)		
Activity Type	Frequency	Percent (%)	Activity Type	Frequency	Percent (%)	Activity Type	Frequency	Percent (%)
Work	1847	82.1	Home	1336	30.6	Home	2341	51.5
BringGet	113	5.0	Work	666	15.3	Work	493	10.8
Home	96	4.3	Groceries	430	9.9	Groceries	446	9.8
Business	53	2.4	BringGet	412	9.4	BringGet	387	8.5
Leisure	38	1.7	Leisure	383	8.8	Leisure	271	6.0
Groceries	37	1.6	Social	357	8.2	Social	198	4.4
Social	21	0.9	Business	268	6.1	Business	155	3.4
Services	16	0.7	Services	187	4.3	Services	95	2.1
Other	14	0.6	Touring	151	3.5	Touring	69	1.5
Touring	12	0.5	Other	91	2.1	Other	58	1.3
NonGroc	2	0.1	NonGroc	80	1.8	NonGroc	33	0.7
Total	2249	100.0	Total	4361	100.0	Total	4546	100.0

Based on the discussion above, it is reasonable to divide the original TAZs, 4-digit PCA, into smaller communities which consist of a number of *edges*. Briefly speaking, the finer TAZs are defined according to the main functions of the buildings in each unit and the physical borders (built roads). As shown in Figure 30, the study area with only two PCAs previously (the south area is an incomplete PCA) is now divided into 15 smaller communities. For supplementary PCAs, namely, 5611, residual 5612, 5622, 5625 and 5631, each of them keeps the same level and is defined as a TAZ which represent the whole PCA. These finer analysis units will become the new TAZs for the traffic simulation.

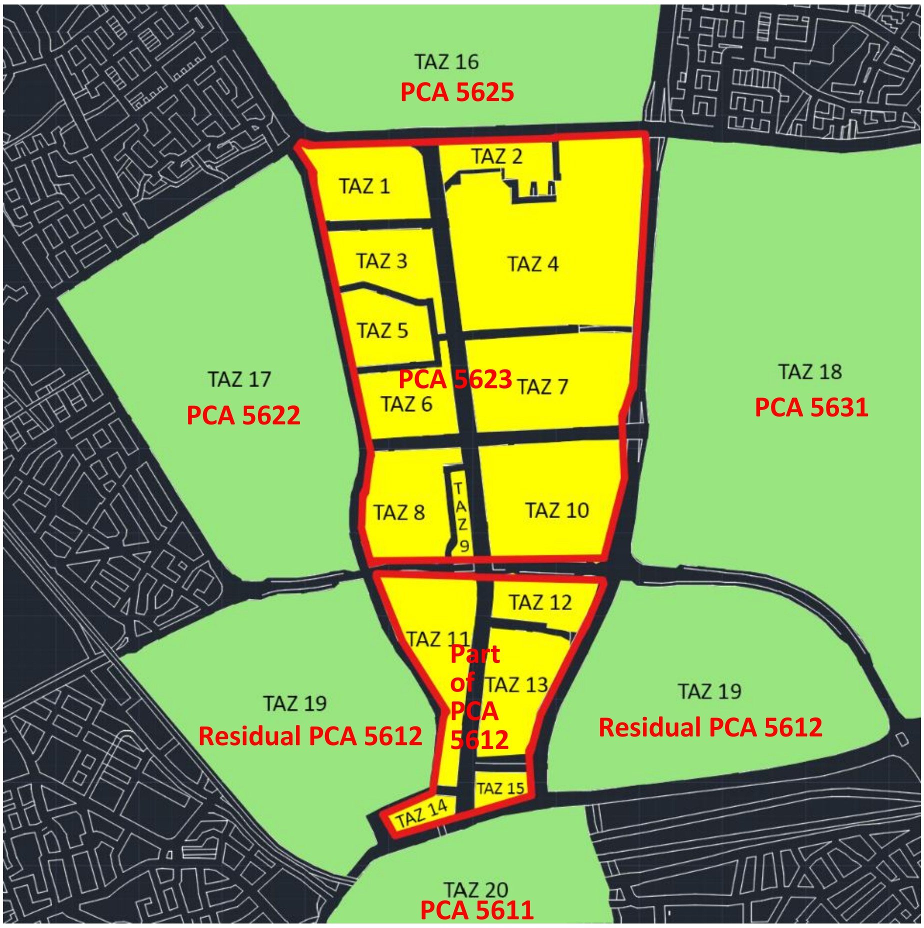

***Figure 30** The study area with finer traffic analysis zones.*

The information about redefined TAZs with their original PCAs can be found in Table 18. Most TAZs in the study area provide residential function for the residents. Since the accurate population statistics of each TAZ are not available, the distribution of traffic demands is processed in a different way: firstly,

[10] These tables are generated based on the activity-travel diary from Albatross.

the area of each TAZ is measured based on the Eindhoven map (Eindhoven Municipality, 2020); and then the shares of each refined TAZ in the PCA are calculated in the table as proportions. Noted that an assumption is made that the number of trips start from or arrive at in a specific TAZ is proportional to the area of the community in the whole postal code area. In other words, the traffic demands are distributed based on the areas of TAZs.

Table 18 *The refined TAZ list.*

PCA	TAZ id	Function	Area (m^2)[a]	Proportion (%)
5623	1	special	115321.4	8.2
	2	special	54109.5	3.9
	3	residential	92290.4	6.6
	4	residential	418298.9	29.8
	5	industry	76947.2	5.5
	6	residential	88478.5	6.3
	7	residential	202161.2	14.4
	8	special	130945.3	9.3
	9	residential	15641.1	1.1
	10	residential	207816.8	14.8
5612	11	residential	142491.8	6.9
	12	special	65819	3.2
	13	residential	110301.1	5.4
	14	special	22694.3	1.1
	15	special	22733.9	1.1
Residual 5612	19	mixed	1694379.6	82.3
5625	16	mixed	-	-
5622	17	mixed	-	-
5631	18	mixed	-	-
5611	20	mixed	-	-

[a]The area of each TAZ is measured based on the map; therefore they don't have an official status.

With the refined TAZs and preliminary OD matrices in Table 14, Table 15 and Table 16, the final OD matrices are generated (see Appendix A.7). Table 19 is NOT complete but is meant to show the layout: each 4-digit PCA is split into several refined TAZs using the id listed in Table 18 and frequency represent the number of trips between the designated origin and destination.

Table 19 *Part of the prepared OD matrix during morning peak hours (06:30 - 09:30).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	**5612**	**73**	**5622**	**5611**	**53**	**5625**	**5611**	**93**
20	11	5	17	20	53	16	20	93
20	12	2						
20	13	4						
20	14	1						
20	15	1						
20	19	60						
5611	**5622**	**38**	**5622**	**5612**	**77**	**5625**	**5612**	**100**
20	17	38	17	11	5	16	11	7
			17	12	2	16	12	3
			17	13	4	16	13	5
			17	14	1	16	14	1
			17	15	1	16	15	1
			17	19	63	16	19	82
…								
…								
5612	**5625**	**25**	**5623**	**5625**	**22**	**5631**	**5625**	**11**
11	16	2	1	16	2	18	16	11
12	16	1	2	16	1			
13	16	1	3	16	1			
14	16	0	4	16	7			
15	16	0	5	16	1			
19	16	21	6	16	1			
			7	16	3			
			8	16	2			
			9	16	0			
			10	16	3			
5612	**5631**	**16**	**5623**	**5631**	**15**	**All**	**All**	**2249**
11	18	1	1	18	1			
12	18	1	2	18	1			
13	18	1	3	18	1			
14	18	0	4	18	4			
15	18	0	5	18	1			
19	18	13	6	18	1			
			7	18	2			
			8	18	1			
			9	18	0			
			10	18	2			

However, for the sake of simplification not all *edges* in one TAZ are selected to represent the emitters in the simulation, for the study area (TAZ 1 – TAZ 15), only the roads which connect to the junctions of the secondary road are chosen. For the supplementary area (TAZ 16 – TAZ 20), only the primary or secondary roads are selected to emitter vehicles. For *edges* in the same TAZ, the opportunities for them being chosen are the same. The script that translates this information to define traffic analysis zones in SUMO can be found in Appendix B.4.

5.2.2.2 Route Assignment

Before assigning the routes for private traffic, two terms have to be clarified beforehand according to German Aerospace Center (DLR) (2019b): a *trip* is a vehicle movement from one place to another defined by the starting edge, the destination edge, and the departure time. A *route* is an expanded trip which contains more information, not only the first and the last edge but also the intermediate edges in between.

The basic idea of route assignment is firstly generating *trip* list which contain the information about origin and destination roads and the corresponding departure time for each vehicle. Then a user assignment algorithm is used to compute the accordingly complete paths through the network, resulting in a list of vehicle *routes*. With such routes, and the network itself (and some additional information), the private traffic simulation can then be built.

The import process includes the following two steps, which are both directly supported by SUMO tools:

- Convert the OD matrix into a list of single-vehicle *trip* information, consisting of the departure time and the origin and the destination road;
- Perform a user assignment to obtain a realistic set of *routes* through the network.

For the first step, each cell of the prepared OD matrices describes the respective traffic demand as the number of trips by passenger cars. To convert such OD matrices into individual trips, the tool OD2TRIPS (German Aerospace Center (DLR), 2019f) is invoked as the format shown below. Basically, OD2TRIPS reads all matrix cells and generates trip definitions. Three private traffic trip files *od_file.odtrips_begin.time-end.time.xml* are then created automatically.

It is noted that because each cell in OD matrices describes the number of vehicles to be inserted into the network within a certain period, OD2TRIPS has to compute the vehicle's explicit departure times. Normally, it can be done by using a random time or a uniform time within the time interval a cell describes. Thus, in order to show the density of private traffic (the amount of trips happened in one unit time) in different periods, three OD matrices aiming three periods were prepared separately, which answers the question proposed earlier in section 5.2.2.1 that why these periods are not merged into one long period.

```
od2trips -c od2trips.config.xml -n taz_file.taz.xml -d OD_file_begin.time-end.time.od -o
od_file.odtrips_begin.time-end.time.xml
```

-c configuration file
-n taz file
-d additional files
-o output file

Once three vehicle *trip* lists are generated, user assignment can be executed for understanding the traffic state of the investigated network during each simulation period. Currently, three tools are provided by the SUMO-package for this specific task (German Aerospace Center (DLR), 2019i): DUAROUTER, One-shot and MAROUTER. The main differences between these assignment tools are their assignment principles (Dynamic User Equilibrium (DUE), Stochastic User Equilibrium (SUE)) and perspectives (microscopic or macroscopic) and are summarized in Table 20.

Table 20 *Characteristics of different assignment tools.*

User Assignment Tools	Principles	Perspectives	Key points
DUAROUTER	DUE	Microscopic	Iterative user assignment; shortest-path computation;
One-shot	DUE	Macroscopic	Incremental assignment; fastest-path computation;
MAROUTER	SUE	Macroscopic	Iterative user assignment without time-consuming microscopic simulation;

Among these tools, DUAROUTER is the optimal assignment tool for this project because it computes *routes* based on DUE from a microscopic perspective. It is responsible for importing routes or their definitions from other simulation packages and for computing routes using the shortest-path algorithm by Dijkstra (German Aerospace Center (DLR), 2020a).

Three route files *od_route_file.odtrips_begin.time-end.time.rou.xml* are generated by invoking the corresponding command (see Appendix B.5 *Code of duarcfg_file.trips2routes.duarcfg*). The format of the command is shown below:

```
duarouter –c duarcfg_file.trips2routes_begin.time-end.time.duarcfg
```

-c configuration file

Once three vehicle-route lists are generated, they can then be put into one route list which sorts all routes according to their departure time. As shown in Table 21, a total of 10,727 routes (96.15% of 11,156 trips) are assigned while a few part of trips cannot be created with valid routes and thus are eliminated. It can be concluded that the private traffic routes simulated in this way are credible.

Table 21 *The valid routes during each simulation period.*

Simulation period	Valid routes	Total Trips	Percentage (%)
06:30 – 09:30	2,155	2,249	95.82
09:31 – 15:29	4,186	4,361	95.99
15:30 – 19:00	4,386	4,546	96.59
06:30 – 19:00	10,727	11,156	96.15

5.2.3 Public Transport Simulation

From the perspective of simulation, public transport can be regarded as a specialised form of generic transport (Morenz, 2007). Basically, public transport vehicles adhere to the same driving behaviour models as the private transport. The differences between them mainly lie in the route generation and stopping behaviour.

5.2.3.1 Bus Schedule Preparation

Looking at the study area, a total of five bus lines (line 9, 322, 400, 405, 406) travel along the entire investigated road, Veldmaarschalk Montgomerylaan street, and another two lines (line 2, 3) pass through part of the road (including WoensXL/ZH Catharina Station). Thus, the bus schedules of investigated bus lines (2, 3, 9, 322, 400, 405 and 406) are retrieved from the bus operating company, Bravo, in Zuidoost-Brabant area (Eindhoven, Helmond, De Kempen and De Peel) (Bravo & Hermes, 2019a).

As an example shown in Table 22, it indicates the origin station, terminal and main stops in between and most importantly, the estimated departure time of each bus trip from each bus stop. **Table 22** only shows the bus line 9 trips with even numbers. Another part of bus line 9 trips with odd numbers is listed in another group of tables and they travel in the opposite direction, i.e., from Best, Station to Eindhoven, Station. The complete extracted bus schedules for the simulated bus routes can be found in Appendix A.8.

Table 22 *Part of bus Line 9b timetable.*

Bus stop name	Trip	2	4	6	8	10	12
Eindhoven, Station	from	6 36	7 06	7 33	8 03	8 33	9 06
Eindhoven, Fontys Rachelsmolen		6 39	7 09	7 36	8 06	8 36	9 09
Eindhoven, WoensXL/ZH Catharina		6 42	7 12	7 40	8 10	8 40	9 12
Eindhoven, Pieter Eijffuhuis		6 47	7 17	7 46	8 16	8 46	9 17
Eindhoven, Estafettelaan		6 49	7 19	7 48	8 18	8 48	9 19
Eindhoven, Boschdijk/Steenoven		6 53	7 23	7 52	8 22	8 52	9 23
Best, Wilhelminaplein		6 59	7 29	7 58	8 28	8 58	9 29
Best, Nazarethstraat		7 05	7 35	8 05	8 35	9 05	9 35
Best, Station	to	7 11	7 41	8 11	8 41	9 11	9 41

To construct bus flows, some additional conversions on bus schedules need to be made: firstly, *Flow* needs the attribute *Period* (see Figure 15) which means the interval time between inserted buses. By checking timetables of each bus route with the consideration of each simulation periods, Table 23 points out average *Period* for each bus route during different simulation periods. It can be seen from the table that *Periods* for most routes do not vary between simulation periods.

Table 23 *The interval time for different bus routes.*

Bus Route	Period (s)		
	Morning peak hours	Daytime off-peak hours	Evening peak hours
2	600	900	600
3	1800	1800	1800
9	1800	1800	1800
322	1800	1800	1800
400	600	600	600
405	900	900	900
406	900	900	900

Secondly, due to the time unit specified in SUMO, the departure time in bus schedules has to be converted to seconds for attribute *Begin* in *Flow* by using equation [5-1].

$$time^{i}_{departure} = \left(hour^{i} + \frac{min^{i}}{60}\right) * 3600 \qquad [5-1]$$

Where

$time^{i}_{departure}$ is the departure time of bus flow i;

$hour^i$ is the hour bus flow i departs from the bus stop;

min^i is the minute bus flow i departs from the bus stop.

Lastly, the dwell time which takes up most of *total bus stop time* (see section 4.1.3.2) has to be specified for each bus stop. Considering the passenger capacities of different bus stops, usually the dwell time at busy bus stops is longer than less-occupied stops. According to this principle, the dwell time at Eindhoven, WoensXL/ZH Catharina is set 10 seconds longer than other small bus stops. It is noted that although Eindhoven, Station would be the busiest bus stop in Eindhoven area, the dwell time at this bus stop is set as 0 seconds to make the departure time of buses exactly the same as the time listed on the bus timetable. Table 24 lists the dwell time for different bus stops.

Table 24 *The dwell time set for different bus stops.*

Bus Stop	$time^i_{dwell}$ (s)
Eindhoven, Station	0
Eindhoven, WoensXL/ZH Catharina	30
Others	20

5.2.3.2 Route Assignment

As a special form of the general traffic, the way to generate routes for public transport is totally different from that of private traffic routes. As indicated earlier, the bus routes are built based on the bus schedules which give the information of the specific route followed by the specific bus line and the bus stops on the route.

With the combination of the bus route map, element *Flow* is used to generate designated bus flows. As the example codes shown below. It describes the bus flow of line 9 during morning peak hours (06:30 -- 09:30) from Eindhoven, Station bus stop to the boundary of the study area (see Figure 31).

Figure 31 *The bus route of line 9 (study area in yellow). Source: hermes.nl*

Element *Flow* firstly defines flow id, referenced vehicle type, begin street, end street, line name, begin time, end time and interval time between buses. The child element *Stop* gives the name and Total Bus Stop Time of passing bus stops in their correct order.

```
<flow id="line9b_MP[11]” type="bus" from="48837441" to="-gneE127" line="9b" begin="23760" end="34200"
period="1800">
        <stop busStop="busstop_CentraalStation_9" duration="0"/>
        <stop busStop="busstop_Gildelaand_2_9_322_405_406b" duration="20"/>
        <stop busStop="busstop_FontysRachelsmolen_2_9_322_405_406b" duration="20"/>
        <stop busStop="busstop_Europalaan_9_322_405_406b" duration="20"/>
        <stop busStop="busstop_GeneraalPattonlaan_9_322_405_406b" duration="20"/>
        <stop busStop="busstop_WoensXLZHCatharina_3_9_400_405_406b" duration="30"/>
</flow>
```

The example code shows the morning peak bus flow of line 9 which begins the journey from Eindhoven Station bus stop at 23760s (6:36 am as shown on the bus schedule) to the area border. However the departure time for buses running the direction to the city centre, i.e., trips labelled with “a”, would use the departure time which is earlier than the time listed on the bus schedule in Appendix A.8 because they start the trip at the boundary of the area but not Eindhoven, WoensXL/ZH Catharina bus stop. Thus the compensation time will be considered in the bus simulation and it would vary from 60 seconds to 180 seconds based on the distance between the starting street and WoensXL/ZH Catharina bus stop for different bus routes (see Table 25).

Table 25 *The compensation time for each bus route.*

Bus route	Compensation time (seconds)
3a	60
2a, 9a, 400a, 405a, 406a	120
322a	180

In total, 42 bus flows happened during three simulation periods are created as the example code shows. However, the bus flows created for line 400 are a little different (see codes below). Although line 400 buses only stop at WoensXL/ZH Catharina on Veldmaarschalk Montgomerylaan in reality, other bus stops on this road are also included in the *Stop* element to make line 400 buses drive on the dedicated bus lanes and the durations are set as 0.

```
<flow id="line400b_MP" type="bus" from="48837439" to="457077915#1.495" line="400b" begin="24120"
end="34200" period="600">
        <stop busStop="busstop_CentraalStation_400" duration="0"/>
        <stop busStop="busstop_Gildelaand_2_9_322_405_406b" duration="0"/>
        <stop busStop="busstop_FontysRachelsmolen_2_9_322_405_406b" duration="0"/>
        <stop busStop="busstop_Europalaan_9_322_405_406b" duration="0"/>
        <stop busStop="busstop_GeneraalPattonlaan_9_322_405_406b" duration="0"/>
        <stop busStop="busstop_WoensXLZHCatharina_3_9_400_405_406b" duration="30"/>
</flow>
```

Nevertheless, there are still two things that don’t match with the actual situations in this process. Firstly, in reality buses are usually reassigned to continue to run another route (may be the opposite direction or another route) after reaching the terminal stop. The bus is not considered as reusable for trips in the simulation meaning that one bus is dedicated for one trip and it will disappear after reaching its destination. Secondly, line 3 buses do not follow the actual bus route because the simulated area doesn’t include all the bus stations they serves (see Figure 32). Because buses following this route won’t travel along the whole Veldmaarschalk Montgomerylaan street and the influence brought by this can be neglected.

[11] MP means morning peak hours, similarly, OP for daytime off-peak hours and EP for evening peak hours.

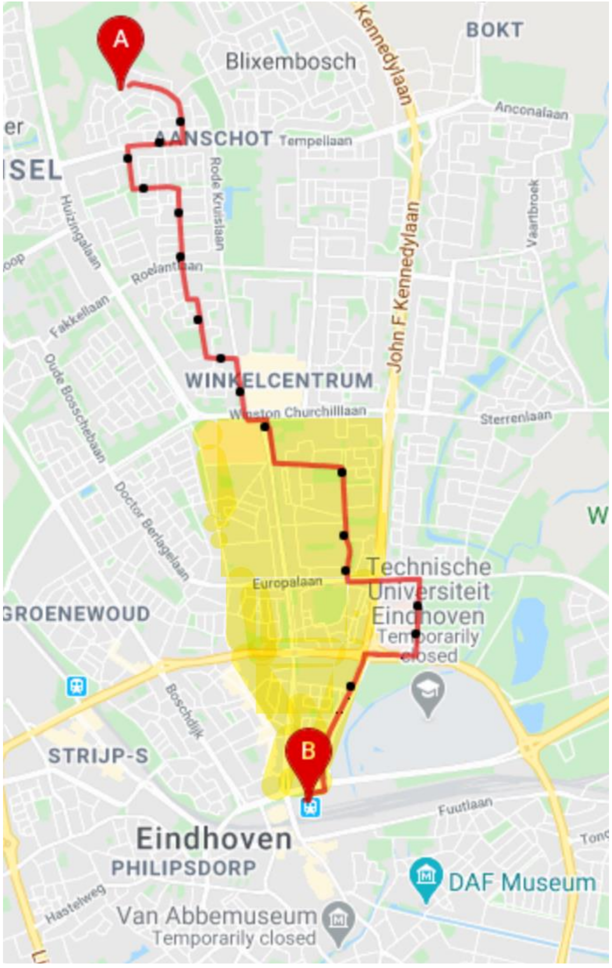

Figure 32 *The bus route of line 3 (study area in yellow). Source: hermes.nl*

Until this step, the traffic simulation has been set up based on the current bus lane policy as close as possible. In total 10,727 passenger car trips and 42 bus flows are simulated in the road network. With input data like network configuration file, routes file and additional information, the baseline urban traffic scenario in the study area has been simulated in SUMO (see Appendix B.6 *Code of simulation.sumocfg*).

Figure 33 and Figure 34 show the traffic situations through the simulation period regarding the number of running vehicles and the average speed (the traffic simulation was run for several times to ensure that the values were generated based on a steady state) in the whole simulation network. It can be found from the figures that before evening peak hours, the traffic flow keeps almost unchanged and only several fluctuations are seen regarding the average speed. After entering the evening peak hours, the traffic flow increased dramatically, resulting in a peak of vehicle numbers around 18:00 and the corresponding low speed. Such a trend matches the actual situation seen in Figure 26.

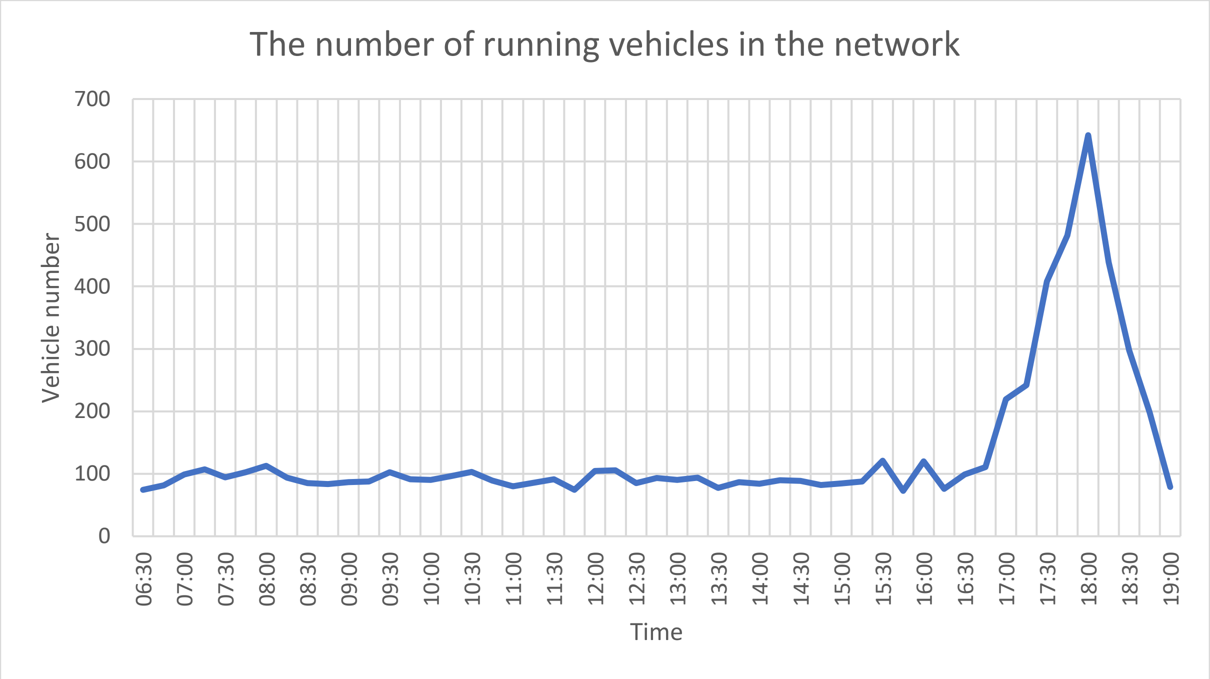

***Figure 33** The number of running vehicles in the network.*

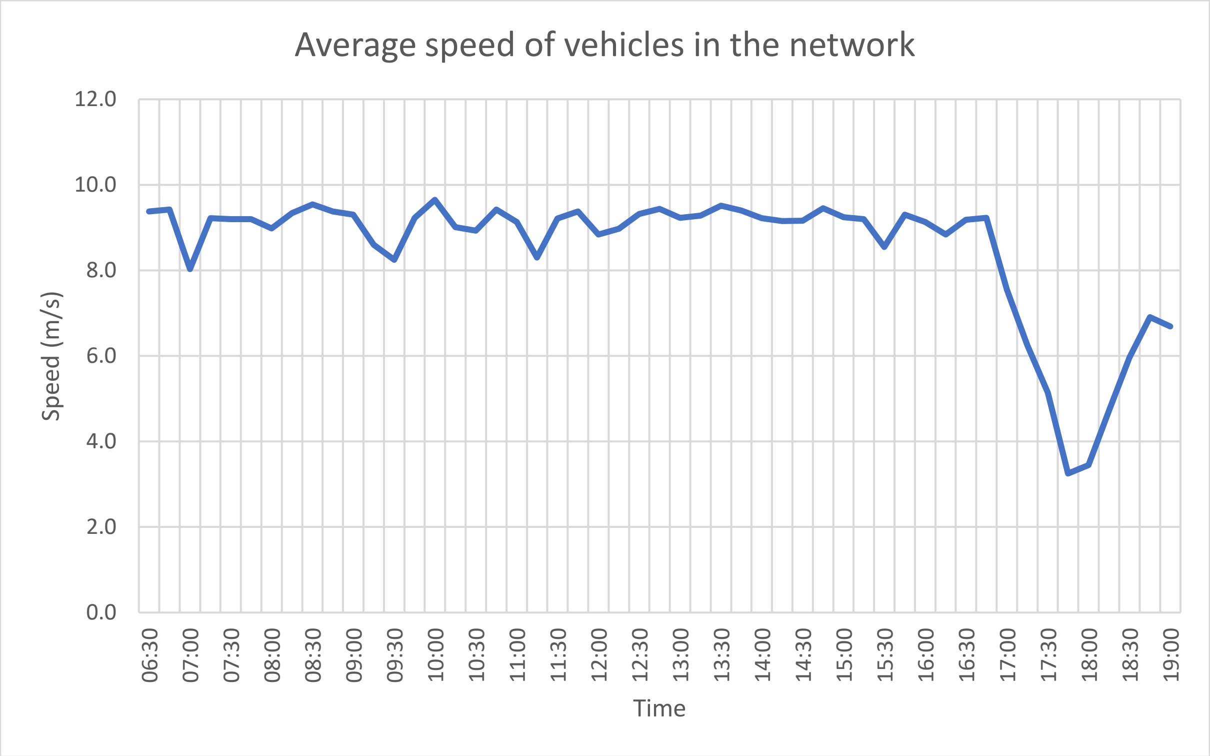

***Figure 34** The average speed (m/s) of vehicles in the network.*

The flow chart in **Figure 35** clarifies the various stages and specific steps taken in the traffic simulation.

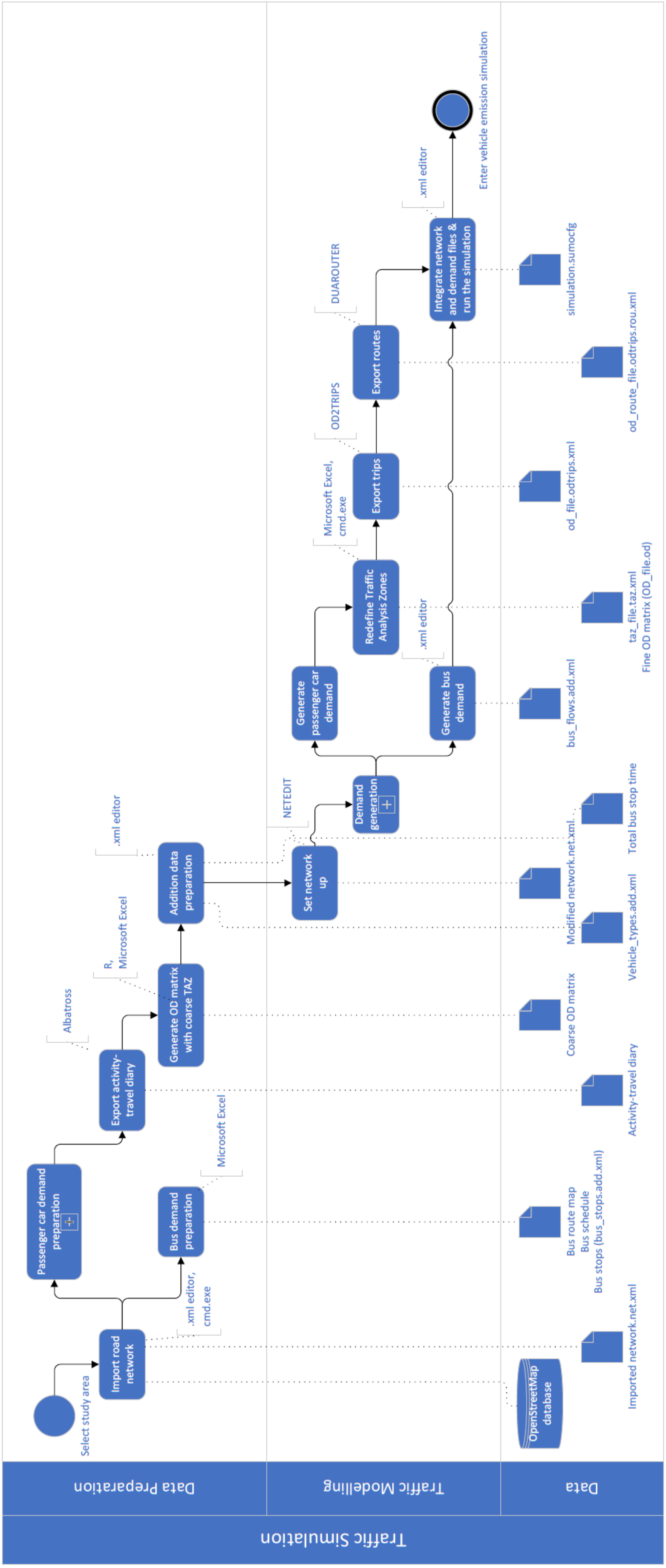

Figure 35 *Detailed process of traffic flow modelling.*

5.3 VEHICLE EMISSION SIMULATION

As explained before, vehicle emission modelling is essentially the process of assigning *emission classes* and corresponding *emission factors* (gram/vehicle kilometre) to different types of passenger cars, and then multiplying by their *total driven mileages* (vehicle kilometres travelled) on each street to obtain the *street vehicle emissions* (gram) for a certain period.

With the methodology and data preparation described in the previous chapters, the *emission class* and *emission factor* from VERSIT+ modelling and street-based *total driven mileage* from SUMO traffic simulation have been prepared, the calculation results of *street vehicle emission* for the investigated streets in the study area are partly given:

Table 26 shows some example streets that have the most passing vehicles through the day, the complete information regarding the emissions on all investigated streets can be found in Annex *vehicle emissions_06.30-19.00.xlsx*.

Table 26 *The streets with the heaviest emissions (most mileages) during 06:30-19:00 in the study area.*

Edge_id	Vehicle count	Street length (km)	Mileage (km)	Pollutant (g)							
				CO	VOC for combustion (CH_4 included)	NO_x	PM_{10} for combustion	NH_3	N_2O	EC	CO_2
457063056	1438	0.21	306.50	1236.1	87.0	92.0	1.1	7.3	2.0	0.5	66401.0
-390646733	1193	0.24	291.68	1176.4	82.8	87.5	1.0	6.9	1.9	0.5	63190.6
-457063056	1365	0.21	290.94	1173.4	82.6	87.3	1.0	6.9	1.9	0.5	63030.2
390646733	1141	0.24	278.96	1125.1	79.2	83.7	1.0	6.6	1.9	0.5	60436.3
7157726#1	704	0.34	242.07	976.31	68.7	72.6	0.8	5.8	1.6	0.4	52443.6

Since VERSIT+ is not provided by SUMO, the results generated by the emission model cannot be imported back to the traffic simulation software, the visualization results of the whole road network could not be generated temporarily. Only the streets with heaviest emissions in the study area are selected and shown in Figure 36, which suggests possible modelling domains for air quality modelling later.

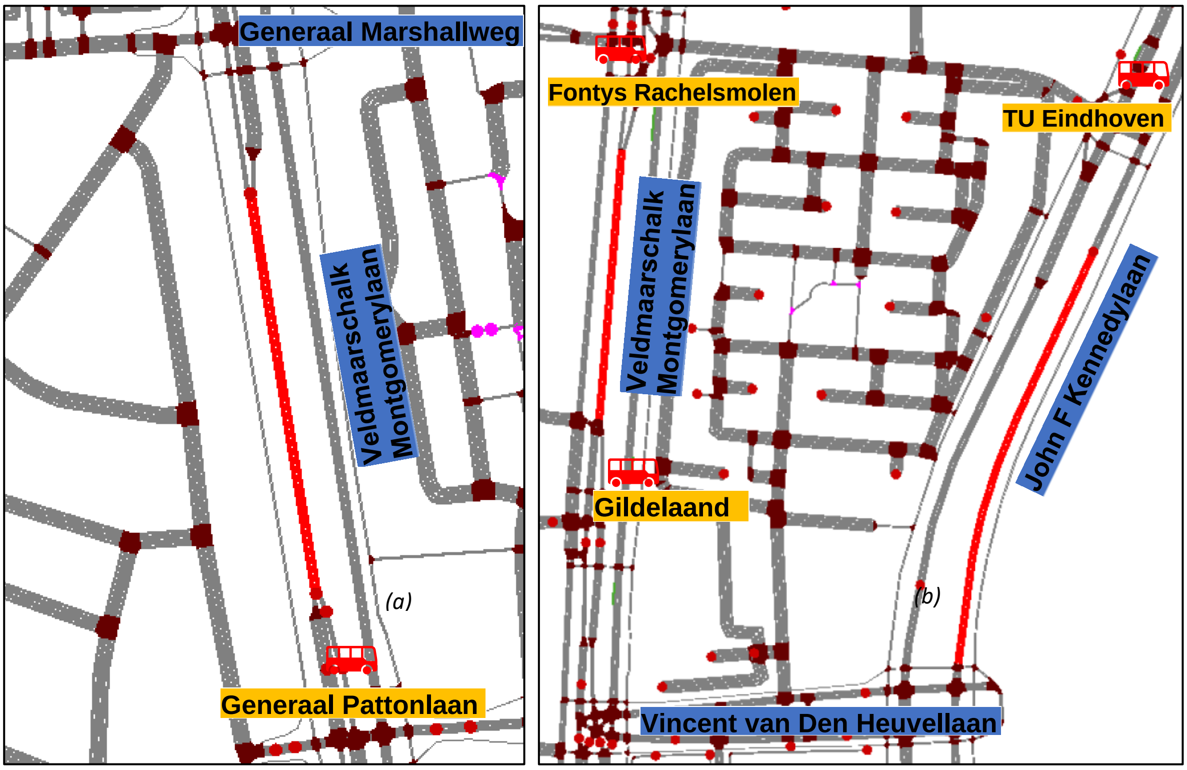

Figure 36 *The most polluted streets (in red) in the study area: (a) one polluted road segment close to Generaal Pattonlaan bus stop; (b) two polluted road segments close to Fontys Rachelsmolen bus stop, Gildelaand bus stop and TU Eindhoven bus stop.*

The flow chart below shows how the information is delivered from traffic modelling to emission modelling within this modelling process.

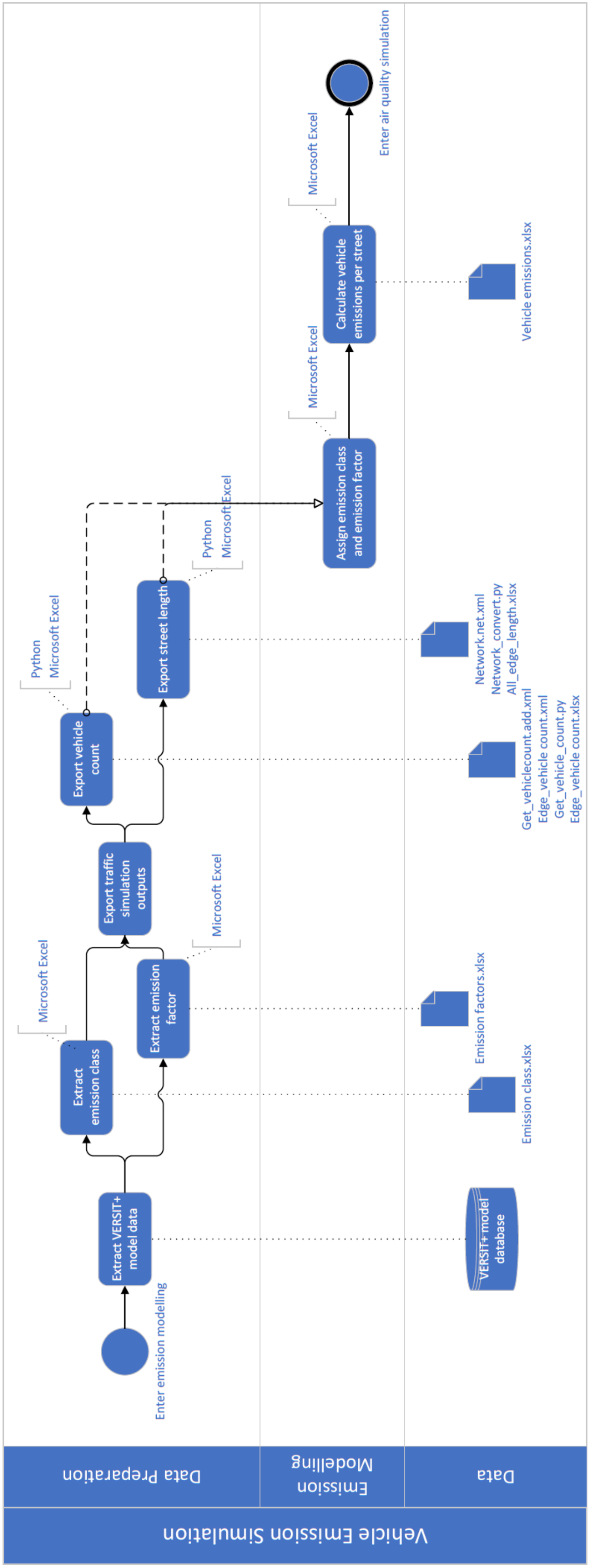

Figure 37 *Detailed process of vehicle emission modelling.*

5.4 Air Quality Simulation

Dispersion of particles in the real world would be a very complex process which depends on the factors like meteorological conditions (wind, heat and humidity), the design of surrounding infrastructures (the width of a street, the height of buildings at roadsides), the intensity of emission sources, and more. It has to be admitted that the dispersion modelling conducted in this study is a simplified air quality simulation. The process of computing the pollutant concentrations is described below: section 5.4.1 gives the setting parameters to match the simulation environment. Due to project time constraints, the scope of simulation and the simulated pollutants were limited as described in section 5.4.2. Based on the prepared data as well as specified range, the concentration results are presented in section 5.4.3. Similarly, a process diagram is given in the end.

5.4.1 General Settings

Before editing the detailed simulation environment, the general setting parameters for dispersion modelling have to be defined (see Figure 38). Most parameters in this tab are kept as the preferred mode of GRAL (i.e., the computation of steady-state concentration fields[12] for classified meteorological conditions) (Öttl, 2020).

Since the simulation will be performed multiple times to calculate the concentration distribution at different locations, the parameters that can control the computation time are changed to decrease the required time for each round but sacrifice the accuracy in an acceptable range. Besides, the parameters related to resolutions (e.g., horizontal grid resolution, heights of horizontal slices, and etc.) are also adjusted to appropriate values.

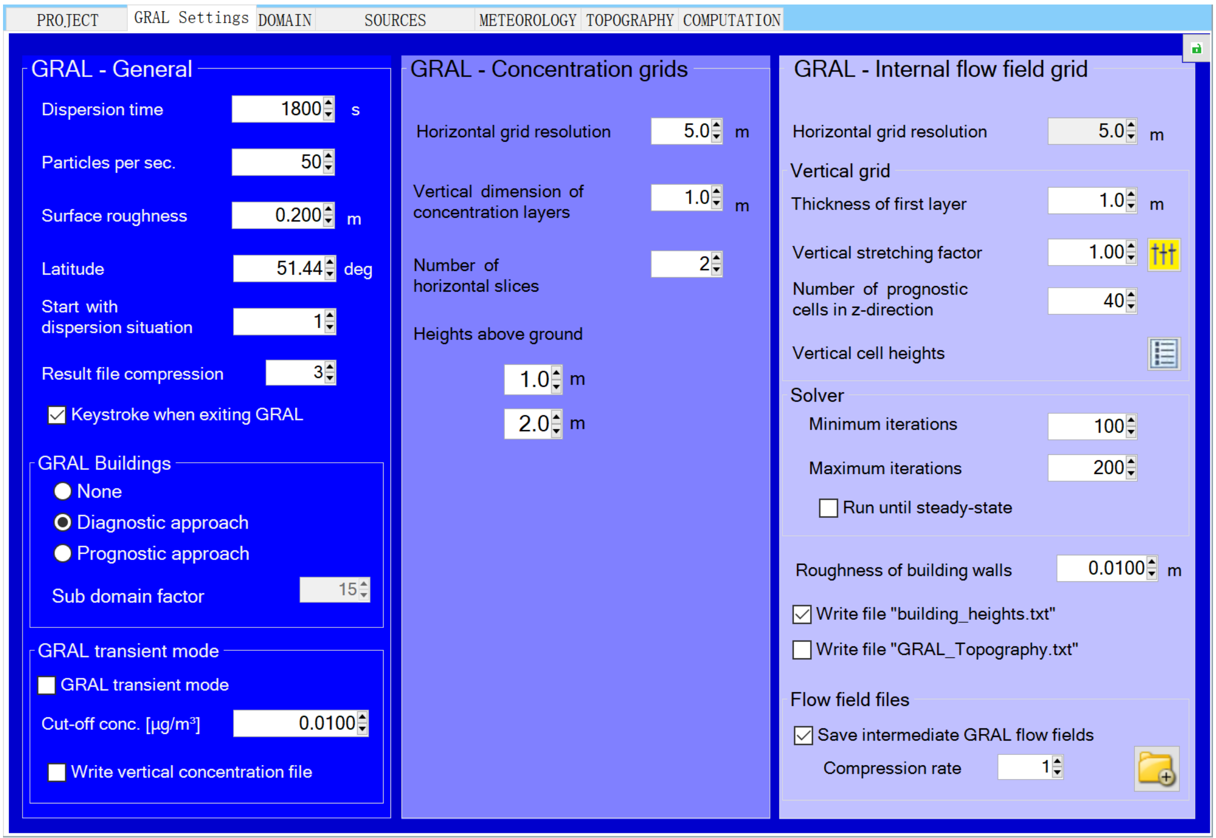

Figure 38 *General setting parameters for the GRAL simulation.*

Detailed explanations on the meaning of each parameter can be referred to the GRAL user manual (Öttl & Kuntner, 2020). There are several parameters that should be clarified:

[12] Computation of steady-state concentration fields: in this case particles are tracked until they leave the model domain regardless the time they need to do so (Öttl, 2020).

The first two parameters control the total amount of particles emitted in the dispersion model. It is the product of "Dispersion time" times "Particle per sec.". The higher the number of particles, the smoother the concentration fields. According to the user manual, typical values are 25 particles for 1800 seconds for an area smaller than 250 x 250 m^2 and 1000 particles for 3600 seconds for an area larger than 20x20 km^2 and enormous emission sources (Öttl & Kuntner, 2020). Considering the geographical space of the chosen modelling domains (see section 5.4.2.1) and the necessity to improve the accuracy, "Dispersion time" is set to 1800 seconds and "Particles per sec." is set to 50.

Figure 39 below is generated as emission rate variation which shows the list of modulation factors and it will be used when defining the emission sources.

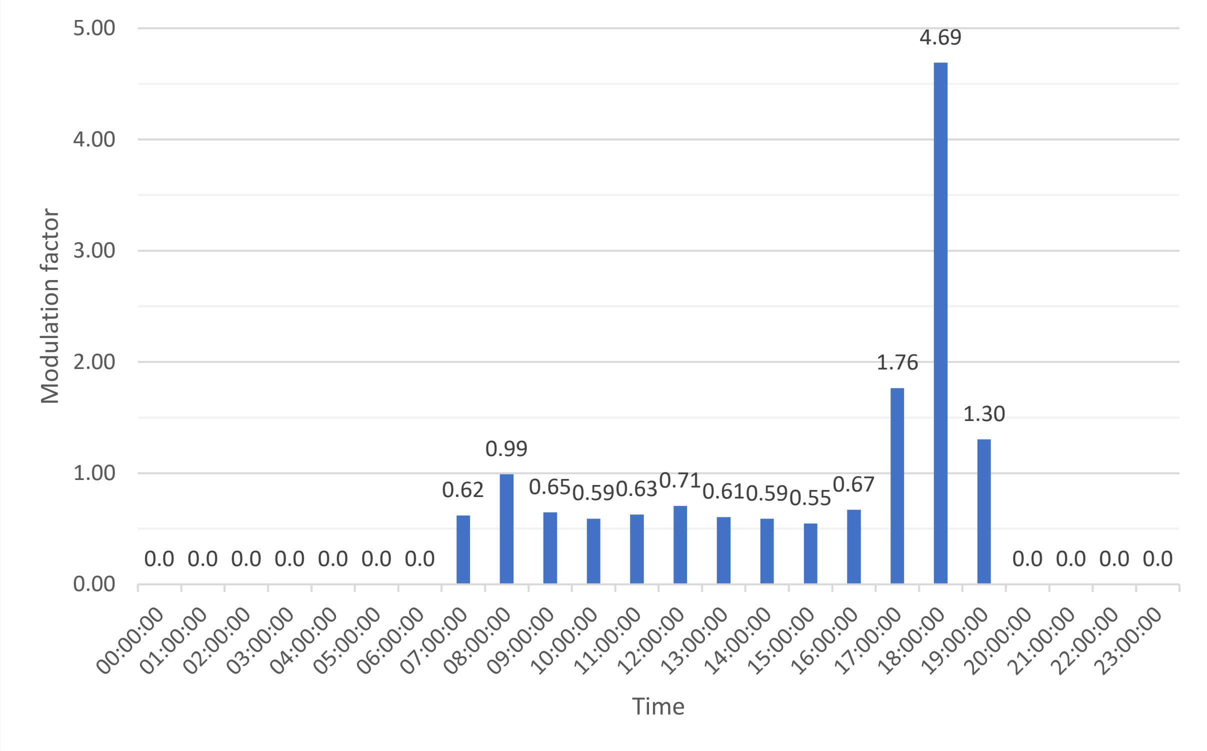

Figure 39 *The diurnal modulation factors.*

The next set of parameters is related to the topography. Since the terrain in the study area does not change significantly (see Figure 40), the dispersion simulation is set to be performed on a "flat" terrain.

Eindhoven, North Brabant, Netherlands (51.43926 5.47863)

Figure 40 *The topographical map for the study area (retrieved from topographic-map.com).*

5.4.2 Selection of Simulation Objects

Next to the general setting parameters for setting up dispersion modelling, it is also important to select simulation objects due to the limited project time. The selection of objects here refers to the selection of simulated locations and pollutants. Its purpose is to demonstrate the impact of the proposed traffic scenario for the sake of comprehensiveness.

5.4.2.1 Modelling Domain

Due to the poor compatibility between emission modelling outputs and the GRAL simulation platform, it is not realistic to perform the dispersion simulation for the whole simulated road network or even the whole Veldmaarschalk Montgomerylaan road. Therefore, the modelling domain is specified at first to set the simulation environment.

With the suggestions given by the vehicle emission simulation (see Figure 36), in order to cover the investigated main road as much as possible, two road segments (close to Generaal Pattonlaan bus stop and Fontys Rachelsmolen bus stop) and one intersection in between (at the crossroad of Europalaan and Veldmaarschalk Montgomerylaan) on Veldmaarschalk Montgomerylaan are chosen (see Figure 41). Table 27 lists the basic situations of modelling domains.

***Table 27** The basic situations of modelling domains.*

Modelling domain	Scope	Simulated building groups (No.)	Simulated vegetations (No.)	Approximate modelling area (m^2)
Street i	North to Generaal Marshallweg, south to Generaal Pattonlaan with the length of 430 m;	15	7	75,200
Intersection	Extend from the crossroads as the centre from 100 metres to 200 metres;	19	8	100,750
Street ii	North to Rachelsmolen, south to Vincent van Den Heuvellaa with the length of 550 m;	6	5	105,000

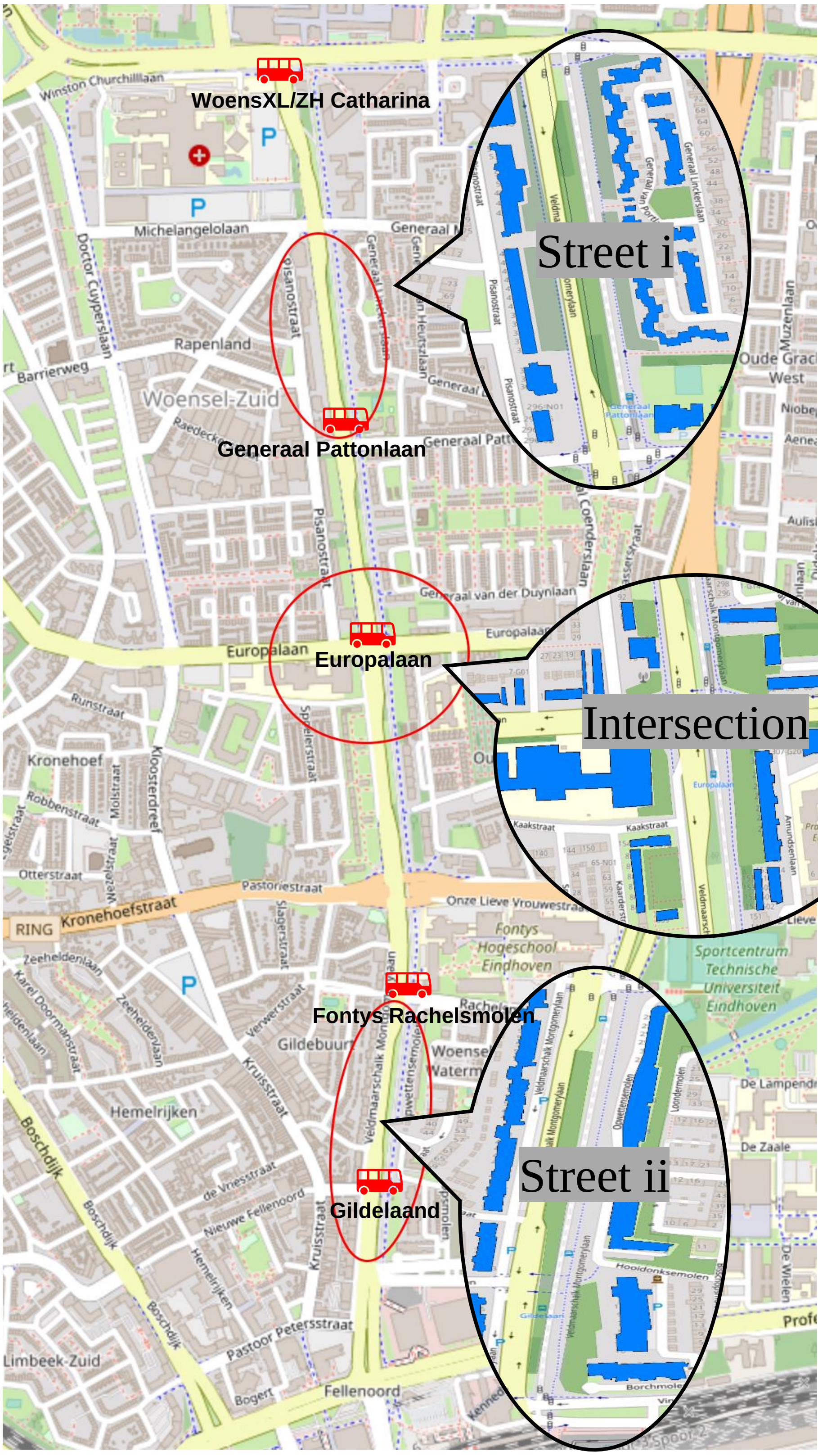

Figure 41 *The selection of modelling domains.*

The georeferenced map of three small areas, retrieved from the OpenStreetMap database (see the callout bubbles in Figure 41), can be used to define the geometries of buildings and vegetations along the roads and locate the emission sources.

5.4.2.2 Modelling Pollutant

Lim, Hughes, & Hellawell (2005) stated that the emission inventory must be compatible with the dispersion model to facilitate data transfer between the two. It is of importance to select proper pollutants for dispersion modelling. As discussed before in the emission modelling, the emission inventory provided by the VERSIT+ database includes carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x), particulate matter 10 micrometres or less (PM_{10}), elemental carbon (EC), ammonia (NH_3), Nitrous oxide (N_2O) and carbon dioxide (CO_2). On the other hand, the GRAL model can simulate on carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), nitrogen dioxide (NO_2), particulate matter 10 micrometres or less (PM_{10}), particulate matter 2.5 micrometres or less ($PM_{2.5}$), ammonia (NH_3), sulphur dioxide (SO_2), hydrocarbon (HC), and etc. The common options based on the two databases are: CO, NO_x, PM_{10}, and NH_3 (see Table 28).

Table 28 *The pollutant options given in both databases.*

Database	Pollutant								
	Common pollutants				Different pollutants				
VERSIT+	CO	NO_x	PM_{10}	NH_3	VOC	EC	N_2O	CO_2	
GRAL	CO	NO_x	PM_{10}	NH_3	NMVOC	HC	NO_2	SO_2	$PM_{2.5}$

These four common pollutants are tested in the domain of the intersection of Europalaan and Veldmaarschalk Montgomerylaan. The daily max concentration of four pollutants are simulated and shown in Figure 42.

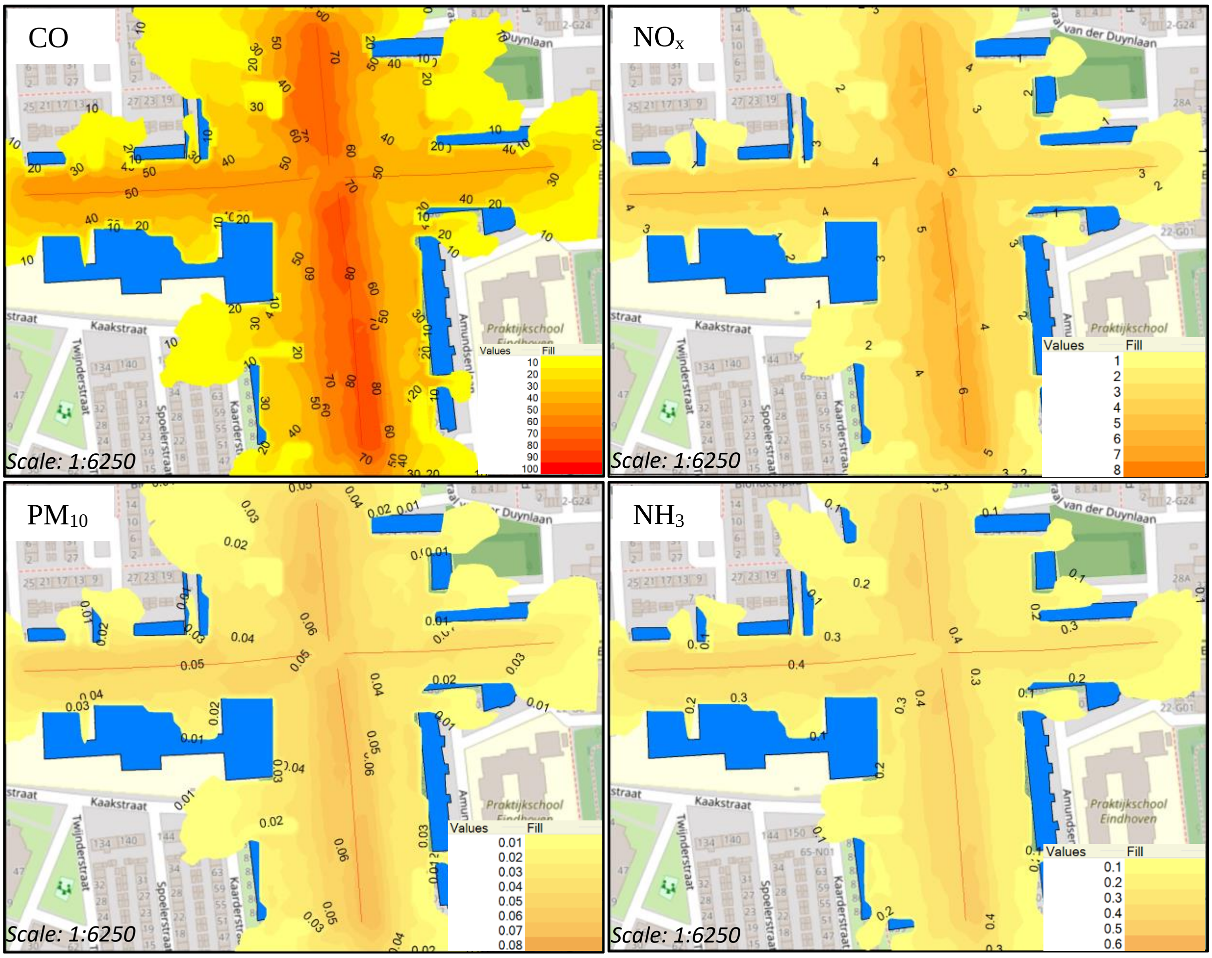

Figure 42 *The simulated daily max concentration (μg/m³) of CO (left top), NO_x (right top), PM_{10} (left bottom) and NH_3 (right bottom) on a typical workday in the intersection modelling domain.*

It can be seen from Figure 42 that the concentration distribution of four pollutants are similar that the most polluted area is located on the Veldmaarschalk Montgomerylaan road which has more traffic flow. The main difference regarding their concentration values can be explained by their emission rates. The reason for this phenomenon may be the factors dominating the dispersal of pollutants in the dispersion modelling remain nearly unchanged. According to European Environment Agency (2016), pollutant dispersal is affected by many factors:

- meteorological conditions (especially wind speed, wind direction and atmospheric stability),
- the emission height (e.g., ground level sources such as road traffic or high-level sources such as tall chimneys),
- local and regional geographical features,
- the source (e.g., fixed point, such as a chimney, or a diffuse number of sources such as cars and solvents).

Venkatram et al., (2007) stressed that the most important factors driving the dispersion of traffic-generated emissions are wind speed and wind direction which are kept the same in all dispersion simulations. It can be concluded that the dispersal situations of pollutants depend mainly on external conditions and the influences (on dilution, separation, accumulation, chemical reactions) brought by the physical and chemical properties of pollutants are neglected in this study.

Among these pollutants, CO typically originates from incomplete combustion of carbon fuels, such as that which occurs in car engines and power plants, while the main sources for other pollutants are mechanical processes (e.g., construction, mineral dust, agriculture) and biological particles (e.g., pollen, bacteria, mould). As a result, based on the common options given by the VERSIT+ and GRAL databases and consideration on pollutant sources, CO is chosen as the indicator to show the air quality of the ambient environment.

5.4.3 Concentration Results

With the definition of modelling domain and pollutant, the emission modelling outputs aiming specific streets for pollutant CO can be retrieved and the dispersion simulations will be performed for CO diffusion situations at different locations on Veldmaarschalk Montgomerylaan.

Table 29 lists basic parameters regarding the emission line sources created in each modelling domain and their basic information. It can be found from the table that in all these modelling domains that the emission rates on north-south segments are higher than the east-west segments, which is consistent with the volume of traffic flows in the traffic simulation.

Table 29 *Results of emission modelling for the chosen domains.*

	Street i[a]				
Emission source	N1	N2	M	S1	S2
Length (m)	51.7	40.7	251.9	42.0	45.8
Width (m)	35	20	15	20	35
Emission rate (kg/h/km)	0.743	0.745	0.746	0.753	0.753
	Intersection[b]				
Emission source	VM-N	VM-S	Eu-E	Eu-W	
Length (m)	96.1	176.4	145.8	200.2	
Width (m)	35	35	25	25	
Emission rate (kg/h/km)	0.801	0.851	0.261	0.361	
	Street ii				
Emission source	N	M	S		
Length (m)	78.2	236.0	221.0		
Width (m)	35	15	20		
Emission rate (kg/h/km)	0.904	0.904	0.996		

[a]N for northern segments, S for southern segments, E for eastern segments, W for western segments, M for middle segments;
[b]VM for Veldmaarschalk Montgomerylaan street, Eu for Europalaan street.

Once all parameters are set, the dispersion simulation can be started, daily max concentrations are calculated for the sum for all source groups in the modelling domain. Notes that daily max means the maximum daily mean concentration, this function uses the diurnal modulation for each source group. Figure 43 shows the daily max concentration distribution in each modelling domain.

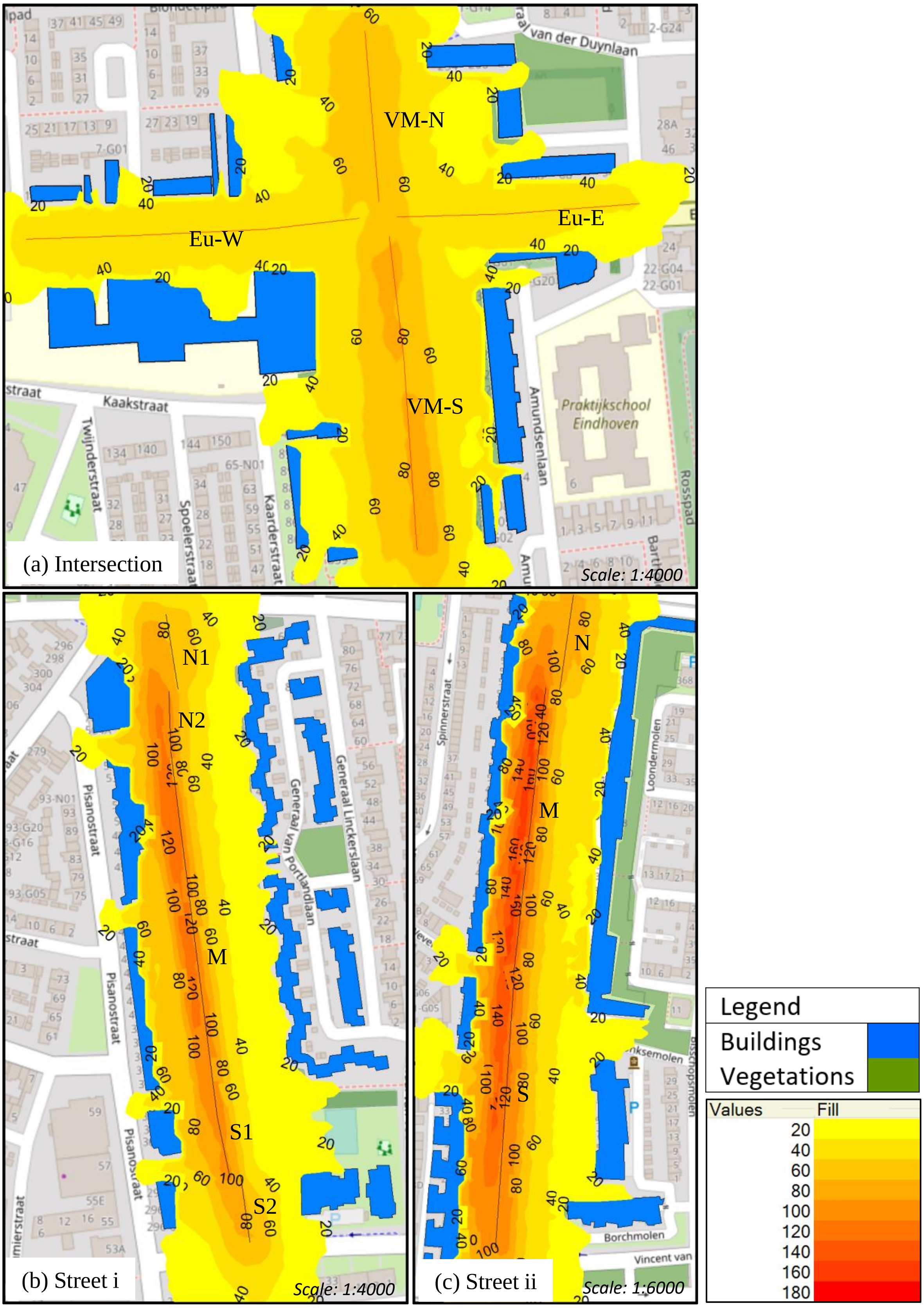

Figure 43 *The daily max concentration (μg/m³) of CO on a typical workday in different modelling domains.*

Figure 43 illustrates the spatial distribution of the CO concentrations by gradient concentration contour lines. Compared with the intersection, two street canyons bear heavier traffic flows and higher CO concentrations can be observed on these road segments. In addition, higher pollutant amount is observed on the west side of street canyons, which is probably due to the mitigation effect caused by the vegetations between the existing passenger car lanes and the bus lane.

Figure 44 depicts the process of extracting external data as well as the internal information to compute the distribution of roadside pollutant concentrations.

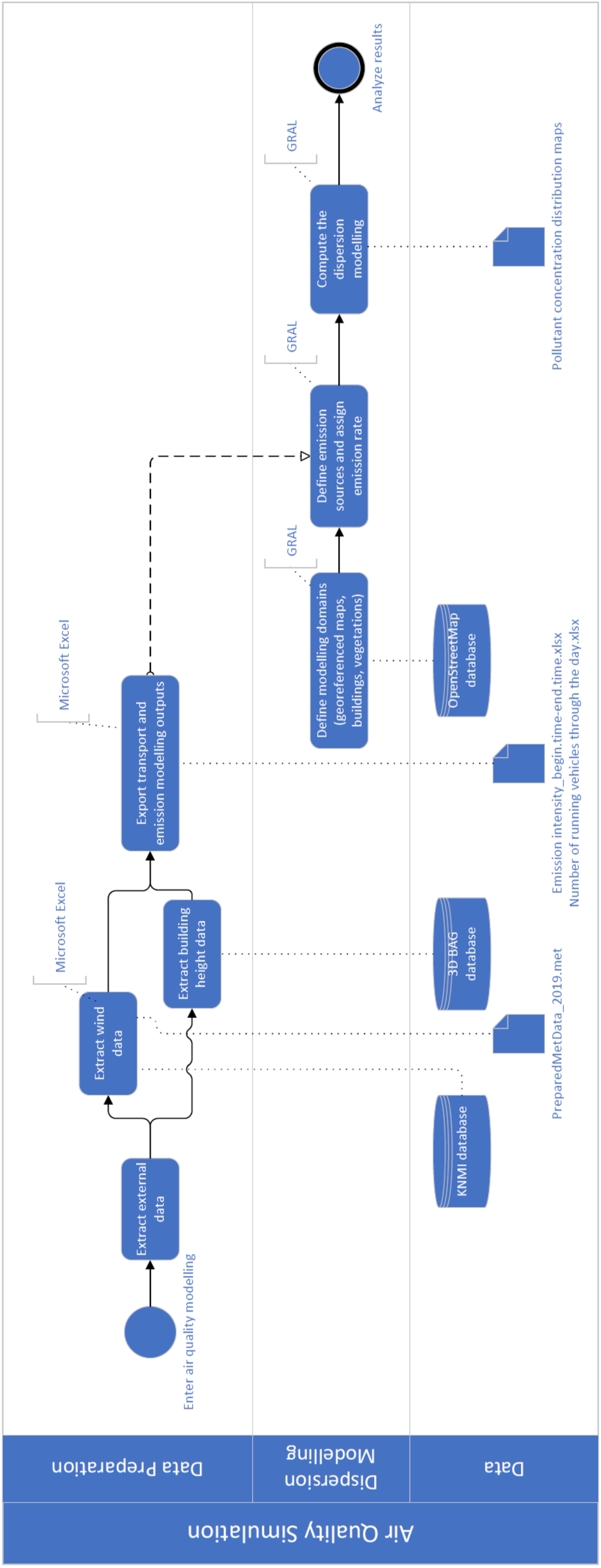

Figure 44 *Detailed process of air quality modelling.*

5.5 FRAMEWORK VALIDATION

According to what we learned from the literature review, the developed integration framework based on the SUMO, VERSIT+, and GRAL models was the first time. For a single model, its ability to appropriately simulate objects and combine with other tools has been discussed a lot by many other studies, for instance, traffic simulations by SUMO (Kamishetty et al., 2020; Rakipi et al., 2018; Stolfi & Alba, 2018); vehicle emission simulation by VERSIT+ (Madireddy et al., 2011; Quaassdorff et al., 2016); dispersion simulation by GRAL (Ling et al., 2020; Oettl & Kuntner, 2012). However, an assessment of the performance of the complete system is appropriate and needed.

Two perspectives, traffic situation and air quality comparison, are planned in this section, which is more on the practical aspects of the model performance about the comparisons between observed (scheduled) and predicted (simulated) values.

5.5.1 Traffic Simulation Validation

To acquire data from the simulation, SUMO offers several kinds of detectors which can be placed in the network, including Instantaneous Induction Loop detectors, E1 detectors, E2 detectors and E3 detectors. These detectors can be used to gather vehicle counts and average speeds over an arbitrary amount of time (Morenz, 2007). The main difference between these detectors is that they can generate different outputs as required. For instance, E1 detectors can measure the number of vehicles that have completely passed the detector within the interval but E2 detectors can further measure the number of vehicles that entered or left the detector in the corresponding interval.

To validate the difference between the simulation traffic flows and real ones, Instantaneous Induction Loop detectors are selected to generate the output of the time when each bus leaves the bus stops. These detectors are placed next to each bus stop along the Veldmaarschalk Montgomerylaan street (see Figure 45).

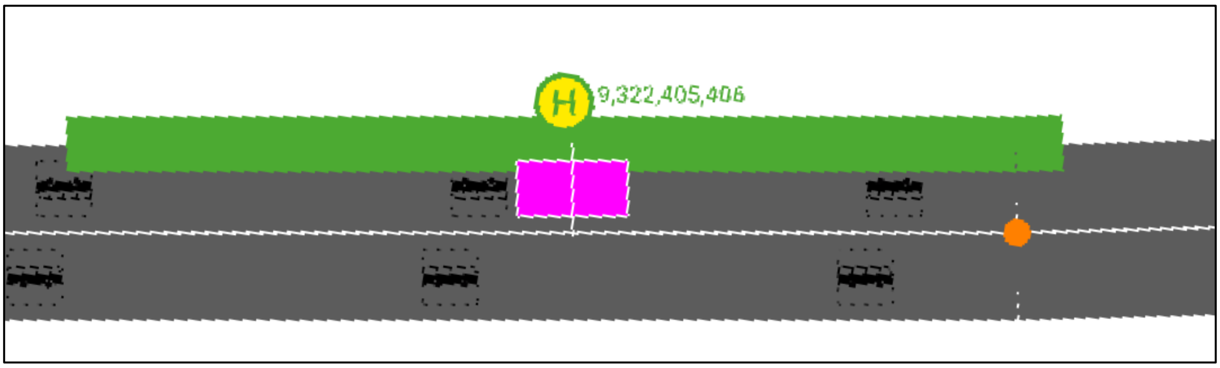

Figure 45 *The instantaneous induction loop detectors.*

As shown in Table 23, the interval periods between inserted buses for most simulated bus lines keep the same through the day, especially for the buses passing through the whole Veldmaarschalk Montgomerylaan street (i.e., line 9, 322, 400, 405 and 406). The characteristic of bus operation, namely stability, happens to be used to validate the traffic simulation, and line 9 buses are chosen as an example.

With the placed detectors, outputs can be then generated from the traffic and part of the generated outputs is listed below. The attribute *time* records the time when each *leave* event occurred (German Aerospace Center (DLR), 2020c) to indicate the departure time of each bus at each bus stop.

```
<instantOut id="instantInductionLoop_9" time="23986.19" state="leave" vehID="line9a_MP.0"
speed="0.65" length="18.00" type="bus" occupancy="36.42"/>
 <instantOut id="instantInductionLoop_7" time="24374.83" state="leave" vehID="line9a_MP.0"
speed="4.00" length="18.00" type="bus" occupancy="27.28"/>
<instantOut id="instantInductionLoop_5" time="24440.10" state="leave" vehID="line9a_MP.0"
speed="1.02" length="18.00" type="bus" occupancy="26.33"/>
<instantOut id="instantInductionLoop_3" time="24532.13" state="leave" vehID="line9a_MP.0"
speed="1.06" length="18.00" type="bus" occupancy="24.96"/>
<instantOut id="instantInductionLoop_1" time="24594.70" state="leave" vehID="line9a_MP.0"
speed="3.87" length="18.00" type="bus" occupancy="28.55"/>
<instantOut id="instantInductionLoop_0" time="24705.00" state="leave" vehID="line9a_MP.0"
speed="2.64" length="18.00" type="bus"/>
```


Combined with the departure time on bus schedules, Figure 46 and Figure 47 plot the deviation time between the simulated time and the scheduled time regarding different bus trips using equation [3-5] explained in section 3.3.1.

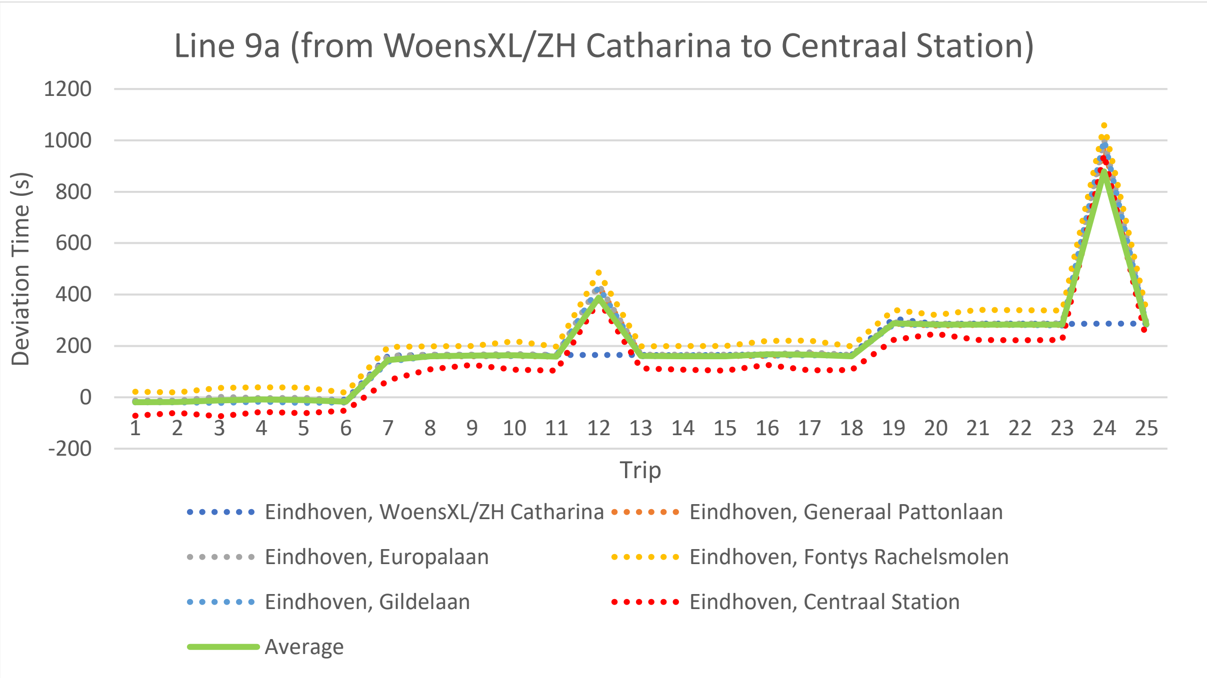

Figure 46 *The deviation time between modelled time and schedule time of line 9a buses.*

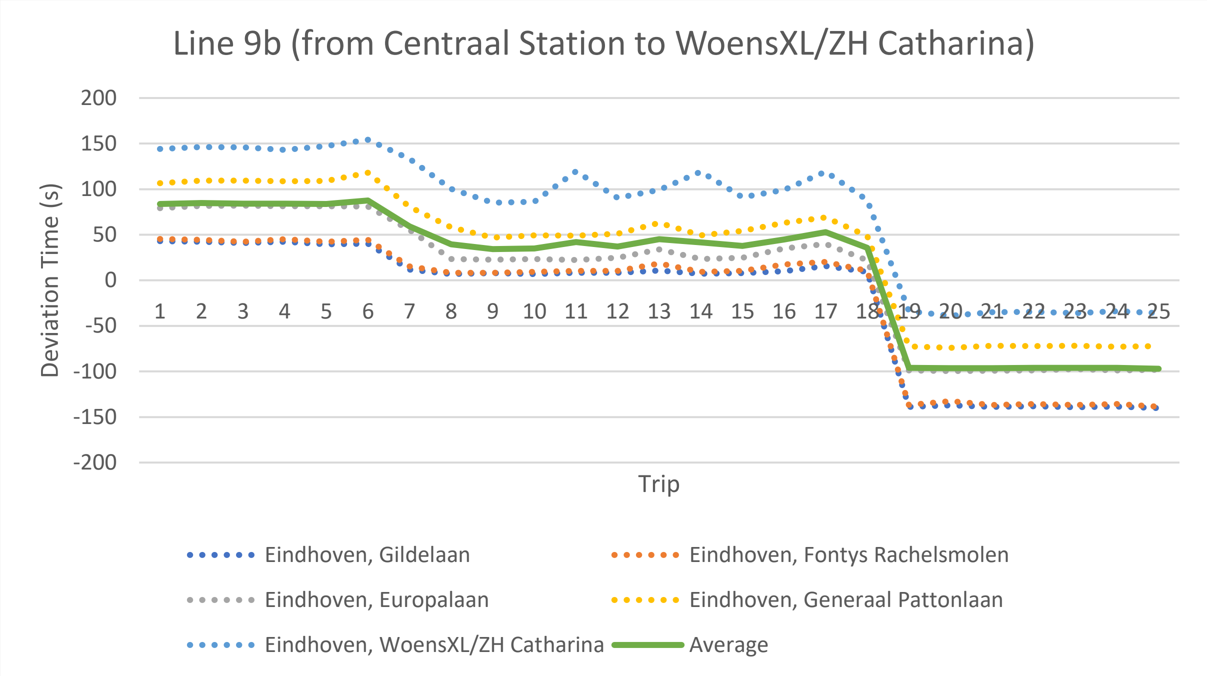

***Figure 47** The deviation time between modelled time and schedule time of line 9b buses.*

As seen from Figure 46, for trips from WoensXL/ZH Catharina to Centraal Station they have experienced two relatively large jumps and two obvious fluctuations. Two jumps happened between trip 6 (schedule time 09:10) and trip 7 (schedule time 09:40), and trip 18 (schedule time 15:10) and trip 19 (schedule time 15:40). The first jump happened before the end of the morning peak, which indicates that the line 9 buses have been affected a lot by other vehicles (passenger cars or other buses) from the northern city to the city centre. Similarly, the second jump happened after the start of the evening peak can be explained by the increasing traffic flows from the city centre to outsides. As for two huge fluctuations seen at trip 12 (schedule time 12:10) and trip 24 (18:10), the reasons behind these delayed trips are the congestions occurred at intersections of the main road, which will be explained later in the scenario analysis chapter by the comparison of different scenarios.

Unlike the trips to the city centre, the trips towards city ring road show a different trend (see Figure 47): one gradual mitigation was seen from trip 6 (scheduled time 9:08) to trip 9 (scheduled time 10:38) and the average deviation time was reduced from around 90 seconds to 35 seconds. Another big fluctuation was seen between trip 18 (schedule time 15:08) and trip 19 (schedule time 15:38) that buses got an average delay of about 50 seconds at the beginning of the evening peak and the dedicated bus lane succeeded in reducing the delay time and even make the simulated bus arrive earlier than the schedule. Because the bus trips of this direction are closer to the departure station (Centraal Station), the deviation time on each bus stop increases with the distance from the departure station.

Both line charts depict the deviation time of line 9 buses through the day and except the mentioned fluctuations, the simulated departure time for different trips keeps almost the same time difference from the planned time, which proves the stability of the bus operation in the traffic simulation.

5.5.2 Air Quality Validation

Another validation is performed by comparing the computed pollutant concentrations with the monitored values by air quality stations. As can be seen from the results (see Table 30), the maximum value of daily CO concentrations in three modelling domains obtained by GRAL (174.73 μg/m^3) and obtained from the air quality website BreezoMeter (2020) (96.21 μg/m^3) are significantly low compared to the maximum daily 8-hour mean[13] (10 mg/m^3) defined by the current European Directive 2008/50/CE (European Parliament and Council, 2015).

***Table 30** The daily max CO concentrations for the modelling domains.*

Daily Max Concentration (µg/m^3)	Street i	Intersection	Street ii
Modelled	141.69	87.91	174.73
Monitored by BreezoMeter[14]	96.21	95.94	95.26
Deviation from monitored	47.3%	-8.4%	83.4%

On the other hand, a significant difference between the model outputs and the air quality measured data was found. The reasons why a gap of up to 80% can be seen between the simulated and observed values can be threefold:

Firstly, as explained before, it is not possible to accurately quantify the vehicle emissions and further pollutant concentrations due to the complex and varied nature of the data and calculations associated with emissions, like uncertainties in activity data (about 30% less daily traffic in Eindhoven area due to COVID-19 restrictions (TomTom, 2020)), the distribution of emission classes and emission factors, uncomplete modulation factors (the modulation factors outside the study period are set to 0), and etc.;

Secondly, it is always the case that government monitoring stations represent the ground truth for air quality reporting, but only at their exact location and there can often be miles and miles without a monitoring station in sight (only three monitoring stations in Eindhoven area, see Figure 48). In order to determine the air quality levels down to city-block level, BreezoMeter uses data from many sources like governmental monitoring stations, satellite measurements, meteorological and traffic data, and data regarding types of land cover (BreezoMeter, 2020). It can be deduced that these monitored values are calculated based on other supplementary data rather than the actual measured values from monitoring stations. The fact that monitored values are quite close also proves this.

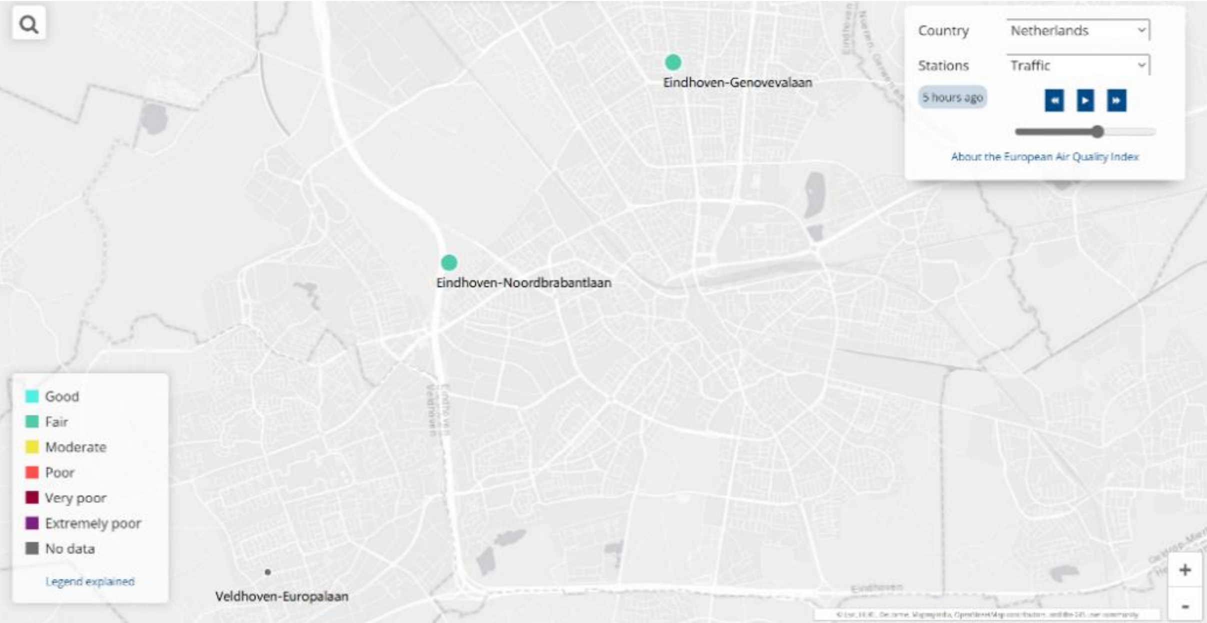

***Figure 48** The meteorological monitoring stations in Eindhoven area (European Environment Agency, 2020).*

[13] The maximum daily 8-hour mean concentration will be selected by examining eight hour running averages, calculated from hourly data and updated each hour. Each eight hour average so calculated will be assigned to the day on which it ends, i.e., the first calculation period for any one day will be the period from 17:00 on the previous day to 01:00 on that day; the last calculation period for any one day will be the period from 16:00 to 24:00 on that day (European Parliament and Council, 2015).

[14] Retrieved on Monday, 27 July 2020 from https://breezometer.com/air-quality-map/city/eindhoven. The original concentration unit is in ppb (parts per billion) which can be converted by 1 ppb = 1.145 µg/m^3 for CO.

Thirdly, the dispersion modelling of this project is computed in the small selected modelling domains which cover only about 0.1 km^2 while similar studies usually simulate an area from a few to dozens of square kilometres (Dias et al., 2014; Hatzopoulou & Miller, 2010; Ježek et al., 2018). A small modelling domain area may bring the fact that the computed concentrations are too concentrated on the only street and unable to spread to low concentration areas.

Despite the simulation deviation, this study is a comparative research which means it focuses on the change in the results brought by different traffic scenarios. Compared to the difference between simulated results and observed results, the variance of different results is more meaningful to the analysis of this study.

5.6 Conclusion

To summarize, this chapter aimed to replicate the current bus lane policy and set up the baseline traffic scenario in the simulation environment, including integrating three different simulation models and validating the framework. The process is described below:

As an important urban arterial in the Eindhoven urban area, the Veldmaarschalk Montgomerylaan street and its neighbouring blocks were chosen as the study domain. The road connects the city centre with the Woensel shopping area and bears a traffic volume of thousands of passenger cars per day. Additionally, there are 7 bus lines and hundreds of bus trips pass through the road every day, which is an appropriate location for experimenting with different traffic scenarios.

Traffic simulation was performed in the second part which includes setting up the road network, simulating the movement of both private traffic and public transport. It is worth noting that it was the difference between the movement of private and public transport vehicles that made the different approaches of generating routes and assigning routes to two types of vehicles.

Based on the methodology and data preparation described in the previous chapters, the third section gave the vehicle emissions simulation results about *street vehicle emission* and the most polluted streets were depicted in the map.

Due to the limit of project time, three small modelling areas along Veldmaarschalk Montgomerylaan street were selected to set the GRAL modelling domain and show the effect of road transport on the ambient air quality from a microscopic perspective.

With the successful adoption of three models, the baseline scenario regarding traffic flow, vehicle emission and air quality situations under the current bus lane policy have been presented in this chapter. In general, the traffic flow would experience a dramatic increase during evening peak hours, which brought the corresponding lowest speed. Although the results generated in vehicle emission and air quality modelling could not show the variation in time series, the computed vehicle emissions per street still indicated that the Veldmaarschalk Montgomerylaan street suffered more vehicle pollution than other roads in the study area. Besides, the generated distribution of pollutant concentration in the selected modelling domain implied that the emission in the intersection area was lighter than that of the two street canyons and the closer to the city centre, the more polluted the streets would be.

In addition, to validate the framework the simulation results were compared with actual situations. Although the results of the traffic modelling and air quality modelling were not perfectly consistent with reality, the validation still proved the stability of the integration framework.

In conclusion, in the scope of this work the application of the integrated system for quantifying vehicle emissions from road transport under baseline scenario and its impact on the ambient air quality was presented.

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Chapter 6 Scenario Analysis

In chapter 4 and chapter 5, the established methodology was applied to set up the baseline scenario. Based on the integrated framework, the purpose of this chapter is to investigate several alternative traffic scenarios that are trying to find a balance between private traffic and public transport. Section 6.1 introduces five scenario options as well as two supporting strategies behind them. The first two scenarios focus on the dynamic bus lane policy which involves the separation of private and public transport. In addition to this, the other three scenarios are set up in combination with dynamic bus lane strategy and adaptive traffic light system to study the impact of introducing modern signalized intersections on traffic flow. After establishing reasonable simulation scenarios, the qualitative and quantitative analysis will be given from two perspectives in section 6.2.

- 6.1 Introduction of Traffic Management Schemas
- 6.2 Simulation Results
- 6.3 Conclusion

6.1 Introduction of Traffic Management Schemas

This section aims to design five possible scenarios based on two strategies: dynamic bus lane and adaptive traffic light. In short, the dynamic bus lane strategy influences the route choice of private traffic by determining the openness of bus lanes according to different periods (classified based on traffic volumes). The adaptive traffic light, on the other hand, has an impact on both passenger cars and buses when they are about to pass through intersections equipped with reprogrammed traffic lights.

These scenarios are implemented either by adjusting control parameters in the framework or using control interface from the SUMO packages. The details of setting up four scenarios will be illustrated below.

6.1.1 Dynamic Bus Lane

The first two scenarios are set up based on the policy named dynamic bus lane (DBL). As stated by Anderson & Geroliminis (2020), in most fixed dedicated bus lane cases, complete separation of buses and cars may not be necessary, because when the frequency of buses is not high, buses often underutilize the road space. Mixed traffic operation can work reasonably well as long as the inflow of cars (to bus lanes) is restricted to maintain bus performance.

The main idea of this strategy is that the period of activating the bus lane is not fixed but dynamic. In other words, the general traffic can use the bus lane when the bus lane is not activated. To be specific, the implementation could be allowing the private traffic to use bus lanes during certain periods of a day. In this way, road capacity can be better utilized, and congestions can significantly be decreased on other lanes when the bus lanes are open to the general traffic although the flow of vehicles on bus lanes can increase by a considerable amount. In the case of activation of bus-only lanes, it is prohibited for the private traffic to use these dedicated lanes to make way for buses.

As seen from the adopted methodology for simulating the private traffic (see details in section 5.2.2), routes of passenger cars have been computed and assigned to them before the traffic simulation. Therefore, it is not possible for drivers to change their routes in real time according to the opening of the bus lane during the traffic simulation, in other words, the car driver has to plan the route to the destination before the trip begins, which is common for most drivers who do not rely on navigation software. Considering this shortcoming, it is more feasible to keep the current road network and determine the openness of bus lanes according to a fixed time schedule.

Thus the DBL strategy is achieved by defining the allowed vehicle type for the original bus lanes in two separate network files: one used the original network model while the other one cancelled the establishment of the bus lane and made it open for all vehicles (see examples in Figure 49). Since the trips of private cars are aggregated according to periods (see section 5.2.2.1), when they are computed and converted into routes based on different network models, the dynamic opening of the bus lane in different periods can be realized. It is noted that the total trip number of vehicles and the corresponding departure time based on two network files are kept the same.

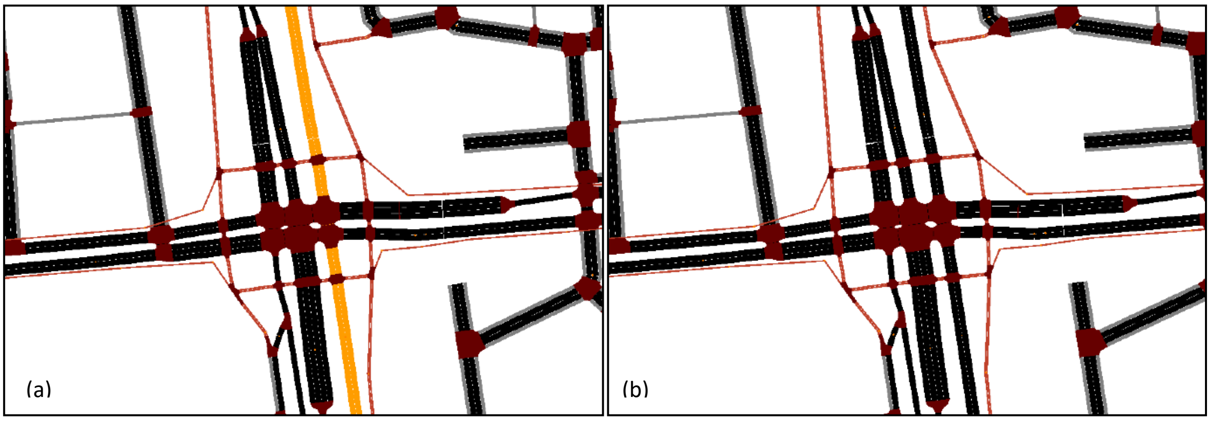


Figure 49 *The network models at the intersection of Europalaan and Veldmaarschalk Montgomerylaan for (a) with the fixed bus lane (in orange) and (b) without the fixed bus lane.*

By implementing scenarios based on the DBL strategy, it is expected to discuss the necessity of completely separating buses and cars, to make better use of road infrastructure capacity in the future.

Scenario 1: Off-peak Bus Lane

With the road network unchanged, scenario 1 describes the plan to activate the bus lane only in the off-peak hours (09:31-15:29) during the day. The general traffic is able to use the bus lane during peak hours, as shown in Table 31. There were no major changes to the bus routes that they still follow the current routes and time schedules as defined in the data preparation chapter.

Scenario 2: Peak Bus Lane

Contrary to scenario 1, the bus lane is activated during peak hours (06:30-09:30; 15:30-19:00) in this scenario and passenger cars are allowed to travel bus lanes during off-peak hours.

Table 31 *The settings regarding the bus lane of baseline scenario, scenario 1 & scenario 2.*

Scenario	Bus lane		
	Morning peak hours (06:30-09:30)	Daytime off-peak hours (09:31-15:29)	Evening peak hours (15:30-19:00)
Baseline	Closed	Closed	Closed
Scenario 1	Open	Closed	Open
Scenario 2	Closed	Open	Closed

In a word, both scenarios do not require the change on the network model but only modify the allowed vehicle type of certain lanes to accommodate the DBL strategy. Additionally, from the perspective of public transport, infrastructures related to bus operation are kept as the current setting that no extra adjustments are required from their side.

6.1.2 Adaptive Traffic Light

In addition to the above alternatives designed based on the dynamic bus lane strategy, the traffic light is also an important traffic control tool to influence the priority of public transport. In most cases, similar to the built-up methodology in chapter 4, the traffic simulation in SUMO would assume fixed programs for the traffic lights controlling the junctions in the default setting (Gudwin, 2016), i.e. the behaviour of these traffic lights are defined automatically by SUMO and all the lights run with fixed controllers.

However, SUMO allows external programs to interact with the simulation, being able to extract information from each involved object (vehicles, people, traffic lights, inductive loops, and etc.) in the simulation. The interaction with external programs is made available using TraCI (Traffic Control Interface) which gives access to a running traffic simulation and allows to retrieve values of simulated objects and to manipulate their behaviour "on-line" (German Aerospace Center (DLR), 2020f).

Briefly speaking, TraCI uses a Transmission Control Protocol (TCP) based client/server architecture to provide access to SUMO which acts as a server in this structure, as shown in Figure 50. The client application sends commands to SUMO to control the simulation run, to influence single object's behaviour or to ask for environmental details. SUMO answers with a *Status*-response to each command and additional results that depend on the given command.

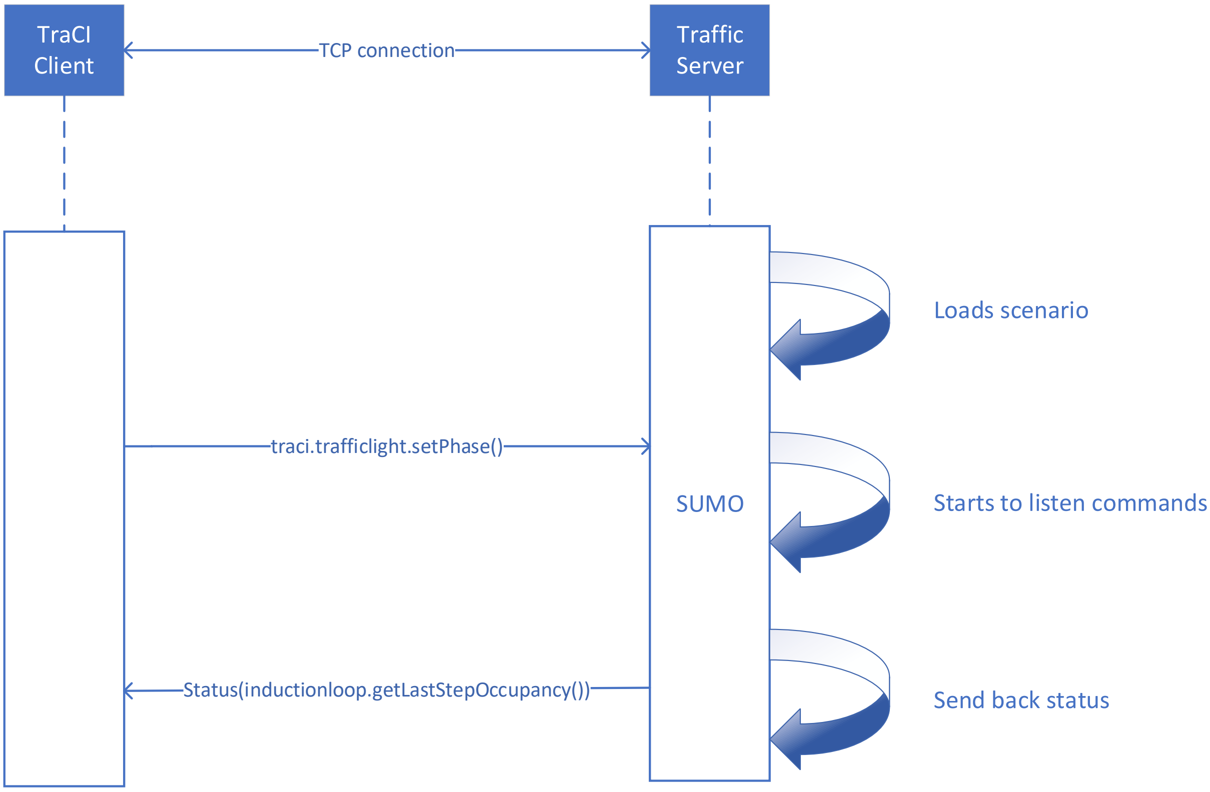


Figure 50 *System architecture and an operation example of the command-response TraCI connection between client and SUMO adapted from German Aerospace Center (DLR) (2020).*

By this technique for interlinking road traffic simulators and external control commands, it permits the user to control the behaviour of objects during the simulation, thereby making it possible to implement the strategy of adaptive traffic light. The main steps of setting up the adaptive traffic light strategy are described below:

First of all, it has to be clarified that adaptive traffic lights will be employed before signalized intersections in order to ensure that major traffic flows (including buses) running in the north-south direction can rapidly pass through the intersections than the baseline scenario. To achieve this, the design idea is shown in Figure 50 that the information will be queried at every simulation step by detectors that are put on the road before the intersection and once the traffic situation is met with certain conditions, then TraCI will set the traffic light status accordingly for the next simulation step to achieve the desired effect.

To extract the needed information from the traffic simulation, detectors are selected in the second step. As discussed in section 5.5, SUMO provides four kinds of detectors which can be installed in a network:

- Induction loop detectors (E1 Detectors);
- Lane area detectors (E2 Detectors);
- Multi-entry-exit detectors (E3 Detectors);
- Instantaneous induction loop detectors;

Considering the type of information that can be generated by different detectors, E1 detector that can compute the values by determining the times the vehicle enters and leaves the detector is enough to implement the adaptive traffic light system.

Lastly, as one of the most complex classes provided by TraCI for interacting the SUMO simulation (Gudwin, 2016), the operation on *TrafficLight* is the most difficult part of using TraCI. Usually when a road map is imported from OSM or other tools, the NETCONVERT tool generates a set of traffic lights phases which is feasible and usable in the simulation, without creating crossing flows which might cause accidents, but the automatically generated program would not always be the best choice for all traffic lights. Especially for traffic lights, the controller provided by TraCI can reprogram the state, phase, phase duration, program, and more, with the *TrafficLight* class (German Aerospace Center (DLR), 2019j). The phase of the traffic light is selected here to be altered once the conditions are met.

Using the system architecture shown in Figure 50, the client will send a TraCI command (*trafficlight.SetPhase*) to SUMO and requires SUMO to answer with the status of certain roads by TraCI command (*Inductionloop.getLastStepOccupancy*) which returns the percentage of the time the detector was occupied by a vehicle. This information can be queried at each simulation step and can be used by the control algorithms in order to decide the traffic lights state for the next simulation step. This TraCI connection corresponds to the system which makes vehicles from the major traffic flow direction (north-south direction) have the priority to pass through the intersection. Only when the detectors set on the east-west road are occupied by a vehicle for a certain percentage of time (that is, there is a waiting queue before the intersection), the traffic lights will give a proceed signal to the vehicles in the east-west direction. Otherwise, during the most time of the simulation period, the traffic light is kept as green for north-south vehicles.

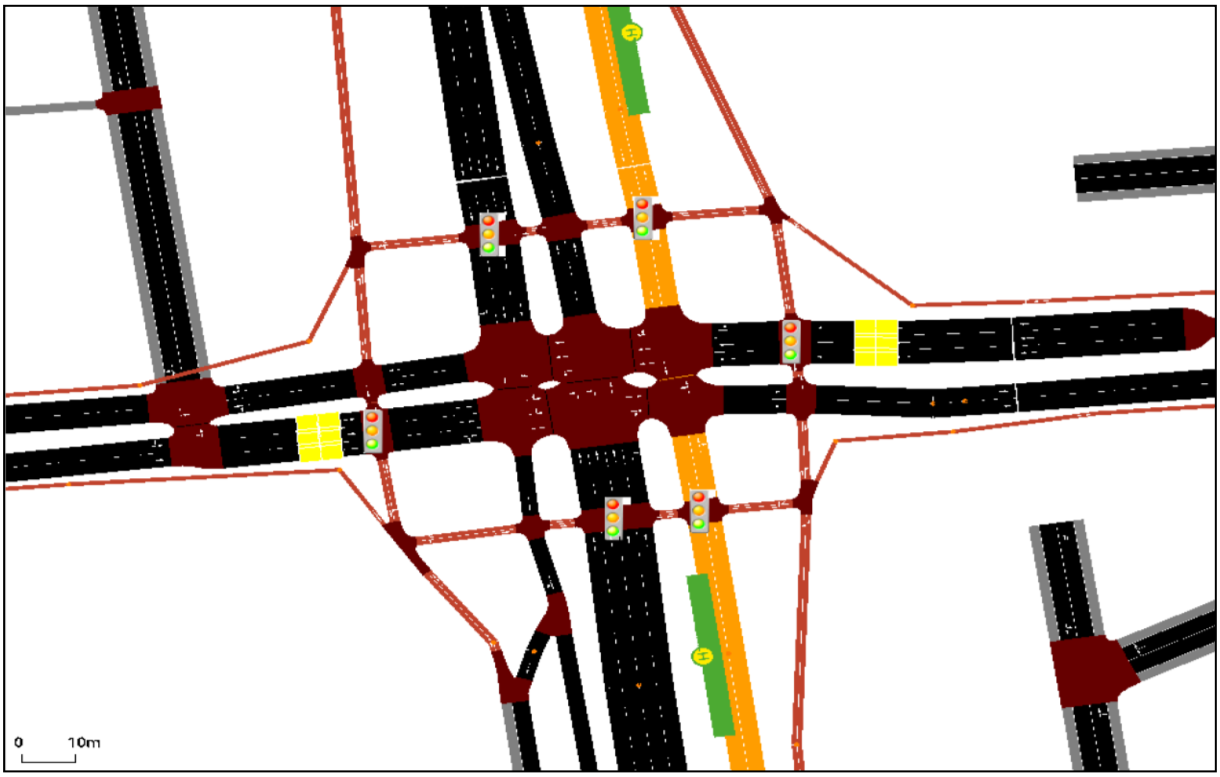


Figure 51 *The intersection of Europalaan and Veldmaarschalk Montgomerylaan equipped with E1 detectors (yellow boxes).*

To include induction loops in the simulation, the definition of all induction loop detectors must be defined in an additional file (see Appendix C.1 *code of detector_ATL.add.xml*) and included in the SUMO configuration file. An example of the placement of E1 detector is shown in Figure 51.

In the following three scenarios, the normal signalized intersections are upgraded and equipped with detectors that can recognize the congestions and feed it back to the traffic lights so that the major traffic flow including buses can rapidly pass through intersections. The main goal of this system is controlling the traffic lights phases at several intersections on Veldmaarschalk Montgomerylaan, so they can mitigate the negative effects brought by additional vehicles attracted by the dynamic bus lane strategy. Thus, the adaptive traffic light strategy will be combined with the DBL strategy to investigate the synergy with the previous policy.

The ATL system will not be employed at all intersections but only three busiest intersections on Veldmaarschalk Montgomerylaan as shown in Figure 52.

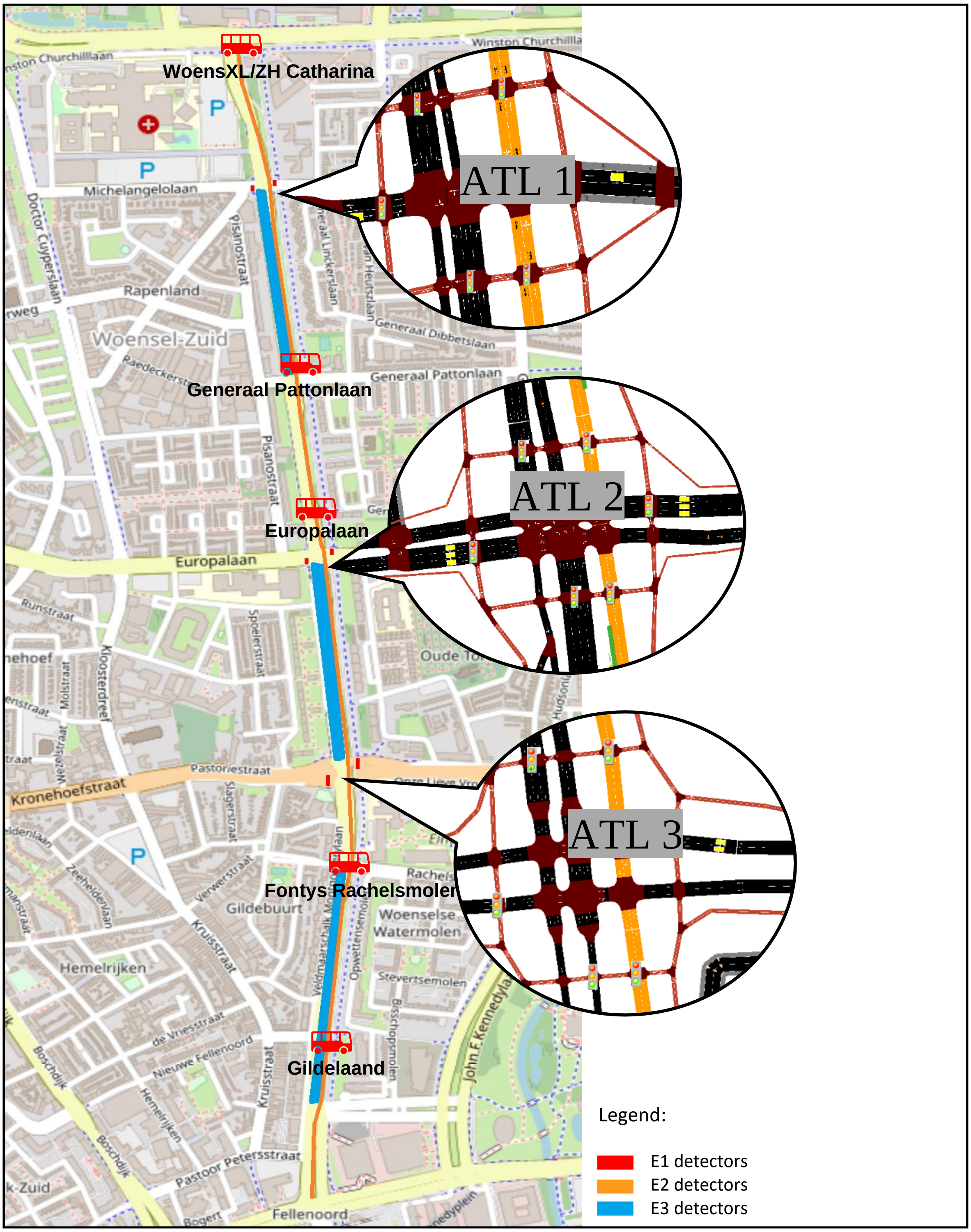


***Figure 52** The placement of detectors and the location of the ATL-equipped intersections on Veldmaarschalk Montgomerylaan.*

As described above, the ATL system cannot be set up only by the traffic simulator, and the script of the TraCI controller is also needed (see Appendix C.2 *code of runner.py*). This script gives the following functions at each simulation step: identification of traffic flow, movement of vehicles before ATL intersections, evaluation of the occupancy rate of detectors, change of traffic light phases if necessary.

With the use of the TraCI controller, it is possible to adapt traffic light phases for better use of road capacity. Figure 53 gives an example that how the ATL system changes the traffic signal phases.

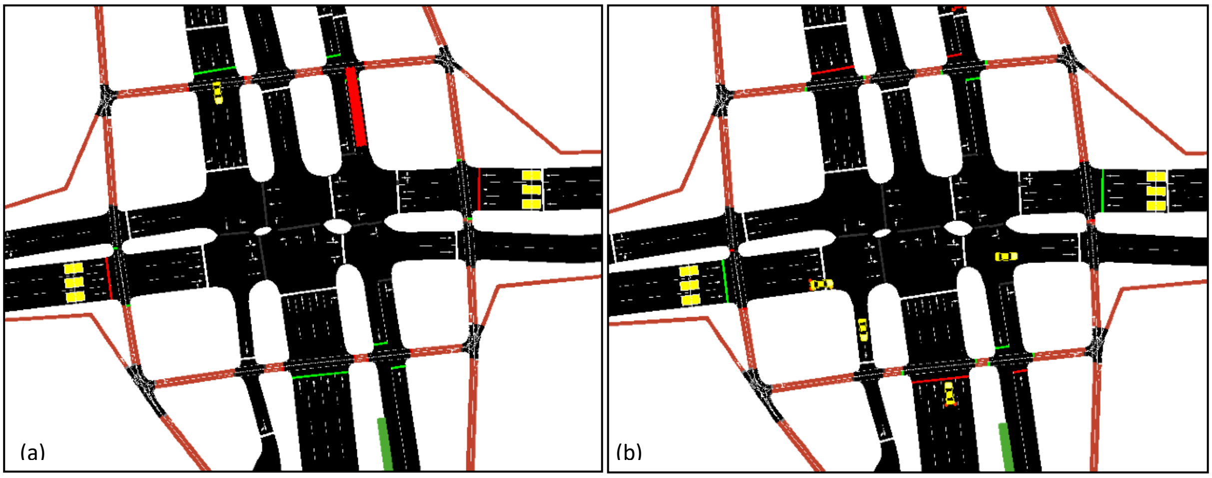


***Figure 53** An ATL system example at the intersection of Europalaan and Veldmaarschalk Montgomerylaan for (a) signal state of allowing vehicles from north or south and (b) signal state of allowing vehicles from west or east.*

Table 32 lists the threshold values of the ATL system at each intersection and the corresponding results. Normally. the higher the value, the stricter the condition and therefore the less likely the traffic light to change its phase. In order to set reasonable values, several rounds of simulation were performed based on the baseline scenario to test the feasibility of the ATL system with a 10% gradient (the simulated traffic volume and average vehicle speed results of the tests can be found in Appendix C.3).

As shown in the table that the value at the intersection of Europalaan and Veldmaarschalk Montgomerylaan (ATL 2) is higher than the other two intersections. This is because there are buses (line 2 and line 3) driving in the east-west lanes of the other two intersections. In order to avoid them being blocked in front of the intersections, the judgment values of these two intersections are set to be lower. On the intersection of ATL 2, buses only run in the north-south direction.

***Table 32** The conditions and results set for ATL systems.*

Location	Condition	Result[a]
ATL 1	traci.inductionloop.getLastStepOccupancy("e1Detector_ATL1_0") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL1_1") > 20%	traci.trafficlight.setPhase("TL1_0", 0[b]) traci.trafficlight.setPhase("TL1_1", 0) traci.trafficlight.setPhase("TL1_2", 0) traci.trafficlight.setPhase("TL1_3", 0) traci.trafficlight.setPhase("TL1_4", 2[c]) traci.trafficlight.setPhase("TL1_5", 2)
ATL 2	traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_0") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_1") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_2") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_3") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_4") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL2_5") > 40%	traci.trafficlight.setPhase("TL2_0", 0) traci.trafficlight.setPhase("TL2_1", 0) traci.trafficlight.setPhase("TL2_2", 0) traci.trafficlight.setPhase("TL2_3", 0) traci.trafficlight.setPhase("TL2_4", 2) traci.trafficlight.setPhase("TL2_5", 2)
ATL 3	traci.inductionloop.getLastStepOccupancy("e1Detector_ATL3_0") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL3_0") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL3_0") or traci.inductionloop.getLastStepOccupancy("e1Detector_ATL3_0") > 20%	traci.trafficlight.setPhase("TL3_0", 0) traci.trafficlight.setPhase("TL3_1", 0) traci.trafficlight.setPhase("TL3_2", 0) traci.trafficlight.setPhase("TL3_3", 0) traci.trafficlight.setPhase("TL3_4", 2) traci.trafficlight.setPhase("TL3_5", 2)

[a]TLs end with 1,2,3,4 represent the traffic lights controlling the vehicles in the north-south direction and TLs end with 5&6 are traffic lights on the east-west roads;
[b]Phase 0 is used to represent phase red here. It is not always the case in the real simulation but used for the sake of simplicity here;
[c]Phase 2 is used to represent phase green here.

With the successful setup of the adaptive traffic light system, three scenarios can be then defined:

Scenario 3: Fixed Bus Lane with Adaptive Traffic Light

The third scenario is set up based on the baseline scenario, which includes the current fixed bus lane strategy and the ATL system at three intersections.

Scenario 4: Off-peak Bus Lane with Adaptive Traffic Light

The next two scenarios are the combination of the dynamic bus lane strategy and the adaptive traffic light system. Scenario 4, based on scenario 1, is going to measure the synergy of off-peak bus lane situation with the ATL system.

Scenario 5: Peak Bus Lane with Adaptive Traffic Light

Similar to scenario 4, scenario 5 is created on the basis of scenario 2 with the additional ATL system.

The main idea of these three scenarios is that the phases of the traffic light on certain intersections are modified automatically to create a smooth traffic situation for the major traffic flow direction.

In summary, scenario 3 is set up to examine the impact of ATL system while both scenario 4 and scenario 5 combine the previous scenarios to investigate the synergy of the DBL strategy and the ATL system (see the summarized situations in Table 33).

Table 33 *The basic situation of strategies used in each scenario.*

Scenario	Bus lane			Adaptive traffic light
	Morning peak hours (06:30-09:30)	Daytime off-peak hours (09:31-15:29)	Evening peak hours (15:30-19:00)	
Baseline	Closed	Closed	Closed	No
Scenario 1	Open	Closed	Open	No
Scenario 2	Closed	Open	Closed	No
Scenario 3	Closed	Closed	Closed	Yes
Scenario 4	Open	Closed	Open	Yes
Scenario 5	Closed	Open	Closed	Yes

6.2 Simulation Results

In this section, the proposed integrated framework including the simulation tools, SUMO, VERSIT+, and GRAL are jointly used to examine these traffic management schemes, and the impacts of the scenarios are compared regarding the traffic situations and corresponding ambient air quality. Following this structure, this section is divided into two parts: comparison of traffic situations and comparison of air quality.

In order to fully evaluate the advantages and disadvantages of different scenarios, the following indices are used to evaluate the different scenarios: traffic volume, velocity, travel time (delay) and pollutant concentrations (see Table 34).

***Table 34** Indices for evaluating scenarios.*

Target of evaluation	Range for evaluation	Indices
All traffic	Whole simulation network	Running vehicle number (veh) Average travel speed (m/s)
General traffic[15]	Veldmaarschalk Montgomerylaan	Traffic volume (veh/h) Average speed (m/s) Mean time loss (s)
	Normal lane on Veldmaarschalk Montgomerylaan	Traffic volume (veh/h) Average speed (m/s) Mean time loss (s)
Bus	Bus lane on Veldmaarschalk Montgomerylaan	Traffic volume (veh/h) Average speed (m/s) Average deviation time for line 9 buses (s)
Air quality	Intersection	CO Daily max concentration (μg/m^3) CO Daily mean concentration (μg/m^3)
	Street i[16]	CO Daily max concentration (μg/m^3) CO Daily mean concentration (μg/m^3)
	Street ii	CO Daily max concentration (μg/m^3) CO Daily mean concentration (μg/m^3)

6.2.1 Traffic Situation Comparison

Generally speaking, the most obvious independent variable among these scenarios is the openness of the bus lane, which will inevitably influence the route choice about using these extra lanes, and therefore the traffic situations are expected to be varied than the baseline scenario. In this section, selected indices will be measured and discussed to evaluate various established scenarios.

6.2.1.1 For the Whole Network

First of all, the changes in the traffic situations of the whole simulation network are discussed. Before that, the simplified system dynamic loops in Figure 54 illustrate the reasons for adopting the two strategies (DBL and ATL).

[15] General traffic refers to passenger cars in this study.
[16] The modelling domains of street i and street ii are described in section 5.4.2.1.

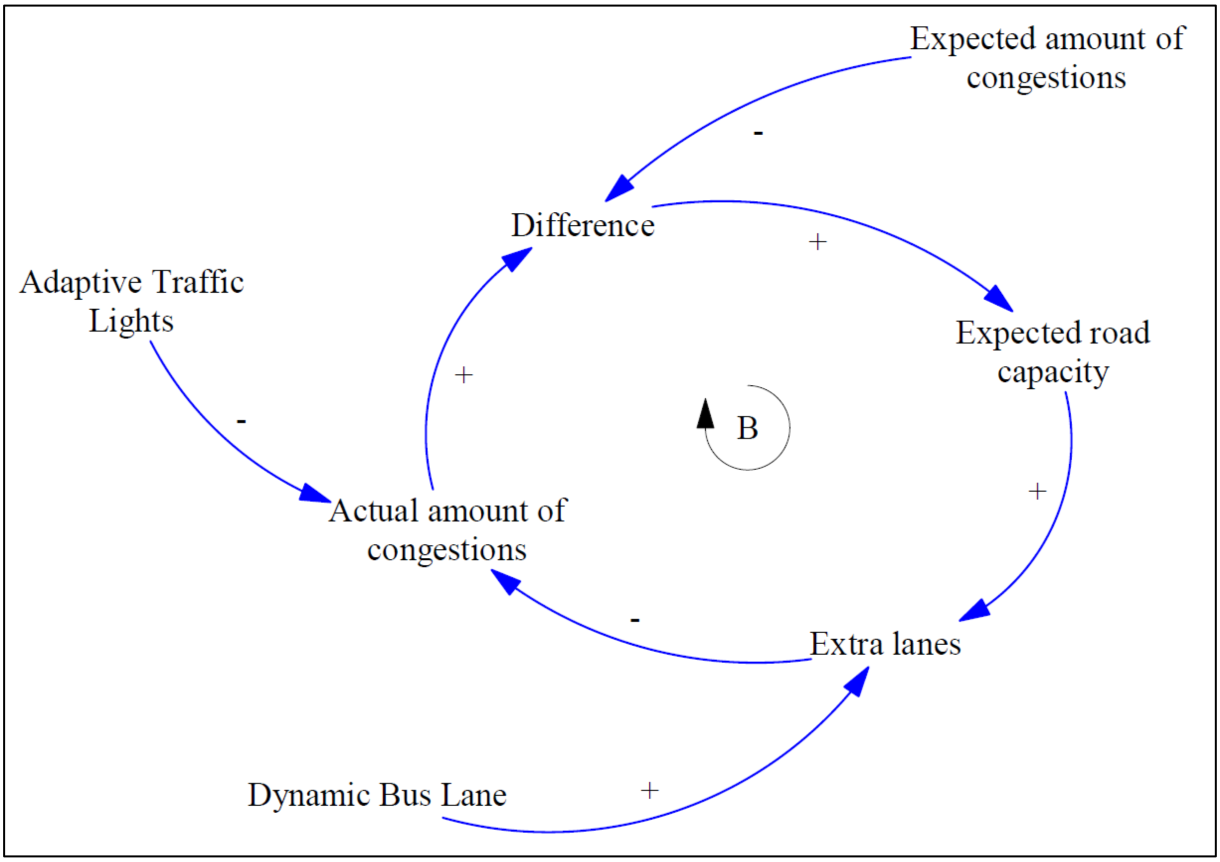


Figure 54 *Simplified system dynamic loops of the adopted strategies (+ for positive feedback; - for negative feedback; B for balancing loops).*

Basically, the dynamic bus lane strategy is designed to expand the *road capacity* for private traffic by allowing them to enter the *extra lane* (bus lane) during a certain period of time if the operation of buses does not deteriorate a lot. The adaptive traffic light system, on the other hand, is proposed to be able to reduce the time for vehicles to pass through the main road and therefore the amount of traffic congestions. By implementing these plans, it is possible to narrow the gap between the *actual amount of congestions* and the *expected amount of congestions*.

As the overall traffic situations are shown in Figure 55 and Figure 56, a significant impact brought by two traffic management schemas can be observed in terms of traffic flows and average speed on the whole network. During the daytime, the performances of different scenarios were almost the same regarding the traffic flow in the whole network. For the average speed, small drops were seen at 7:00, 8:00, 9:30, 11:15 for most scenarios and the most congested time happened after entering the evening peak at around 18:00.

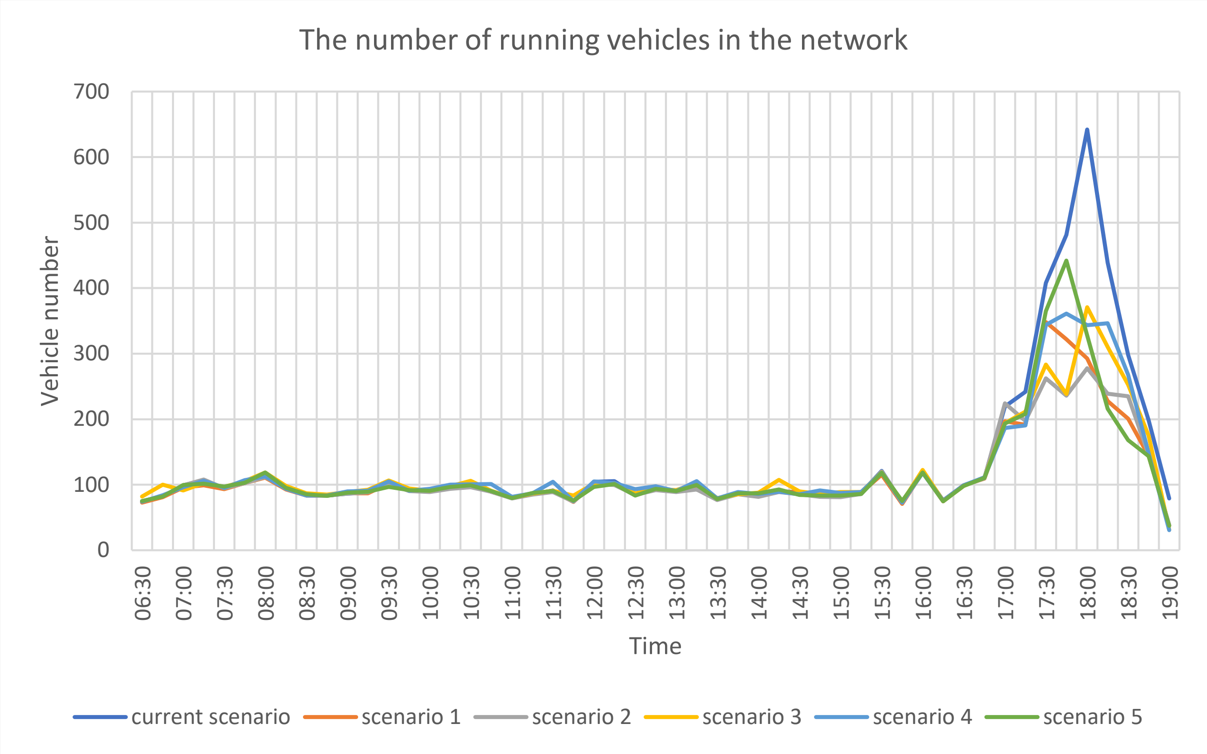


***Figure 55** The number of running vehicles in the network under six scenarios.*

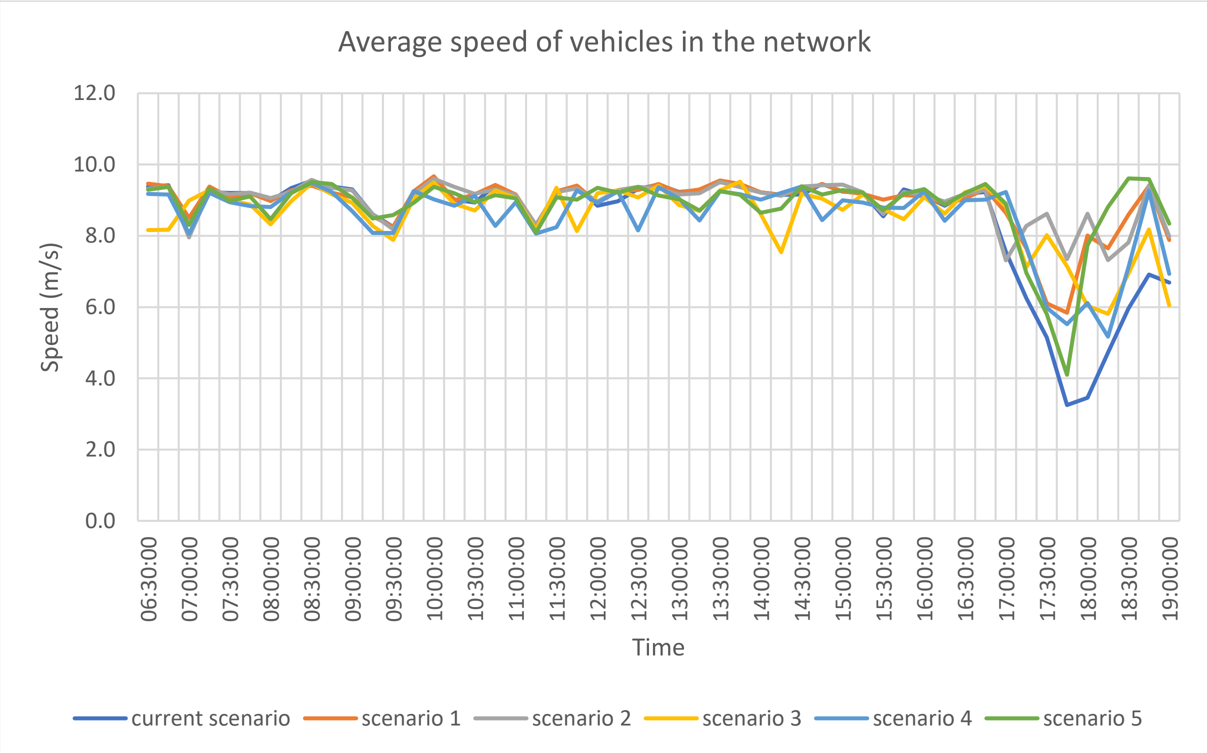


***Figure 56** The average speed of vehicles in the network under six scenarios.*

However, the effects of these two strategies were different. As for evening peak hours, the peak bus lane plan (scenario 2) brought the best mitigation effect on the traffic congestions (with some fluctuations) that the evening peak value had been reduced by 56.7% compared to the baseline scenario and the average speed was kept to oscillate around 8 m/s. The off-peak bus lane plan (scenario 1) alleviated the traffic jams as well but the evening peak had been shifted from 18:00 to 17:45. Compared to the dynamic bus lane strategy, the ATL system (scenario 3) performed slightly different, i.e., the average speed of the vehicles in the whole network became more unstable and the traffic flow peak was 57.8% of the current peak value. In general, the peak traffic flow during the evening peak hours decreased and the average speed performed better in all schemas.

The setup of scenario 4 and scenario 5 was used to investigate the synergy of the DBL plan and ATL system. Scenario 1 and scenario 4 (scenario 1 with the ATL system) acted quite similarly that both peaks were barely higher the 50% (54.2% and 56.2% respectively) of the current peak and shifted from 18:00 to 17:45. The only difference is that the peak was held for a longer period for scenario 4 while the peak had dropped immediately after reaching the peak in scenario 1. With the ATL system, the traffic flow in scenario 5 varied a lot compared to scenario 2 that the peak value was even higher with the ATL system and the peak has also occurred earlier. In the meanwhile, the corresponding average speed fluctuates accordingly to the number of running vehicles, i.e., the higher the number the lower the average speed of all vehicles in the network.

In conclusion, the opening time of bus lanes for general traffic does have a significant impact on traffic situations. As for the reason why the scenarios when the bus lanes are closed to general traffic during rush hours can perform better than opening bus lanes will be explained in the next section with the traffic flow on separated lanes of Veldmaarschalk Montgomerylaan road. Simultaneously, in terms of the traffic flow and average speed of the whole network, combined with different bus lane opening strategies, the impact of the adaptive traffic light system on the traffic situation is also mixed.

6.2.1.2 For Veldmaarschalk Montgomerylaan

This section is designed to measure how the traffic situations only on Veldmaarschalk Montgomerylaan vary under different conditions. The measurement is conducted separately for different vehicle types, i.e., passenger cars and buses.

Before describing the performances of designed scenarios, the selection and the placement of measurement detectors are necessary to be explained. To match the evaluation range and indices, two types of detectors, namely, lane area detectors (E2 Detectors) and multi-entry-exit detectors (E3 Detectors), were applied along the main road (see Figure 52) and the interval time (the aggregation period during which the values collected by the detector shall be summed up) of both detectors are defined as 1,800 seconds as half an hour (the scripts of these detectors can be found in Annex *detector_measurement.add.xml*).

Passenger cars

The multi-entry-exit detectors are planned for passenger cars and three representative road segments (see three blue road segments in Figure 52) are chosen. A multi-entry-exit detector can include a set of entry- and a set of exit-cross-sections and capture measurement values of the passed vehicles in the interval. The values captured from three road segments will be aggregated to show the average traffic situations of the whole road. It is noted that due to the implementation of the dynamic bus lane policy, in the designed scenarios, the dedicated bus lane was also used by private traffic. Therefore, their operation performances were also recorded by E3 detectors and aggregated with the values measured from normal lanes. In other words, only when there were passenger cars running on the bus lanes, their data will be added to the average traffic values. Otherwise, only the values from normal lanes will be used to compute the average traffic situations for the whole road. Table 35 lists the measured indices and their explanations.

***Table 35** Descriptions on the private traffic indices.*

Target of evaluation	Indices	Description
General traffic	Traffic volume (veh/h)	The number of vehicles that have left the area during the interval.
	Average speed (m/s)	The mean speed of vehicles that have passed the area. Averaged over the interval and vehicles.
	Mean time loss (s)	The average time loss for all vehicles that have passed the area.

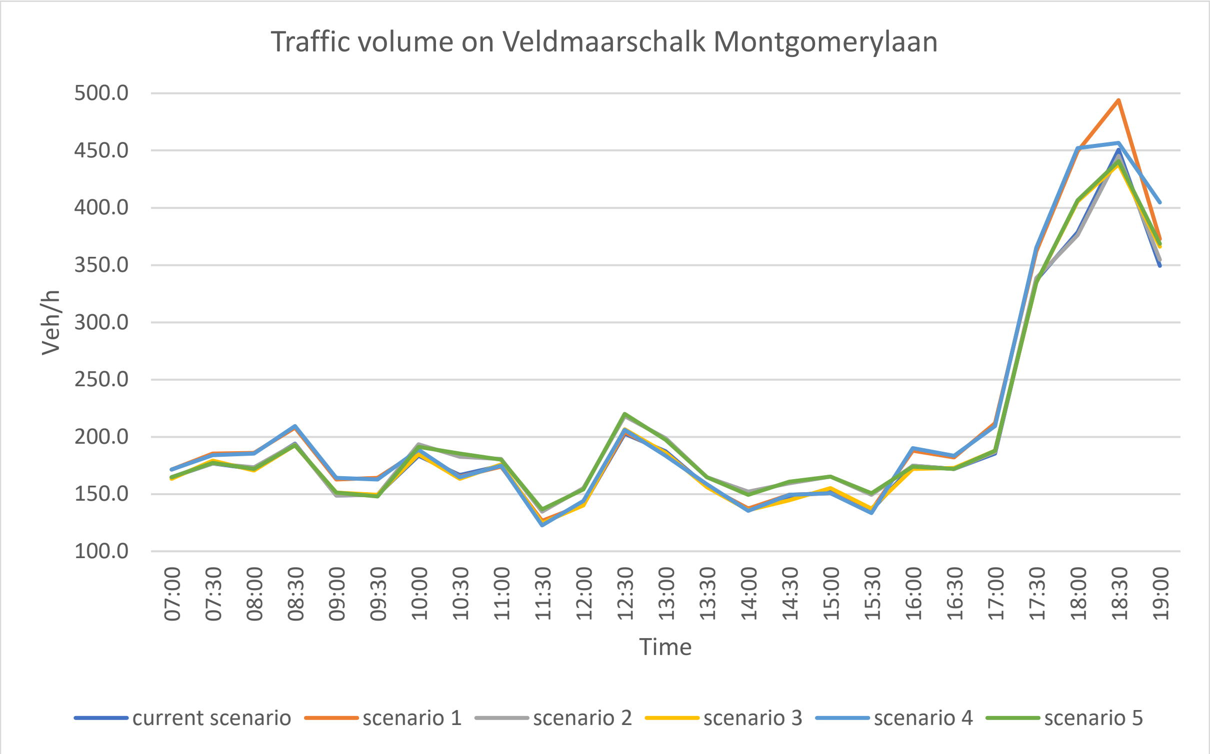


Figure 57 *Traffic volume of private traffic on Veldmaarschalk Montgomerylaan under six scenarios.*

As shown in Figure 57, the traffic flow fluctuations in different scenarios are relatively close, with a difference of only a few dozen vehicles at most. Figure 58 is then generated based on equation [3-4] to show the *traffic volume comparisons* C_i between the designed scenario *i* and the baseline scenario.

As shown in Figure 58, a more straightforward result between the scenarios, in which comparisons over time series can be found. On average, designed scenarios brought more traffic flow on Veldmaarschalk Montgomerylaan: scenario 1 brought 4.6% more traffic, 3.7% for scenario 2, 0.3% for scenario 3, 4.6% for scenario 4, and 4.2% for scenario 5.

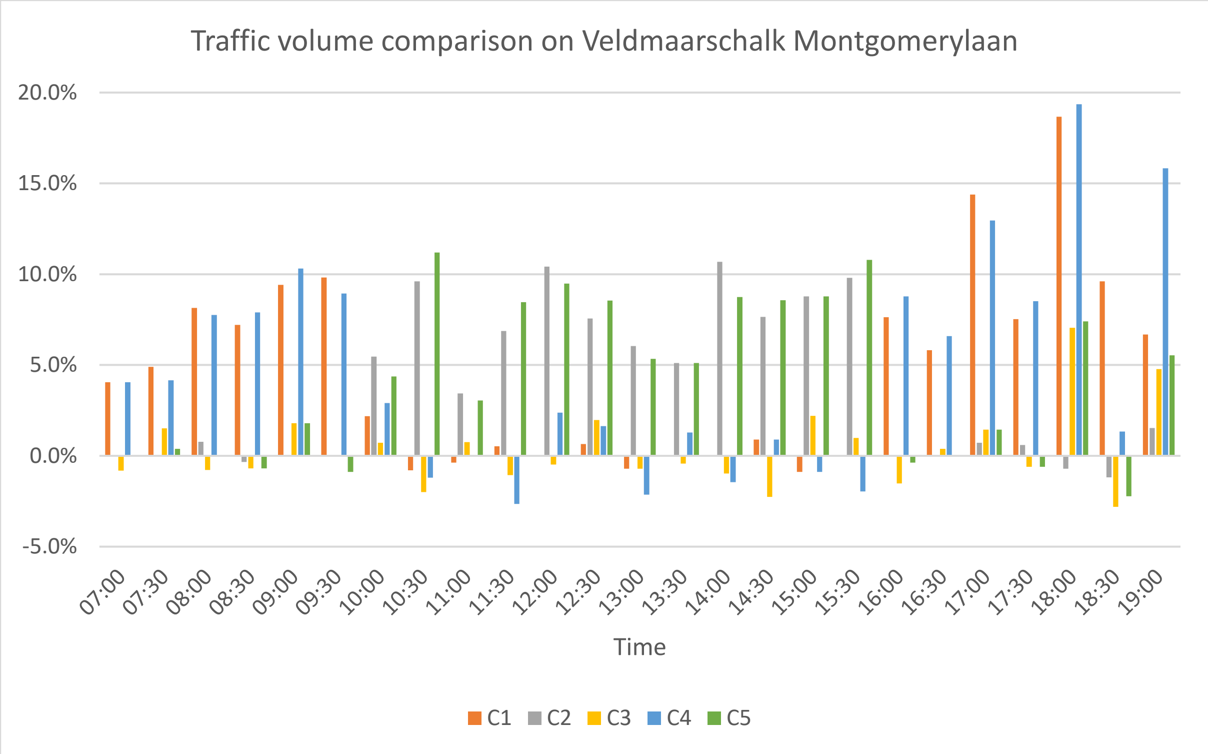


***Figure 58** Traffic volume comparisons between designed scenarios and the baseline scenario.*

To be specific, when the ATL system was not applied (i.e., baseline scenario, scenario 1 and 2), opening bus lanes for the general traffic during peak hours (scenario 1) brought a maximum increase of 18.7% in car flow during the half an hour of 17:30 - 18:00. When opening bus lanes during off-peak hours (scenario 2), the Veldmaarschalk Montgomerylaan road could attract an increase on traffic flows up to 10.7% around 14:00.

On the other hand, when looking at the scenarios equipped with the ATL system (i.e., scenario 3, 4 and 5), the impact of introducing the ATL system itself (scenario 3) was not quite significant that for most period of the day, the traffic flow difference compared with the baseline scenario was less than 3% and only 7.0% more cars were attracted around 18:00. The synergy effect of introducing the DBL strategy and the ATL system was amplified compared with the corresponding one-strategy scenario (i.e., compare scenario 4 to scenario 1; scenario 5 to scenario 2). In other words, the fluctuations in traffic volumes (including rising and falling) of two-strategy scenarios are more significant compared with one-strategy scenarios: in scenario 4 (open bus lanes during peak hours and apply the ATL system), the maximum growth was 19.4% around 18:00 but fell to only 1.3% after half an hour; the amplification effect in scenario 5 (open bus lanes during off-peak hours and apply the ATL system) was less but still fluctuated strongly than scenario 2.

In conclusion, Veldmaarschalk Montgomerylaan in designed scenarios could carry more traffic volumes compared with the baseline scenario, and the simultaneous application of the two strategies would bring about the amplification effect regarding the traffic volume fluctuations.

When the overall traffic situations of the main road have been depicted, the change happened only on normal lanes is also necessary to be investigated. It can be seen from Figure 59 and Figure 60 that most of the traffic flow on Veldmaarschalk Montgomerylaan comes from normal lanes but the direction of traffic volume fluctuation was opposite compared with Figure 57: scenario 1 and 4 helped to remove passenger cars from normal lanes during peak hours when the bus lanes were open to the general traffic; scenario 2 and 5 also decreased the traffic flow running on normal lanes during off-peak hours when the bus lanes were available.

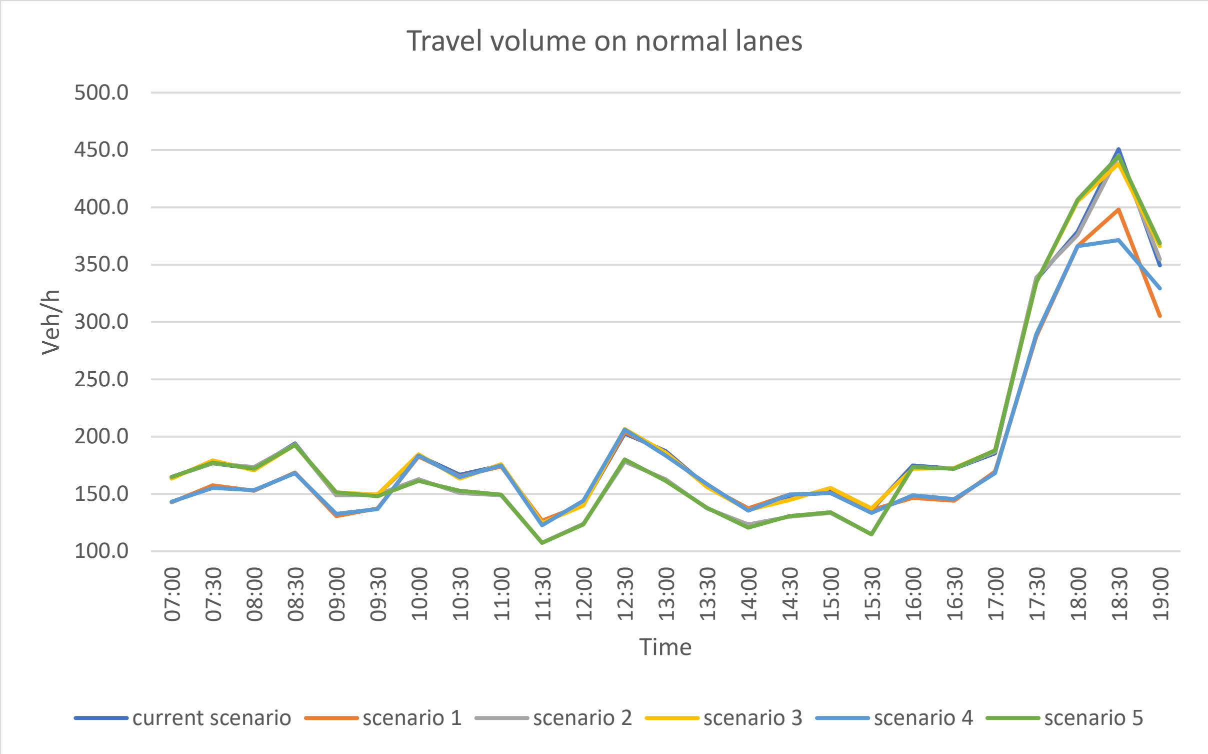


Figure 59 *Traffic volume of private traffic on normal lanes under six scenarios.*

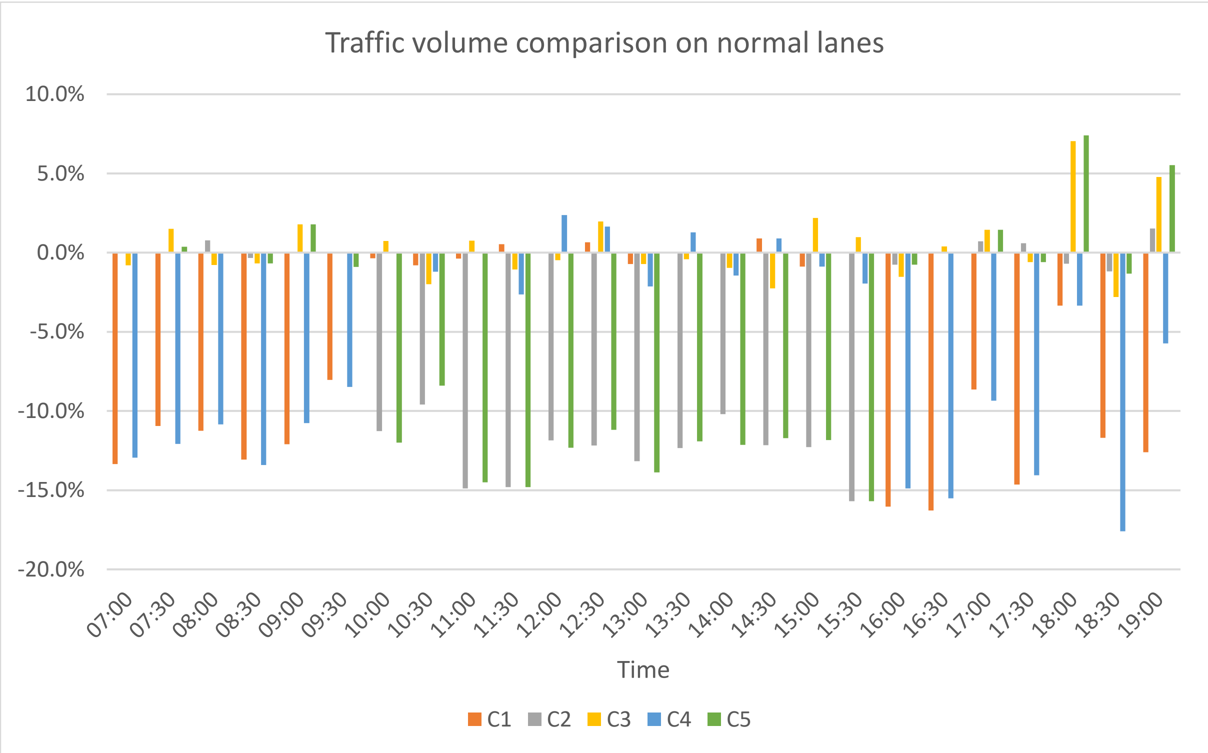


Figure 60 *Traffic volume comparisons between designed scenarios and the baseline scenario[17].*

What can be drawn from Figure 59 and Figure 60 is that for designed scenarios, although the traffic flows on the normal lanes have been decreased compared with the current traffic situation (on average, -6.1% for scenario 1, -6.0% for scenario 2, 0.3% for scenario 3, -6.1% scenario 4, -5.5% for scenario 5), the dynamic opening of bus lanes would still attract more passenger cars from other roads and bring the

[17]Generated by using equation [3-4].

increase in the traffic volume of the whole road. The average speed and mean time loss of vehicles on normal lanes are illustrated in Figure 61.

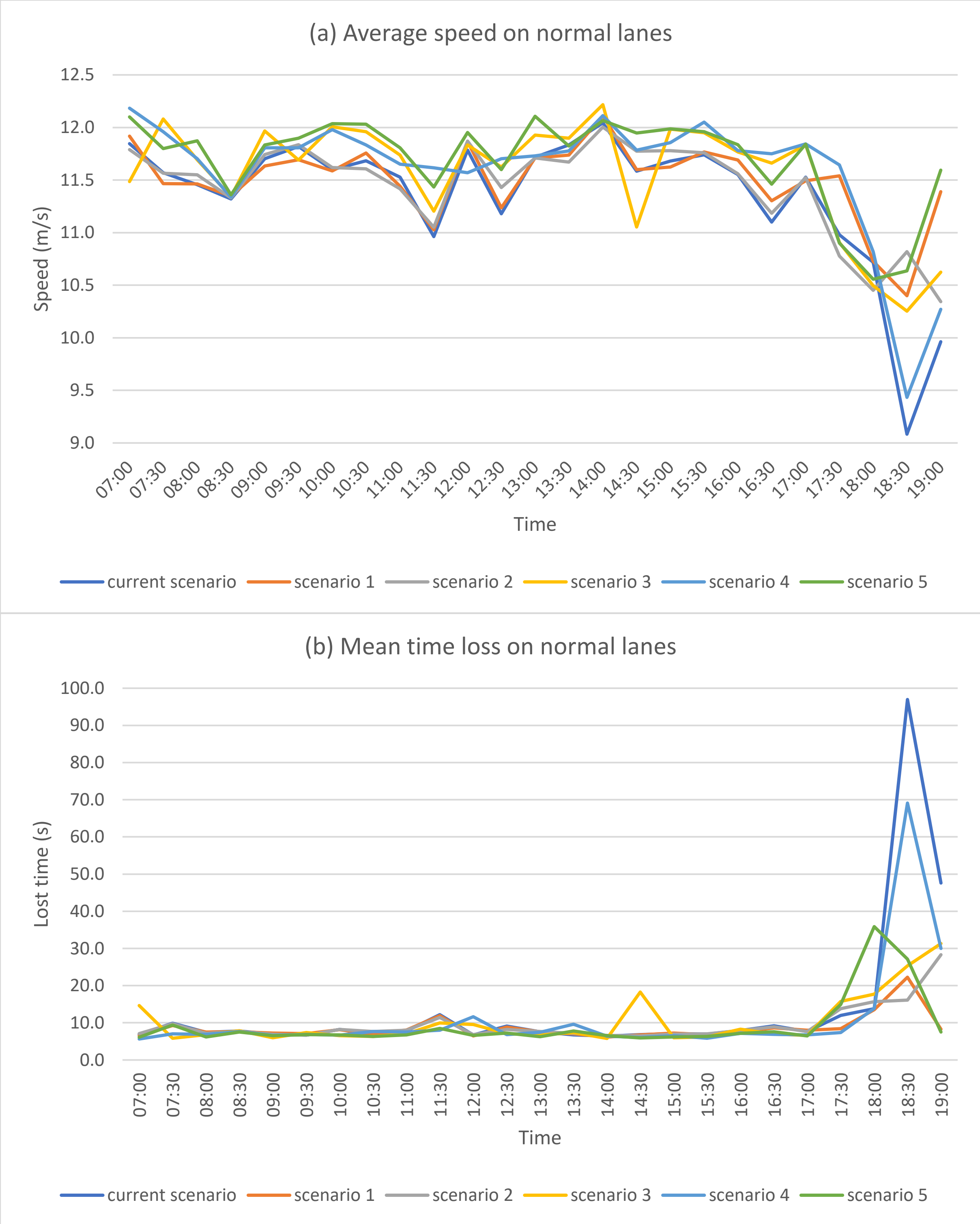


Figure 61 *Average traffic situations of private traffic on normal lanes under six scenarios: (a) average speed and (b) mean time loss.*

From the perspective of vehicles, Figure 61 depicts the average speed and mean time loss on normal lanes under different scenarios. Except for a few moments, the baseline scenario had the worst traffic situations during most of the day. Especially at the traffic peak (18:30) during the evening peak hours, the average speed on normal lanes under the baseline scenario (9.1 m/s) is 1.9 m/s slower than the best-performing scenario 2 (10.8 m/s), and the corresponding mean time loss is even more than 80 seconds.

In addition, when comparing different scenarios, it can be found that restricting the use of bus lanes by passenger cars during peak hours (i.e., scenarios 2 and 5) made the traffic situations on normal lanes better than letting cars use bus lanes (i.e., scenarios 1 and 4), which answers the remaining question in section 6.2.1.1 that scenarios when the bus lanes are closed to general traffic during rush hours performed better than opening bus lanes. And the traffic situations of private traffic on the bus lane can be found in Appendix C.4.

In total the flows of passenger cars on Veldmaarschalk Montgomerylaan were increased by a minor amount due to the opening of the bus lane but the traffic situations on normal lanes still performed better compared with the baseline scenario. Based on the discussion above, if the evaluation target is limited only to passenger cars, scenario 5 was performing better in terms of the discussed indices.

Buses

Next to the investigation on the variances in private traffic, the operation situations of buses also need to be confirmed that no serious deterioration happened to prevent people from using the public transport.

The lane area detectors (E2 detectors) were placed along the whole bus lane on Veldmaarschalk Montgomerylaan (see the orange line in Figure 52) to measure the operation performance of buses. A lane area detector can capture traffic on an area along a lane or lanes, which would be similar to a vehicle tracking cameras (German Aerospace Center (DLR), 2019g). The detectors are designed to compute indices of traffic volume, average speed and average deviation time. Table 36 lists the measured indices as well as the detailed explanations.

Table 36 *Descriptions on the public transport indices.*

Target of evaluation	Indices	Description
Bus	Traffic volume (veh/h)	The number of vehicles that were on the detector in the corresponding interval.
	Average speed (m/s)	The mean velocity over all collected data samples.
	Average deviation time for line 9 buses (s)	The average deviation time of each trip of line 9 buses.

Figure 62 shows the average operating situations of buses travelling on bus lanes. Comparing the traffic volumes generated under designed scenarios with the baseline scenario shows that no significant impact on the scheduled bus operating plan was found except for a steep increase under scenario 4 at the end of the simulation. This sharp increase also validates the synergy of opening bus lanes during peak hours and applying the ATL system, and proves that this combination of strategies may not be applicable for this road.

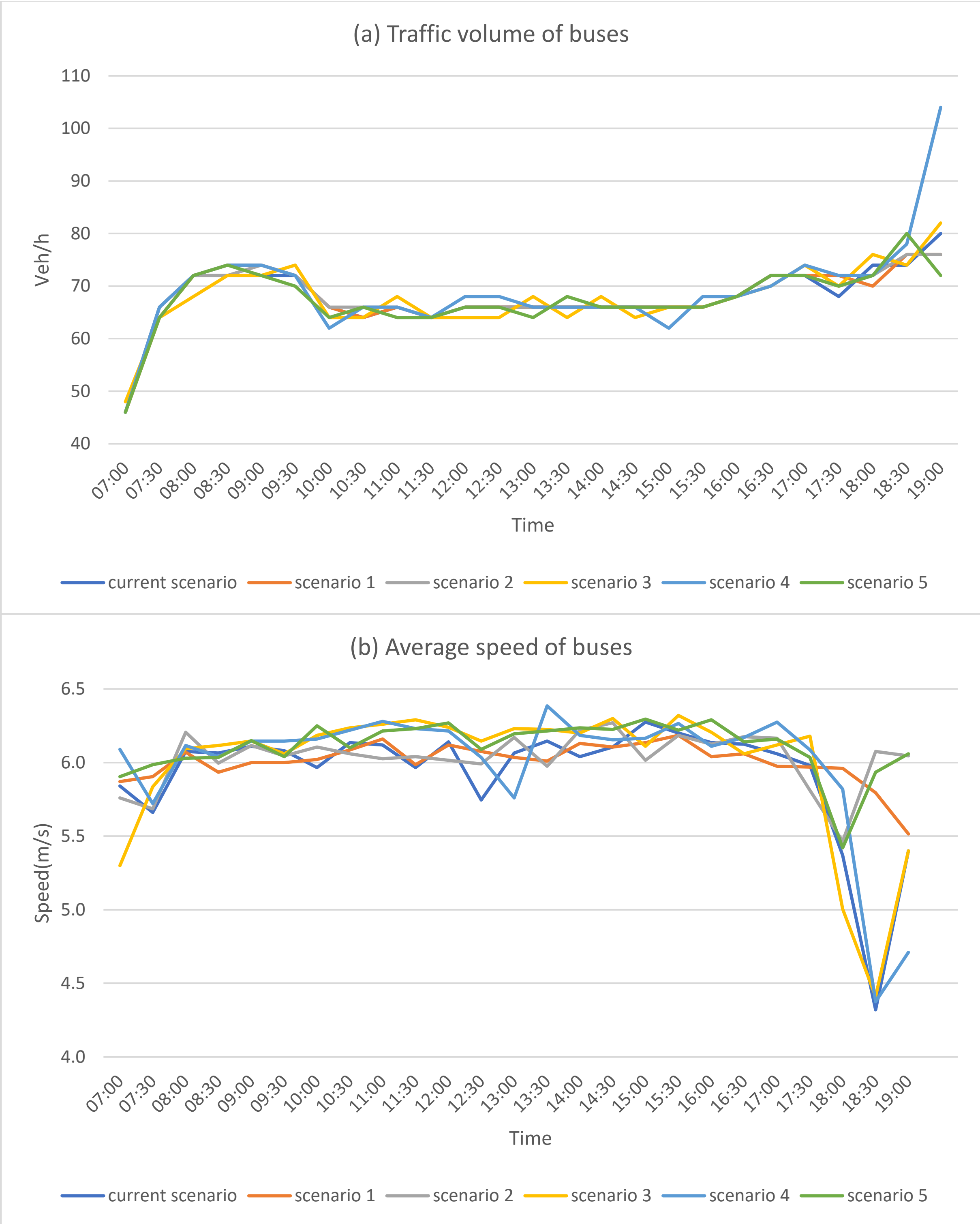
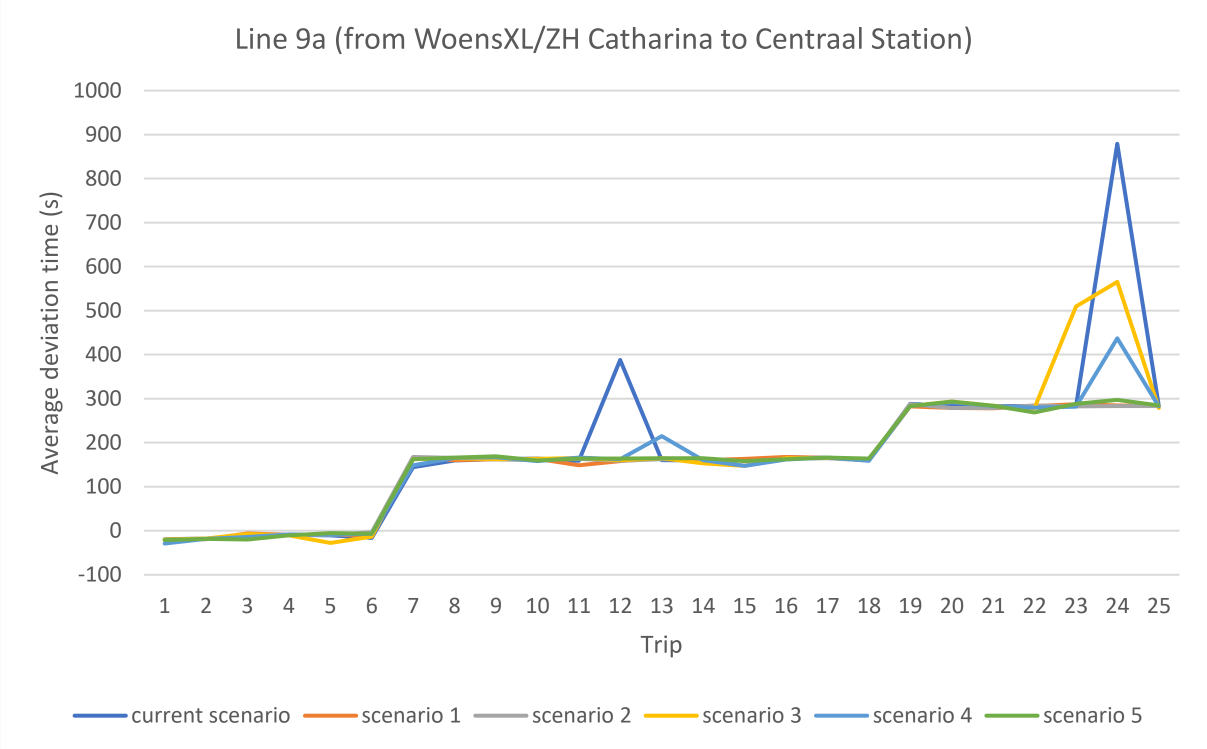


Figure 62 *Average traffic situations of public transport on bus lanes under six scenarios: (a) traffic volume and (b) average speed.*

Additionally, Figure 62 (b) illustrates that before entering the evening peak hours, the driving speed of buses on the dedicated lane was not significantly affected by the adopted strategies (only a few speed reductions in some scenarios occurred at noon). However, when the road traffic volume reached the peak during evening rush hours, the bus lanes in different scenarios showed different carrying capacities.

Specifically, the buses in scenario 3 and scenario 4 experienced a dramatic slowdown (obviously congestions occurred on the measured road segments), but the congestions in scenario 3 were alleviated soon and the average speed was increased while the resilience of scenario 4 was not satisfactory. In contrast, scenario 1, scenario 2, and scenario 5 have better performance in maintaining bus speed. Not only the minimum average speed is higher than other scenarios, but they also allowed the speed to quickly return to the normal level.

To discuss more details on the operation of public transport, one more indicator on buses is measured based on equation [3-5] described in section 3.3.1 that the average deviation time of each trip of line 9 buses is generated (see Figure 63).



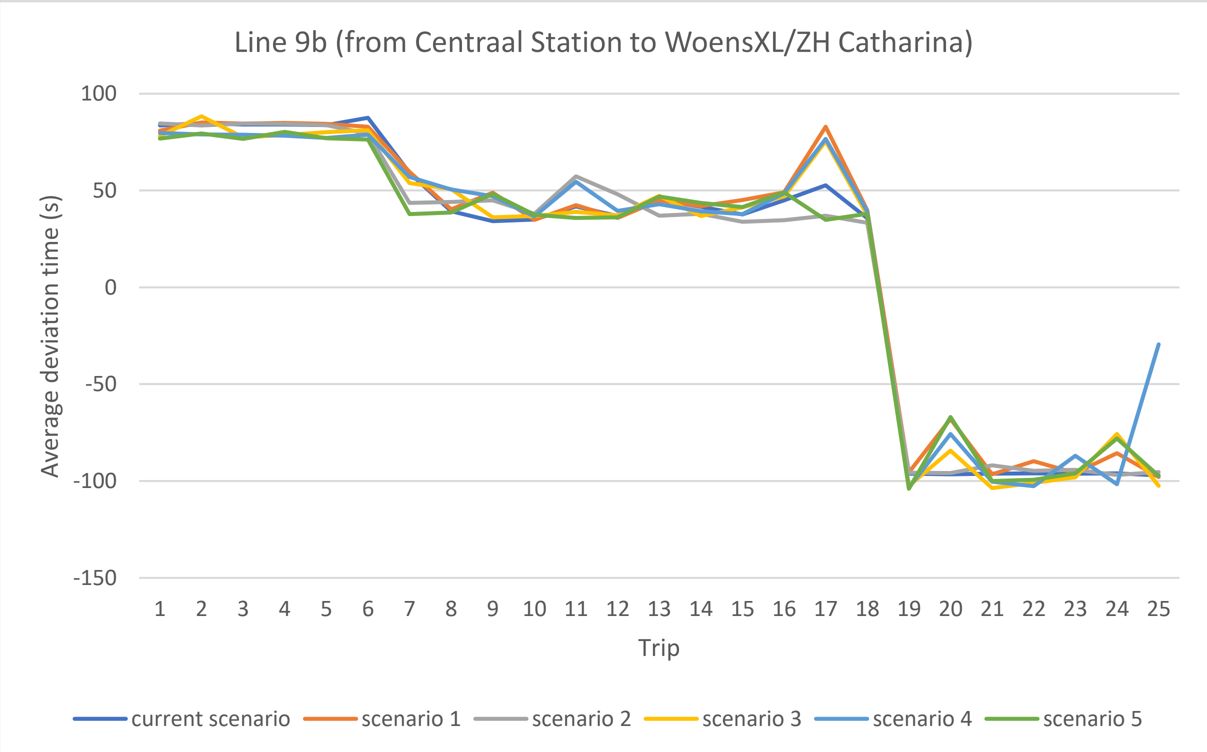


Figure 63 *The average deviation time of line 9 buses under six scenarios.*

In general, all bus trips have experienced two same deviation time changes (at the end of the morning peak hours and the begin of evening peak hours) no matter which direction they are heading to. As for the direction from the outside of the city to the centre, the closer to the city centre, the more delayed time buses would get. However, most designed scenarios performed better compared with the baseline scenario that two significant rebounds in the baseline scenario were flattened (except for scenario 3 and scenario 4). On the contrary, for the opposite-direction trips, buses got less and less delayed when they were leaving from the city centre and the difference among scenarios was not as significant as the previous one.

From the perspective of public transport, the designed scenarios could bring better results regarding the operation situations of buses than the baseline scenario (including maintaining the bus volume and driving speed on the bus lane and reducing the deviation time from the timetable). There exist some differences in the performance of the designed scenarios. Based on the above discussion, scenario 3 and scenario 4 did not offer the same results as other scenarios in maintaining the bus driving speed and reducing the deviation time.

6.2.2 Vehicle Emission and Air Quality Comparison

In addition to the comparison of traffic situations between scenarios, the evaluation about the impact of introduced strategies on the ambient air quality is another important part. This section will use the integrated framework described in previous chapters to generate the vehicle emissions as well as the concentrations of the specific pollutant in the selected modelling domains to depict the average level on the Veldmaarschalk Montgomerylaan road.

Table 37 *The average emission rate of streets in the selected domains under six scenarios.*

	Average Emission rate (kg/h/km)					
	Emission source	N1	N2	M	S1	S2
	Baseline	0.743	0.745	0.746	0.753	0.753
	Scenario 1	0.763	0.763	0.763	0.762	0.762
Street i[a]	Scenario 2	0.761	0.761	0.761	0.761	0.761
	Scenario 3	0.756	0.756	0.756	0.756	0.756
	Scenario 4	0.762	0.762	0.762	0.762	0.762
	Scenario 5	0.761	0.761	0.761	0.761	0.761
	Emission source	VM-N	VM-S	Eu-E	Eu-W	
	Baseline	0.801	0.851	0.261	0.361	
	Scenario 1	0.827	0.882	0.263	0.417	
Intersection[b]	Scenario 2	0.820	0.869	0.263	0.420	
	Scenario 3	0.803	0.852	0.261	0.421	
	Scenario 4	0.828	0.882	0.266	0.417	
	Scenario 5	0.820	0.869	0.263	0.420	
	Emission source	N	M	S		
	Baseline	0.904	0.904	0.996		
	Scenario 1	0.986	0.986	1.066		
Street ii	Scenario 2	0.953	0.953	1.015		
	Scenario 3	0.905	0.905	0.973		
	Scenario 4	0.986	0.986	1.043		
	Scenario 5	0.953	0.953	1.013		

[a]N for northern segments, S for southern segments, E for eastern segments, W for western segments, M for middle segments;
[b]VM for Veldmaarschalk Montgomerylaan street, Eu for Europalaan street.

Following the steps described in section 3.3.2, the average emission rate shown in Table 37 can be generated. In general, the results of emission modelling demonstrate that the vehicle emissions produced in designed scenarios were slightly higher than the baseline scenario (the increase varies from 1% to 15%) since more passenger cars were attracted by the opening of bus lanes.

Keeping all external factors like meteorological conditions and infrastructure design parameters are the same for designed scenarios, diurnal modulation factors which are related to the traffic volume fluctuations is another decisive factor (the modulation factors under different scenarios can be found in Appendix C.5). Therefore the difference in the modelled results of the pollutant CO concentration under different scenarios is more obvious than the difference in the emission rate (see Figure 64, Figure 65 and Figure 66).

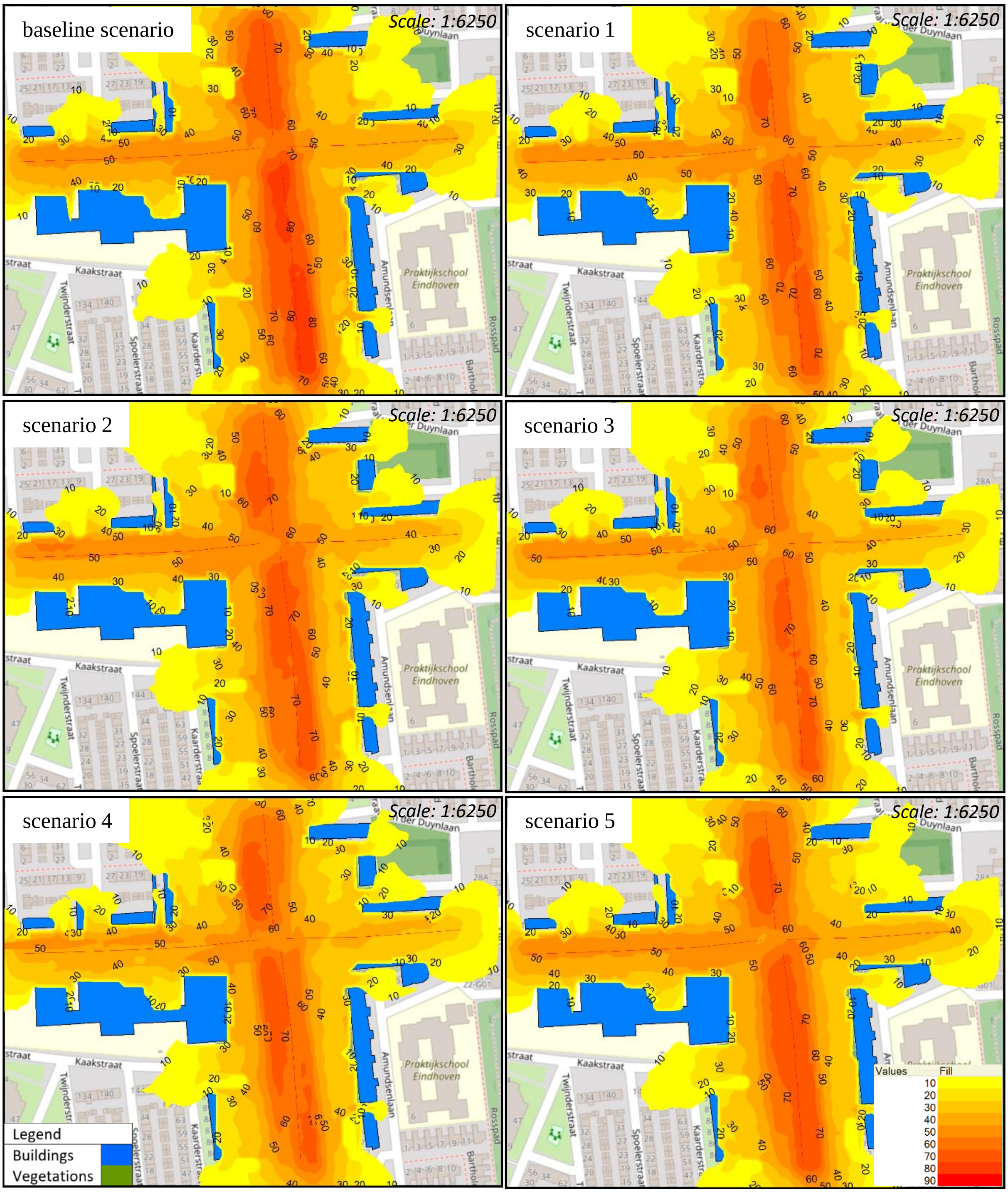


Figure 64 *The CO daily max concentration (µg/m3) at the intersection under different scenarios.*

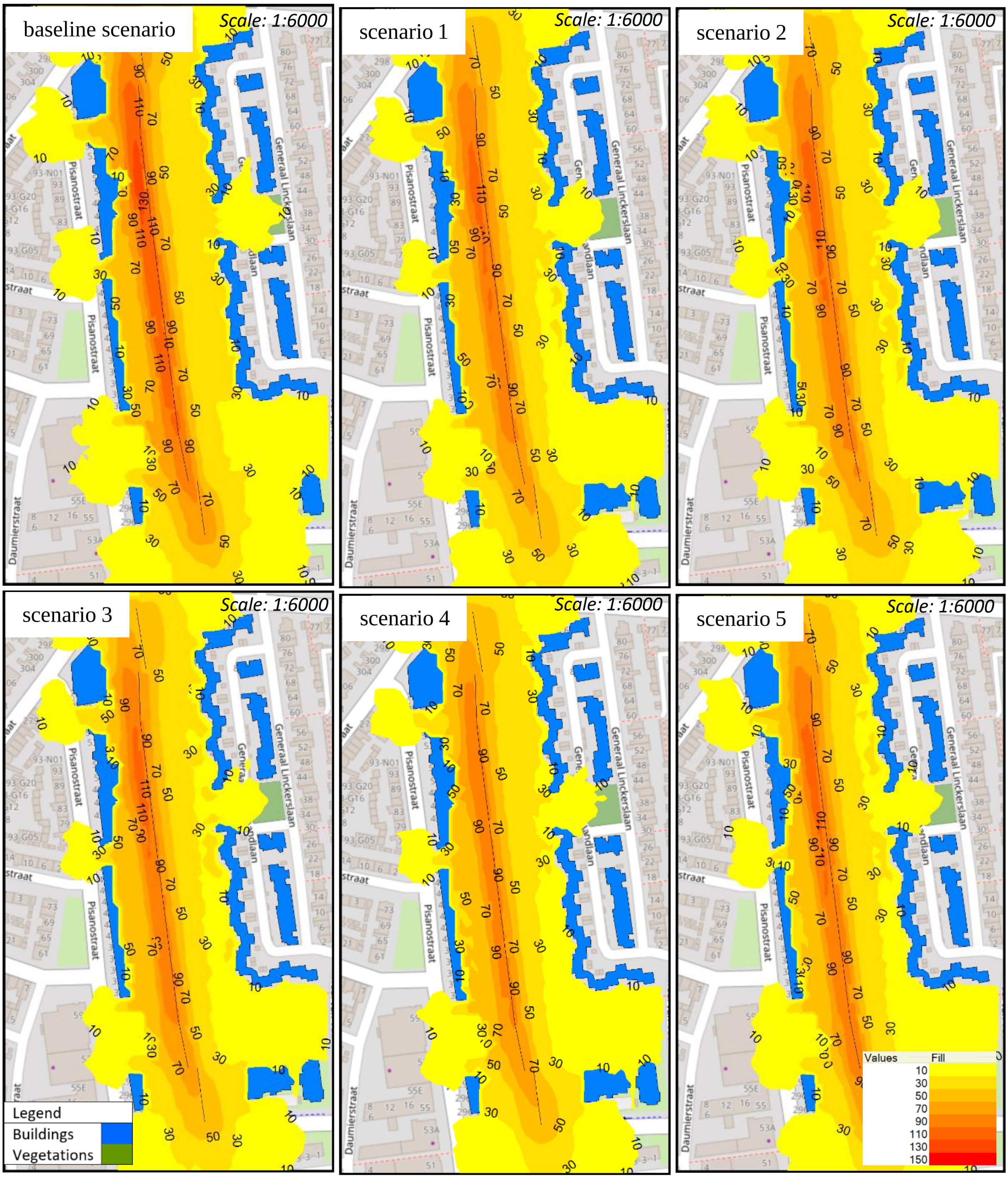


Figure 65 *The CO daily max concentration (μg/m3) on street i under different scenarios.*

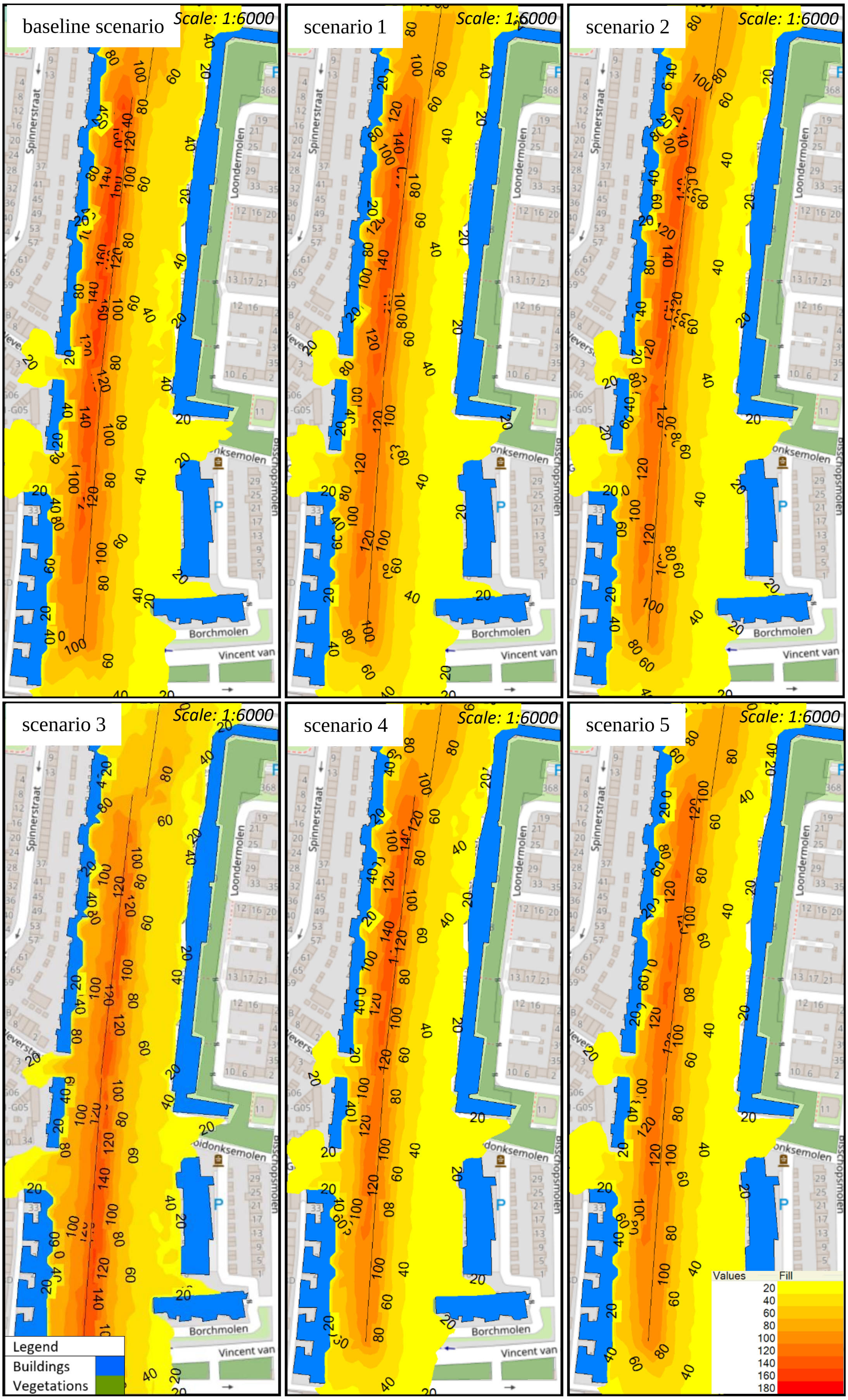


***Figure 66** The CO daily max concentration (µg/m3) on street ii under different scenarios.*

Additionally, the max values in each map were extracted in Table 38. Based on these concentration maps as well as the map max values, the importance of modulation factors is proved because almost the same emission rates produced pretty different concentration values.

***Table 38** The max values in CO daily max concentration maps.*

Scenario	Max value (μg/m^3)			Average (μg/m^3)
	Street i	Intersection	Street ii	
Baseline	141.69	87.91	174.73	131.32
Scenario 1	120.25	78.52	161.20	119.99
Scenario 2	125.12	78.03	159.28	120.81
Scenario 3	121.28	76.16	170.39	122.61
Scenario 4	108.25	80.23	156.09	114.86
Scenario 5	121.48	81.61	148.79	117.29

Comparing the concentrations from three locations, the conclusions drawn in section 5.4.3 are valid for all scenarios that two selected road segments suffer more vehicle emissions and denser pollutants than the intersection (the pollution on street ii is worst).

From the perspective of scenarios, the following conclusions can be drawn after comparing the concentration maps generated from six scenarios: first, considering only the impact of the DBL strategy and looking into the baseline scenario, scenario 1 and scenario 2, both plans of opening the bus lane during different periods can reduce the pollutant concentrations while both plans worked pretty close, it is probably because the opening durations of the bus lanes for the two plans are close.; second, the ATL system can also ease the impact of vehicle emissions to the ambient air quality that scenario 3 even performed the best in reducing the concentrations at the intersection; third, speaking of the synergy effect of the two policies, scenario 4 and scenario 5 performed pretty close when mitigating the pollutant concentrations in the intersection area but not the best among all scenarios, and they had the best mitigation effect on the street canyons (scenario 4 worked best for street i and scenario 5 for street ii respectively[18]).

Concludingly, from the perspective of impacts of these scenarios on reducing the pollutant concentrations, the designed scenarios could achieve their initial intention of improving air quality and had different effective locations, which proves the effectiveness of the DBL and ATL strategies.

6.3 CONCLUSION

In this chapter, five additional scenarios were designed based on the introduction of two strategies: the dynamic bus lane policy and the adaptive traffic light system. Both of them were developed from the perspective of traffic simulation and implemented through modifying parameters in SUMO. The first strategy, dynamic bus lane, could affect the route choice made by passenger cars based on the accessibility of bus lanes during different periods. The DBL strategy was essentially designed with the purpose of exploring the potential of road capacity. And the second strategy, adaptive traffic light, took the traffic volume in different directions into account and influences the needed time for vehicles to pass the intersections by adaptive traffic lights, which was planned to improve the traffic efficiency at intersections.

Based on the introduced strategies, five scenarios were implemented in the traffic simulations. The corresponding emission modelling and dispersion modelling of each scenario were also conducted. The first two scenarios examined the DBL plan with different opening time for the bus lane and scenario 3 investigated the ATL system to see the impact of advanced traffic signals on traffic flows. The last two scenarios aimed at discussing the synergy effect of both strategies.

The comparisons on the simulation results of the baseline scenario as well as other five designed scenarios were depicted in the second section and reviewed from two perspectives: (a) traffic situations and (b) vehicle emission and air quality situations. As for traffic situations in the whole simulation network, five designed scenarios created better traffic systems which could accommodate more traffic

[18] This is also proved by the simulated CO daily mean concentration maps which can be found in Appendix C.6.

flow, ease the traffic pressure faster and maintaining vehicle speed during peak hours. Furthermore, the comparison between the scenarios also revealed that the scenarios with closed bus lanes to general traffic during peak hours performed better than those scenarios with open bus lanes.

Narrow down the focus only on the Veldmaarschalk Montgomerylaan road, for passenger cars, designed scenarios attracted around 4% more traffic flows (0.3% more for scenario 3 which only adopts the ATL system) compared with the baseline scenario, and it was found that the simultaneous adoption of the DBL strategy and the ATL system amplificated the traffic fluctuations. In addition, further investigation on the passenger cars on normal lanes showed that the DBL strategy did help to remove vehicles to bus lanes and when they were open to general traffic and the congestions on normal lanes got mitigated that the average speed and mean time loss were improved. Among the evaluated scenarios, scenario 5 which opened the bus lane during off-peak hours and used the ATL system performed slightly better than others. On the other hand, for buses on Veldmaarschalk Montgomerylaan, the public transport system performance under different scenarios was evaluated as well: in general, most designed scenarios could maintain the operation performance while scenario 3 and scenario 4 (that opens the bus lane during peak hours and uses the ATL system) did not achieve an equivalent effect because they caused more congestions on the measured road segments. It is reasonable to conclude that with the adoption of two strategies, in total the flow of private traffic in the Veldmaarschalk Montgomerylaan arterial increased by a slight amount but the performance of both private traffic and public transport were kept or even improved under most scenarios.

Last but not least, the integrated framework also generated the results of average emission rate on streets and the ambient air quality in the selected modelling domains. Although the adoption of the DBL and ATL strategies brought more traffic and a slight increase in the average emission rate, the air quality on the streets remarkably showed a trend of improvement under all scenarios. The DBL strategy was effective for both road types (intersections and street canyons), while the ATL system only had a significant effect on the intersection area. Furthermore, the synergy of both strategies was also analyzed that different opening periods of bus lanes could generate similar results: once these two strategies were combined, the scenario would work better for mitigating the pollutant concentrations in street canyons but the effect on the intersection area was not as good as the scenarios when only one strategy was implemented.

Through analyzing the impact of two strategies on traffic system and air quality, what came to light is the proof of their effectiveness and they have different suitable locations. Since the costs of scenario implementation are not considered in this study, scenario 5, which allowed private traffic to access the bus lane during off-peak hours and employed the adaptive traffic light system, was the most feasible schema which had a balanced performance regarding the improvement in traffic situations as well as the air quality.

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Chapter 7 Conclusion and Discussion

This chapter aims to give the conclusion by reviewing the research questions proposed earlier and discuss sufficiently to explore the scientific and societal relevance, and limitations of this research.

- 7.1 Conclusion
- 7.2 Discussion

7.1 Conclusion

Through the research process, this study succeeded in integrating microscopic simulation models and using multiple data sources to give a comprehensive evaluation framework for assessing bus lane policies. In this section, the responses to sub-questions are given first and the conclusion for the main research question is drawn at the end.

- *From what perspectives can the impact of the bus lane policy be evaluated? What simulators are present in the market that are suitable for the research?*

The response to this sub-question was mainly based on the literature review. Three evaluation aspects were recognized gradually during the process of literature research, namely traffic flow, vehicle emission and air quality. Considerable efforts have been made in recent years to improve the understanding of the application of simulation in each mentioned aspect or a combination of two aspects or even integration of three aspects. Based on the literature research on simulation methods in three different fields, and considering the evaluation object and the study area, the following requirements are proposed: firstly, the simulation tools are required to be open-source and can provide the necessary functions to achieve an accurate simulation; secondly, the selected tools can reflect the characteristics of the study case; finally, there should be a significant and reliable correlation between the selected models so that they can be integrated into one framework.

Thus, simulators for three simulations were selected as: SUMO for traffic modelling, VERSIT+ for vehicle emission modelling, GRAL for air quality modelling. The choice was made precisely based on these demands that all models are open and free-to-use; SUMO is designed for microscopic traffic simulations, VERSIT+ is built based on a reliable database measured in the Netherlands and GRAL can represent traffic emission sources properly (using line sources). Additionally, there are internal data flows through the simulation flow that connects models.

- *How to establish an integrated framework based on the selected simulation models?*

After selecting the suitable simulation models, the integrated modelling framework was designed for predicting the impact of traffic management scenarios on urban traffic and corresponding vehicle emissions and air quality. As emphasized in Figure 7, the key components to link simulation models are two internal simulation results, *total driven mileage* and *emission source intensity*. The former used the data, including *vehicle count* and *street length* from traffic modelling and acted as the input for vehicle emission modelling. The latter dataset composed of *average emission rate* and *emission modulation factors* was generated based on both traffic and vehicle emission modelling and then was imported into air quality modelling. By implementing the simulation flow, three simulation models were connected intuitively, and the integrated framework was therefore established. Moreover, the framework was validated after setting up the baseline scenario by comparison with the actual situations, which proved the stability of the framework.

- *What available data sources are suitable to be used, and how can the data be prepared?*

With the established integrated modelling framework, available data source options from external sources have been investigated with the aim of setting up a simulation environment close to the reality as much as possible. For input data from external sources, due to the sequence of simulation and the propagation of model uncertainty (Vallero, 2019), the input for the basic simulation, traffic simulation, deserves more attention compared with other two simulation models. As depicted in Figure 7, the microscopic traffic simulator requires two primary data sources, including network configuration data as well as traffic demand data for private and public transport, respectively. In this research, the data from OpenStreetMap source worked as the input for network configuration, and it was compatible with SUMO. On the other hand, private traffic demand was generated based on the OD matrices from Albatross, but the compatibility of this data source with SUMO did not meet expectations, which will be elaborated in the section 7.2.3. Public transport was created by using the bus time schedules which could be imported into SUMO as expected. Next, for vehicle emission modelling, the input data includes emission class and emission factor from VERSIT+ model by considering the distribution of Dutch road vehicles. Additionally, meteorological data (wind speed and wind direction) and infrastructure design data (street width, vegetation area, roadside building contour and their average height) for air quality modelling were also needed and prepared.

- *What is the situation under the current bus lane policy in the simulation environment?*

In order to test the applicability of the integrated modelling framework, the neighbourhoods around Veldmaarschalk Montgomerylaan street (Rapenland, Generalenbuurt, Kronehoef, Oude Toren, Gildebuurt and Woenselse Watermolen) account for around 2.2 square kilometres were chosen. The traffic situations in this small area were simulated from 06:30 to 19:00 on a typical weekday, covering peak and daytime off-peak hours, while vehicle emissions were calculated on those streets where vehicles passed, and air quality computation was performed at two road segments (street canyons) and one intersection. With the current bus lane policy, the traffic in the area would experience dramatic fluctuations during peak periods (especially evening peaks). The traffic congestions happened frequently in the network during peak hours and the lowest vehicle speed measured during evening peak hours also fell below half of the speed measured during the off-peak-period (see Figure 33 and Figure 34). Although the computed vehicle emissions and air quality could not show the variation in time series, the results still indicated that the emission on the Veldmaarschalk Montgomerylaan street was serious. Besides, the computed distribution of CO concentrations shown in Figure 43 illustrated the fact that the pollutant concentration in the street canyons was denser than that of the intersection, and the closer to the city centre, the more polluted the streets would be.

- *Is there any suitable alternative policy can be established in the microscopic simulation, and what are the impacts of these alternatives compared with the current bus lane policy?*

After establishing the baseline scenario, the framework has been used to evaluate the rationality of the current bus lane policy. The assessment was based on two perspectives, namely, the comparison of traffic situations and vehicle emission/air quality under different scenarios. With the aim of making better use of road capacity, the current fixed bus lane policy was redesigned as dynamic bus lane (DBL) policy which allowed the private traffic to use the bus lane during certain periods of a day. The adaptive traffic light (ATL) system was implemented at selected intersections to prevent the possible deterioration on the bus operation by additional passenger cars on the bus lane. Thus, after the permutation and combination of the two strategies, five different scenarios were designed to compare with the baseline scenario.

From the perspective of traffic situations, a significant improvement brought by two introduced management schemas was seen during evening peak hours in terms of traffic flows and average speed for vehicles in the whole network (see Figure 55 and Figure 56). However, the impacts of the two strategies were also different, while the influence of DBL was slightly more significant. Noted that combined with different bus lane opening strategies, the impact of the ATL system on the traffic situation was also mixed. Narrow down the focus to only Veldmaarschalk Montgomerylaan street, it can be seen from the traffic volume comparisons between designed scenarios and the baseline scenario that the traffic volume on the normal lanes has decreased but the total flow of the road has increased due to the opening of bus lanes (see Figure 58 and Figure 60). It can be concluded that the opening of bus lanes has indeed shifted the traffic pressure from normal lanes, and also increased the road capacity of the investigated road. Furthermore, the monitoring of the traffic situations of passenger cars also showed the effectiveness of the designed scenarios (see Figure 61). Based on the simulated results, if the evaluation target is limited only to passenger cars, the scenario of opening the bus lane during off-peak hours and applying the ATL system together (scenario 5) performed better than others in terms of the discussed indices. When shifting the evaluation object to buses, the scenario of only applying the ATL system (scenario 3) and opening the bus lane during peak hours and applying the ATL system together (scenario 4) were proved as not competent as other scenarios in terms of improving the stability of bus operations (see Figure 62 and Figure 63).

From the perspective of air quality situations, all scenarios could decrease the pollutant concentrations in the chosen modelling domains compared with the baseline scenario. However, they have their own suitable locations. For instance, the ATL system worked better for the intersection area. Regarding air quality, no scenario had an overall advantage over other scenarios, so no strong preference can be given based on this aspect. It is of worth to note the variance in the distribution of pollutant concentration mainly lies in the difference in emission modulation factors generated from different scenarios rather than the difference in the average emission rate (see Table 37).

In brief, from different evaluation perspectives, the same conclusion can be generated that it is beneficial to change the fixed bus lanes to dynamic ones and make them open to private traffic when appropriate, which will help improve traffic performance and air quality in the study area. Noted that the cost of implementing traffic management strategies was not considered in this research.

The main research question: *How to evaluate the bus lane policy based on data from different sources through simulation methodology?*

The main research question can be divided into two parts: *How to use data from different sources? How to evaluate the bus lane policy through simulation methodology?* Correspondingly, the answer is also based on two perspectives.

As shown in Figure 7, three open-source simulation models have been chosen to set up the evaluation framework, and multiple external data sources, including road network configurations, traffic demand, emission class, emission factor, meteorological parameters, and infrastructure design parameters, have been identified, extracted and included in the integrated framework. Besides, the internally simulated outputs, including vehicle count, street length, and emission modulation factors from traffic modelling, average emission rate from vehicle emission modelling, generated in the simulation process were also used to link three simulation models. Thus, a comprehensive framework, which can make good use of data from external sources and internally generated results, is established.

Secondly, to investigate the subtle balance between public transport and private traffic, five additional traffic management schemas were designed based on the combination of dynamic bus lane policy and adaptive traffic light system for the chosen study area. The established simulation framework provides us with the function of presenting the traffic situations of vehicles under each scenario by specific traffic performance indices (including traffic volume comparison and bus deviation time) and computing vehicle emissions and the distribution of pollutant concentrations in selected modelling domains. With these simulated results, the bus lane policy can be evaluated from the perspectives of both traffic situation and vehicle emission/air quality perspectives.

It can be reasonably concluded that the established integrated framework based on the three simulation models, and detailed scenario analysis are valuable responses to the main research question.

7.2 Discussion

7.2.1 Scientific Relevance

The main contribution of this research regarding its scientific relevance was the established open-source architecture that couples three models: a microscopic traffic simulator (SUMO), a Dutch vehicle emission calculator (VERSIT+) and a pollutant concentration simulator (GRAL). In the setup process of such a realistic structure, the traffic and network simulator acted as the foundation for the following models that parameters were changed in the model and different route files were generated under different traffic management scenarios, enabling the subsequent calculation on vehicle emissions and pollutant concentrations. Thus the vehicle movement was influenced by different scenario settings in the traffic simulator and was successfully reflected in the change in vehicle emissions and air quality. It can be claimed that this approach allows to fully evaluate the impact of traffic management schemas in realistic traffic situations.

Besides, the new integrated framework also set a ground for implementing the TraCI controller which succeeded in measuring the traffic situations in the network and changed the status of traffic-related elements (the traffic light phase in this research) in real-time. This contribution works as an example for future research to create a generic API for controlling the traffic simulator so that it can be coupled with any other simulator that needs to control the road traffic.

7.2.2 Societal Relevance

This research was initially established based on the phenomenon of inefficient use of bus lanes to discuss the necessity of completely separating buses and cars. Therefore this research designed the new bus lane policy, dynamic bus lane, which allows private traffic to use the bus lane during specific periods of the day. According to the simulation results, an appropriate opening of bus lanes (no matter it is open during peak or off-peak hours) can make better use of the road capacity, and lead passenger cars from normal lanes or even other roads into bus lanes. This additional private traffic part did not have a significant impact on the operation of buses. On the contrary, due to the improvement of overall road traffic efficiency, the operation of buses has also been improved. From the perspective of overall social welfare, the necessity to entirely separate public and private transport is worthy of further discussion in future urban planning.

Furthermore, as a compensation measure for the dynamic bus lane policy, the adaptive traffic light system was designed to mitigate the possible deteriorating effects on the bus caused by additional passenger cars on the bus lane. However, next to priority signals, there are many other options for raising the priority of public transport, such as refurbishing bus lanes and bus stops[19], setting up bus gates or transit malls. They were not considered in this research because in the study area, the Veldmaarschalk Montgomerylaan road was refurbished several years ago and the bus lanes were separated from normal lanes by vegetations. It would be unreasonable to rebuild the existing roads into the old configuration (bus lanes and bus stops were placed at roadsides in the corresponding direction instead of the separated bus lanes). Besides, the expenses of setting up bus gates or transit malls would be too high. However, these are the characteristics of the chosen study area, when future research looks into different locations, the local attributes are ought to be taken into account, and other public transport priority measures could be reasonable alternatives.

Moreover, the adopted traffic simulation methodology can well reflect those driving situations that drivers do not rely entirely on the live traffic update navigation software for route choices because the passenger cars were not able to change their routes according to the expected congestions during the simulation.

7.2.3 Limitations

During the research process, several limitations regarding different aspects of the study have been identified:

First of all, regarding the demand generation of traffic simulation, a notable limitation was the compatibility caused by the different granularities of the traffic analysis zone (TAZ) unit in Albatross and SUMO. The OD matrices generated from Albatross are composed of 4-digit postal code areas (PCA) whose unit was too coarse to be directly imported into SUMO while the origins or destinations of trips in the SUMO simulator are specific streets. The main reason for this phenomenon is that the original activity-trip data used to train the Albatross system is in units of 4-digit PCA. Although this gap was bridged by an ingenious way in this study, it inevitably lost part of the information (e.g., the departure time of the trip) during the importation. For the SUMO simulator, the ideal OD input data should indicate the specific departure and arrival streets. Only in this case can the traffic be simulated as close to reality as possible.

The second limitation is the inevitable estimation, assumption or even neglect of some parameters due to lack of data. For instance, the traffic light controllers set in the Eindhoven city are working in combination with induction loops, which would turn these traffic signals into intelligent traffic light system (iVRs) (Gemeente Eindhoven, 2018; SynchroniCity, 2020) to analyze traffic patterns and adapt traffic light phases for vulnerable groups. However, the algorithms running in these controllers and sensors were not open to the public, causing the fact the traffic light plans in the simulation had to adopt the default plan set in SUMO. Assumptions were made when calculating the dwell time for each bus

[19] Refurbishment of lanes and bus stops here refers placing the bus lanes and stops in the outermost lane at two sides of the road instead of the current lane distribution where the bus lanes are completely separated from the normal lanes by vegetations.

stop, computing total driven mileage by vehicle count and street length, or extracting some infrastructure design parameters (i.e., the contour of roadside buildings and vegetations) as mentioned earlier. Besides, one part of emission sources (the stationary sources, e.g., central heating systems and electrical power plants), the aerodynamic effects of street/building geometry and traffic-induced turbulence, the chemistry change process of pollutants, and different pollutant deposition velocities in different weathers were ignored due to lack of data when modelling air quality.

A more notable limitation of the research is the validation process that only included the comparison between simulated bus operating situations and pollutant concentrations with actual data. As mentioned before, the simulation results of the baseline scenario were not perfectly consistent with reality, which could be explained by the imperfect simulation methods but also it may be due to the shortcomings of the selected validation indices. To be specific, the bus traffic only accounted for a small part of the total traffic (a few hundred bus trips to tens of thousands of private car trips), such verification indicator (bus deviation time) may lack sufficient representativeness. Also, the existence of a significant difference between simulated pollutant concentrations and monitored air quality from monitoring stations was explained in section 5.5.2.

Another disadvantage lies in air quality modelling, which was brought by the restrictions of the GRAL simulator. Due to the fact it only provided several pollutant options which were not much overlapped with VERSIT+ database, and it cannot simulate multiple pollutants simultaneously, only one pollutant was selected to be simulated and represent the air quality. If multiple pollutants can be computed at the same time in GRAL or there are other suitable open dispersion modelling tools, it is better to set up a complete evaluation system which covers more pollutants and considers the pollution degree to people and therefore is able to generate more comprehensive results like Air Quality Index.

Lastly, note that in this study, only a short-term impact of the proposed traffic management schemas was simulated, that is, only the routes of vehicles were influenced and changed through different scenarios. If the time factor is taken into consideration, traffic participants can possibly switch their transport modes for a better commuting experience from a mid or long-term perspective. For instance, if the dynamic bus lane strategy proposed in the scenario analysis is implemented in reality, the congestions on the road will decrease from a short-term perspective. However, since there are fewer congestions on the road, the desire of travellers to use their cars will gradually raise for shorter commuting time and more comfortable commuting environment, which would decrease the attractiveness of public transport and increase the number of vehicles on the road, consequently bringing more congestions, vehicle emissions and pollutant concentrations on the road. In the end, although a new balance between private traffic and public transport will be achieved, it will show an opposite expectation out of the original intention of the designed strategy from a mid or long-term perspective. Figure 67 depicts the complete system dynamic loops for this phenomenon based on Figure 54.

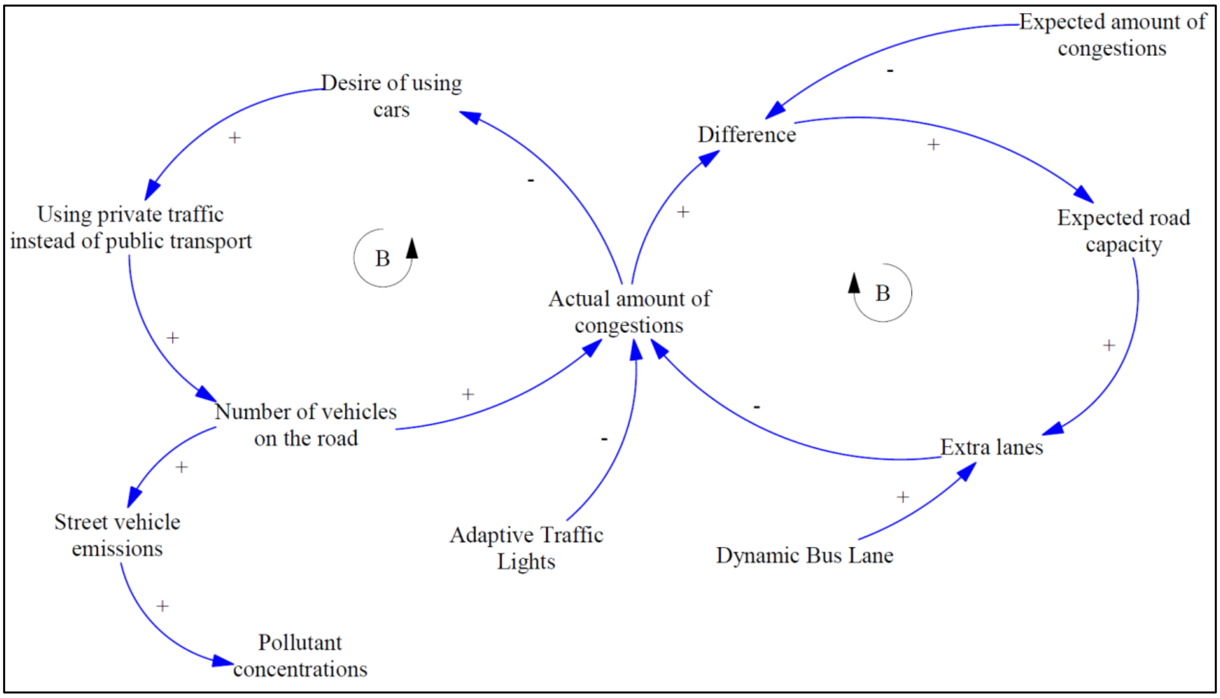

***Figure 67** Complete system dynamic loops of the adopted strategies with the consideration of time factor (+ for positive feedback; - for negative feedback; B for balancing loops).*

Hence, the results are therefore expected to be slightly conservative as the time factor was not considered in the study, let alone the consideration on active transport modes (cycling and walking) on this basis, which leaves an interesting topic for future research.

7.2.4 Recommendations

For future research

Five limitations that pointed out the shortcomings of this research could be the first part to be improved in future research. Secondly, other traffic management strategies could be the research object and investigated thoroughly. Thirdly, a trade-off between the level of detail and the computation accuracy should be carefully weighed when selecting the simulation models. Fourthly, the integrated framework of three simulation models can be extended further to incorporate more models. For instance, if an additional health impact model that can estimate the exposure of pedestrians and cyclists to roadside vehicle emissions is included and provided with the generated air quality conditions, it can feed those data back to the traffic simulation model. This allows traffic participants to consider outdoor environment quality and choose a proper transport mode (shown as dash lines in Figure 68). In this case, the algorithm of the integrated framework will become a self-updated loop, making the results continuously updated and close to reality.

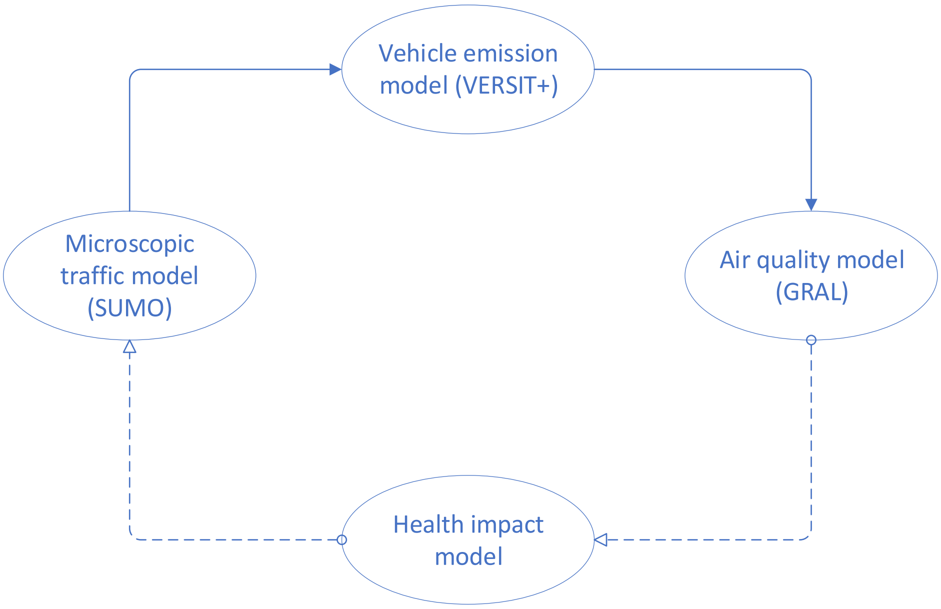

Figure 68 *A proposed integrated framework for future work.*

For urban planners

The balance between public transport and private traffic should be thought twice when designing a traffic management schema. Excessive emphasis on the priority of public transport may lead to a result that the actual situations are different or even opposite to the original intention of the policy.

For traffic engineers

Simulations are often used to test new systems before implementing them into the real world. The methodology proposed in this research would be helpful and provide them with a vivid example of how to set up a simulation environment through simulation methods by open data and open simulators. Not only the bus lane policy which was evaluated in this research but also other traffic management schemas (e.g., private traffic restriction measures, parking pricing, and more) or elements (e.g., bus transit malls, traffic lights, and more) can be tested before the implementation.

For bus operating companies

Although public transport is designed for the “public”, which inevitably adds the social welfare attribute to the bus operating companies, they can still use simulation methodology to evaluate the possible impacts of future traffic management policies on bus operations. If using it correctly, the companies can plan their operation plans (e.g., bus schedules, shift to electric buses) in advance to achieve the goal of reducing expenditure and increasing revenue.

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APPENDICES

APPENDIX A EXPLANATION TO DATA PREPARATION

A.1 Network Data Model

Table 1 *Lane object attributes.*

Attributes Name	Value Type	Default	Description
LaneID	id (string)	-	The name of the lane.
LaneIndex	integer	0	The enumeration index of the lane (0 is the rightmost lane, -1 is the leftmost one).
Allow	list of vehicle classes (enum)	-	List of permitted vehicle classes.
Disallow	list of vehicle classes (enum)	-	List of forbidden vehicle classes.
Speed	float	-	The maximum speed allowed on the lane (in m/s).
Width	float	-1.00	The width for the lane (used for visualization) (in meter).

Table 2 *Connection object attributes.*

Attributes Name	Value Type	Default	Description
From	referenced edge id (string)	-	The name of the edge the vehicles leave.
To	referenced edge id (string)	-	The name of the edge the vehicles may reach when leaving "from".
FromLane	Integer	0	The lane index of the incoming lane.
ToLane	Integer	0	The lane index of the outgoing lane.
KeepClear	Boolean	“True”	If set to false, vehicles which pass this (lane-2-lane) connection) will not worry about blocking the intersection.

Table 3 *Junction object attributes.*

Attributes Name	Value Type	Default	Description
JunctionID	id (string)	-	The name of the node.
Type	enum	"priority"	An optional type for the node.
X-position	Float	-	The x-position of the node on the plane in meters.
Y-position	float	-	The y-position of the node on the plane in meters.
TlType	enum	"static”	An optional type for the traffic light algorithm.
Tl	id(string)	-	An optional id for the traffic light program. Nodes with the same tl-value will be joined into a single program.
Radius	positive float	1.5	Optional turning radius (for all corners) for that node (in meter).

***Table 4** Edge object attributes.*

Attributes Name	Value Type	Default	Description
EdgeID	id (string)	-	The id of the edge (must be unique).
From	referenced node id (string)	-	The name of a node within the nodes-file the edge shall start at.
To	referenced node id (string)	-	The name of a node within the nodes-file the edge shall end at.
NumLanes	integer	1	The number of lanes of the edge.
Speed	float	-	The maximum speed allowed on the edge (in m/s).
Priority	integer	-1	The priority of the edge.
Type	referenced type id (string)	-	The name of a type within the SUMO edge type file.
Allow	list of vehicle classes (enum)	-	List of permitted vehicle classes.
Disallow	list of vehicle classes (enum)	-	List of forbidden vehicle classes.
Width	float	-1.00	Lane width for all lanes of this edge (used for visualization) (in meter).

A.2 Private Traffic Data Model

Table 5 *Passenger car object attributes.*

Attributes Name	Value Type	Default	Description
VehicleID	id (string)	-	The name of the vehicle.
VehicleType	string	“car”	The id of the vehicle type to use for this vehicle.
Route	string	-	The edge id list that the bus is going to follow.
DepartTime	float	-	The time at which the vehicle shall enter the network.
DepartLane	string	“free”	The lane on which the vehicle shall be inserted. default: "first"
DepartSpeed	string	“max”	The speed with which the vehicle shall enter the network.

Table 6 *OD matrix object attributes.*

Attributes Name	Value Type	Default	Description
Origin	string	-	The id of the origin TAZ.
Destination	string	-	The id of the destination TAZ.
TripNum	integer	-	The number of trips with the same origin and the same destination.

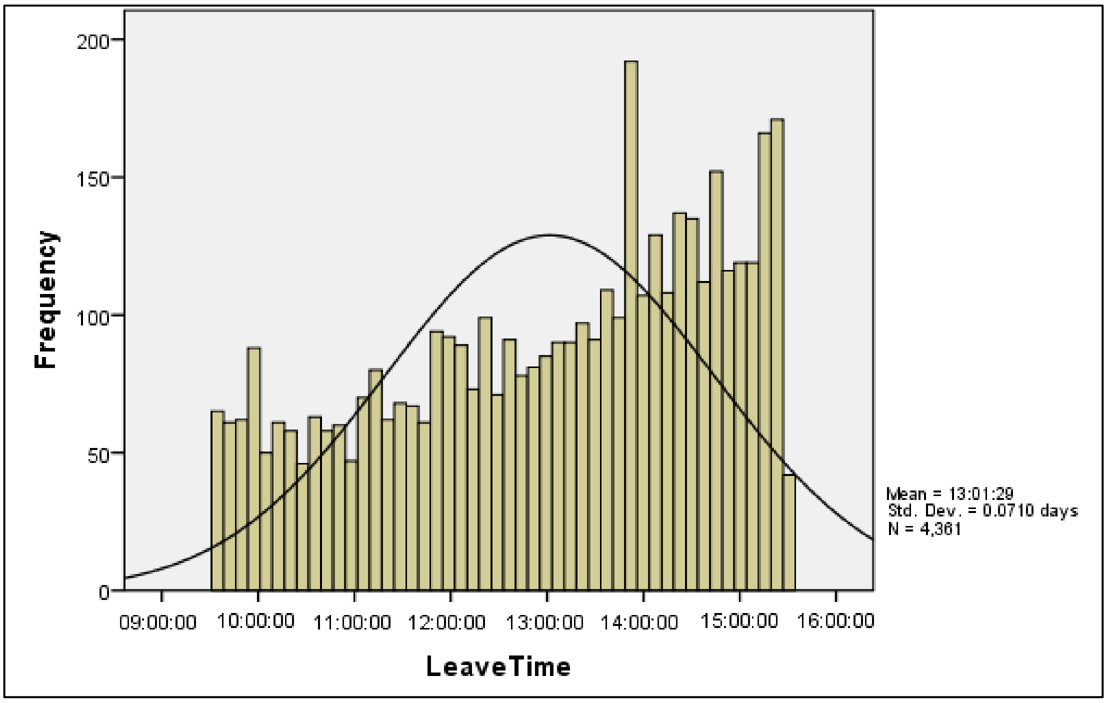


Figure 1 *Histograms of trips happened during daytime off-peak hours by LeaveTime.*

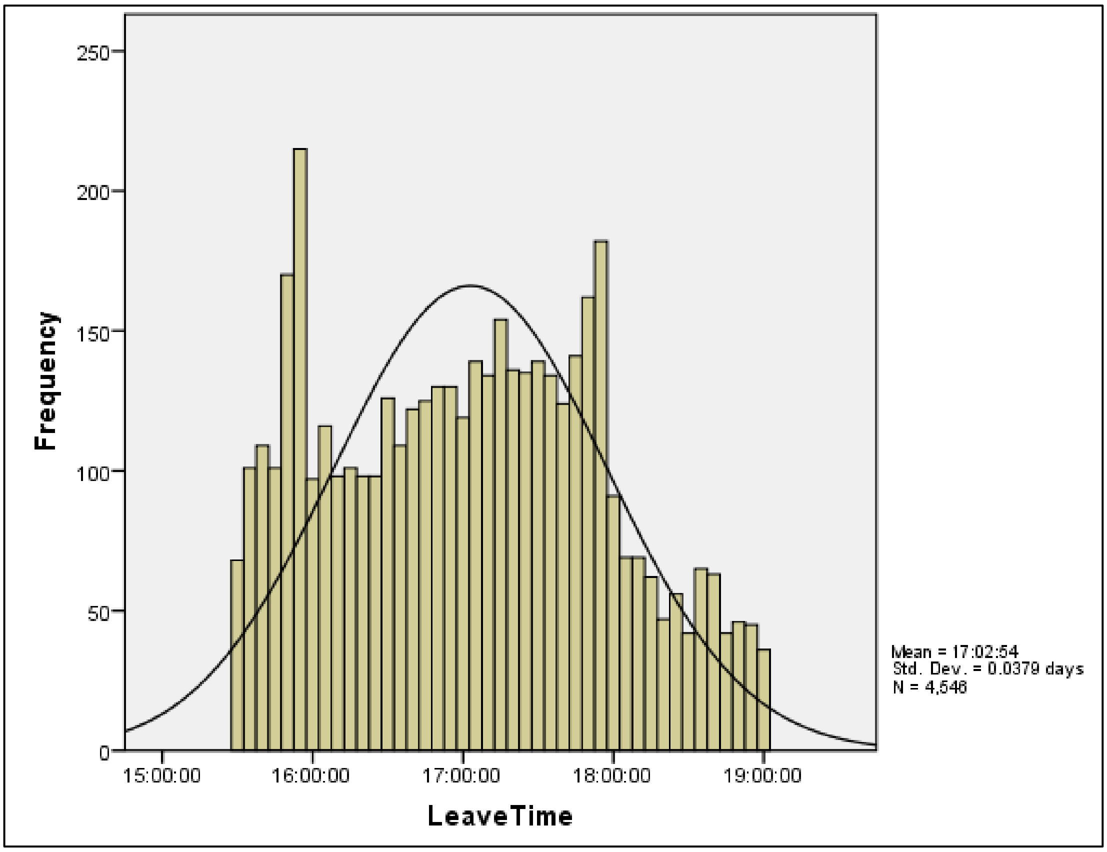


***Figure 2** Histograms of trips happened during evening peak hours by LeaveTime.*

A.3 Public Transport Data Model

***Table 7** Bus schedule object attributes.*

Attributes Name	Value Type	Default	Description
Day	string	“weekday”	The day of the week.
Line	string	-	The line number of bus routes.
DepartureTime	time	-	The departure time for the bus.

***Table 8** Bus flow object attributes.*

Attributes Name	Value Type	Default	Description
FlowID	id (string)	-	The name of the flow.
VehicleType	string	“bus”	The id of the vehicle type to use for this vehicle.
From	string	-	The id of the begin edge.
To	string	-	The is of the end edge.
Line	string	-	The line number of bus routes.
Begin	integer	-	The begin time to insert the flow.
End	integer	-	The end time to close the flow.
Period	integer	-	The interval time between inserted vehicles.

***Table 9** Bus stop object attributes.*

Attributes Name	Value Type	Default	Description
BusStopID	id (string)	-	The ID of the bus stop; must be unique.
LaneID	string	-	The name of the lane the bus stop shall be located at.
StartPos	float	-	The begin position on the lane (the lower position on the lane) in meters.
EndPos	float	lane.length	The end position on the lane (the higher position on the lane) in meters, must be larger than startPos by more than 0.1m.
Name	string	-	Bus stop name. This is only used for visualization purposes.
Lines	string list	-	Meant to be the names of the bus lines that stop at this bus stop. This is only used for visualization purposes.
Duration	integer	30	The dwell time set at each bus stop (in seconds).
PersonCapacity	integer	-	The passenger capacity of the bus stop.
FriendlyPos	boolean	“false”	Whether invalid stop positions should be corrected automatically.

***Table 10** Bus technical specifications.*

Type	CITEA SLFA-181 Electric
Overall length	18,150 mm
Overall width	2,550 mm
Overall height*	3,290 mm
Wheelbase	5,250 mm
Wheelbase 2nd and 3rd axle	6,750 mm
Front overhang	2,750 mm
Rear overhang	3,400 mm
Interior saloon height (low floor)	2,416 mm
Turning circle	23,360 mm
Unladen vehicle weight**	+/- 19,150kg
Max. total technical weight***	29,000 kg
Capacity (passengers)**	+/- 133

* Including roof skirts, excluding optional pantograph.
** Kerb weight and capacity depend on the selected battery pack.
*** According to European legislation, individual country legislation may differ.

A.4 Vehicle Type

***Table 11** Vehicle type object attributes.*

Attributes Name	Value Type	Default	Description
ID	id (string)	-	The name of the vehicle type.
Acceleration	float	2.6	The acceleration ability of vehicles of this type (in m/s^2).
Deceleration	float	4.5	The deceleration ability of vehicles of this type (in m/s^2).
Length	float	5.0	The vehicle's **net** length (length) (in m).
MinGap	float	2.5	Empty space after leader (in m).
MaxSpeed	float	55.55 (200 km/h) for vehicles, 1.39 (5 km/h) for pedestrians	The vehicle's maximum velocity (in m/s).
VehicleClass	class (enum)	"passenger"	An abstract vehicle class.
LaneChangeModel	lane changing model name (string)	"LC2013"	The model used for changing lanes.
CarFollowModel	car following model name (string)	"Krauss"	The model used for car following.
PersonCapacity	integer	4	The number of persons (excluding an autonomous driver) the vehicle can transport.
BoardingDuration	float	0.5	The time required by a person to board the vehicle.

***Table 12** The number of vehicles according to vehicle type (CBS, 2020; CBS & RDW, 2020).*

Vehicle Type			Year								
			2018			2019			2020		
Passenger cars	Total		8,373,244			8,530,584			8,677,911		
	Gasoline			6,649,496			6,804,125			6,954,271	
	Diesel			1,306,960			1,275,081			1,193,136	
	LPG			132,989			123,669			115,039	
	Electricity			271,785			314,563			402,205	
	CNG			9,001			9,890			9,799	
	Other/ Unknown			3,013			3,256			3,461	
Commercial vehicles	Total		2,252,134			2,299,373			2,345,661		
	Commercial motor vehicles	Total		1,092,291			1,126,630			1,152,931	
		Delivery van			883,350			914,766			939,801
		Lorry			62,581			62,963			63,081
		Road tractor			77,075			80,078			81,553
		Special purpose vehicle			59,371			59,106			58,620
		Bus			9,914			9,717			9,876
	Trailers and semi-trailers	Total		1,159,843			1,172,743			1,192,730	
		Trailer			1,002,771			1,008,731			1,024,217
		Semi-trailer			157,072			164,012			168,513
Motorcycle	Total		661,639			665,880			679,848		
Total			11,287,017			11,495,837			11,703,420		

Table 13 *Vehicle type descriptions.*

Vehicle Type	Description
Passenger cars	Road motor vehicle, other than a moped or a motorcycle, intended for the carriage of passengers and designed to seat no more than nine persons (including the driver). Included are: passenger cars; vans designed and used primarily for transport of passengers; taxis; hire cars; ambulances; motor homes.
Commercial vehicles	Vehicle exclusively or primarily designed for the commercial transport of goods and passengers, for special purposes or to haul semi-trailers. Included are: vans, lorries, road tractors, special purpose vehicles, buses, trailers and semi-trailers.
Motorcycles	Two-, three- or four-wheeled road motor vehicle not exceeding 400 kg (900lb) of unladen weight. All such vehicles with a cylinder capacity over 50 cc are included, as are those under 50 cc which do not meet the definition of moped.

A.5 VERSIT Class Coding System

Table 14 *The coding rules of VERSIT class.*

Property	Categorization
Weight class	L: light M: medium Z: heavy B: bus
Vehicle type	AB: bus BA: light commercial vehicle BF: moped MF: motorbike PA: passenger car PH: full-hybrid passenger car PE: plug-in hybrid passenger car VA: truck TR: tractor
Fuel type	B: petrol D: diesel L: LPG C: CNG and LNG A: Ethanol (E85) E: Electric
Environment class	PR82: vehicles older than 1982 19** : vehicles younger than 1981 and older than 1993 O3WC: non-regulated 3-way catalyst R3WC: regulated 3-way catalyst EDE5: first generation Euro-V heavy-duty EUG5: second generation Euro-V heavy-duty EEV5: Euro-5 EEV, for buses only Euro-0 up to Euro-6
Extra info	ANH: with trailer DPF: closed or wall-flow diesel particulate filter HOF: retrofitted half-open DPF LCH: indicating a segment of light vehicles within an overall vehicle type; distinction on the basis of gross vehicle mass for LBADs and MVAs, and for trailers combined with MVAs and ZTRs. ZWA: indicating a segment of heavy vehicles within an overall vehicle type; distinction on the basis of gross vehicle mass for LBADs and MVAs, and for trailers combined with MVAs and ZTRs. EGR: Exhaust Gas Recirculation SCR: Selective Catalytic Reduction RET: CNG retrofit category

A.6 Basic Emission Factors for Road Traffic (2018)

***Table 15** Emission factors per VERSIT class per road type.*

Versit+ class	Vehicle category	Fuel type	Environment class	Manufacture year(s)	CO			VOC for combustion (CH4 included)			NOx			PM10 for combustion			NH3			N2O			EC			CO2		
					RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3	RT1	RT2	RT3
					grams/vehicle km																							
BABEZEEV	Bus	Electricity	-	all	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LPABEUR1	Passenger car	Petrol	Euro-1	1993-1996	10.033	4.575	1.655	0.636	0.304	0.081	0.724	0.475	0.250	0.007	0.007	0.002	0.070	0.132	0.074	0.027	0.013	0.008	0.002	0.002	0.001	288.200	140.600	203.400
LPABEUR2	Passenger car	Petrol	Euro-2	1995-2000	10.683	4.399	3.407	0.513	0.233	0.065	0.468	0.213	0.198	0.005	0.002	0.005	0.085	0.149	0.084	0.017	0.004	0.002	0.001	0.001	0.001	284.700	143.300	203.000
LPABEUR3	Passenger car	Petrol	Euro-3	2000-2004	6.647	3.291	1.885	0.437	0.215	0.022	0.300	0.300	0.300	0.002	0.001	0.002	0.058	0.030	0.065	0.006	0.002	0.001	0.000	0.000	0.000	254.600	152.600	203.600
LPABEUR4	Passenger car	Petrol	Euro-4	2003-2010	5.615	2.873	1.652	0.420	0.212	0.019	0.259	0.254	0.252	0.002	0.001	0.002	0.038	0.029	0.065	0.003	0.001	0.001	0.000	0.000	0.000	235.900	149.200	194.800
LPABEUR5	Passenger car	Petrol	Euro-5	2009-2014	4.492	2.299	1.322	0.336	0.169	0.015	0.043	0.020	0.012	0.002	0.001	0.002	0.018	0.029	0.065	0.003	0.001	0.001	0.000	0.000	0.000	213.200	134.900	176.100
LPABEUR6	Passenger car	Petrol	Euro-6	2014 and later	4.492	2.299	1.322	0.336	0.169	0.015	0.043	0.020	0.012	0.002	0.001	0.002	0.009	0.029	0.065	0.003	0.001	0.001	0.000	0.000	0.000	191.000	120.800	157.700
LPADEUR1	Passenger car	Diesel	Euro-1	1991-1996	1.279	0.411	0.169	0.230	0.090	0.044	1.058	0.453	0.694	0.236	0.101	0.081	0.001	0.001	0.001	0.002	0.004	0.004	0.165	0.071	0.057	243.500	131.900	186.900
LPADEUR2	Passenger car	Diesel	Euro-2	1996-2000	0.716	0.241	0.061	0.124	0.043	0.017	0.800	0.548	0.666	0.111	0.045	0.092	0.003	0.003	0.003	0.004	0.006	0.006	0.089	0.036	0.074	245.900	135.900	182.700
LPADEUR3	Passenger car	Diesel	Euro-3	2000-2006	0.404	0.172	0.010	0.026	0.013	0.005	0.796	0.549	0.702	0.031	0.026	0.052	0.003	0.003	0.003	0.011	0.004	0.004	0.027	0.022	0.044	231.000	140.400	184.800
LPADEUR3HOF	Passenger car	Diesel	Euro-3 half open particulate filter	2000-2006	0.404	0.172	0.010	0.026	0.013	0.005	0.796	0.549	0.702	0.020	0.017	0.034	0.003	0.003	0.003	0.011	0.004	0.004	0.016	0.013	0.027	231.000	140.400	184.800
LPADEUR4	Passenger car	Diesel	Euro-4	2005-2009	0.501	0.140	0.020	0.011	0.005	0.004	0.431	0.376	0.515	0.033	0.016	0.035	0.002	0.002	0.002	0.011	0.004	0.004	0.026	0.013	0.035	248.800	128.800	191.100
LPADEUR4DPF	Passenger car	Diesel	Euro-4 closed particulate filter	2005-2011	0.501	0.140	0.020	0.011	0.005	0.004	0.431	0.376	0.515	0.001	0.001	0.001	0.002	0.002	0.002	0.011	0.004	0.004	0.001	0.001	0.000	248.800	128.800	191.100
LPADEUR4HOF	Passenger car	Diesel	Euro-4 half open particulate filter	2005-2011	0.501	0.140	0.020	0.011	0.005	0.004	0.431	0.376	0.515	0.021	0.011	0.023	0.002	0.002	0.002	0.011	0.004	0.004	0.017	0.008	0.023	248.800	128.800	191.100
LPADEUR5	Passenger car	Diesel	Euro-5	2008-2014	0.035	0.020	0.008	0.006	0.004	0.003	0.675	0.531	0.588	0.001	0.001	0.002	0.002	0.002	0.002	0.011	0.004	0.004	0.001	0.001	0.001	188.100	148.600	153.400
LPADEUA6	Passenger car	Diesel	Euro-6A	2014 and later	0.000	0.000	0.000	0.016	0.010	0.010	0.428	0.344	0.410	0.001	0.001	0.002	0.001	0.000	0.000	0.011	0.004	0.004	0.001	0.001	0.001	180.600	134.600	135.800
LPALPR82MED	Passenger car	LPG	Pre-Euro medium weight	before 1983	4.616	1.829	1.223	1.759	1.174	2.377	1.408	1.321	2.458	0.027	0.021	0.044	0.002	0.002	0.002	0.000	0.000	0.000	0.005	0.004	0.009	282.600	168.600	138.300
LPALPR82ZWA	Passenger car	LPG	Pre-Euro heavy	before 1983	5.386	2.152	1.334	2.372	1.569	2.814	1.776	1.722	2.943	0.024	0.019	0.039	0.002	0.002	0.002	0.000	0.000	0.000	0.005	0.004	0.008	282.600	168.600	138.300
LPALEUR1	Passenger car	LPG	Euro-1	1993-1996	13.912	5.633	1.275	0.927	0.428	0.112	0.910	0.727	0.577	0.009	0.005	0.005	0.070	0.132	0.074	0.027	0.013	0.008	0.002	0.001	0.001	247.500	173.900	149.800
LPALEUR2	Passenger car	LPG	Euro-2	1995-2000	7.198	3.133	1.404	0.464	0.220	0.026	1.225	0.334	0.435	0.009	0.005	0.005	0.085	0.149	0.084	0.016	0.003	0.002	0.002	0.001	0.001	237.700	131.400	187.300
LPALEUR3	Passenger car	LPG	Euro-3	2000-2004	4.618	2.665	1.323	0.369	0.171	0.016	0.412	0.205	0.167	0.005	0.002	0.005	0.058	0.030	0.065	0.006	0.002	0.001	0.001	0.000	0.001	231.800	130.600	185.500
LPALEUR4	Passenger car	LPG	Euro-4	2003-2010	2.644	1.475	1.371	0.315	0.160	0.027	0.181	0.089	0.102	0.004	0.002	0.005	0.038	0.029	0.065	0.006	0.002	0.001	0.001	0.000	0.001	218.700	115.100	185.700
LPALEUR5	Passenger car	LPG	Euro-5	2009-2014	2.115	1.180	1.097	0.252	0.128	0.021	0.144	0.071	0.082	0.004	0.002	0.005	0.018	0.029	0.065	0.006	0.002	0.001	0.001	0.000	0.001	197.700	104.100	167.900
LPALEUR6	Passenger car	LPG	Euro-6	2014 and later	2.115	1.180	1.057	0.252	0.128	0.021	0.144	0.071	0.079	0.004	0.002	0.005	0.009	0.029	0.065	0.006	0.002	0.001	0.001	0.000	0.001	178.600	94.000	149.100
LPACEUR1	Passenger car	CNG	Euro-1	1992-1994	8.868	4.031	1.655	0.574	0.275	0.081	0.520	0.343	0.183	0.067	0.007	0.002	0.070	0.132	0.074	0.027	0.013	0.008	0.017	0.002	0.001	220.800	107.700	155.800
LPACEUR2	Passenger car	CNG	Euro-2	1995-2000	9.886	4.027	3.407	0.456	0.207	0.065	0.318	0.145	0.133	0.005	0.002	0.005	0.085	0.149	0.084	0.017	0.004	0.002	0.001	0.001	0.001	218.100	109.700	155.500
LPACEUR3	Passenger car	CNG	Euro-3	2000-2004	6.647	3.291	1.885	0.437	0.215	0.022	0.148	0.059	0.036	0.005	0.002	0.005	0.058	0.030	0.065	0.006	0.002	0.001	0.001	0.000	0.001	195.100	116.900	156.000
LPACEUR4	Passenger car	CNG	Euro-4	2003-2010	2.334	1.492	1.164	0.396	0.186	0.084	0.163	0.071	0.057	0.005	0.002	0.005	0.038	0.029	0.065	0.003	0.001	0.001	0.001	0.000	0.001	190.800	99.300	156.400
LPACEUR5	Passenger car	CNG	Euro-5	2008-2013	1.867	1.193	0.931	0.317	0.149	0.067	0.130	0.057	0.046	0.004	0.002	0.005	0.018	0.029	0.065	0.003	0.001	0.001	0.001	0.000	0.001	172.500	89.700	141.400
LPACEUR6	Passenger car	CNG	Euro-6	2014 and later	1.867	1.193	0.895	0.317	0.149	0.065	0.130	0.057	0.044	0.004	0.002	0.005	0.009	0.029	0.065	0.003	0.001	0.001	0.001	0.000	0.001	155.800	81.100	125.500
LPAEZEEV	Passenger car	Electricity	-	all	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

RT 1 = Urban Areas
RT 2 = Rural Roads
RT 3 = Motorway

A.7 Prepared OD Matrices

***Table 16** The prepared OD matrix during morning peak hours (06:30 – 09:30).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	**5612**	**73**	**5622**	**5611**	**53**	**5625**	**5611**	**93**
20	11	5	17	20	53	16	20	93
20	12	2						
20	13	4						
20	14	1						
20	15	1						
20	19	60						
5611	**5622**	**38**	**5622**	**5612**	**77**	**5625**	**5612**	**100**
20	17	38	17	11	5	16	11	7
			17	12	2	16	12	3
			17	13	4	16	13	5
			17	14	1	16	14	1
			17	15	1	16	15	1
			17	19	63	16	19	82
5611	**5623**	**63**	**5622**	**5623**	**33**	**5625**	**5622**	**11**
20	1	5	17	1	3	16	17	11
20	2	2	17	2	1			
20	3	4	17	3	2			
20	4	19	17	4	10			
20	5	3	17	5	2			
20	6	4	17	6	2			
20	7	9	17	7	5			
20	8	6	17	8	3			
20	9	1	17	9	0			
20	10	9	17	10	5			
5611	**5625**	**30**	**5622**	**5625**	**12**	**5625**	**5623**	**35**
20	16	30	17	16	12	16	1	3
						16	2	1
						16	3	2
						16	4	10
						16	5	2
						16	6	2
						16	7	5
						16	8	3
						16	9	0
						16	10	5
5611	**5631**	**25**	**5622**	**5631**	**9**	**5625**	**5631**	**11**
20	18	25	17	18	9	16	18	11
5612	**5611**	**91**	**5623**	**5611**	**59**	**5631**	**5611**	**15**
11	20	6	1	20	5	18	20	15
12	20	3	2	20	2			
13	20	5	3	20	4			
14	20	1	4	20	18			
15	20	1	5	20	3			
19	20	75	6	20	4			
			7	20	9			
			8	20	6			
			9	20	1			
			10	20	9			
5612	**5612**	**609**	**5623**	**5612**	**58**	**5631**	**5612**	**31**
11	11	3	1	11	0	18	11	2
11	12	1	1	12	0	18	12	1
11	13	2	1	13	0	18	13	2
11	14	0	1	14	0	18	14	0
11	15	0	1	15	0	18	15	0
11	19	35	1	19	4	18	19	26
12	11	1	2	11	0			
12	12	1	2	12	0			
12	13	1	2	13	0			
12	14	0	2	14	0			
12	15	0	2	15	0			
12	19	16	2	19	2			
13	11	2	3	11	0			
13	12	1	3	12	0			
13	13	2	3	13	0			
13	14	0	3	14	0			
13	15	0	3	15	0			
13	19	27	3	19	3			
14	11	0	4	11	1			
14	12	0	4	12	1			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
14	13	0	4	13	1			
14	14	0	4	14	0			
14	15	0	4	15	0			
14	19	6	4	19	14			
15	11	0	5	11	0			
15	12	0	5	12	0			
15	13	0	5	13	0			
15	14	0	5	14	0			
15	15	0	5	15	0			
15	19	6	5	19	3			
19	11	35	6	11	0			
19	12	16	6	12	0			
19	13	27	6	13	0			
19	14	6	6	14	0			
19	15	6	6	15	0			
19	19	413	6	19	3			
			7	11	1			
			7	12	0			
			7	13	0			
			7	14	0			
			7	15	0			
			7	19	7			
			8	11	0			
			8	12	0			
			8	13	0			
			8	14	0			
			8	15	0			
			8	19	4			
			9	11	0			
			9	12	0			
			9	13	0			
			9	14	0			
			9	15	0			
			9	19	1			
			10	11	1			
			10	12	0			
			10	13	0			
			10	14	0			
			10	15	0			
			10	19	7			
5612	**5622**	**17**	**5623**	**5622**	**35**	**5631**	**5622**	**24**
11	17	1	1	17	3	18	17	24
12	17	1	2	17	1			
13	17	1	3	17	2			
14	17	0	4	17	10			
15	17	0	5	17	2			
19	17	14	6	17	2			
			7	17	5			
			8	17	3			
			9	17	0			
			10	17	5			
5612	**5623**	**38**	**5623**	**5623**	**499**	**5631**	**5623**	**21**
11	1	0	1	1	3	18	1	2
11	2	0	1	2	2	18	2	1
11	3	0	1	3	3	18	3	1
11	4	1	1	4	12	18	4	6
11	5	0	1	5	2	18	5	1
11	6	0	1	6	3	18	6	1
11	7	0	1	7	6	18	7	3
11	8	0	1	8	4	18	8	2
11	9	0	1	9	0	18	9	0
11	10	0	1	10	6	18	10	3
12	1	0	2	1	2			
12	2	0	2	2	1			
12	3	0	2	3	1			
12	4	0	2	4	6			
12	5	0	2	5	1			
12	6	0	2	6	1			
12	7	0	2	7	3			
12	8	0	2	8	2			
12	9	0	2	9	0			
12	10	0	2	10	3			
13	1	0	3	1	3			
13	2	0	3	2	1			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
13	3	0	3	3	2			
13	4	1	3	4	10			
13	5	0	3	5	2			
13	6	0	3	6	2			
13	7	0	3	7	5			
13	8	0	3	8	3			
13	9	0	3	9	0			
13	10	0	3	10	5			
14	1	0	4	1	12			
14	2	0	4	2	6			
14	3	0	4	3	10			
14	4	0	4	4	44			
14	5	0	4	5	8			
14	6	0	4	6	9			
14	7	0	4	7	21			
14	8	0	4	8	14			
14	9	0	4	9	2			
14	10	0	4	10	22			
15	1	0	5	1	2			
15	2	0	5	2	1			
15	3	0	5	3	2			
15	4	0	5	4	8			
15	5	0	5	5	2			
15	6	0	5	6	2			
15	7	0	5	7	4			
15	8	0	5	8	3			
15	9	0	5	9	0			
15	10	0	5	10	4			
19	1	3	6	1	3			
19	2	1	6	2	1			
19	3	2	6	3	2			
19	4	9	6	4	9			
19	5	2	6	5	2			
19	6	2	6	6	2			
19	7	5	6	7	5			
19	8	3	6	8	3			
19	9	0	6	9	0			
19	10	5	6	10	5			
			7	1	6			
			7	2	3			
			7	3	5			
			7	4	21			
			7	5	4			
			7	6	5			
			7	7	10			
			7	8	7			
			7	9	1			
			7	10	11			
			8	1	4			
			8	2	2			
			8	3	3			
			8	4	14			
			8	5	3			
			8	6	3			
			8	7	7			
			8	8	4			
			8	9	1			
			8	10	7			
			9	1	0			
			9	2	0			
			9	3	0			
			9	4	2			
			9	5	0			
			9	6	0			
			9	7	1			
			9	8	1			
			9	9	0			
			9	10	1			
			10	1	6			
			10	2	3			
			10	3	5			
			10	4	22			
			10	5	4			
			10	6	5			
			10	7	11			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
			10 10 10	8 9 10	7 1 11			
5612	**5625**	**25**	**5623**	**5625**	**22**	**5631**	**5625**	**11**
11 12 13 14 15 19	16 16 16 16 16 16	2 1 1 0 0 21	1 2 3 4 5 6 7 8 9 10	16 16 16 16 16 16 16 16 16 16	2 1 1 7 1 1 3 2 0 3	18	16	11
5612	**5631**	**16**	**5623**	**5631**	**15**	**All**	**All**	**2249**
11 12 13 14 15 19	18 18 18 18 18 18	1 1 1 0 0 13	1 2 3 4 5 6 7 8 9 10	18 18 18 18 18 18 18 18 18 18	1 1 1 4 1 1 2 1 0 2			

***Table 17** The prepared OD matrix during daytime off-peak hours (09:31 – 15:29).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	**5612**	**147**	**5622**	**5611**	**102**	**5625**	**5611**	**139**
20	11	10	17	20	102	16	20	139
20	12	5						
20	13	8						
20	14	2						
20	15	2						
20	19	121						
5611	**5622**	**89**	**5622**	**5612**	**65**	**5625**	**5612**	**87**
20	17	89	17	11	4	16	11	6
			17	12	2	16	12	3
			17	13	3	16	13	5
			17	14	1	16	14	1
			17	15	1	16	15	1
			17	19	54	16	19	72
5611	**5623**	**97**	**5622**	**5623**	**43**	**5625**	**5622**	**24**
20	1	8	17	1	4	16	17	24
20	2	4	17	2	2			
20	3	6	17	3	3			
20	4	29	17	4	13			
20	5	5	17	5	2			
20	6	6	17	6	3			
20	7	14	17	7	6			
20	8	9	17	8	4			
20	9	1	17	9	0			
20	10	14	17	10	6			
5611	**5625**	**122**	**5622**	**5625**	**25**	**5625**	**5623**	**42**
20	16	122	17	16	25	16	1	3
						16	2	2
						16	3	3
						16	4	13
						16	5	2
						16	6	3
						16	7	6
						16	8	4
						16	9	0
						16	10	6
5611	**5631**	**48**	**5622**	**5631**	**23**	**5625**	**5631**	**25**
20	18	48	17	18	23	16	18	25
5612	**5611**	**139**	**5623**	**5611**	**105**	**5631**	**5611**	**51**
11	20	10	1	20	9	18	20	51
12	20	4	2	20	4			
13	20	7	3	20	7			
14	20	2	4	20	31			
15	20	2	5	20	6			
19	20	114	6	20	7			
			7	20	15			
			8	20	10			
			9	20	1			
			10	20	16			
5612	**5612**	**1358**	**5623**	**5612**	**77**	**5631**	**5612**	**67**
11	11	7	1	11	0	18	11	5
11	12	3	1	12	0	18	12	2
11	13	5	1	13	0	18	13	4
11	14	1	1	14	0	18	14	1
11	15	1	1	15	0	18	15	1
11	19	77	1	19	5	18	19	55
12	11	3	2	11	0			
12	12	1	2	12	0			
12	13	2	2	13	0			
12	14	0	2	14	0			
12	15	0	2	15	0			
12	19	36	2	19	2			
13	11	5	3	11	0			
13	12	2	3	12	0			
13	13	4	3	13	0			
13	14	1	3	14	0			
13	15	1	3	15	0			
13	19	60	3	19	4			
14	11	1	4	11	2			
14	12	0	4	12	1			
14	13	1	4	13	1			
14	14	0	4	14	0			
14	15	0	4	15	0			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
14	19	12	4	19	19			
15	11	1	5	11	0			
15	12	0	5	12	0			
15	13	1	5	13	0			
15	14	0	5	14	0			
15	15	0	5	15	0			
15	19	12	5	19	3			
19	11	77	6	11	0			
19	12	36	6	12	0			
19	13	60	6	13	0			
19	14	12	6	14	0			
19	15	12	6	15	0			
19	19	920	6	19	4			
			7	11	1			
			7	12	0			
			7	13	1			
			7	14	0			
			7	15	0			
			7	19	9			
			8	11	0			
			8	12	0			
			8	13	0			
			8	14	0			
			8	15	0			
			8	19	6			
			9	11	0			
			9	12	0			
			9	13	0			
			9	14	0			
			9	15	0			
			9	19	1			
			10	11	1			
			10	12	0			
			10	13	1			
			10	14	0			
			10	15	0			
			10	19	9			
5612	**5622**	**67**	**5623**	**5622**	**57**	**5631**	**5622**	**24**
11	17	5	1	17	5	18	17	24
12	17	2	2	17	2			
13	17	4	3	17	4			
14	17	1	4	17	17			
15	17	1	5	17	3			
19	17	55	6	17	4			
			7	17	8			
			8	17	5			
			9	17	1			
			10	17	8			
5612	**5623**	**64**	**5623**	**5623**	**999**	**5631**	**5623**	**29**
11	1	0	1	1	7	18	1	2
11	2	0	1	2	3	18	2	1
11	3	0	1	3	5	18	3	2
11	4	1	1	4	25	18	4	9
11	5	0	1	5	5	18	5	2
11	6	0	1	6	5	18	6	2
11	7	1	1	7	12	18	7	4
11	8	0	1	8	8	18	8	3
11	9	0	1	9	1	18	9	0
11	10	1	1	10	12	18	10	4
12	1	0	2	1	3			
12	2	0	2	2	1			
12	3	0	2	3	3			
12	4	1	2	4	12			
12	5	0	2	5	2			
12	6	0	2	6	2			
12	7	0	2	7	6			
12	8	0	2	8	4			
12	9	0	2	9	0			
12	10	0	2	10	6			
13	1	0	3	1	5			
13	2	0	3	2	3			
13	3	0	3	3	4			
13	4	1	3	4	20			
13	5	0	3	5	4			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
13	6	0	3	6	4			
13	7	0	3	7	9			
13	8	0	3	8	6			
13	9	0	3	9	1			
13	10	1	3	10	10			
14	1	0	4	1	25			
14	2	0	4	2	12			
14	3	0	4	3	20			
14	4	0	4	4	89			
14	5	0	4	5	16			
14	6	0	4	6	19			
14	7	0	4	7	43			
14	8	0	4	8	28			
14	9	0	4	9	3			
14	10	0	4	10	44			
15	1	0	5	1	5			
15	2	0	5	2	2			
15	3	0	5	3	4			
15	4	0	5	4	16			
15	5	0	5	5	3			
15	6	0	5	6	3			
15	7	0	5	7	8			
15	8	0	5	8	5			
15	9	0	5	9	1			
15	10	0	5	10	8			
19	1	4	6	1	5			
19	2	2	6	2	2			
19	3	3	6	3	4			
19	4	16	6	4	19			
19	5	3	6	5	3			
19	6	3	6	6	4			
19	7	8	6	7	9			
19	8	5	6	8	6			
19	9	1	6	9	1			
19	10	8	6	10	9			
			7	1	12			
			7	2	6			
			7	3	9			
			7	4	43			
			7	5	8			
			7	6	9			
			7	7	21			
			7	8	13			
			7	9	2			
			7	10	21			
			8	1	8			
			8	2	4			
			8	3	6			
			8	4	28			
			8	5	5			
			8	6	6			
			8	7	13			
			8	8	9			
			8	9	1			
			8	10	14			
			9	1	1			
			9	2	0			
			9	3	1			
			9	4	3			
			9	5	1			
			9	6	1			
			9	7	2			
			9	8	1			
			9	9	0			
			9	10	2			
			10	1	12			
			10	2	6			
			10	3	10			
			10	4	44			
			10	5	8			
			10	6	9			
			10	7	21			
			10	8	14			
			10	9	2			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
			10	10	22			
5612	**5625**	**99**	**5623**	**5625**	**39**	**5631**	**5625**	**21**
11	16	7	1	16	3	18	16	21
12	16	3	2	16	2			
13	16	5	3	16	3			
14	16	1	4	16	12			
15	16	1	5	16	2			
19	16	81	6	16	2			
			7	16	6			
			8	16	4			
			9	16	0			
			10	16	6			
5612	**5631**	**58**	**5623**	**5631**	**29**	**All**	**All**	**4361**
11	18	4	1	18	2			
12	18	2	2	18	1			
13	18	3	3	18	2			
14	18	1	4	18	9			
15	18	1	5	18	2			
19	18	48	6	18	2			
			7	18	4			
			8	18	3			
			9	18	0			
			10	18	4			

***Table 18** The prepared OD matrix during evening peak hours (15:30 - 19:00).*

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
5611	**5612**	**179**	**5622**	**5611**	**101**	**5625**	**5611**	**128**
20	11	12	17	20	101	16	20	128
20	12	6						
20	13	10						
20	14	2						
20	15	2						
20	19	147						
5611	**5622**	**111**	**5622**	**5612**	**47**	**5625**	**5612**	**94**
20	17	111	17	11	3	16	11	7
			17	12	2	16	12	3
			17	13	3	16	13	5
			17	14	1	16	14	1
			17	15	1	16	15	1
			17	19	39	16	19	77
5611	**5623**	**118**	**5622**	**5623**	**54**	**5625**	**5622**	**21**
20	1	10	17	1	4	16	17	21
20	2	5	17	2	2			
20	3	8	17	3	4			
20	4	35	17	4	16			
20	5	6	17	5	3			
20	6	7	17	6	3			
20	7	17	17	7	8			
20	8	11	17	8	5			
20	9	1	17	9	1			
20	10	17	17	10	8			
5611	**5625**	**174**	**5622**	**5625**	**24**	**5625**	**5623**	**55**
20	16	174	17	16	24	16	1	5
						16	2	2
						16	3	4
						16	4	16
						16	5	3
						16	6	3
						16	7	8
						16	8	5
						16	9	1
						16	10	8
5611	**5631**	**73**	**5622**	**5631**	**22**	**5625**	**5631**	**34**
20	18	73	17	18	22	16	18	34
5612	**5611**	**143**	**5623**	**5611**	**109**	**5631**	**5611**	**58**
11	20	10	1	20	9	18	20	58
12	20	5	2	20	4			
13	20	8	3	20	7			
14	20	2	4	20	33			
15	20	2	5	20	6			
19	20	118	6	20	7			
			7	20	16			
			8	20	10			
			9	20	1			
			10	20	16			
5612	**5612**	**1266**	**5623**	**5612**	**83**	**5631**	**5612**	**61**
11	11	6	1	11	0	18	11	4
11	12	3	1	12	0	18	12	2
11	13	5	1	13	0	18	13	3
11	14	1	1	14	0	18	14	1
11	15	1	1	15	0	18	15	1
11	19	72	1	19	6	18	19	50
12	11	3	2	11	0			
12	12	1	2	12	0			
12	13	2	2	13	0			
12	14	0	2	14	0			
12	15	0	2	15	0			
12	19	33	2	19	3			
13	11	5	3	11	0			
13	12	2	3	12	0			
13	13	4	3	13	0			
13	14	1	3	14	0			
13	15	1	3	15	0			
13	19	56	3	19	4			
14	11	1	4	11	2			
14	12	0	4	12	1			
14	13	1	4	13	1			
14	14	0	4	14	0			
14	15	0	4	15	0			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
14	19	11	4	19	20			
15	11	1	5	11	0			
15	12	0	5	12	0			
15	13	1	5	13	0			
15	14	0	5	14	0			
15	15	0	5	15	0			
15	19	12	5	19	4			
19	11	72	6	11	0			
19	12	33	6	12	0			
19	13	56	6	13	0			
19	14	11	6	14	0			
19	15	12	6	15	0			
19	19	858	6	19	4			
			7	11	1			
			7	12	0			
			7	13	1			
			7	14	0			
			7	15	0			
			7	19	10			
			8	11	1			
			8	12	0			
			8	13	0			
			8	14	0			
			8	15	0			
			8	19	6			
			9	11	0			
			9	12	0			
			9	13	0			
			9	14	0			
			9	15	0			
			9	19	1			
			10	11	1			
			10	12	0			
			10	13	1			
			10	14	0			
			10	15	0			
			10	19	10			
5612	**5622**	**83**	**5623**	**5622**	**36**	**5631**	**5622**	**21**
11	17	6	1	17	3	18	17	21
12	17	3	2	17	1			
13	17	4	3	17	2			
14	17	1	4	17	11			
15	17	1	5	17	2			
19	17	68	6	17	2			
			7	17	5			
			8	17	3			
			9	17	0			
			10	17	5			
5612	**5623**	**99**	**5623**	**5623**	**926**	**5631**	**5623**	**43**
11	1	1	1	1	6	18	1	4
11	2	0	1	2	3	18	2	2
11	3	0	1	3	5	18	3	3
11	4	2	1	4	23	18	4	13
11	5	0	1	5	4	18	5	2
11	6	0	1	6	5	18	6	3
11	7	1	1	7	11	18	7	6
11	8	1	1	8	7	18	8	4
11	9	0	1	9	1	18	9	0
11	10	1	1	10	11	18	10	6
12	1	0	2	1	3			
12	2	0	2	2	1			
12	3	0	2	3	2			
12	4	1	2	4	11			
12	5	0	2	5	2			
12	6	0	2	6	2			
12	7	0	2	7	5			
12	8	0	2	8	3			
12	9	0	2	9	0			
12	10	0	2	10	5			
13	1	0	3	1	5			
13	2	0	3	2	2			
13	3	0	3	3	4			
13	4	2	3	4	18			
13	5	0	3	5	3			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
13	6	0	3	6	4			
13	7	1	3	7	9			
13	8	0	3	8	6			
13	9	0	3	9	1			
13	10	1	3	10	9			
14	1	0	4	1	23			
14	2	0	4	2	11			
14	3	0	4	3	18			
14	4	0	4	4	82			
14	5	0	4	5	15			
14	6	0	4	6	17			
14	7	0	4	7	40			
14	8	0	4	8	26			
14	9	0	4	9	3			
14	10	0	4	10	41			
15	1	0	5	1	4			
15	2	0	5	2	2			
15	3	0	5	3	3			
15	4	0	5	4	15			
15	5	0	5	5	3			
15	6	0	5	6	3			
15	7	0	5	7	7			
15	8	0	5	8	5			
15	9	0	5	9	1			
15	10	0	5	10	8			
19	1	7	6	1	5			
19	2	3	6	2	2			
19	3	5	6	3	4			
19	4	24	6	4	17			
19	5	4	6	5	3			
19	6	5	6	6	4			
19	7	12	6	7	8			
19	8	8	6	8	5			
19	9	1	6	9	1			
19	10	12	6	10	9			
			7	1	11			
			7	2	5			
			7	3	9			
			7	4	40			
			7	5	7			
			7	6	8			
			7	7	19			
			7	8	12			
			7	9	1			
			7	10	20			
			8	1	7			
			8	2	3			
			8	3	6			
			8	4	26			
			8	5	5			
			8	6	5			
			8	7	12			
			8	8	8			
			8	9	1			
			8	10	13			
			9	1	1			
			9	2	0			
			9	3	1			
			9	4	3			
			9	5	1			
			9	6	1			
			9	7	1			
			9	8	1			
			9	9	0			
			9	10	2			
			10	1	11			
			10	2	5			
			10	3	9			
			10	4	41			
			10	5	8			
			10	6	9			
			10	7	20			
			10	8	13			
			10	9	2			

Origin	Destination	Frequency	Origin	Destination	Frequency	Origin	Destination	Frequency
			10	10	20			
5612	**5625**	**144**	**5623**	**5625**	**69**	**5631**	**5625**	**32**
11	16	10	1	16	6	18	16	32
12	16	5	2	16	3			
13	16	8	3	16	5			
14	16	2	4	16	21			
15	16	2	5	16	4			
19	16	119	6	16	4			
			7	16	10			
			8	16	6			
			9	16	1			
			10	16	10			
5612	**5631**	**85**	**5623**	**5631**	**53**	**All**	**All**	**4546**
11	18	6	1	18	4			
12	18	3	2	18	2			
13	18	5	3	18	3			
14	18	1	4	18	16			
15	18	1	5	18	3			
19	18	70	6	18	3			
			7	18	8			
			8	18	5			
			9	18	1			
			10	18	8			

A.8 Extracted Bus Timetables

maandag t/m vrijdag

2a

van BLIXEMBOSCH Oost naar EINDHOVEN Station

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

plaats en haltenaam	ritnr	1	3	5	7	9	11	13	15	17
Eindhoven, Opera	V	6 04	6 34	6 46	6 56	7 06	7 16	7 26	7 36	7 46
Eindhoven, Belgieplein		6 08	6 38	6 51	7 01	7 11	7 21	7 31	7 41	7 51
Eindhoven, WoensXL/ZH Catharina		6 12	6 42	6 56	7 06	7 16	7 27	7 37	7 47	7 57
Eindhoven, Sint Petruskerk		6 17	6 47	7 01	7 11	7 21	7 33	7 43	7 53	8 03
Eindhoven, Fontys Rachelsmolen		6 20	6 50	7 04	7 14	7 24	7 37	7 47	7 57	8 07
Eindhoven, Station	A	6 25	6 55	7 09	7 19	7 29	7 42	7 52	8 02	8 12

plaats en haltenaam	ritnr	19	21	23	25	27	29	31	33	35
Eindhoven, Opera	V	7 56	8 06	8 16	8 26	8 36	8 46	8 56	9 11	9 26
Eindhoven, Belgieplein		8 01	8 11	8 21	8 31	8 41	8 51	9 01	9 16	9 31
Eindhoven, WoensXL/ZH Catharina		8 07	8 17	8 27	8 37	8 47	8 57	9 07	9 22	9 37
Eindhoven, Sint Petruskerk		8 13	8 23	8 33	8 43	8 53	9 03	9 13	9 28	9 43
Eindhoven, Fontys Rachelsmolen		8 17	8 27	8 37	8 47	8 57	9 07	9 17	9 32	9 47
Eindhoven, Station	A	8 22	8 32	8 42	8 52	9 02	9 12	9 22	9 37	9 52

plaats en haltenaam	ritnr	37	39	41	43	45	47	49	51	53
Eindhoven, Opera	V	9 41	9 56	10 11	10 26	10 41	10 56	11 11	11 26	11 41
Eindhoven, Belgieplein		9 46	10 01	10 16	10 31	10 46	11 01	11 16	11 31	11 46
Eindhoven, WoensXL/ZH Catharina		9 52	10 07	10 22	10 37	10 52	11 07	11 22	11 37	11 52
Eindhoven, Sint Petruskerk		9 58	10 13	10 28	10 43	10 58	11 13	11 28	11 43	11 58
Eindhoven, Fontys Rachelsmolen		10 02	10 17	10 32	10 47	11 02	11 17	11 32	11 47	12 02
Eindhoven, Station	A	10 07	10 22	10 37	10 52	11 07	11 22	11 37	11 52	12 07

plaats en haltenaam	ritnr	55	57	59	61	63	65	67	69	71
Eindhoven, Opera	V	11 56	12 11	12 28	12 43	12 58	13 13	13 28	13 43	13 58
Eindhoven, Belgieplein		12 01	12 16	12 33	12 48	13 03	13 18	13 33	13 48	14 03
Eindhoven, WoensXL/ZH Catharina		12 07	12 22	12 39	12 54	13 09	13 24	13 39	13 54	14 09
Eindhoven, Sint Petruskerk		12 13	12 28	12 45	13 00	13 15	13 30	13 45	14 00	14 15
Eindhoven, Fontys Rachelsmolen		12 17	12 32	12 49	13 04	13 19	13 34	13 49	14 04	14 19
Eindhoven, Station	A	12 22	12 37	12 54	13 09	13 24	13 39	13 54	14 09	14 24

maandag t/m vrijdag

2a

van BLIXEMBOSCH Oost naar EINDHOVEN Station

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

plaats en haltenaam	ritnr	73	75	77	79	81	83	85	87	89
Eindhoven, Opera	V	14 13	14 28	14 43	14 58	15 13	15 28	15 43	15 53	16 03
Eindhoven, Belgieplein		14 18	14 33	14 48	15 03	15 18	15 33	15 48	15 58	16 08
Eindhoven, WoensXL/ZH Catharina		14 24	14 39	14 54	15 09	15 24	15 39	15 54	16 04	16 14
Eindhoven, Sint Petruskerk		14 30	14 45	15 00	15 15	15 30	15 45	16 00	16 10	16 20
Eindhoven, Fontys Rachelsmolen		14 34	14 49	15 04	15 19	15 34	15 49	16 04	16 14	16 24
Eindhoven, Station	A	14 39	14 54	15 09	15 24	15 39	15 54	16 09	16 19	16 29

plaats en haltenaam	ritnr	91	93	95	97	99	101	103	105	107
Eindhoven, Opera	V	16 13	16 23	16 33	16 43	16 53	17 03	17 13	17 23	17 33
Eindhoven, Belgieplein		16 18	16 28	16 38	16 48	16 58	17 08	17 18	17 28	17 38
Eindhoven, WoensXL/ZH Catharina		16 24	16 34	16 44	16 54	17 04	17 14	17 24	17 34	17 44
Eindhoven, Sint Petruskerk		16 30	16 40	16 50	17 00	17 10	17 20	17 30	17 40	17 50
Eindhoven, Fontys Rachelsmolen		16 34	16 44	16 54	17 04	17 14	17 24	17 34	17 44	17 54
Eindhoven, Station	A	16 39	16 49	16 59	17 09	17 19	17 29	17 39	17 49	17 59

plaats en haltenaam	ritnr	109	111	113	115	117	119	121	123	125
Eindhoven, Opera	V	17 43	17 53	18 03	18 13	18 23	18 33	18 58	19 28	19 58
Eindhoven, Belgieplein		17 48	17 58	18 08	18 18	18 28	18 38	19 03	19 33	20 03
Eindhoven, WoensXL/ZH Catharina		17 54	18 04	18 14	18 24	18 34	18 44	19 08	19 38	20 08
Eindhoven, Sint Petruskerk		18 00	18 10	18 20	18 30	18 40	18 50	19 13	19 43	20 13
Eindhoven, Fontys Rachelsmolen		18 04	18 14	18 24	18 34	18 44	18 54	19 16	19 46	20 16
Eindhoven, Station	A	18 09	18 19	18 29	18 39	18 49	18 59	19 21	19 51	20 21

plaats en haltenaam	ritnr	127	129	131	133	135	137	139	cxx	cxx
Eindhoven, Opera	V	20 28	20 58	21 28	21 58	22 28	22 56	23 26		
Eindhoven, Belgieplein		20 33	21 02	21 32	22 02	22 32	23 00	23 30		
Eindhoven, WoensXL/ZH Catharina		20 38	21 06	21 36	22 06	22 36	23 04	23 34		
Eindhoven, Sint Petruskerk		20 43	21 11	21 41	22 11	22 41	23 09	23 39		
Eindhoven, Fontys Rachelsmolen		20 46	21 14	21 44	22 14	22 44	23 12	23 42		
Eindhoven, Station	A	20 51	21 19	21 49	22 19	22 49	23 17	23 47		

maandag t/m vrijdag

2b

van EINDHOVEN Station naar BLIXEMBOSCH Oost

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

plaats en haltenaam	ritnr	2	4	6	8	10	12	14	16	18
Eindhoven, Station	V	6 36	7 06	7 16	7 26	7 34	7 44	7 54	8 04	8 14
Eindhoven, Fontys Rachelsmolen		6 38	7 08	7 18	7 28	7 36	7 46	7 56	8 06	8 16
Eindhoven, Sint Petruskerk		6 40	7 10	7 20	7 30	7 38	7 48	7 58	8 08	8 18
Eindhoven, WoensXL/ZH Catharina		6 44	7 14	7 24	7 34	7 43	7 53	8 03	8 13	8 23
Eindhoven, Belgieplein		6 49	7 19	7 29	7 39	7 49	7 59	8 09	8 19	8 29
Eindhoven, Opera	A	6 56	7 26	7 36	7 46	7 56	8 06	8 16	8 26	8 36

plaats en haltenaam	ritnr	20	22	24	26	28	30	32	34	36
Eindhoven, Station	V	8 24	8 34	8 49	9 04	9 19	9 34	9 49	10 04	10 19
Eindhoven, Fontys Rachelsmolen		8 26	8 36	8 51	9 06	9 21	9 36	9 51	10 06	10 21
Eindhoven, Sint Petruskerk		8 28	8 38	8 53	9 08	9 23	9 38	9 53	10 08	10 23
Eindhoven, WoensXL/ZH Catharina		8 33	8 43	8 58	9 13	9 28	9 43	9 58	10 13	10 28
Eindhoven, Belgieplein		8 39	8 49	9 04	9 19	9 34	9 49	10 04	10 19	10 34
Eindhoven, Opera	A	8 46	8 56	9 11	9 26	9 41	9 56	10 11	10 26	10 41

plaats en haltenaam	ritnr	38	40	42	44	46	48	50	52	54
Eindhoven, Station	V	10 34	10 49	11 04	11 19	11 34	11 49	12 04	12 19	12 34
Eindhoven, Fontys Rachelsmolen		10 36	10 51	11 06	11 21	11 36	11 51	12 07	12 22	12 37
Eindhoven, Sint Petruskerk		10 38	10 53	11 08	11 23	11 38	11 53	12 09	12 24	12 39
Eindhoven, WoensXL/ZH Catharina		10 43	10 58	11 13	11 28	11 43	11 58	12 14	12 29	12 44
Eindhoven, Belgieplein		10 49	11 04	11 19	11 34	11 49	12 04	12 20	12 35	12 50
Eindhoven, Opera	A	10 56	11 11	11 26	11 41	11 56	12 11	12 28	12 43	12 58

plaats en haltenaam	ritnr	56	58	60	62	64	66	68	70	72
Eindhoven, Station	V	12 49	13 04	13 19	13 34	13 49	14 04	14 19	14 34	14 49
Eindhoven, Fontys Rachelsmolen		12 52	13 07	13 22	13 37	13 52	14 07	14 22	14 37	14 52
Eindhoven, Sint Petruskerk		12 54	13 09	13 24	13 39	13 54	14 09	14 24	14 39	14 54
Eindhoven, WoensXL/ZH Catharina		12 59	13 14	13 29	13 44	13 59	14 14	14 29	14 44	14 59
Eindhoven, Belgieplein		13 05	13 20	13 35	13 50	14 05	14 20	14 35	14 50	15 05
Eindhoven, Opera	A	13 13	13 28	13 43	13 58	14 13	14 28	14 43	14 58	15 13

maandag t/m vrijdag

2b

van EINDHOVEN Station naar BLIXEMBOSCH Oost

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

plaats en haltenaam	ritnr	74	76	78	80	82	84	86	88	90
Eindhoven, Station	V	15 04	15 19	15 29	15 39	15 49	15 59	16 09	16 19	16 29
Eindhoven, Fontys Rachelsmolen		15 07	15 22	15 32	15 42	15 52	16 02	16 12	16 22	16 32
Eindhoven, Sint Petruskerk		15 09	15 24	15 34	15 44	15 54	16 04	16 14	16 24	16 34
Eindhoven, WoensXL/ZH Catharina		15 14	15 29	15 39	15 49	15 59	16 09	16 19	16 29	16 39
Eindhoven, Belgieplein		15 20	15 35	15 45	15 55	16 05	16 15	16 25	16 35	16 45
Eindhoven, Opera	A	15 28	15 43	15 53	16 03	16 13	16 23	16 33	16 43	16 53

plaats en haltenaam	ritnr	92	94	96	98	100	102	104	106	108
Eindhoven, Station	V	16 39	16 49	16 59	17 09	17 19	17 29	17 39	17 49	17 59
Eindhoven, Fontys Rachelsmolen		16 42	16 52	17 02	17 12	17 22	17 32	17 42	17 52	18 02
Eindhoven, Sint Petruskerk		16 44	16 54	17 04	17 14	17 24	17 34	17 44	17 54	18 04
Eindhoven, WoensXL/ZH Catharina		16 49	16 59	17 09	17 19	17 29	17 39	17 49	17 59	18 09
Eindhoven, Belgieplein		16 55	17 05	17 15	17 25	17 35	17 45	17 55	18 05	18 15
Eindhoven, Opera	A	17 03	17 13	17 23	17 33	17 43	17 53	18 03	18 13	18 23

plaats en haltenaam	ritnr	110	112	114	116	118	120	122	124	126
Eindhoven, Station	V	18 09	18 21	18 36	18 51	19 06	19 36	20 06	20 36	21 06
Eindhoven, Fontys Rachelsmolen		18 12	18 23	18 38	18 53	19 08	19 38	20 08	20 38	21 08
Eindhoven, Sint Petruskerk		18 14	18 25	18 40	18 55	19 10	19 40	20 10	20 40	21 10
Eindhoven, WoensXL/ZH Catharina		18 19	18 30	18 45	19 00	19 15	19 45	20 15	20 45	21 15
Eindhoven, Belgieplein		18 25	18 36	18 51	19 06	19 21	19 51	20 21	20 51	21 21
Eindhoven, Opera	A	18 33	18 43	18 58	19 13	19 28	19 58	20 28	20 58	21 28

plaats en haltenaam	ritnr	128	130	132	134	136	138	cxx	cxx	cxx
Eindhoven, Station	V	21 36	22 06	22 36	23 06	23 36	0 09			
Eindhoven, Fontys Rachelsmolen		21 38	22 08	22 38	23 08	23 38	0 11			
Eindhoven, Sint Petruskerk		21 40	22 10	22 40	23 10	23 40	0 13			
Eindhoven, WoensXL/ZH Catharina		21 45	22 15	22 44	23 14	23 44	0 17			
Eindhoven, Belgieplein		21 51	22 21	22 49	23 19	23 49	0 22			
Eindhoven, Opera	A	21 58	22 28	22 56	23 26	23 56	0 29			

maandag t/m vrijdag

3a

van BLIXEMBOSCH West naar EINDHOVEN Station

plaats en haltenaam	ritnr	1	3	5	7	9	11	13	15	17
Eindhoven, Bronziet	V	6 15	6 45	7 12	7 42	8 12	8 42	9 18	9 48	10 18
Eindhoven, Noordzeelaan		6 20	6 50	7 18	7 48	8 18	8 48	9 24	9 54	10 24
Eindhoven, WoensXL/ZH Catharina		6 25	6 55	7 23	7 53	8 23	8 53	9 29	9 59	10 29
Eindhoven, Generaal Coenderslaan		6 29	6 59	7 28	7 58	8 28	8 58	9 34	10 04	10 34
Eindhoven, MMC Eindhoven		6 32	7 02	7 31	8 01	8 31	9 01	9 37	10 07	10 37
Eindhoven, Station	A	6 40	7 10	7 40	8 12	8 42	9 10	9 46	10 16	10 46

plaats en haltenaam	ritnr	19	21	23	25	27	29	31	33	35
Eindhoven, Bronziet	V	10 48	11 18	11 48	12 18	12 48	13 18	13 48	14 18	14 48
Eindhoven, Noordzeelaan		10 54	11 24	11 54	12 24	12 54	13 24	13 54	14 24	14 54
Eindhoven, WoensXL/ZH Catharina		10 59	11 29	11 59	12 29	12 59	13 29	13 59	14 29	14 59
Eindhoven, Generaal Coenderslaan		11 04	11 34	12 04	12 34	13 04	13 34	14 04	14 34	15 04
Eindhoven, MMC Eindhoven		11 07	11 37	12 07	12 37	13 07	13 37	14 07	14 37	15 07
Eindhoven, Station	A	11 16	11 46	12 16	12 46	13 16	13 46	14 16	14 46	15 16

plaats en haltenaam	ritnr	37	39	41	43	45	47	49	51	53
Eindhoven, Bronziet	V	15 18	15 48	16 18	16 48	17 18	17 48	18 15	18 45	19 45
Eindhoven, Noordzeelaan		15 24	15 54	16 24	16 54	17 24	17 53	18 20	18 50	19 50
Eindhoven, WoensXL/ZH Catharina		15 29	15 59	16 29	16 59	17 29	17 58	18 25	18 55	19 55
Eindhoven, Generaal Coenderslaan		15 34	16 04	16 34	17 04	17 34	18 02	18 29	18 59	19 59
Eindhoven, MMC Eindhoven		15 37	16 07	16 37	17 07	17 37	18 05	18 32	19 02	20 02
Eindhoven, Station	A	15 46	16 16	16 46	17 16	17 46	18 13	18 40	19 10	20 10

plaats en haltenaam	ritnr	55	57	59	61					
Eindhoven, Bronziet	V	20 45	21 42	22 42	23 42					
Eindhoven, Noordzeelaan		20 50	21 47	22 47	23 47					
Eindhoven, WoensXL/ZH Catharina		20 54	21 51	22 51	23 51					
Eindhoven, Generaal Coenderslaan		20 57	21 54	22 54	23 54					
Eindhoven, MMC Eindhoven		20 59	21 56	22 56	23 56					
Eindhoven, Station	A	21 05	22 02	23 02	0 02					

maandag t/m vrijdag

3b

van EINDHOVEN Station naar BLIXEMBOSCH West

plaats en haltenaam	ritnr	2	4	6	8	10	12	14	16	18
Eindhoven, Station	V	6 24	6 51	7 21	7 48	8 18	8 54	9 24	9 54	10 24
Eindhoven, MMC Eindhoven		6 27	6 54	7 24	7 52	8 22	8 58	9 28	9 58	10 28
Eindhoven, Generaal Coenderslaan		6 30	6 57	7 27	7 55	8 25	9 01	9 31	10 01	10 31
Eindhoven, WoensXL/ZH Catharina		6 34	7 01	7 31	7 59	8 29	9 05	9 35	10 05	10 35
Eindhoven, Noordzeelaan		6 39	7 06	7 36	8 05	8 35	9 11	9 41	10 11	10 41
Eindhoven, Bronziet	A	6 45	7 12	7 42	8 12	8 42	9 18	9 48	10 18	10 48

plaats en haltenaam	ritnr	20	22	24	26	28	30	32	34	36
Eindhoven, Station	V	10 54	11 24	11 54	12 24	12 54	13 24	13 54	14 24	14 54
Eindhoven, MMC Eindhoven		10 58	11 28	11 58	12 28	12 58	13 28	13 58	14 28	14 58
Eindhoven, Generaal Coenderslaan		11 01	11 31	12 01	12 31	13 01	13 31	14 01	14 31	15 01
Eindhoven, WoensXL/ZH Catharina		11 05	11 35	12 05	12 35	13 05	13 35	14 05	14 35	15 05
Eindhoven, Noordzeelaan		11 11	11 41	12 11	12 41	13 11	13 41	14 11	14 41	15 11
Eindhoven, Bronziet	A	11 18	11 48	12 18	12 48	13 18	13 48	14 18	14 48	15 18

plaats en haltenaam	ritnr	38	40	42	44	46	48	50	52	54
Eindhoven, Station	V	15 24	15 54	16 24	16 54	17 24	17 54	18 24	19 24	20 24
Eindhoven, MMC Eindhoven		15 28	15 58	16 28	16 58	17 28	17 57	18 27	19 27	20 27
Eindhoven, Generaal Coenderslaan		15 31	16 01	16 31	17 01	17 31	18 00	18 30	19 30	20 30
Eindhoven, WoensXL/ZH Catharina		15 35	16 05	16 35	17 05	17 35	18 04	18 34	19 34	20 34
Eindhoven, Noordzeelaan		15 41	16 11	16 41	17 11	17 41	18 09	18 39	19 39	20 39
Eindhoven, Bronziet	A	15 48	16 18	16 48	17 18	17 48	18 15	18 45	19 45	20 45

plaats en haltenaam	ritnr	56	58	60	62					
Eindhoven, Station	V	21 24	22 24	23 24	0 09					
Eindhoven, MMC Eindhoven		21 27	22 27	23 27	0 12					
Eindhoven, Generaal Coenderslaan		21 29	22 29	23 29	0 14					
Eindhoven, WoensXL/ZH Catharina		21 32	22 32	23 32	0 17					
Eindhoven, Noordzeelaan		21 36	22 36	23 36	0 21					
Eindhoven, Bronziet	A	21 42	22 42	23 42	0 27					

maandag t/m vrijdag

9a

van BEST Station naar EINDHOVEN Station

plaats en haltenaam	ritnr	1	3	5	7	9	11	13	15	17
Best, Station	V	6 19	6 49	7 19	7 49	8 19	8 49	9 19	9 49	10 19
Best, Nazarethstraat		6 21	6 51	7 21	7 51	8 21	8 51	9 21	9 51	10 21
Best, Wilhelminaplein		6 26	6 56	7 26	7 56	8 26	8 56	9 26	9 56	10 26
Eindhoven, Boschdijk/Steenoven		6 31	7 02	7 32	8 03	8 33	9 02	9 32	10 02	10 32
Eindhoven, Estafettelaan		6 34	7 06	7 36	8 07	8 37	9 06	9 36	10 06	10 36
Eindhoven, Pieter Eijffhuis		6 36	7 08	7 38	8 09	8 39	9 08	9 38	10 08	10 38
Eindhoven, WoensXL/ZH Catharina		6 40	7 13	7 43	8 15	8 45	9 13	9 43	10 13	10 43
Eindhoven, Fontys Rachelsmolen		6 44	7 17	7 47	8 20	8 50	9 17	9 47	10 17	10 47
Eindhoven, Station	A	6 49	7 22	7 52	8 25	8 55	9 22	9 52	10 22	10 52

plaats en haltenaam	ritnr	19	21	23	25	27	29	31	33	35
Best, Station	V	10 49	11 19	11 49	12 19	12 49	13 19	13 49	14 19	14 49
Best, Nazarethstraat		10 51	11 21	11 51	12 21	12 51	13 21	13 51	14 21	14 51
Best, Wilhelminaplein		10 56	11 26	11 56	12 26	12 56	13 26	13 56	14 26	14 56
Eindhoven, Boschdijk/Steenoven		11 02	11 32	12 02	12 32	13 03	13 33	14 03	14 33	15 03
Eindhoven, Estafettelaan		11 06	11 36	12 06	12 36	13 07	13 37	14 07	14 37	15 07
Eindhoven, Pieter Eijffhuis		11 08	11 38	12 08	12 38	13 09	13 39	14 09	14 39	15 09
Eindhoven, WoensXL/ZH Catharina		11 13	11 43	12 13	12 43	13 15	13 45	14 15	14 45	15 15
Eindhoven, Fontys Rachelsmolen		11 17	11 47	12 17	12 47	13 20	13 50	14 20	14 50	15 20
Eindhoven, Station	A	11 22	11 52	12 22	12 52	13 25	13 55	14 25	14 55	15 25

plaats en haltenaam	ritnr	37	39	41	43	45	47	49	51	53
Best, Station	V	15 19	15 49	16 19	16 49	17 19	17 49	18 19	18 49	19 19
Best, Nazarethstraat		15 21	15 51	16 21	16 51	17 21	17 51	18 21	18 51	19 21
Best, Wilhelminaplein		15 26	15 56	16 26	16 56	17 26	17 56	18 26	18 56	19 26
Eindhoven, Boschdijk/Steenoven		15 33	16 03	16 33	17 03	17 33	18 02	18 32	19 02	19 31
Eindhoven, Estafettelaan		15 37	16 07	16 37	17 07	17 37	18 06	18 36	19 06	19 34
Eindhoven, Pieter Eijffhuis		15 39	16 09	16 39	17 09	17 39	18 08	18 38	19 08	19 36
Eindhoven, WoensXL/ZH Catharina		15 45	16 15	16 45	17 15	17 45	18 13	18 43	19 13	19 40
Eindhoven, Fontys Rachelsmolen		15 50	16 20	16 50	17 20	17 50	18 17	18 47	19 17	19 44
Eindhoven, Station	A	15 55	16 25	16 55	17 25	17 55	18 22	18 52	19 22	19 49

plaats en haltenaam	ritnr	55	57	59	61					
Best, Station	V	19 49	20 49	21 49	22 49					
Best, Nazarethstraat		19 51	20 51	21 51	22 51					
Best, Wilhelminaplein		19 56	20 56	21 56	22 56					
Eindhoven, Boschdijk/Steenoven		20 01	21 01	22 01	23 01					
Eindhoven, Estafettelaan		20 04	21 04	22 04	23 04					
Eindhoven, Pieter Eijffhuis		20 06	21 06	22 06	23 06					
Eindhoven, WoensXL/ZH Catharina		20 10	21 10	22 10	23 10					
Eindhoven, Fontys Rachelsmolen		20 14	21 14	22 14	23 14					
Eindhoven, Station	A	20 19	21 19	22 19	23 19					

maandag t/m vrijdag

9b

van EINDHOVEN Station naar BEST Station

plaats en haltenaam	ritnr	2	4	6	8	10	12	14	16	18
Eindhoven, Station	V	6 36	7 06	7 33	8 03	8 33	9 06	9 36	10 06	10 36
Eindhoven, Fontys Rachelsmolen		6 39	7 09	7 36	8 06	8 36	9 09	9 39	10 09	10 39
Eindhoven, WoensXL/ZH Catharina		6 42	7 12	7 40	8 10	8 40	9 12	9 42	10 12	10 42
Eindhoven, Pieter Eijffhuis		6 47	7 17	7 46	8 16	8 46	9 17	9 47	10 17	10 47
Eindhoven, Estafettelaan		6 49	7 19	7 48	8 18	8 48	9 19	9 49	10 19	10 49
Eindhoven, Boschdijk/Steenoven		6 53	7 23	7 52	8 22	8 52	9 23	9 53	10 23	10 53
Best, Wilhelminaplein		6 59	7 29	7 58	8 28	8 58	9 29	9 59	10 29	10 59
Best, Nazarethstraat		7 05	7 35	8 05	8 35	9 05	9 35	10 05	10 35	11 05
Best, Station	A	7 11	7 41	8 11	8 41	9 11	9 41	10 11	10 41	11 11

plaats en haltenaam	ritnr	20	22	24	26	28	30	32	34	36
Eindhoven, Station	V	11 06	11 36	12 06	12 36	13 03	13 33	14 03	14 33	15 03
Eindhoven, Fontys Rachelsmolen		11 09	11 39	12 09	12 39	13 06	13 36	14 06	14 36	15 06
Eindhoven, WoensXL/ZH Catharina		11 12	11 42	12 12	12 42	13 10	13 40	14 10	14 40	15 10
Eindhoven, Pieter Eijffhuis		11 17	11 47	12 17	12 47	13 16	13 46	14 16	14 46	15 16
Eindhoven, Estafettelaan		11 19	11 49	12 19	12 49	13 18	13 48	14 18	14 48	15 18
Eindhoven, Boschdijk/Steenoven		11 23	11 53	12 23	12 53	13 22	13 52	14 22	14 52	15 22
Best, Wilhelminaplein		11 29	11 59	12 29	12 59	13 28	13 58	14 28	14 58	15 28
Best, Nazarethstraat		11 35	12 05	12 35	13 05	13 35	14 05	14 35	15 05	15 35
Best, Station	A	11 41	12 11	12 41	13 11	13 41	14 11	14 41	15 11	15 41

plaats en haltenaam	ritnr	38	40	42	44	46	48	50	52	54
Eindhoven, Station	V	15 33	16 03	16 33	17 03	17 33	18 06	18 36	19 06	20 06
Eindhoven, Fontys Rachelsmolen		15 36	16 06	16 36	17 06	17 36	18 09	18 39	19 09	20 08
Eindhoven, WoensXL/ZH Catharina		15 40	16 10	16 40	17 10	17 40	18 12	18 42	19 12	20 11
Eindhoven, Pieter Eijffhuis		15 46	16 16	16 46	17 16	17 46	18 17	18 47	19 17	20 15
Eindhoven, Estafettelaan		15 48	16 18	16 48	17 18	17 48	18 19	18 49	19 19	20 17
Eindhoven, Boschdijk/Steenoven		15 52	16 22	16 52	17 22	17 52	18 23	18 53	19 23	20 20
Best, Wilhelminaplein		15 58	16 28	16 58	17 28	17 58	18 29	18 59	19 29	20 25
Best, Nazarethstraat		16 05	16 35	17 05	17 35	18 05	18 35	19 05	19 35	20 31
Best, Station	A	16 11	16 41	17 11	17 41	18 11	18 41	19 11	19 41	20 37

plaats en haltenaam	ritnr	56	58	cxx	cxx	cxx	cxx	cxx	cxx	cxx
Eindhoven, Station	V	21 06	22 06							
Eindhoven, Fontys Rachelsmolen		21 08	22 08							
Eindhoven, WoensXL/ZH Catharina		21 11	22 11							
Eindhoven, Pieter Eijffhuis		21 15	22 15							
Eindhoven, Estafettelaan		21 17	22 17							
Eindhoven, Boschdijk/Steenoven		21 20	22 20							
Best, Wilhelminaplein		21 25	22 25							
Best, Nazarethstraat		21 31	22 31							
Best, Station	A	21 37	22 37							

maandag t/m vrijdag

321a **322a**

van UDEN(322) en GEMERT(321) naar EINDHOVEN Station

lijnnummer		322	322	321	322	321	322	321	321	321
plaats en haltenaam	**ritnr**	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**
								a		a
Uden, Busstation Uden	V									
Volkel, Schoolstraat										
Boekel, Kerkstraat					6 28		6 58			
Gemert, Slenk/Lopense				6 16	|	6 46	|		7 16	
Gemert, Pastoor Poellplein	A			6 22	6 37	6 52	7 07		7 22	
Gemert, Pastoor Poellplein	V	5 33	6 01	6 23	6 38	6 53	7 08	7 15	7 23	7 28
Gemert, West-Om/Heuvel		5 35	6 03	6 25	6 40	6 56	7 11	7 18	7 26	7 31
Beek en Donk, Lieshoutseweg		5 40	6 08	6 31	6 46	7 02	7 17	7 25	7 33	7 38
Lieshout, Bavaria		5 42	6 10	6 34	6 49	7 05	7 20	7 28	7 36	7 41
Gerwen, Kerkakkers		5 48	6 16	6 40	6 55	7 12	7 27	7 35	7 43	7 48
Nuenen, Nuenen Centrum		5 51	6 19	6 43	6 58	7 15	7 30	7 40	7 48	7 53
Eindhoven, Summa College Sterrenln		5 58	6 26	|	7 06	|	7 39	|	|	|
Eindhoven, WoensXL/ZH Catharina		6 01	6 30	|	7 11	|	7 44	|	|	|
Eindhoven, Fontys Rachelsmolen		6 04	6 34	|	7 16	|	7 49	|	|	|
Eindhoven, Station	A	6 10	6 40	7 00	7 22	7 33	7 55	8 01	8 09	8 14

lijnnummer		322	322	321	321	321	321	322	321	321
plaats en haltenaam	**ritnr**	**19**	**21**	**23**	**25**	**27**	**29**	**31**	**33**	**35**
		a		a	a		a		a	
Uden, Busstation Uden	V		7 13					7 43		
Volkel, Schoolstraat			7 21					7 51		
Boekel, Kerkstraat			7 28					7 58		
Gemert, Slenk/Lopense			|			7 46		|		8 16
Gemert, Pastoor Poellplein	A		7 37			7 52		8 07		8 22
Gemert, Pastoor Poellplein	V	7 33	7 38	7 43	7 48	7 53	8 00	8 08	8 15	8 23
Gemert, West-Om/Heuvel		7 36	7 41	7 46	7 51	7 56	8 03	8 11	8 18	8 26
Beek en Donk, Lieshoutseweg		7 43	7 48	7 53	7 58	8 03	8 10	8 18	8 25	8 33
Lieshout, Bavaria		7 46	7 51	7 56	8 01	8 06	8 13	8 21	8 28	8 36
Gerwen, Kerkakkers		7 53	7 58	8 03	8 08	8 13	8 20	8 28	8 35	8 43
Nuenen, Nuenen Centrum		7 58	8 03	8 08	8 13	8 18	8 25	8 33	8 40	8 48
Eindhoven, Summa College Sterrenln		8 07	8 12	|	|	|	|	8 42	|	|
Eindhoven, WoensXL/ZH Catharina		8 13	8 18	|	|	|	|	8 48	|	|
Eindhoven, Fontys Rachelsmolen		8 19	8 24	|	|	|	|	8 54	|	|
Eindhoven, Station	A	8 25	8 30	8 29	8 34	8 39	8 46	9 00	9 01	9 09

a = Rijdt NIET van 22 december 2019 t/m 4 januari 2020, 23 t/m 29 februari, 10 april, 19 april t/m 4 mei, 22 mei 5 juli t/m 29 augustus en 18 t/m 24 oktober 2020.

maandag t/m vrijdag

321a 322a

van UDEN(322) en GEMERT(321) naar EINDHOVEN Station

lijnnummer		321	322	321	322	321	322	321	322	321
plaats en haltenaam	**ritnr**	**37**	**39**	**41**	**43**	**45**	**47**	**49**	**51**	**53**
		a								
Uden, Busstation Uden	V		8 13		8 45		9 15		9 45	
Volkel, Schoolstraat			8 21		8 52		9 22		9 52	
Boekel, Kerkstraat			8 28		8 58		9 28		9 58	
Gemert, Slenk/Lopense			|	8 46	|	9 16	|	9 46	|	10 16
Gemert, Pastoor Poellplein	A		8 37	8 52	9 07	9 22	9 37	9 52	10 07	10 22
Gemert, Pastoor Poellplein	V	8 30	8 38	8 53	9 08	9 23	9 38	9 53	10 08	10 23
Gemert, West-Om/Heuvel		8 33	8 41	8 56	9 11	9 25	9 40	9 55	10 10	10 25
Beek en Donk, Lieshoutseweg		8 40	8 47	9 02	9 17	9 31	9 46	10 01	10 16	10 31
Lieshout, Bavaria		8 43	8 50	9 05	9 20	9 34	9 49	10 04	10 19	10 34
Gerwen, Kerkakkers		8 50	8 57	9 12	9 27	9 40	9 55	10 10	10 25	10 40
Nuenen, Nuenen Centrum		8 55	9 00	9 15	9 30	9 43	9 58	10 13	10 28	10 43
Eindhoven, Summa College Sterrenln		|	9 09	|	9 39	|	10 06	|	10 36	|
Eindhoven, WoensXL/ZH Catharina		|	9 14	|	9 44	|	10 11	|	10 41	|
Eindhoven, Fontys Rachelsmolen		|	9 19	|	9 49	|	10 16	|	10 46	|
Eindhoven, Station	A	9 16	9 25	9 33	9 55	10 00	10 22	10 30	10 52	11 00

lijnnummer		322	321	322	321	322	321	322	321	322
plaats en haltenaam	**ritnr**	**55**	**57**	**59**	**61**	**63**	**65**	**67**	**69**	**71**
Uden, Busstation Uden	V	10 15		10 45		11 15		11 45		12 15
Volkel, Schoolstraat		10 22		10 52		11 22		11 52		12 22
Boekel, Kerkstraat		10 28		10 58		11 28		11 58		12 28
Gemert, Slenk/Lopense		|	10 46	|	11 16	|	11 46	|	12 16	|
Gemert, Pastoor Poellplein	A	10 37	10 52	11 07	11 22	11 37	11 52	12 07	12 22	12 37
Gemert, Pastoor Poellplein	V	10 38	10 53	11 08	11 23	11 38	11 53	12 08	12 23	12 38
Gemert, West-Om/Heuvel		10 40	10 55	11 10	11 25	11 40	11 55	12 10	12 25	12 40
Beek en Donk, Lieshoutseweg		10 46	11 01	11 16	11 31	11 46	12 01	12 16	12 31	12 46
Lieshout, Bavaria		10 49	11 04	11 19	11 34	11 49	12 04	12 19	12 34	12 49
Gerwen, Kerkakkers		10 55	11 10	11 25	11 40	11 55	12 10	12 25	12 40	12 55
Nuenen, Nuenen Centrum		10 58	11 13	11 28	11 43	11 58	12 13	12 28	12 43	12 58
Eindhoven, Summa College Sterrenln		11 06	|	11 36	|	12 06	|	12 36	|	13 06
Eindhoven, WoensXL/ZH Catharina		11 11	|	11 41	|	12 11	|	12 41	|	13 11
Eindhoven, Fontys Rachelsmolen		11 16	|	11 46	|	12 16	|	12 46	|	13 16
Eindhoven, Station	A	11 22	11 30	11 52	12 00	12 22	12 30	12 52	13 00	13 22

a = Rijdt NIET van 22 december 2019 t/m 4 januari 2020, 23 t/m 29 februari, 10 april, 19 april t/m 4 mei, 22 mei 5 juli t/m 29 augustus en 18 t/m 24 oktober 2020.

maandag t/m vrijdag

321a **322a**

van UDEN(322) en GEMERT(321) naar EINDHOVEN Station

lijnnummer		321	322	321	322	321	322	321	322	321
plaats en haltenaam	ritnr	73	75	77	79	81	83	85	87	89
Uden, Busstation Uden	V		12 45		13 15		13 45		14 15	
Volkel, Schoolstraat			12 52		13 22		13 52		14 22	
Boekel, Kerkstraat			12 58		13 28		13 58		14 28	
Gemert, Slenk/Lopense		12 46	|	13 16	|	13 46	|	14 16	|	14 46
Gemert, Pastoor Poellplein	A	12 52	13 07	13 22	13 37	13 52	14 07	14 22	14 37	14 52
Gemert, Pastoor Poellplein	V	12 53	13 08	13 23	13 38	13 53	14 08	14 23	14 38	14 53
Gemert, West-Om/Heuvel		12 55	13 10	13 25	13 40	13 55	14 10	14 25	14 40	14 55
Beek en Donk, Lieshoutseweg		13 01	13 16	13 31	13 46	14 01	14 16	14 31	14 46	15 01
Lieshout, Bavaria		13 04	13 19	13 34	13 49	14 04	14 19	14 34	14 49	15 04
Gerwen, Kerkakkers		13 10	13 25	13 40	13 55	14 10	14 25	14 40	14 55	15 10
Nuenen, Nuenen Centrum		13 13	13 28	13 43	13 58	14 13	14 28	14 43	14 58	15 13
Eindhoven, Summa College Sterrenln		|	13 36	|	14 06	|	14 36	|	15 06	|
Eindhoven, WoensXL/ZH Catharina		|	13 41	|	14 11	|	14 41	|	15 11	|
Eindhoven, Fontys Rachelsmolen		|	13 46	|	14 16	|	14 46	|	15 16	|
Eindhoven, Station	A	13 30	13 52	14 00	14 22	14 30	14 52	15 00	15 22	15 30

lijnnummer		322	321	322	321	322	321	322	321	322
plaats en haltenaam	ritnr	91	93	95	97	99	101	103	105	107
Uden, Busstation Uden	V	14 45		15 15		15 45		16 22		16 52
Volkel, Schoolstraat		14 52		15 22		15 52		16 30		17 00
Boekel, Kerkstraat		14 58		15 28		15 58		16 37		17 07
Gemert, Slenk/Lopense		|	15 16	|	15 46	|	16 25	|	16 55	|
Gemert, Pastoor Poellplein	A	15 07	15 22	15 37	15 52	16 07	16 31	16 46	17 01	17 16
Gemert, Pastoor Poellplein	V	15 08	15 23	15 38	15 53	16 08	16 32	16 47	17 02	17 17
Gemert, West-Om/Heuvel		15 10	15 25	15 40	15 55	16 10	16 34	16 49	17 04	17 19
Beek en Donk, Lieshoutseweg		15 16	15 31	15 46	16 01	16 16	16 40	16 55	17 10	17 25
Lieshout, Bavaria		15 19	15 34	15 49	16 04	16 19	16 43	16 58	17 13	17 28
Gerwen, Kerkakkers		15 25	15 40	15 55	16 10	16 25	16 49	17 04	17 19	17 34
Nuenen, Nuenen Centrum		15 28	15 43	15 58	16 13	16 28	16 52	17 07	17 22	17 37
Eindhoven, Summa College Sterrenln		15 36	|	16 06	|	16 36	|	17 15	|	17 45
Eindhoven, WoensXL/ZH Catharina		15 41	|	16 11	|	16 41	|	17 20	|	17 50
Eindhoven, Fontys Rachelsmolen		15 46	|	16 16	|	16 46	|	17 25	|	17 55
Eindhoven, Station	A	15 52	16 00	16 22	16 30	16 52	17 09	17 31	17 39	18 01

maandag t/m vrijdag

321a **322a**

van UDEN(322) en GEMERT(321) naar EINDHOVEN Station

lijnnummer		321	322	321	322	321	322	321	322	322
plaats en haltenaam	ritnr	109	111	113	115	117	119	121	123	125
Uden, Busstation Uden	V		17 24		17 54		18 24		18 55	19 25
Volkel, Schoolstraat			17 31		18 01		18 31		19 02	19 32
Boekel, Kerkstraat			17 37		18 07		18 37		19 08	19 38
Gemert, Slenk/Lopense		17 25	|	17 55	|	18 25	|	18 55	|	|
Gemert, Pastoor Poellplein	A	17 31	17 46	18 01	18 16	18 31	18 46	19 01	19 16	19 46
Gemert, Pastoor Poellplein	V	17 32	17 47	18 02	18 17	18 32	18 47	19 02	19 17	19 47
Gemert, West-Om/Heuvel		17 34	17 49	18 04	18 19	18 34	18 49	19 04	19 19	19 49
Beek en Donk, Lieshoutseweg		17 40	17 54	18 09	18 24	18 39	18 54	19 09	19 24	19 54
Lieshout, Bavaria		17 43	17 57	18 12	18 27	18 42	18 57	19 12	19 27	19 57
Gerwen, Kerkakkers		17 49	18 03	18 18	18 33	18 48	19 03	19 18	19 33	20 03
Nuenen, Nuenen Centrum		17 52	18 05	18 20	18 35	18 50	19 05	19 20	19 35	20 05
Eindhoven, Summa College Sterrenln		|	18 12	|	18 42	|	19 12	|	19 42	20 12
Eindhoven, WoensXL/ZH Catharina		|	18 16	|	18 46	|	19 16	|	19 46	20 16
Eindhoven, Fontys Rachelsmolen		|	18 20	|	18 50	|	19 20	|	19 50	20 20
Eindhoven, Station	A	18 09	18 26	18 36	18 56	19 06	19 26	19 36	19 56	20 26

lijnnummer		322	322	322	322	322	322	322	322	
plaats en haltenaam	ritnr	127	129	131	133	135	137	139	141	
Uden, Busstation Uden	V		20 25		21 25		22 25		23 25	
Volkel, Schoolstraat			20 32		21 32		22 32		23 32	
Boekel, Kerkstraat			20 38		21 38		22 38		23 38	
Gemert, Slenk/Lopense			|		|		|		|	
Gemert, Pastoor Poellplein	A		20 46		21 46		22 46		23 46	
Gemert, Pastoor Poellplein	V	20 17	20 47	21 17	21 47	22 17	22 47	23 17	23 47	
Gemert, West-Om/Heuvel		20 19	20 49	21 19	21 49	22 19	22 49	23 19	23 49	
Beek en Donk, Lieshoutseweg		20 24	20 54	21 24	21 54	22 24	22 54	23 24	23 54	
Lieshout, Bavaria		20 27	20 57	21 26	21 56	22 26	22 56	23 26	23 56	
Gerwen, Kerkakkers		20 33	21 03	21 32	22 02	22 32	23 02	23 32	0 02	
Nuenen, Nuenen Centrum		20 35	21 05	21 35	22 05	22 35	23 05	23 35	0 05	
Eindhoven, Summa College Sterrenln		20 42	21 12	21 42	22 12	22 42	23 12	23 42		
Eindhoven, WoensXL/ZH Catharina		20 46	21 16	21 45	22 15	22 45	23 15	23 45		
Eindhoven, Fontys Rachelsmolen		20 50	21 20	21 48	22 18	22 48	23 18	23 48		
Eindhoven, Station	A	20 56	21 26	21 54	22 24	22 54	23 24	23 54		

maandag t/m vrijdag

321b **322b**

van EINDHOVEN Station naar GEMERT (321) en UDEN (322)

lijnnummer		322	322	321	322	321	322	321	322	322
plaats en haltenaam	**ritnr**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16** a	**18**
Eindhoven, Station	V		6 33	6 53	7 00	7 21	7 30	7 51	7 54	8 00
Eindhoven, Fontys Rachelsmolen			6 36	|	7 03	|	7 33	|	7 57	8 03
Eindhoven, WoensXL/ZH Catharina			6 39	|	7 07	|	7 37	|	8 01	8 07
Eindhoven, Summa College Sterrenln			6 42	|	7 11	|	7 41	|	8 05	8 11
Nuenen, Nuenen Centrum		6 19	6 49	7 04	7 18	7 33	7 48	8 03		8 18
Gerwen, Kerkakkers		6 22	6 52	7 07	7 21	7 36	7 51	8 06		8 21
Lieshout, Bavaria		6 28	6 58	7 13	7 27	7 42	7 57	8 12		8 27
Beek en Donk, Lieshoutseweg		6 31	7 01	7 16	7 30	7 45	8 00	8 15		8 30
Gemert, West-Om/Heuvel		6 38	7 08	7 23	7 38	7 53	8 08	8 23		8 38
Gemert, Pastoor Poellplein	A	6 43	7 13	7 28	7 43	7 58	8 13	8 28		8 43
Gemert, Pastoor Poellplein	V	6 44	7 14	7 29	7 44	7 59	8 14	8 29		8 44
Gemert, Slenk/Lopense		|	|	7 41	|	8 12	|	8 42		|
Boekel, Kerkstraat		6 51	7 21		7 51		8 21			8 51
Volkel, Schoolstraat		6 58	7 28		7 58		8 28			8 57
Uden, Busstation Uden	A	7 11	7 41		8 11		8 41			9 09

lijnnummer		322	321	322	322	322	322	322	322	321
plaats en haltenaam	**ritnr**	**20** a	**22**	**24** a	**26** a	**28**	**30** a	**32** a	**34** a	**36**
Eindhoven, Station	V	8 13	8 21	8 23	8 27	8 30	8 34	8 42	8 47	8 53
Eindhoven, Fontys Rachelsmolen		8 16	|	8 26	8 30	8 33	8 37	8 45	8 50	|
Eindhoven, WoensXL/ZH Catharina		8 20	|	8 30	8 34	8 37	8 41	8 49	8 54	|
Eindhoven, Summa College Sterrenln		8 24	|	8 34	8 38	8 41	8 45	8 53	8 58	|
Nuenen, Nuenen Centrum			8 33			8 48				9 04
Gerwen, Kerkakkers			8 36			8 51				9 07
Lieshout, Bavaria			8 42			8 57				9 13
Beek en Donk, Lieshoutseweg			8 45			9 00				9 16
Gemert, West-Om/Heuvel			8 53			9 08				9 23
Gemert, Pastoor Poellplein	A		8 58			9 13				9 28
Gemert, Pastoor Poellplein	V		8 59			9 14				9 29
Gemert, Slenk/Lopense			9 12			|				9 41
Boekel, Kerkstraat						9 20				
Volkel, Schoolstraat						9 26				
Uden, Busstation Uden	A					9 37				

lijnnummer		322	322	322	321	322	321	322	321	322
plaats en haltenaam	**ritnr**	**38** a	**40** a	**42**	**44**	**46**	**48**	**50**	**52**	**54**
Eindhoven, Station	V	8 54	8 59	9 03	9 23	9 33	9 53	10 03	10 23	10 33
Eindhoven, Fontys Rachelsmolen		8 57	9 02	9 06	|	9 36	|	10 06	|	10 36
Eindhoven, WoensXL/ZH Catharina		9 01	9 06	9 09	|	9 39	|	10 09	|	10 39
Eindhoven, Summa College Sterrenln		9 05	9 10	9 12	|	9 42	|	10 12	|	10 42
Nuenen, Nuenen Centrum				9 19	9 34	9 49	10 04	10 19	10 34	10 49
Gerwen, Kerkakkers				9 22	9 37	9 52	10 07	10 22	10 37	10 52
Lieshout, Bavaria				9 28	9 43	9 58	10 13	10 28	10 43	10 58
Beek en Donk, Lieshoutseweg				9 31	9 46	10 01	10 16	10 31	10 46	11 01
Gemert, West-Om/Heuvel				9 38	9 53	10 08	10 23	10 38	10 53	11 08
Gemert, Pastoor Poellplein	A			9 43	9 58	10 13	10 28	10 43	10 58	11 13
Gemert, Pastoor Poellplein	V			9 44	9 59	10 14	10 29	10 44	10 59	11 14
Gemert, Slenk/Lopense				|	10 11	|	10 41	|	11 11	|
Boekel, Kerkstraat				9 50		10 20		10 50		11 20
Volkel, Schoolstraat				9 56		10 26		10 56		11 26
Uden, Busstation Uden	A			10 07		10 37		11 07		11 37

a = Rijdt NIET van 22 december 2019 t/m 4 januari 2020, 23 t/m 29 februari, 10 april, 19 april t/m 4 mei, 22 mei 5 juli t/m 29 augustus en 18 t/m 24 oktober 2020.

maandag t/m vrijdag

321b **322b**

van EINDHOVEN Station naar GEMERT (321) en UDEN (322)

lijnnummer		321	322	321	322	321	322	321	322	321
plaats en haltenaam	**ritnr**	**56**	**58**	**60**	**62**	**64**	**66**	**68**	**70**	**72**
Eindhoven, Station	V	10 53	11 03	11 23	11 33	11 53	12 03	12 23	12 33	12 53
Eindhoven, Fontys Rachelsmolen		|	11 06	|	11 36	|	12 06	|	12 36	|
Eindhoven, WoensXL/ZH Catharina		|	11 09	|	11 39	|	12 09	|	12 40	|
Eindhoven, Summa College Sterrenln		|	11 12	|	11 42	|	12 12	|	12 44	|
Nuenen, Nuenen Centrum		11 04	11 19	11 34	11 49	12 04	12 19	12 35	12 51	13 05
Gerwen, Kerkakkers		11 07	11 22	11 37	11 52	12 07	12 22	12 38	12 54	13 08
Lieshout, Bavaria		11 13	11 28	11 43	11 58	12 13	12 28	12 44	13 00	13 14
Beek en Donk, Lieshoutseweg		11 16	11 31	11 46	12 01	12 16	12 31	12 47	13 03	13 17
Gemert, West-Om/Heuvel		11 23	11 38	11 53	12 08	12 23	12 38	12 55	13 11	13 25
Gemert, Pastoor Poellplein	A	11 28	11 43	11 58	12 13	12 28	12 43	13 00	13 16	13 30
Gemert, Pastoor Poellplein	V	11 29	11 44	11 59	12 14	12 29	12 44	13 01	13 17	13 31
Gemert, Slenk/Lopense		11 41	|	12 11	|	12 41	|	13 14	|	13 44
Boekel, Kerkstraat			11 50		12 20		12 50		13 23	
Volkel, Schoolstraat			11 56		12 26		12 56		13 29	
Uden, Busstation Uden	A		12 07		12 37		13 07		13 40	

lijnnummer		322	321	322	321	322	321	322	321	322
plaats en haltenaam	**ritnr**	**74**	**76**	**78**	**80**	**82**	**84**	**86**	**88**	**90**
Eindhoven, Station	V	13 03	13 23	13 33	13 53	14 03	14 23	14 33	14 53	15 03
Eindhoven, Fontys Rachelsmolen		13 06	|	13 36	|	14 06	|	14 36	|	15 06
Eindhoven, WoensXL/ZH Catharina		13 10	|	13 40	|	14 10	|	14 40	|	15 10
Eindhoven, Summa College Sterrenln		13 14	|	13 44	|	14 14	|	14 44	|	15 14
Nuenen, Nuenen Centrum		13 21	13 35	13 51	14 05	14 21	14 35	14 51	15 05	15 21
Gerwen, Kerkakkers		13 24	13 38	13 54	14 08	14 24	14 38	14 54	15 08	15 24
Lieshout, Bavaria		13 30	13 44	14 00	14 14	14 30	14 44	15 00	15 14	15 30
Beek en Donk, Lieshoutseweg		13 33	13 47	14 03	14 17	14 33	14 47	15 03	15 17	15 33
Gemert, West-Om/Heuvel		13 41	13 55	14 11	14 25	14 41	14 55	15 11	15 25	15 41
Gemert, Pastoor Poellplein	A	13 46	14 00	14 16	14 30	14 46	15 00	15 16	15 30	15 46
Gemert, Pastoor Poellplein	V	13 47	14 01	14 17	14 31	14 47	15 01	15 17	15 31	15 47
Gemert, Slenk/Lopense		|	14 14	|	14 46	|	15 16	|	15 46	|
Boekel, Kerkstraat		13 53		14 23		14 53		15 24		15 54
Volkel, Schoolstraat		13 59		14 29		14 59		15 30		16 00
Uden, Busstation Uden	A	14 10		14 40		15 10		15 42		16 12

a = Rijdt NIET van 22 december 2019 t/m 4 januari 2020, 23 t/m 29 februari, 10 april, 19 april t/m 4 mei, 22 mei 5 juli t/m 29 augustus en 18 t/m 24 oktober 2020.

maandag t/m vrijdag

321b **322b**

van EINDHOVEN Station naar GEMERT (321) en UDEN (322)

lijnnummer		321	321	322	321	321	322	321	321	321
plaats en haltenaam	**ritnr**	**92**	**94**	**96**	**98**	**100**	**102**	**104**	**106**	**108**
		a			a			a		a
Eindhoven, Station	V	15 13	15 23	15 33	15 43	15 53	16 03	16 13	16 23	16 33
Eindhoven, Fontys Rachelsmolen		|	|	15 36	|	|	16 06	|	|	|
Eindhoven, WoensXL/ZH Catharina		|	|	15 40	|	|	16 10	|	|	|
Eindhoven, Summa College Sterrenln		|	|	15 44	|	|	16 14	|	|	|
Nuenen, Nuenen Centrum		15 26	15 36	15 52	15 56	16 06	16 22	16 26	16 36	16 46
Gerwen, Kerkakkers		15 29	15 39	15 55	15 59	16 09	16 25	16 29	16 39	16 49
Lieshout, Bavaria		15 35	15 45	16 01	16 05	16 15	16 31	16 35	16 45	16 55
Beek en Donk, Lieshoutseweg		15 38	15 50	16 06	16 10	16 20	16 36	16 40	16 50	17 00
Gemert, West-Om/Heuvel		15 46	16 01	16 17	16 21	16 31	16 47	16 51	17 01	17 11
Gemert, Pastoor Poellplein	A	15 51	16 06	16 22	16 26	16 36	16 52	16 56	17 06	17 16
Gemert, Pastoor Poellplein	V		16 07	16 23		16 37	16 53		17 07	
Gemert, Slenk/Lopense			16 22	|		16 52	|		17 22	
Boekel, Kerkstraat				16 30			17 00			
Volkel, Schoolstraat				16 36			17 06			
Uden, Busstation Uden	A			16 48			17 18			

lijnnummer		322	321	321	321	322	321	321	322	321
plaats en haltenaam	**ritnr**	**110**	**112**	**114**	**116**	**118**	**120**	**122**	**124**	**126**
			a		a		a			a
Eindhoven, Station	V	16 33	16 43	16 53	17 03	17 03	17 13	17 23	17 33	17 43
Eindhoven, Fontys Rachelsmolen		16 36	|	|	|	17 06	|	|	17 36	|
Eindhoven, WoensXL/ZH Catharina		16 40	|	|	|	17 10	|	|	17 40	|
Eindhoven, Summa College Sterrenln		16 44	|	|	|	17 14	|	|	17 44	|
Nuenen, Nuenen Centrum		16 52	16 56	17 06	17 16	17 22	17 26	17 36	17 51	17 55
Gerwen, Kerkakkers		16 55	16 59	17 09	17 19	17 25	17 29	17 39	17 54	17 58
Lieshout, Bavaria		17 01	17 05	17 15	17 25	17 31	17 35	17 45	18 00	18 04
Beek en Donk, Lieshoutseweg		17 06	17 10	17 20	17 30	17 36	17 40	17 50	18 03	18 07
Gemert, West-Om/Heuvel		17 17	17 21	17 31	17 41	17 47	17 51	18 01	18 11	18 15
Gemert, Pastoor Poellplein	A	17 22	17 26	17 36	17 46	17 52	17 56	18 06	18 16	18 20
Gemert, Pastoor Poellplein	V	17 23		17 37		17 53		18 07	18 17	
Gemert, Slenk/Lopense		|		17 52		|		18 22	|	
Boekel, Kerkstraat		17 30				17 59			18 23	
Volkel, Schoolstraat		17 36				18 05			18 29	
Uden, Busstation Uden	A	17 48				18 16			18 40	

a = Rijdt NIET van 22 december 2019 t/m 4 januari 2020, 23 t/m 29 februari, 10 april, 19 april t/m 4 mei, 22 mei 5 juli t/m 29 augustus en 18 t/m 24 oktober 2020.

maandag t/m vrijdag

321b **322b**

van EINDHOVEN Station naar GEMERT (321) en UDEN (322)

lijnnummer		321	322	321	322	321	322	321	322	321
plaats en haltenaam	**ritnr**	**128**	**130**	**132**	**134**	**136**	**138**	**140**	**142**	**144**
Eindhoven, Station	V	17 53	18 03	18 23	18 33	18 53	19 03	19 23	19 33	19 53
Eindhoven, Fontys Rachelsmolen		|	18 06	|	18 36	|	19 06	|	19 36	|
Eindhoven, WoensXL/ZH Catharina		|	18 09	|	18 39	|	19 09	|	19 39	|
Eindhoven, Summa College Sterrenln		|	18 12	|	18 42	|	19 12	|	19 42	|
Nuenen, Nuenen Centrum		18 05	18 19	18 34	18 49	19 04	19 19	19 34	19 49	20 04
Gerwen, Kerkakkers		18 08	18 22	18 37	18 52	19 07	19 22	19 37	19 52	20 07
Lieshout, Bavaria		18 14	18 28	18 43	18 58	19 13	19 28	19 43	19 58	20 13
Beek en Donk, Lieshoutseweg		18 17	18 31	18 46	19 01	19 16	19 31	19 46	20 01	20 16
Gemert, West-Om/Heuvel		18 25	18 38	18 53	19 08	19 23	19 38	19 53	20 08	20 23
Gemert, Pastoor Poellplein	A	18 30	18 43	18 58	19 13	19 28	19 43	19 58	20 13	20 28
Gemert, Pastoor Poellplein	V	18 31	18 44	18 59		19 29	19 44	19 59		20 29
Gemert, Slenk/Lopense		18 46	|	19 14		19 42	|	20 11		20 41
Boekel, Kerkstraat			18 50				19 50			
Volkel, Schoolstraat			18 56				19 56			
Uden, Busstation Uden	A		19 07				20 07			

lijnnummer		322	322	322	322	322	322	322	322	322
plaats en haltenaam	**ritnr**	**146**	**148**	**150**	**152**	**154**	**156**	**158**	**160**	**162**
Eindhoven, Station	V	20 03	20 33	21 03	21 33	22 03	22 33	23 03	23 33	0 09
Eindhoven, Fontys Rachelsmolen		20 06	20 36	21 06	21 36	22 06	22 36	23 05	23 35	0 11
Eindhoven, WoensXL/ZH Catharina		20 09	20 39	21 09	21 39	22 09	22 39	23 08	23 38	0 14
Eindhoven, Summa College Sterrenln		20 12	20 42	21 12	21 42	22 12	22 42	23 11	23 41	0 17
Nuenen, Nuenen Centrum		20 19	20 49	21 19	21 49	22 19	22 49	23 18	23 48	0 24
Gerwen, Kerkakkers		20 22	20 52	21 22	21 52	22 22	22 52	23 20	23 50	0 26
Lieshout, Bavaria		20 28	20 58	21 28	21 58	22 28	22 58	23 26	23 56	0 32
Beek en Donk, Lieshoutseweg		20 31	21 01	21 31	22 01	22 31	23 01	23 29	23 59	0 35
Gemert, West-Om/Heuvel		20 38	21 08	21 38	22 08	22 38	23 08	23 35	0 05	0 41
Gemert, Pastoor Poellplein	A	20 43	21 13	21 43	22 13	22 43	23 13	23 39	0 09	0 45
Gemert, Pastoor Poellplein	V	20 44		21 44		22 44				
Gemert, Slenk/Lopense		|		|		|				
Boekel, Kerkstraat		20 50		21 50		22 50				
Volkel, Schoolstraat		20 56		21 56		22 56				
Uden, Busstation Uden	A	21 07		22 07		23 07				

maandag t/m vrijdag

AIRPORT SHUTTLE **400a**

van EINDHOVEN Airport naar EINDHOVEN Station

LET OP: deze bus stopt NIET bij tussenliggende haltes!
ATTENTION: this bus does NOT stop at intermediate stops!

plaats en haltenaam	ritnr	1	3	5	7	9	11	13	15	17
Eindhoven, Airport	V	7 15	7 25	7 35	7 45	7 55	8 05	8 15	8 25	8 35
Eindhoven, BIC		7 17	7 27	7 37	7 47	7 57	8 07	8 17	8 27	8 37
Eindhoven, WoensXL/ZH Catharina		7 30	7 40	7 50	8 00	8 10	8 20	8 30	8 40	8 50
Eindhoven, Station	A	7 40	7 50	8 00	8 10	8 20	8 30	8 40	8 50	9 00

plaats en haltenaam	ritnr	19	21	23	25	27	29	31	33	35
Eindhoven, Airport	V	8 45	8 55	9 05	9 15	9 25	9 35	9 45	9 55	10 05
Eindhoven, BIC		8 47	8 57	9 07	9 17	9 27	9 37	9 47	9 57	10 07
Eindhoven, WoensXL/ZH Catharina		9 00	9 10	9 20	9 30	9 40	9 50	10 00	10 10	10 20
Eindhoven, Station	A	9 10	9 20	9 30	9 40	9 50	10 00	10 10	10 20	10 30

plaats en haltenaam	ritnr	37	39	41	43	45	47	49	51	53
Eindhoven, Airport	V	10 15	10 25	10 35	10 45	10 55	11 05	11 15	11 25	11 35
Eindhoven, BIC		10 17	10 27	10 37	10 47	10 57	11 07	11 17	11 27	11 37
Eindhoven, WoensXL/ZH Catharina		10 30	10 40	10 50	11 00	11 10	11 20	11 30	11 40	11 50
Eindhoven, Station	A	10 40	10 50	11 00	11 10	11 20	11 30	11 40	11 50	12 00

plaats en haltenaam	ritnr	55	57	59	61	63	65	67	69	71
Eindhoven, Airport	V	11 45	11 55	12 05	12 15	12 25	12 35	12 45	12 55	13 05
Eindhoven, BIC		11 47	11 57	12 07	12 17	12 27	12 37	12 47	12 57	13 07
Eindhoven, WoensXL/ZH Catharina		12 00	12 10	12 20	12 30	12 40	12 50	13 00	13 10	13 20
Eindhoven, Station	A	12 10	12 20	12 30	12 40	12 50	13 00	13 10	13 20	13 30

plaats en haltenaam	ritnr	73	75	77	79	81	83	85	87	89
Eindhoven, Airport	V	13 15	13 25	13 35	13 45	13 55	14 05	14 15	14 25	14 35
Eindhoven, BIC		13 17	13 27	13 37	13 47	13 57	14 07	14 17	14 27	14 37
Eindhoven, WoensXL/ZH Catharina		13 30	13 40	13 50	14 00	14 10	14 20	14 30	14 40	14 50
Eindhoven, Station	A	13 40	13 50	14 00	14 10	14 20	14 30	14 40	14 50	15 00

maandag t/m vrijdag

AIRPORT SHUTTLE 400a

van EINDHOVEN Airport naar EINDHOVEN Station

LET OP: deze bus stopt NIET bij tussenliggende haltes!
ATTENTION: this bus does NOT stop at intermediate stops!

plaats en haltenaam	ritnr	91	93	95	97	99	101	103	105	107
Eindhoven, Airport	V	14 45	14 55	15 05	15 15	15 25	15 35	15 45	15 55	16 05
Eindhoven, BIC		14 47	14 57	15 07	15 17	15 27	15 37	15 47	15 57	16 07
Eindhoven, WoensXL/ZH Catharina		15 00	15 10	15 20	15 30	15 40	15 50	16 00	16 10	16 20
Eindhoven, Station	A	15 10	15 20	15 30	15 40	15 50	16 00	16 10	16 20	16 30

plaats en haltenaam	ritnr	109	111	113	115	117	119	121	123	125
Eindhoven, Airport	V	16 15	16 25	16 35	16 45	16 55	17 05	17 15	17 25	17 35
Eindhoven, BIC		16 17	16 27	16 37	16 47	16 57	17 07	17 17	17 27	17 37
Eindhoven, WoensXL/ZH Catharina		16 30	16 40	16 50	17 00	17 10	17 20	17 30	17 40	17 50
Eindhoven, Station	A	16 40	16 50	17 00	17 10	17 20	17 30	17 40	17 50	18 00

plaats en haltenaam	ritnr	127	129	131	133	135	137	139	141	143
Eindhoven, Airport	V	17 45	17 55	18 05	18 20	18 35	18 50	19 05	19 20	19 35
Eindhoven, BIC		17 47	17 57	18 07	18 22	18 37	18 52	19 07	19 22	19 37
Eindhoven, WoensXL/ZH Catharina		18 00	18 10	18 20	18 35	18 50	19 03	19 18	19 33	19 48
Eindhoven, Station	A	18 10	18 20	18 30	18 45	19 00	19 13	19 28	19 43	19 58

plaats en haltenaam	ritnr	145	147	149	151	153	155	157	159	161
Eindhoven, Airport	V	19 50	20 05	20 20	20 46	21 16	21 46	22 16	22 46	23 16
Eindhoven, BIC		19 52	20 07	20 22	20 48	21 18	21 48	22 18	22 48	23 18
Eindhoven, WoensXL/ZH Catharina		20 03	20 18	20 33	20 59	21 29	21 59	22 29	22 59	23 29
Eindhoven, Station	A	20 13	20 28	20 43	21 09	21 39	22 09	22 39	23 09	23 39

plaats en haltenaam	ritnr	163								
Eindhoven, Airport	V	23 46								
Eindhoven, BIC		23 48								
Eindhoven, WoensXL/ZH Catharina		23 59								
Eindhoven, Station	A	0 09								

maandag t/m vrijdag

AIRPORT SHUTTLE 400b

van EINDHOVEN Station naar EINDHOVEN Airport

LET OP: deze bus stopt NIET bij tussenliggende haltes!
ATTENTION: this bus does NOT stop at intermediate stops!

plaats en haltenaam	ritnr	2	4	6	8	10	12	14	16	18
Eindhoven, Station	V	6 42	6 52	7 02	7 12	7 22	7 32	7 42	7 52	8 02
Eindhoven, WoensXL/ZH Catharina		6 48	6 58	7 08	7 18	7 28	7 38	7 48	7 58	8 08
Eindhoven, BIC		7 03	7 13	7 23	7 33	7 43	7 53	8 03	8 13	8 23
Eindhoven, Airport	A	7 06	7 16	7 26	7 36	7 46	7 56	8 06	8 16	8 26

plaats en haltenaam	ritnr	20	22	24	26	28	30	32	34	36
Eindhoven, Station	V	8 12	8 22	8 32	8 42	8 52	9 02	9 12	9 22	9 32
Eindhoven, WoensXL/ZH Catharina		8 18	8 28	8 38	8 48	8 58	9 08	9 18	9 28	9 38
Eindhoven, BIC		8 33	8 43	8 53	9 03	9 13	9 23	9 33	9 43	9 53
Eindhoven, Airport	A	8 36	8 46	8 56	9 06	9 16	9 26	9 36	9 46	9 56

plaats en haltenaam	ritnr	38	40	42	44	46	48	50	52	54
Eindhoven, Station	V	9 42	9 52	10 02	10 12	10 22	10 32	10 42	10 52	11 02
Eindhoven, WoensXL/ZH Catharina		9 48	9 58	10 08	10 18	10 28	10 38	10 48	10 58	11 08
Eindhoven, BIC		10 03	10 13	10 23	10 33	10 43	10 53	11 03	11 13	11 23
Eindhoven, Airport	A	10 06	10 16	10 26	10 36	10 46	10 56	11 06	11 16	11 26

plaats en haltenaam	ritnr	56	58	60	62	64	66	68	70	72
Eindhoven, Station	V	11 12	11 22	11 32	11 42	11 52	12 02	12 12	12 22	12 32
Eindhoven, WoensXL/ZH Catharina		11 18	11 28	11 38	11 48	11 58	12 08	12 18	12 28	12 38
Eindhoven, BIC		11 33	11 43	11 53	12 03	12 13	12 23	12 33	12 43	12 53
Eindhoven, Airport	A	11 36	11 46	11 56	12 06	12 16	12 26	12 36	12 46	12 56

plaats en haltenaam	ritnr	74	76	78	80	82	84	86	88	90
Eindhoven, Station	V	12 42	12 52	13 02	13 12	13 22	13 32	13 42	13 52	14 02
Eindhoven, WoensXL/ZH Catharina		12 48	12 58	13 08	13 18	13 28	13 38	13 48	13 58	14 08
Eindhoven, BIC		13 03	13 13	13 23	13 33	13 43	13 53	14 03	14 13	14 23
Eindhoven, Airport	A	13 06	13 16	13 26	13 36	13 46	13 56	14 06	14 16	14 26

maandag t/m vrijdag

AIRPORT SHUTTLE 400b

van EINDHOVEN Station naar EINDHOVEN Airport

LET OP: deze bus stopt NIET bij tussenliggende haltes!
ATTENTION: this bus does NOT stop at intermediate stops!

plaats en haltenaam	ritnr	92	94	96	98	100	102	104	106	108
Eindhoven, Station	V	14 12	14 22	14 32	14 42	14 52	15 02	15 12	15 22	15 32
Eindhoven, WoensXL/ZH Catharina		14 18	14 28	14 38	14 48	14 58	15 08	15 18	15 28	15 38
Eindhoven, BIC		14 33	14 43	14 53	15 03	15 13	15 23	15 33	15 43	15 53
Eindhoven, Airport	A	14 36	14 46	14 56	15 06	15 16	15 26	15 36	15 46	15 56

plaats en haltenaam	ritnr	110	112	114	116	118	120	122	124	126
Eindhoven, Station	V	15 42	15 52	16 02	16 12	16 22	16 32	16 42	16 52	17 02
Eindhoven, WoensXL/ZH Catharina		15 48	15 58	16 08	16 18	16 28	16 38	16 48	16 58	17 08
Eindhoven, BIC		16 03	16 13	16 23	16 33	16 43	16 53	17 03	17 13	17 23
Eindhoven, Airport	A	16 06	16 16	16 26	16 36	16 46	16 56	17 06	17 16	17 26

plaats en haltenaam	ritnr	128	130	132	134	136	138	140	142	144
Eindhoven, Station	V	17 12	17 22	17 32	17 47	18 02	18 17	18 32	18 47	19 02
Eindhoven, WoensXL/ZH Catharina		17 18	17 28	17 38	17 53	18 08	18 23	18 38	18 53	19 08
Eindhoven, BIC		17 33	17 43	17 53	18 08	18 23	18 36	18 51	19 06	19 21
Eindhoven, Airport	A	17 36	17 46	17 56	18 11	18 26	18 39	18 54	19 09	19 24

plaats en haltenaam	ritnr	146	148	150						
Eindhoven, Station	V	19 17	19 32	19 47						
Eindhoven, WoensXL/ZH Catharina		19 23	19 38	19 53						
Eindhoven, BIC		19 36	19 51	20 06						
Eindhoven, Airport	A	19 39	19 54	20 09						

maandag t/m vrijdag

405a **406a**

van ACHTSE BARRIER (405) of EKKERSRIJT (406) naar EINDHOVEN Station

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		405	405	405	405	405	406	405	406	405
plaats en haltenaam	ritnr	1	3	5	7	9	11	13	15	17
Son, Meubelplein	V						7 04		7 19	
Eindhoven, Castilielaan							7 10		7 25	
Eindhoven, Calaislaan		5 59	6 14	6 29	6 44	6 56	|	7 11	|	7 26
Eindhoven, Nicehof		6 04	6 19	6 34	6 49	7 01	|	7 16	|	7 31
Eindhoven, Sportpark Eindhoven Nrd		6 08	6 23	6 38	6 53	7 06	7 14	7 21	7 29	7 36
Eindhoven, WoensXL/ZH Catharina		6 12	6 27	6 42	6 57	7 11	7 19	7 26	7 34	7 41
Eindhoven, Fontys Rachelsmolen		6 16	6 31	6 46	7 01	7 16	7 24	7 31	7 39	7 46
Eindhoven, Station	A	6 22	6 37	6 52	7 07	7 22	7 30	7 37	7 45	7 52

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	ritnr	19	21	23	25	27	29	31	33	35
Son, Meubelplein	V	7 34		7 49		8 04		8 19		8 34
Eindhoven, Castilielaan		7 40		7 55		8 10		8 25		8 40
Eindhoven, Calaislaan		|	7 41	|	7 56	|	8 11	|	8 26	|
Eindhoven, Nicehof		|	7 47	|	8 02	|	8 17	|	8 31	|
Eindhoven, Sportpark Eindhoven Nrd		7 44	7 54	7 59	8 09	8 14	8 24	8 29	8 36	8 44
Eindhoven, WoensXL/ZH Catharina		7 49	7 59	8 04	8 14	8 19	8 29	8 34	8 41	8 49
Eindhoven, Fontys Rachelsmolen		7 54	8 04	8 09	8 19	8 24	8 34	8 39	8 46	8 54
Eindhoven, Station	A	8 00	8 10	8 15	8 25	8 30	8 40	8 45	8 52	9 00

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	ritnr	37	39	41	43	45	47	49	51	53
Son, Meubelplein	V		8 49		9 04		9 19		9 34	
Eindhoven, Castilielaan			8 55		9 10		9 25		9 40	
Eindhoven, Calaislaan		8 41	|	8 56	|	9 11	|	9 26	|	9 41
Eindhoven, Nicehof		8 46	|	9 01	|	9 16	|	9 31	|	9 46
Eindhoven, Sportpark Eindhoven Nrd		8 51	8 59	9 06	9 14	9 21	9 29	9 36	9 44	9 51
Eindhoven, WoensXL/ZH Catharina		8 56	9 04	9 11	9 19	9 26	9 34	9 41	9 49	9 56
Eindhoven, Fontys Rachelsmolen		9 01	9 09	9 16	9 24	9 31	9 39	9 46	9 54	10 01
Eindhoven, Station	A	9 07	9 15	9 22	9 30	9 37	9 45	9 52	10 00	10 07

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	ritnr	55	57	59	61	63	65	67	69	71
Son, Meubelplein	V	9 49		10 04		10 19		10 34		10 49
Eindhoven, Castilielaan		9 55		10 10		10 25		10 40		10 55
Eindhoven, Calaislaan		|	9 56	|	10 11	|	10 26	|	10 41	|
Eindhoven, Nicehof		|	10 01	|	10 16	|	10 31	|	10 46	|
Eindhoven, Sportpark Eindhoven Nrd		9 59	10 06	10 14	10 21	10 29	10 36	10 44	10 51	10 59
Eindhoven, WoensXL/ZH Catharina		10 04	10 11	10 19	10 26	10 34	10 41	10 49	10 56	11 04
Eindhoven, Fontys Rachelsmolen		10 09	10 16	10 24	10 31	10 39	10 46	10 54	11 01	11 09
Eindhoven, Station	A	10 15	10 22	10 30	10 37	10 45	10 52	11 00	11 07	11 15

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	ritnr	73	75	77	79	81	83	85	87	89
Son, Meubelplein	V		11 04		11 19		11 34		11 49	
Eindhoven, Castilielaan			11 10		11 25		11 40		11 55	
Eindhoven, Calaislaan		10 56	|	11 11	|	11 26	|	11 41	|	11 56
Eindhoven, Nicehof		11 01	|	11 16	|	11 31	|	11 46	|	12 01
Eindhoven, Sportpark Eindhoven Nrd		11 06	11 14	11 21	11 29	11 36	11 44	11 51	11 59	12 06
Eindhoven, WoensXL/ZH Catharina		11 11	11 19	11 26	11 34	11 41	11 49	11 56	12 04	12 11
Eindhoven, Fontys Rachelsmolen		11 16	11 24	11 31	11 39	11 46	11 54	12 01	12 09	12 16
Eindhoven, Station	A	11 22	11 30	11 37	11 45	11 52	12 00	12 07	12 15	12 22

maandag t/m vrijdag

405a 406a

van ACHTSE BARRIER (405) of EKKERSRIJT (406) naar EINDHOVEN Station

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	**ritnr**	**91**	**93**	**95**	**97**	**99**	**101**	**103**	**105**	**107**
Son, Meubelplein	V	12 04		12 19		12 34		12 49		13 04
Eindhoven, Castilielaan		12 10		12 25		12 40		12 55		13 10
Eindhoven, Calaislaan		|	12 11	|	12 26	|	12 41	|	12 56	|
Eindhoven, Nicehof		|	12 16	|	12 31	|	12 46	|	13 01	|
Eindhoven, Sportpark Eindhoven Nrd		12 14	12 21	12 29	12 36	12 44	12 51	12 59	13 06	13 14
Eindhoven, WoensXL/ZH Catharina		12 19	12 26	12 34	12 41	12 49	12 56	13 04	13 11	13 19
Eindhoven, Fontys Rachelsmolen		12 24	12 31	12 39	12 46	12 54	13 01	13 09	13 16	13 24
Eindhoven, Station	A	12 30	12 37	12 45	12 52	13 00	13 07	13 15	13 22	13 30

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	**ritnr**	**109**	**111**	**113**	**115**	**117**	**119**	**121**	**123**	**125**
Son, Meubelplein	V		13 19		13 34		13 49		14 04	
Eindhoven, Castilielaan			13 25		13 40		13 55		14 10	
Eindhoven, Calaislaan		13 11	|	13 26	|	13 41	|	13 56	|	14 11
Eindhoven, Nicehof		13 16	|	13 31	|	13 46	|	14 01	|	14 16
Eindhoven, Sportpark Eindhoven Nrd		13 21	13 29	13 36	13 44	13 51	13 59	14 06	14 14	14 21
Eindhoven, WoensXL/ZH Catharina		13 26	13 34	13 41	13 49	13 56	14 04	14 11	14 19	14 26
Eindhoven, Fontys Rachelsmolen		13 31	13 39	13 46	13 54	14 01	14 09	14 16	14 24	14 31
Eindhoven, Station	A	13 37	13 45	13 52	14 00	14 07	14 15	14 22	14 30	14 37

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	**ritnr**	**127**	**129**	**131**	**133**	**135**	**137**	**139**	**141**	**143**
Son, Meubelplein	V	14 19		14 34		14 49		15 04		15 19
Eindhoven, Castilielaan		14 25		14 40		14 55		15 10		15 25
Eindhoven, Calaislaan		|	14 26	|	14 41	|	14 56	|	15 11	|
Eindhoven, Nicehof		|	14 31	|	14 46	|	15 01	|	15 16	|
Eindhoven, Sportpark Eindhoven Nrd		14 29	14 36	14 44	14 51	14 59	15 06	15 14	15 21	15 29
Eindhoven, WoensXL/ZH Catharina		14 34	14 41	14 49	14 56	15 04	15 11	15 19	15 26	15 34
Eindhoven, Fontys Rachelsmolen		14 39	14 46	14 54	15 01	15 09	15 16	15 24	15 31	15 39
Eindhoven, Station	A	14 45	14 52	15 00	15 07	15 15	15 22	15 30	15 37	15 45

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	**ritnr**	**145**	**147**	**149**	**151**	**153**	**155**	**157**	**159**	**161**
Son, Meubelplein	V		15 34		15 49		16 04		16 19	
Eindhoven, Castilielaan			15 40		15 55		16 10		16 25	
Eindhoven, Calaislaan		15 26	|	15 41	|	15 56	|	16 11	|	16 26
Eindhoven, Nicehof		15 31	|	15 46	|	16 01	|	16 16	|	16 31
Eindhoven, Sportpark Eindhoven Nrd		15 36	15 44	15 51	15 59	16 06	16 14	16 21	16 29	16 36
Eindhoven, WoensXL/ZH Catharina		15 41	15 49	15 56	16 04	16 11	16 19	16 26	16 34	16 41
Eindhoven, Fontys Rachelsmolen		15 46	15 54	16 01	16 09	16 16	16 24	16 31	16 39	16 46
Eindhoven, Station	A	15 52	16 00	16 07	16 15	16 22	16 30	16 37	16 45	16 52

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	**ritnr**	**163**	**165**	**167**	**169**	**171**	**173**	**175**	**177**	**179**
Son, Meubelplein	V	16 34		16 49		17 04		17 19		17 34
Eindhoven, Castilielaan		16 40		16 55		17 10		17 25		17 40
Eindhoven, Calaislaan		|	16 41	|	16 56	|	17 11	|	17 26	|
Eindhoven, Nicehof		|	16 46	|	17 01	|	17 16	|	17 31	|
Eindhoven, Sportpark Eindhoven Nrd		16 44	16 51	16 59	17 06	17 14	17 21	17 29	17 36	17 44
Eindhoven, WoensXL/ZH Catharina		16 49	16 56	17 04	17 11	17 19	17 26	17 34	17 41	17 49
Eindhoven, Fontys Rachelsmolen		16 54	17 01	17 09	17 16	17 24	17 31	17 39	17 46	17 54
Eindhoven, Station	A	17 00	17 07	17 15	17 22	17 30	17 37	17 45	17 52	18 00

maandag t/m vrijdag

405a **406a**

van ACHTSE BARRIER (405) of EKKERSRIJT (406) naar EINDHOVEN Station

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	ritnr	181	183	185	187	189	191	193	195	197
Son, Meubelplein	V		17 49		18 04		18 19		18 34	
Eindhoven, Castilielaan			17 55		18 10		18 25		18 40	
Eindhoven, Calaislaan		17 41	|	17 56	|	18 11	|	18 26	|	18 41
Eindhoven, Nicehof		17 46	|	18 01	|	18 16	|	18 31	|	18 46
Eindhoven, Sportpark Eindhoven Nrd		17 51	17 59	18 06	18 14	18 21	18 29	18 36	18 44	18 51
Eindhoven, WoensXL/ZH Catharina		17 56	18 04	18 11	18 19	18 26	18 34	18 41	18 49	18 56
Eindhoven, Fontys Rachelsmolen		18 01	18 09	18 16	18 24	18 31	18 39	18 46	18 54	19 01
Eindhoven, Station	A	18 07	18 15	18 22	18 30	18 37	18 45	18 52	19 00	19 07

lijnnummer		406	405	405	406	405	405	406	405	405
plaats en haltenaam	ritnr	199	201	203	205	207	209	211	213	215
Son, Meubelplein	V	18 49			19 19			19 49		
Eindhoven, Castilielaan		18 55			19 25			19 55		
Eindhoven, Calaislaan		|	18 56	19 11	|	19 26	19 41	|	19 56	20 11
Eindhoven, Nicehof		|	19 01	19 16	|	19 31	19 46	|	20 01	20 16
Eindhoven, Sportpark Eindhoven Nrd		18 59	19 06	19 21	19 29	19 36	19 51	19 59	20 05	20 20
Eindhoven, WoensXL/ZH Catharina		19 04	19 11	19 26	19 34	19 41	19 56	20 03	20 09	20 24
Eindhoven, Fontys Rachelsmolen		19 09	19 16	19 31	19 39	19 46	20 01	20 07	20 13	20 28
Eindhoven, Station	A	19 15	19 22	19 37	19 45	19 52	20 07	20 13	20 19	20 34

lijnnummer		406	405	405	406	405	405	406	405	405
plaats en haltenaam	ritnr	217	219	221	223	225	227	229	231	233
Son, Meubelplein	V	20 19			20 49			21 19		
Eindhoven, Castilielaan		20 25			20 55			21 25		
Eindhoven, Calaislaan		|	20 26	20 41	|	20 56	21 11	|	21 26	21 41
Eindhoven, Nicehof		|	20 31	20 46	|	21 01	21 16	|	21 31	21 46
Eindhoven, Sportpark Eindhoven Nrd		20 29	20 35	20 50	20 59	21 05	21 20	21 29	21 35	21 50
Eindhoven, WoensXL/ZH Catharina		20 33	20 39	20 54	21 03	21 09	21 24	21 33	21 39	21 54
Eindhoven, Fontys Rachelsmolen		20 37	20 43	20 58	21 07	21 13	21 28	21 37	21 43	21 58
Eindhoven, Station	A	20 43	20 49	21 04	21 13	21 19	21 34	21 43	21 49	22 04

lijnnummer		406	405	405	405	405	405	405	405	405
plaats en haltenaam	ritnr	235	237	239	241	243	245	247	249	251
Son, Meubelplein	V	21 49								
Eindhoven, Castilielaan		21 55								
Eindhoven, Calaislaan		|	21 53	22 06	22 21	22 36	22 51	23 06	23 21	23 36
Eindhoven, Nicehof		|	21 58	22 11	22 26	22 41	22 56	23 11	23 26	23 41
Eindhoven, Sportpark Eindhoven Nrd		21 59	22 02	22 15	22 30	22 45	23 00	23 15	23 30	23 45
Eindhoven, WoensXL/ZH Catharina		22 03	22 06	22 19	22 34	22 49	23 04	23 19	23 34	23 49
Eindhoven, Fontys Rachelsmolen		22 07	22 10	22 23	22 38	22 53	23 08	23 23	23 38	23 53
Eindhoven, Station	A	22 13	22 16	22 29	22 44	22 59	23 14	23 29	23 44	23 59

maandag t/m vrijdag

405b 406b

van EINDHOVEN Station naar ACHTSE BARRIER (405) of EKKERSRIJT (406)

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		406	405	406	406	405	406	405	406	405
plaats en haltenaam	**ritnr**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**
Eindhoven, Station	V	6 35	6 45	6 50	7 05	7 13	7 20	7 28	7 35	7 43
Eindhoven, Fontys Rachelsmolen		6 38	6 48	6 53	7 08	7 16	7 23	7 31	7 38	7 46
Eindhoven, WoensXL/ZH Catharina		6 42	6 52	6 57	7 12	7 20	7 27	7 35	7 42	7 50
Eindhoven, Sportpark Eindhoven Nrd		6 46	6 56	7 01	7 16	7 24	7 31	7 39	7 46	7 54
Eindhoven, Nicehof		|	7 00	|	|	7 29	|	7 44	|	7 59
Eindhoven, Calaislaan		|	7 10	|	|	7 40	|	7 55	|	8 10
Eindhoven, Castilielaan		6 50		7 05	7 20		7 35		7 50	
Son, Meubelplein	A	6 59		7 14	7 29		7 44		7 59	

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	**ritnr**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**
Eindhoven, Station	V	7 50	7 58	8 05	8 13	8 20	8 28	8 35	8 43	8 50
Eindhoven, Fontys Rachelsmolen		7 53	8 01	8 08	8 16	8 23	8 31	8 38	8 46	8 53
Eindhoven, WoensXL/ZH Catharina		7 57	8 05	8 12	8 20	8 27	8 35	8 42	8 50	8 57
Eindhoven, Sportpark Eindhoven Nrd		8 01	8 09	8 16	8 24	8 31	8 39	8 46	8 54	9 01
Eindhoven, Nicehof		|	8 14	|	8 29	|	8 44	|	8 59	|
Eindhoven, Calaislaan		|	8 25	|	8 40	|	8 55	|	9 10	|
Eindhoven, Castilielaan		8 05		8 20		8 35		8 50		9 05
Son, Meubelplein	A	8 14		8 29		8 44		8 59		9 14

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	**ritnr**	**38**	**40**	**42**	**44**	**46**	**48**	**50**	**52**	**54**
Eindhoven, Station	V	8 58	9 05	9 13	9 20	9 28	9 35	9 43	9 50	9 58
Eindhoven, Fontys Rachelsmolen		9 01	9 08	9 16	9 23	9 31	9 38	9 46	9 53	10 01
Eindhoven, WoensXL/ZH Catharina		9 05	9 12	9 20	9 27	9 35	9 42	9 50	9 57	10 05
Eindhoven, Sportpark Eindhoven Nrd		9 09	9 16	9 24	9 31	9 39	9 46	9 54	10 01	10 09
Eindhoven, Nicehof		9 14	|	9 29	|	9 44	|	9 59	|	10 14
Eindhoven, Calaislaan		9 25	|	9 40	|	9 55	|	10 10	|	10 25
Eindhoven, Castilielaan			9 20		9 35		9 50		10 05	
Son, Meubelplein	A		9 29		9 44		9 59		10 14	

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	**ritnr**	**56**	**58**	**60**	**62**	**64**	**66**	**68**	**70**	**72**
Eindhoven, Station	V	10 05	10 13	10 20	10 28	10 35	10 43	10 50	10 58	11 05
Eindhoven, Fontys Rachelsmolen		10 08	10 16	10 23	10 31	10 38	10 46	10 53	11 01	11 08
Eindhoven, WoensXL/ZH Catharina		10 12	10 20	10 27	10 35	10 42	10 50	10 57	11 05	11 12
Eindhoven, Sportpark Eindhoven Nrd		10 16	10 24	10 31	10 39	10 46	10 54	11 01	11 09	11 16
Eindhoven, Nicehof		|	10 29	|	10 44	|	10 59	|	11 14	|
Eindhoven, Calaislaan		|	10 40	|	10 55	|	11 10	|	11 25	|
Eindhoven, Castilielaan		10 20		10 35		10 50		11 05		11 20
Son, Meubelplein	A	10 29		10 44		10 59		11 14		11 29

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	**ritnr**	**74**	**76**	**78**	**80**	**82**	**84**	**86**	**88**	**90**
Eindhoven, Station	V	11 13	11 20	11 28	11 35	11 43	11 50	11 58	12 05	12 13
Eindhoven, Fontys Rachelsmolen		11 16	11 23	11 31	11 38	11 46	11 53	12 01	12 08	12 16
Eindhoven, WoensXL/ZH Catharina		11 20	11 27	11 35	11 42	11 50	11 57	12 05	12 12	12 20
Eindhoven, Sportpark Eindhoven Nrd		11 24	11 31	11 39	11 46	11 54	12 01	12 09	12 16	12 24
Eindhoven, Nicehof		11 29	|	11 44	|	11 59	|	12 14	|	12 29
Eindhoven, Calaislaan		11 40	|	11 55	|	12 10	|	12 25	|	12 40
Eindhoven, Castilielaan			11 35		11 50		12 05		12 20	
Son, Meubelplein	A		11 44		11 59		12 14		12 29	

maandag t/m vrijdag

405b 406b

van EINDHOVEN Station naar ACHTSE BARRIER (405) of EKKERSRIJT (406)

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	ritnr	92	94	96	98	100	102	104	106	108
Eindhoven, Station	V	12 20	12 28	12 35	12 43	12 50	12 58	13 05	13 13	13 20
Eindhoven, Fontys Rachelsmolen		12 23	12 31	12 38	12 46	12 53	13 01	13 08	13 16	13 23
Eindhoven, WoensXL/ZH Catharina		12 27	12 35	12 42	12 50	12 57	13 05	13 12	13 20	13 27
Eindhoven, Sportpark Eindhoven Nrd		12 31	12 39	12 46	12 54	13 01	13 09	13 16	13 24	13 31
Eindhoven, Nicehof		|	12 44	|	12 59	|	13 14	|	13 29	|
Eindhoven, Calaislaan		|	12 55	|	13 10	|	13 25	|	13 40	|
Eindhoven, Castilielaan		12 35		12 50		13 05		13 20		13 35
Son, Meubelplein	A	12 44		12 59		13 14		13 29		13 44

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	ritnr	110	112	114	116	118	120	122	124	126
Eindhoven, Station	V	13 28	13 35	13 43	13 50	13 58	14 05	14 13	14 20	14 28
Eindhoven, Fontys Rachelsmolen		13 31	13 38	13 46	13 53	14 01	14 08	14 16	14 23	14 31
Eindhoven, WoensXL/ZH Catharina		13 35	13 42	13 50	13 57	14 05	14 12	14 20	14 27	14 35
Eindhoven, Sportpark Eindhoven Nrd		13 39	13 46	13 54	14 01	14 09	14 16	14 24	14 31	14 39
Eindhoven, Nicehof		13 44	|	13 59	|	14 14	|	14 29	|	14 44
Eindhoven, Calaislaan		13 55	|	14 10	|	14 25	|	14 40	|	14 55
Eindhoven, Castilielaan			13 50		14 05		14 20		14 35	
Son, Meubelplein	A		13 59		14 14		14 29		14 44	

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	ritnr	128	130	132	134	136	138	140	142	144
Eindhoven, Station	V	14 35	14 43	14 50	14 58	15 05	15 13	15 20	15 28	15 35
Eindhoven, Fontys Rachelsmolen		14 38	14 46	14 53	15 01	15 08	15 16	15 23	15 31	15 38
Eindhoven, WoensXL/ZH Catharina		14 42	14 50	14 57	15 05	15 12	15 20	15 27	15 35	15 42
Eindhoven, Sportpark Eindhoven Nrd		14 46	14 54	15 01	15 09	15 16	15 24	15 31	15 39	15 46
Eindhoven, Nicehof		|	14 59	|	15 14	|	15 29	|	15 44	|
Eindhoven, Calaislaan		|	15 10	|	15 25	|	15 40	|	15 55	|
Eindhoven, Castilielaan		14 50		15 05		15 20		15 35		15 50
Son, Meubelplein	A	14 59		15 14		15 29		15 44		15 59

lijnnummer		405	406	405	406	405	406	405	406	405
plaats en haltenaam	ritnr	146	148	150	152	154	156	158	160	162
Eindhoven, Station	V	15 43	15 50	15 58	16 05	16 13	16 20	16 28	16 35	16 43
Eindhoven, Fontys Rachelsmolen		15 46	15 53	16 01	16 08	16 16	16 23	16 31	16 38	16 46
Eindhoven, WoensXL/ZH Catharina		15 50	15 57	16 05	16 12	16 20	16 27	16 35	16 42	16 50
Eindhoven, Sportpark Eindhoven Nrd		15 54	16 01	16 09	16 16	16 24	16 31	16 39	16 46	16 54
Eindhoven, Nicehof		15 59	|	16 14	|	16 29	|	16 44	|	16 59
Eindhoven, Calaislaan		16 10	|	16 25	|	16 40	|	16 55	|	17 10
Eindhoven, Castilielaan			16 05		16 20		16 35		16 50	
Son, Meubelplein	A		16 14		16 29		16 44		16 59	

lijnnummer		406	405	406	405	406	405	406	405	406
plaats en haltenaam	ritnr	164	166	168	170	172	174	176	178	180
Eindhoven, Station	V	16 50	16 58	17 05	17 13	17 20	17 28	17 35	17 43	17 50
Eindhoven, Fontys Rachelsmolen		16 53	17 01	17 08	17 16	17 23	17 31	17 38	17 46	17 53
Eindhoven, WoensXL/ZH Catharina		16 57	17 05	17 12	17 20	17 27	17 35	17 42	17 50	17 57
Eindhoven, Sportpark Eindhoven Nrd		17 01	17 09	17 16	17 24	17 31	17 39	17 46	17 54	18 01
Eindhoven, Nicehof		|	17 14	|	17 29	|	17 44	|	17 59	|
Eindhoven, Calaislaan		|	17 25	|	17 40	|	17 55	|	18 10	|
Eindhoven, Castilielaan		17 05		17 20		17 35		17 50		18 05
Son, Meubelplein	A	17 14		17 29		17 44		17 59		18 14

maandag t/m vrijdag

405b 406b

van EINDHOVEN Station naar ACHTSE BARRIER (405) of EKKERSRIJT (406)

NIET geldig in de zomervakantie (11-07 t/m 22-08-2020)

lijnnummer		405	406	405	406	405	405	406	405	405
plaats en haltenaam	**ritnr**	**182**	**184**	**186**	**188**	**190**	**192**	**194**	**196**	**198**
Eindhoven, Station	V	17 58	18 05	18 13	18 20	18 28	18 43	18 50	18 58	19 13
Eindhoven, Fontys Rachelsmolen		18 01	18 08	18 16	18 23	18 31	18 46	18 53	19 01	19 16
Eindhoven, WoensXL/ZH Catharina		18 05	18 12	18 20	18 27	18 35	18 50	18 57	19 05	19 20
Eindhoven, Sportpark Eindhoven Nrd		18 09	18 16	18 24	18 31	18 39	18 54	19 01	19 09	19 24
Eindhoven, Nicehof		18 14	|	18 29	|	18 44	18 59	|	19 14	19 29
Eindhoven, Calaislaan		18 25	|	18 40	|	18 55	19 10	|	19 25	19 40
Eindhoven, Castilielaan			18 20		18 35			19 05		
Son, Meubelplein	A		18 29		18 44			19 14		

lijnnummer		406	405	405	406	405	405	406	405	405
plaats en haltenaam	**ritnr**	**200**	**202**	**204**	**206**	**208**	**210**	**212**	**214**	**216**
Eindhoven, Station	V	19 20	19 28	19 43	19 50	19 58	20 13	20 20	20 28	20 43
Eindhoven, Fontys Rachelsmolen		19 23	19 31	19 46	19 53	20 01	20 16	20 23	20 31	20 46
Eindhoven, WoensXL/ZH Catharina		19 27	19 35	19 50	19 57	20 05	20 20	20 27	20 35	20 50
Eindhoven, Sportpark Eindhoven Nrd		19 31	19 39	19 54	20 01	20 09	20 24	20 31	20 39	20 54
Eindhoven, Nicehof		|	19 44	19 59	|	20 14	20 29	|	20 44	20 59
Eindhoven, Calaislaan		|	19 55	20 10	|	20 25	20 40	|	20 55	21 10
Eindhoven, Castilielaan		19 35			20 05			20 35		
Son, Meubelplein	A	19 44			20 14			20 44		

lijnnummer		406	405	405	406	405	405	405	405	405
plaats en haltenaam	**ritnr**	**218**	**220**	**222**	**224**	**226**	**228**	**230**	**232**	**234**
Eindhoven, Station	V	20 50	20 58	21 13	21 20	21 28	21 39	21 54	22 09	22 24
Eindhoven, Fontys Rachelsmolen		20 53	21 01	21 16	21 23	21 30	21 41	21 56	22 11	22 26
Eindhoven, WoensXL/ZH Catharina		20 57	21 05	21 20	21 27	21 34	21 45	22 00	22 15	22 30
Eindhoven, Sportpark Eindhoven Nrd		21 01	21 09	21 24	21 31	21 38	21 49	22 04	22 19	22 34
Eindhoven, Nicehof		|	21 14	21 29	|	21 42	21 53	22 08	22 23	22 38
Eindhoven, Calaislaan		|	21 25	21 40	|	21 52	22 03	22 18	22 33	22 48
Eindhoven, Castilielaan		21 05			21 35					
Son, Meubelplein	A	21 14			21 44					

lijnnummer		405	405	405	405	405	405			
plaats en haltenaam	**ritnr**	**236**	**238**	**240**	**242**	**244**	**246**			
Eindhoven, Station	V	22 39	22 54	23 09	23 24	23 39	0 09			
Eindhoven, Fontys Rachelsmolen		22 41	22 56	23 11	23 26	23 41	0 11			
Eindhoven, WoensXL/ZH Catharina		22 45	23 00	23 15	23 30	23 45	0 15			
Eindhoven, Sportpark Eindhoven Nrd		22 49	23 04	23 19	23 34	23 49	0 19			
Eindhoven, Nicehof		22 53	23 08	23 23	23 38	23 53	0 23			
Eindhoven, Calaislaan		23 03	23 18	23 33	23 48	0 03	0 33			
Eindhoven, Castilielaan										
Son, Meubelplein	A									

APPENDIX B CODES FOR TRAFFIC SIMULATION

B.1 Code of osmNetconvert.typ.xml

```
<types xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/types_file.xsd">
   <type id="highway.motorway"  numLanes="2" speed="39.44" priority="14" oneway="true" disallow="rail rail_urban rail_electric rail_fast tram ship pedestrian bicycle moped"/>
   <type id="highway.trunk"  numLanes="2" speed="27.78" priority="13" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship pedestrian bicycle"/>
   <type id="highway.primary"  numLanes="2" speed="27.78" priority="12" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.secondary"  numLanes="1" speed="27.78" priority="11" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.tertiary"  numLanes="1" speed="22.22" priority="10" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.motorway_link"  numLanes="1" speed="22.22" priority="9" oneway="true" disallow="rail rail_urban rail_electric rail_fast tram ship pedestrian bicycle moped"/>
   <type id="highway.trunk_link"  numLanes="1" speed="22.22" priority="8" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship pedestrian bicycle"/>
   <type id="highway.primary_link"  numLanes="1" speed="22.22" priority="7" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.secondary_link"  numLanes="1" speed="22.22" priority="6" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.tertiary_link" numLanes="1" speed="22.22" priority="5" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.unclassified"  numLanes="1" speed="13.89" priority="4" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.residential"  numLanes="1" speed="13.89" priority="3" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.living_street" numLanes="1" speed="2.78" priority="2" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.track"  numLanes="1" speed="5.56" priority="1" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.unsurfaced"  numLanes="1" speed="8.33" priority="1" oneway="false" disallow="rail rail_urban rail_electric rail_fast tram ship"/>
   <type id="highway.service"  numLanes="1" speed="5.56" priority="1" oneway="false" allow="delivery pedestrian bicycle"/>

   <!-- everything which serves mainly pedestrians is oneway because all current pedestrian models do not care about direction -->
   <type id="highway.footway"  numLanes="1" speed="2.78" priority="1" oneway="true" width="2" allow="pedestrian"/>
   <type id="highway.pedestrian"  numLanes="1" speed="2.78" priority="1" oneway="true" width="2" allow="pedestrian"/>
   <type id="highway.path"  numLanes="1" speed="2.78" priority="1" oneway="true" width="2" allow="pedestrian bicycle"/>
   <type id="highway.bridleway"  numLanes="1" speed="2.78" priority="1" oneway="true" width="2" allow="pedestrian"/>
   <type id="highway.cycleway"  numLanes="1" speed="8.33" priority="1" oneway="false" width="1" allow="bicycle"/>
   <type id="highway.step"  numLanes="1" speed="1.39" priority="1" oneway="true" width="2" allow="pedestrian"/>
   <type id="highway.steps"  numLanes="1" speed="1.39" priority="1" oneway="true" width="2" allow="pedestrian"/>
   <type id="highway.stairs"  numLanes="1" speed="1.39" priority="1" oneway="true" width="2" allow="pedestrian"/>
```

```
   <type id="highway.bus_lane"      numLanes="1" speed="27.78" priority="1"  oneway="true"  allow="bus"/>
   <type id="highway.raceway"       numLanes="2" speed="83.33" priority="15" oneway="false" allow="vip"/>
   <type id="highway.ford"          numLanes="1" speed="2.78"  priority="1"  oneway="false" allow="army"/>

   <type id="railway.preserved"     numLanes="1" speed="27.78" priority="16" oneway="true"  allow="rail"/>
   <type id="railway.tram"          numLanes="1" speed="13.89" priority="17" oneway="true"  allow="tram"/>
   <type id="railway.subway"        numLanes="1" speed="27.78" priority="18" oneway="true"
allow="rail_urban"/>
   <type id="railway.light_rail"    numLanes="1" speed="27.78" priority="19" oneway="true"
allow="rail_urban"/>
   <type id="railway.rail"          numLanes="1" speed="44.44" priority="20" oneway="true"  allow="rail"/>
   <type id="railway.highspeed"     numLanes="1" speed="69.44" priority="21" oneway="true"
allow="rail_fast"/>

</types>
```

B.2 Code of osmNetconvertUrbanDe.typ.xml

```
<types xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/types_file.xsd">
   <type id="highway.motorway"       speed="27.78"/>
   <type id="highway.motorway_link"  speed="16.67"/>
   <type id="highway.trunk"          speed="13.89"/>
   <type id="highway.trunk_link"     speed="13.89"/>
   <type id="highway.primary"        speed="13.89"/>
   <type id="highway.primary_link"   speed="13.89"/>
   <type id="highway.secondary"      speed="13.89"/>
   <type id="highway.secondary_link" speed="13.89"/>
   <type id="highway.tertiary"       speed="13.89"/>
   <type id="highway.tertiary_link"  speed="13.89"/>
   <type id="highway.bus_lane"       speed="13.89"/>
</types>
```

B.3 Code of Generate_OD.R

```
## Set working directory
setwd("C:/Users/90665/OneDrive - TU Eindhoven/02 Graduation Project/02 Graduation Thesis/002 Data/1.0
OD matrices")

## Load the installed packages
require("tidyr")
require("tidyverse")

## Read data
# Household information data
hh<-read.table("hh.txt",sep=",",header = T)
# Activity-travel diary data
sched<-read.table("sched.txt",sep=",",header = T)

## Change time related variables from factor to POSIXct date/time object
sched$LeaveTime<-(as.POSIXct(sched$LeaveTime,format="%Y-%m-%d %H:%M:%S"))
sched$BeginTime<-(as.POSIXct(sched$BeginTime,format="%Y-%m-%d %H:%M:%S"))
sched$EndTime<-(as.POSIXct(sched$EndTime,format="%Y-%m-%d %H:%M:%S"))

## Note that filtering process is additive a step by step procedure as below.
## Filter activity schedule data by transport mode (passenger car (PC) driver)
sched_PC<-sched[sched$Mode %in% c("Car"),]

## Filter activity schedule data by both transport mode (PC)
## and leave time during the morning peak hours (between 06:30 and 09:30)
sched_PC_MP <- sched_PC %>%
  filter(between(LeaveTime, as.POSIXct("2020-05-23 06:30"), as.POSIXct("2020-05-23 09:30")))

## Filter activity schedule data by chosen 4-digit post code areas (for both origin/destination) as the third
condition
sched_PC_MP_Ein <-
  sched_PC_MP[sched_PC_MP$OrigLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631) &
              sched_PC_MP$DestLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631),]

## Use plot histogram by time to examine the data
hist(sched_PC_MP_Ein$LeaveTime,breaks="hours")
hist(sched_PC_MP_Ein$BeginTime,breaks="hours")
hist(sched_PC_MP_Ein$EndTime,breaks="hours")

## Create OD matrix with the filtered dataset
OD<-as.data.frame(table(origin=sched_PC_MP_Ein$OrigLoc,dest=sched_PC_MP_Ein$DestLoc))

## Extract OD pairs with at least 1 trip
OD<-OD[OD$Freq>0,]

## Sort OD matrix by origin and destination (smallest to largest)
OD<-OD[with(OD, order(origin, dest)), ]

# Export OD matrix to working directory
write.csv(OD, "OD_06.30-09.30.csv")

## Filter activity schedule data by both transport mode (PC)
## and leave time during daytime off-peak hours (between 09:31 and 15:29)
sched_PC_OP <- sched_PC %>%
  filter(between(LeaveTime, as.POSIXct("2020-05-23 09:31"), as.POSIXct("2020-05-23 15:29")))
```

```
## Filter activity schedule data by chosen 4-digit post code areas (for both origin/destination) as the third condition
sched_PC_OP_Ein <-
  sched_PC_OP[sched_PC_OP$OrigLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631) &
              sched_PC_OP$DestLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631),]

## Use plot histogram by time to examine the data
hist(sched_PC_OP_Ein$LeaveTime,breaks="hours")
hist(sched_PC_OP_Ein$BeginTime,breaks="hours")
hist(sched_PC_OP_Ein$EndTime,breaks="hours")

## Create OD matrix with the filtered dataset
OD<-as.data.frame(table(origin=sched_PC_OP_Ein$OrigLoc,dest=sched_PC_OP_Ein$DestLoc))

## Extract OD pairs with at least 1 trip
OD<-OD[OD$Freq>0,]

## Sort OD matrix by origin and destination (smallest to largest)
OD<-OD[with(OD, order(origin, dest)), ]

# Export OD matrix to working directory
write.csv(OD, "OD_09.31-15.29.csv")

## Filter activity schedule data by both transport mode (PC)
## and leave time during the evening peak hours (between 15:30 and 19:00)
sched_PC_EP <- sched_PC %>%
  filter(between(LeaveTime, as.POSIXct("2020-05-23 15:30"), as.POSIXct("2020-05-23 19:00")))

## Filter activity schedule data by chosen 4-digit post code areas (for both origin/destination) as the third condition
sched_PC_EP_Ein <-
  sched_PC_EP[sched_PC_EP$OrigLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631) &
              sched_PC_EP$DestLoc %in% c(5611, 5612, 5622, 5623, 5625, 5631),]

## Use plot histogram by time to examine the data
hist(sched_PC_EP_Ein$LeaveTime,breaks="hours")
hist(sched_PC_EP_Ein$BeginTime,breaks="hours")
hist(sched_PC_EP_Ein$EndTime,breaks="hours")

## Create OD matrix with the filtered dataset
OD<-as.data.frame(table(origin=sched_PC_EP_Ein$OrigLoc,dest=sched_PC_EP_Ein$DestLoc))

## Extract OD pairs with at least 1 trip
OD<-OD[OD$Freq>0,]

## Sort OD matrix by origin and destination (smallest to largest)
OD<-OD[with(OD, order(origin, dest)), ]

# Export OD matrix to working directory
write.csv(OD, "OD_15.30-19.00.csv")
```

B.4 Code of taz_file.taz.xml

```
<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/additional_file.xsd">
<tazs>
<taz id="1" edges="-gneE111 gneE111 -gneE114 gneE114 110805032 110804525#1 110806313
404686512">
</taz>
<taz id="2" edges="573131264#0 573131261#1 274267630 -274267630 -7161288#1 7161288#1">
</taz>
<taz id="3" edges="-gneE87 gneE87 -7161735 7161735 7161572 -7161572 -7161639 7161639">
</taz>
<taz id="4" edges="-734290656#2 734290656#2 -7161310#4 7161310#4 -7161310#0 7161310#0 7161380#0
-7161380#0 7161695#0 -7161695#0.88">
</taz>
<taz id="5" edges="-gneE103 gneE103 gneE102 -gneE102 -7161772#0 7161772#0 -7161765#4 7161765#4 -
734290652 734290652 7161639 -7161639 7161572 -7161572">
</taz>
<taz id="6" edges="-7161553 7161553 -7161551 7161551 -7161545 7161545 -7161765#3 7161765#3
7161765#0 -7161765#0 7161755#0 -7161755#0 7161750#0 -7161750#0 7161759 -7161759">
</taz>
<taz id="7" edges="-7161776#0.25 7161776#0 7161797 -7161797 -7161374  7161374 -7161419 7161419 -
7161427 7161427 -7161434 7161434 -7161162#9 7161162#9 113003967#0 111299768#1 7161211#1 -
7161211#1">
</taz>
<taz id="8" edges="-7161809 7161809 7166354 -7166354 7166477#1 -7166477#1 7166454 -7166454
7161644 -7161644">
</taz>
<taz id="9" edges="389349233#0 -389349233#0 7161518 -7161518 -7166453#0 7166453#0 389349233#6 -
389349233#6">
</taz>
<taz id="10" edges="-22948617#0.95 22948617#0.19 -22948616.50 22948616.28 150553278 111538118
111299771 -7161198 7161198">
</taz>
<taz id="11" edges="7166299#0 786580509#4 788612013 7166213#3 -7166213#3 788612017 -7166469#0
7166469#0 7166416#0 7166448#1 -gneE1.63 gneE1">
</taz>
<taz id="12" edges="-712114430#1.7 712114430#1.14 452969724#0.5 -452969724#0.12 453527470#3 -
452969723#6 452969723#6 -452969725 452969725">
</taz>
<taz id="13" edges="-7157566#3 7157566#3 -7157553#1 7157553#1 -7157531#3 7157531#3 380070473
541765792 7157662#0 -7157662#0">
</taz>
<taz id="14" edges="-7166273#8 7166273#8 7166307#0 180563743.154 -7166273#0 7166273#0">
</taz>
<taz id="15" edges="-786250762#0 786250762#0">
</taz>
<taz id="16" edges="457077915#1.495 7161935#0 7161822 7161821#1.37 7160671#0 573144189#1
540527264 7157770#1.1765">
</taz>
<taz id="17" edges="-gneE127 gneE127 -gneE132 gneE132 573166393.65.17 7161846#0
349864937#2.23.24 607992346#0">
</taz>
<taz id="18" edges="7161461 536175678 7161442.12 7161446.49 7157769#0">
</taz>
<taz id="19" edges="7157758#2 22948623#1 22948624#0 7157378 540531874#0.108 540531878#1.19
gneE160 -gneE160">
```

```
</taz>
<taz id="20" edges="111558126#0 7166099 7166553#0 gneE48 736800089#1 540444668">
</taz>
</tazs>
</additional>
```

B.5 Code of duarcfg_file.trips2routes.duarcfg

```
<?xml version="1.0" encoding="UTF-8"?>

<!-- <configuration xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/duarouterConfiguration.xsd-->
<configuration>
<!-- The duarouter configuration file takes as input your network and the OD Trips File and output
the route file -->
<input>
	<net-file value="Network.net.xml"/>
	<route-files value="od_file.odtrips.xml"/>
</input>

<output>
	<output-file value="od_route_file.odtrips.rou.xml"/>
</output>
<report>
	<xml-validation value="never"/>
	<no-step-log value="true"/>
</report>

</configuration>
```

B.6 Code of simulation.sumocfg under Baseline Scenario

```
<?xml version="1.0" encoding="UTF-8"?>

<configuration xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/sumoConfiguration.xsd">
	<input>
		<net-file value="Network.net.xml"/>
		<additional-files
value="vehicle_types.add.xml,bus_stops.add.xml,bus_flows.add.xml,detector_validation.add.xml,get_vehicl
ecount.add.xml,detector_measurement.add.xml"/>
		<route-files value="od_route_file.odtrips_06.30-19.00.rou.xml"/>
	</input>
	<time>
		<begin value="23400"/>
		<end value="68400"/>
	</time>
</configuration>
```

Appendix C Supplementary Information for Scenario Analysis

C.1 Code of detector_ATL.add.xml


```xml
<?xml version="1.0" encoding="UTF-8"?>

<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/additional_file.xsd">
   <e1Detector id="e1Detector_-7161733#0_0_12" lane="-7161733#0_0" pos="5.68" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_-734290656#2_1_10" lane="-734290656#2_1" pos="12.37" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_133220171#2_0_4" lane="133220171#2_0" pos="1.87" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_133220171#2_1_5" lane="133220171#2_1" pos="1.85" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_133220171#2_2_6" lane="133220171#2_2" pos="1.81" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_607994420_0_0" lane="607994420_0" pos="6.76" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_607994420_1_1" lane="607994420_1" pos="7.21" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_607994421_0_3" lane="607994421_0" pos="217.35" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_607994421_1_2" lane="607994421_1" pos="217.54" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_7161733#0_0_13" lane="7161733#0_0" pos="4.25" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_7161835#0_0_9" lane="7161835#0_0" pos="18.28" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_7161835#0_1_8" lane="7161835#0_1" pos="18.37" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_7161835#0_2_7" lane="7161835#0_2" pos="18.63" freq="30.00" file="e1Detector.xml"/>
   <e1Detector id="e1Detector_734290656#2_1_11" lane="734290656#2_1" pos="11.35" freq="30.00" file="e1Detector.xml"/>
</additional>
```

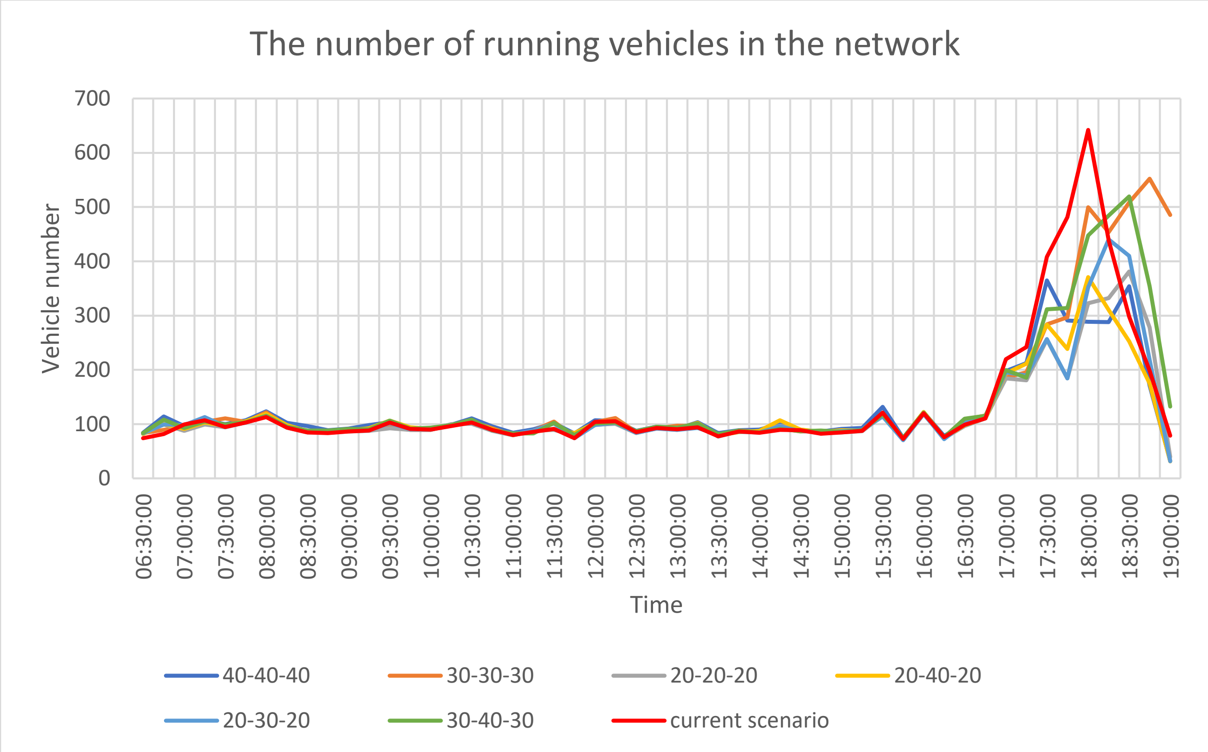
C.2 Code of runner.py

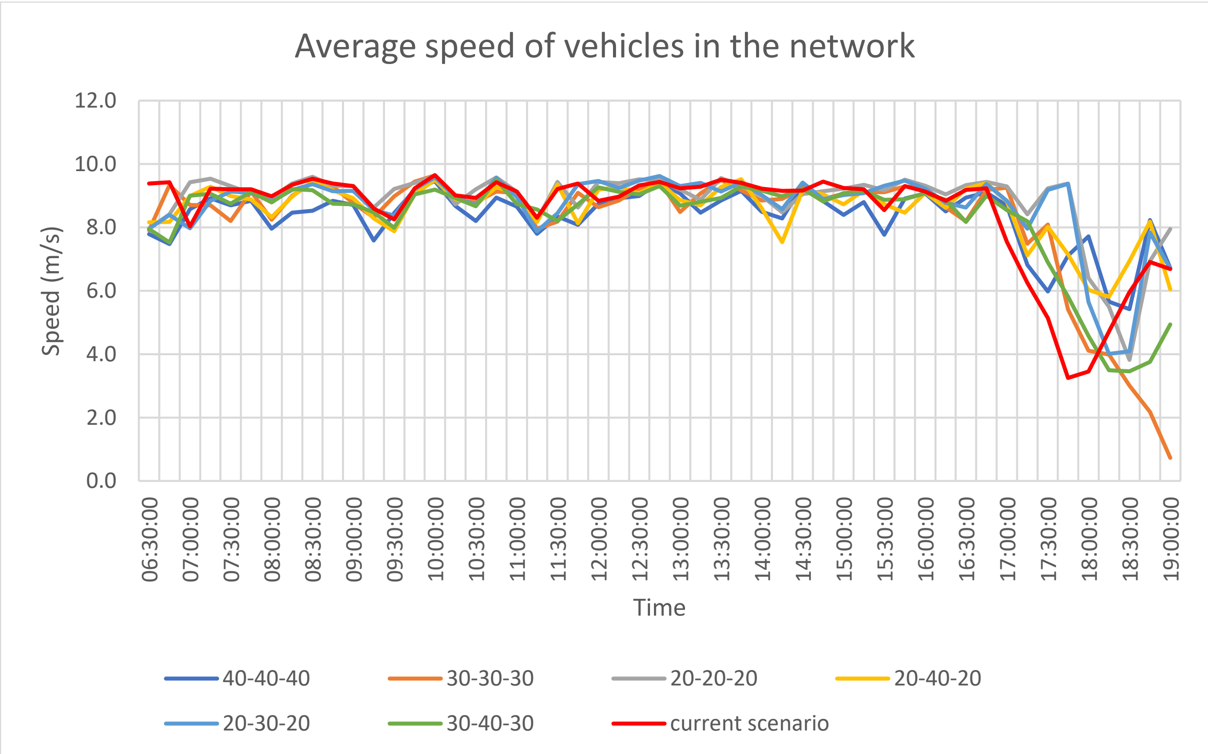
```
from __future__ import absolute_import
from __future__ import print_function

import os
import sys
import optparse

# we need to import python modules from the $SUMO_HOME/tools directory
if 'SUMO_HOME' in os.environ:
    tools = os.path.join(os.environ['SUMO_HOME'], 'tools')
    sys.path.append(tools)
else:
    sys.exit("please declare environment variable 'SUMO_HOME'")

from sumolib import checkBinary  # noqa
import traci  # noqa

# The program looks like this
#    <tlLogic id="5761505957" type="static" programID="0" offset="0">
#        <phase duration="42" state="rGrG"/>
#        <phase duration="3"  state="ryry"/>
#        <phase duration="12" state="GrGG"/>
#        <phase duration="3"  state="yryr"/>
#    </tlLogic>
#    <tlLogic id="gneJ574" type="static" programID="0" offset="0">
#        <phase duration="12" state="GrrG"/>
#        <phase duration="3"  state="yrry"/>
#        <phase duration="42" state="rGGr"/>
#        <phase duration="3"  state="ryyr"/>
#    </tlLogic>


def run():
        """execute the TraCI control loop"""
        step = 23400
        # we start with phase 0 where NS has green
        traci.trafficlight.setPhase("gneJ558", 2)
        traci.trafficlight.setPhase("gneJ562", 0)
        traci.trafficlight.setPhase("6625495454", 2)
        traci.trafficlight.setPhase("5761505957", 0)
        traci.trafficlight.setPhase("gneJ574", 0)
        traci.trafficlight.setPhase("gneJ576", 0)

        traci.trafficlight.setPhase("gneJ426", 2)
        traci.trafficlight.setPhase("gneJ428", 0)
        traci.trafficlight.setPhase("5229152873", 2)
        traci.trafficlight.setPhase("42677735", 0)
        traci.trafficlight.setPhase("gneJ429", 0)
        traci.trafficlight.setPhase("gneJ437", 0)

        traci.trafficlight.setPhase("318155720", 2)
        traci.trafficlight.setPhase("318155719", 0)
        traci.trafficlight.setPhase("6876445151", 2)
        traci.trafficlight.setPhase("42698208", 0)
        traci.trafficlight.setPhase("318155717", 2)
```

```
	traci.trafficlight.setPhase("6876445157", 2)

	while traci.simulation.getMinExpectedNumber() > 0 :
		traci.simulationStep()
		if traci.trafficlight.getPhase("5761505957") == 0:
			# dont switch
			if traci.inductionloop.getLastStepOccupancy("e1Detector_607994420_0_0") > 20
or traci.inductionloop.getLastStepOccupancy("e1Detector_607994420_1_1") > 20 or
traci.inductionloop.getLastStepOccupancy("e1Detector_607994421_1_2") > 20 or
traci.inductionloop.getLastStepOccupancy("e1Detector_607994421_0_3") > 20:
				# 40% of the east road is occupied, switch
				traci.trafficlight.setPhase("gneJ558", 0)
				traci.trafficlight.setPhase("gneJ562", 2)
				traci.trafficlight.setPhase("6625495454", 0)
				traci.trafficlight.setPhase("5761505957", 2)
				traci.trafficlight.setPhase("gneJ574", 2)
				traci.trafficlight.setPhase("gneJ576", 2)
			else:
				# otherwise try to keep green for NS
				traci.trafficlight.setPhase("gneJ558", 2)
				traci.trafficlight.setPhase("gneJ562", 0)
				traci.trafficlight.setPhase("6625495454", 2)
				traci.trafficlight.setPhase("5761505957", 0)
				traci.trafficlight.setPhase("gneJ574", 0)
				traci.trafficlight.setPhase("gneJ576", 0)

		if traci.trafficlight.getPhase("42677735") == 0:
			# dont switch
			if traci.inductionloop.getLastStepOccupancy("e1Detector_133220171#2_0_4") >
40 or traci.inductionloop.getLastStepOccupancy("e1Detector_133220171#2_1_5") > 40 or
traci.inductionloop.getLastStepOccupancy("e1Detector_133220171#2_2_6") > 40 or
traci.inductionloop.getLastStepOccupancy("e1Detector_7161835#0_2_7") > 40 or
traci.inductionloop.getLastStepOccupancy("e1Detector_7161835#0_1_8") > 40 or
traci.inductionloop.getLastStepOccupancy("e1Detector_7161835#0_0_9") > 40:
				# 40% of the east road is occupied, switch
				traci.trafficlight.setPhase("gneJ426", 0)
				traci.trafficlight.setPhase("gneJ428", 2)
				traci.trafficlight.setPhase("5229152873", 0)
				traci.trafficlight.setPhase("42677735", 2)
				traci.trafficlight.setPhase("gneJ429", 2)
				traci.trafficlight.setPhase("gneJ437", 2)
			else:
				# otherwise try to keep green for NS
				traci.trafficlight.setPhase("gneJ426", 2)
				traci.trafficlight.setPhase("gneJ428", 0)
				traci.trafficlight.setPhase("5229152873", 2)
				traci.trafficlight.setPhase("42677735", 0)
				traci.trafficlight.setPhase("gneJ429", 0)
				traci.trafficlight.setPhase("gneJ437", 0)

		if traci.trafficlight.getPhase("42698208") == 0:
			# dont switch
			if traci.inductionloop.getLastStepOccupancy("e1Detector_-
734290656#2_1_10") > 20 or
traci.inductionloop.getLastStepOccupancy("e1Detector_734290656#2_1_11") > 20 or
traci.inductionloop.getLastStepOccupancy("e1Detector_-7161733#0_0_12") > 20 or
traci.inductionloop.getLastStepOccupancy("e1Detector_7161733#0_0_13") > 20:
```

```
                        # 40% of the east road is occupied, switch
                        traci.trafficlight.setPhase("318155720", 0)
                        traci.trafficlight.setPhase("318155719", 2)
                        traci.trafficlight.setPhase("6876445151", 0)
                        traci.trafficlight.setPhase("42698208", 2)
                        traci.trafficlight.setPhase("318155717", 0)
                        traci.trafficlight.setPhase("6876445157", 0)
                    else:
                        # otherwise try to keep green for NS
                        traci.trafficlight.setPhase("318155720", 2)
                        traci.trafficlight.setPhase("318155719", 0)
                        traci.trafficlight.setPhase("6876445151", 2)
                        traci.trafficlight.setPhase("42698208", 0)
                        traci.trafficlight.setPhase("318155717", 2)
                        traci.trafficlight.setPhase("6876445157", 2)

                step += 1
        traci.close()
        sys.stdout.flush()

def get_options():
    optParser = optparse.OptionParser()
    optParser.add_option("--nogui", action="store_true",
                         default=False, help="run the commandline version of sumo")
    options, args = optParser.parse_args()
    return options

# this is the main entry point of this script
if __name__ == "__main__":
    options = get_options()

    # this script has been called from the command line. It will start sumo as a
    # server, then connect and run
    if options.nogui:
        sumoBinary = checkBinary('sumo')
    else:
        sumoBinary = checkBinary('sumo-gui')

    # this is the normal way of using traci. sumo is started as a
    # subprocess and then the python script connects and runs
    traci.start([sumoBinary, "-c", "simulation.sumocfg",
                             "--tripinfo-output", "tripinfo.xml"])
    run()
```

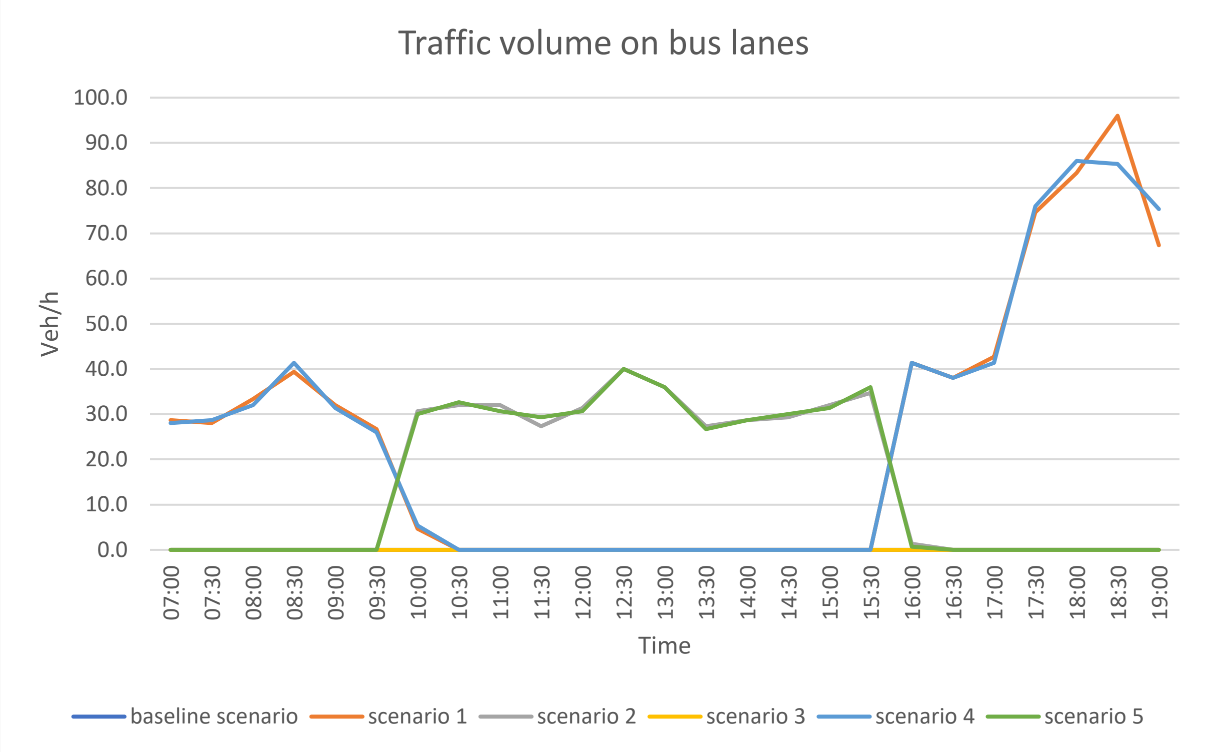
C.3 Measured Traffic Situations of the ATL System Threshold Tests

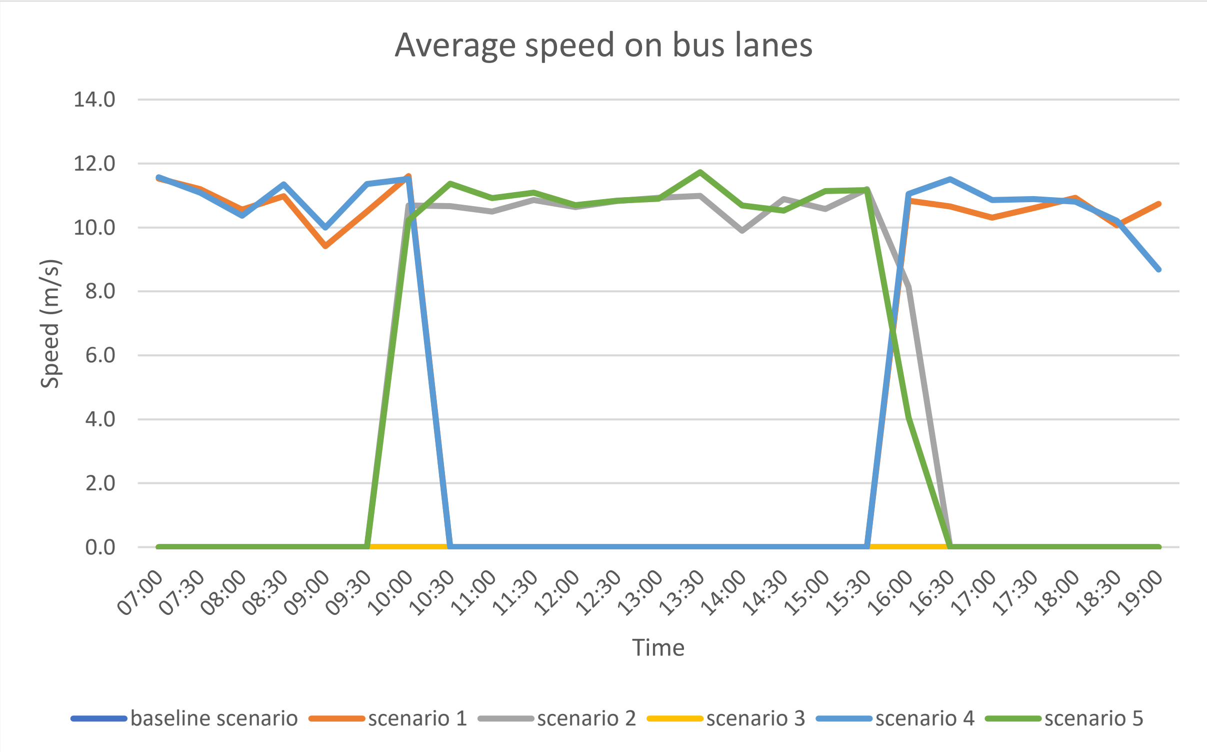


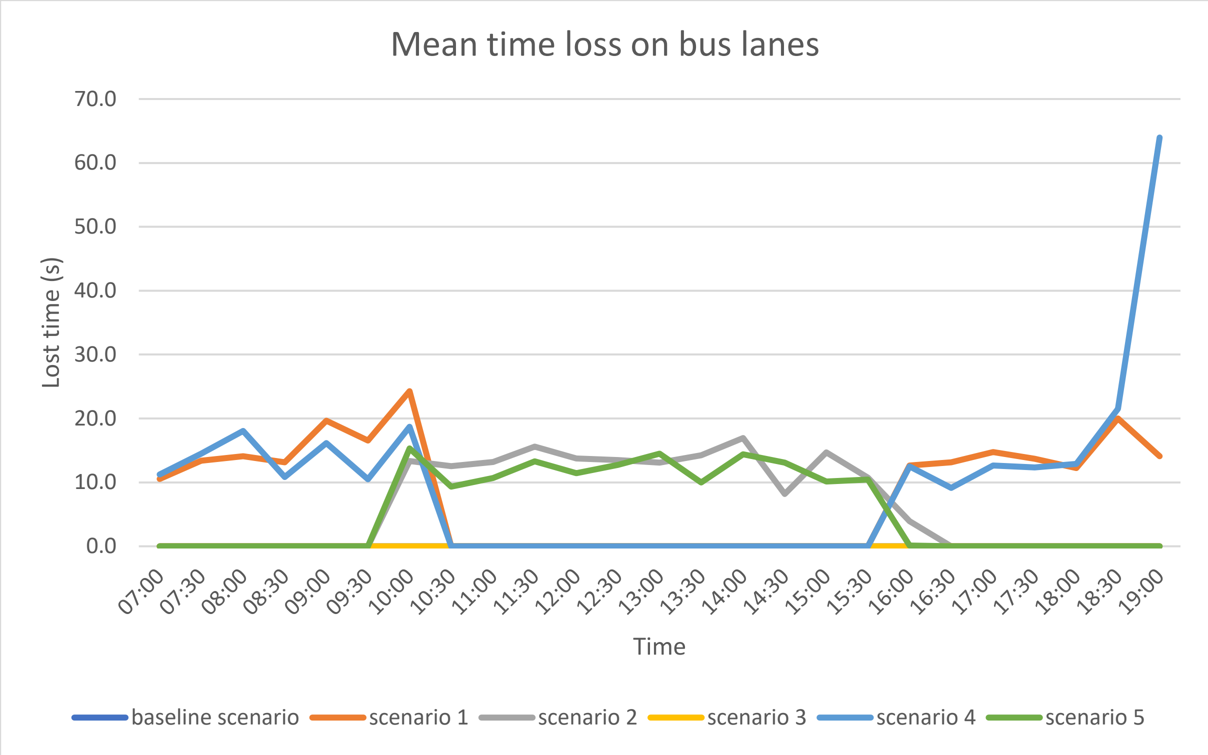


x-y-z means the threshold of ATL 1 was set as x%, y% for ATL 2, z% for ATL 3.

C.4 Measured Traffic Situations on Bus Lanes under Six Scenarios

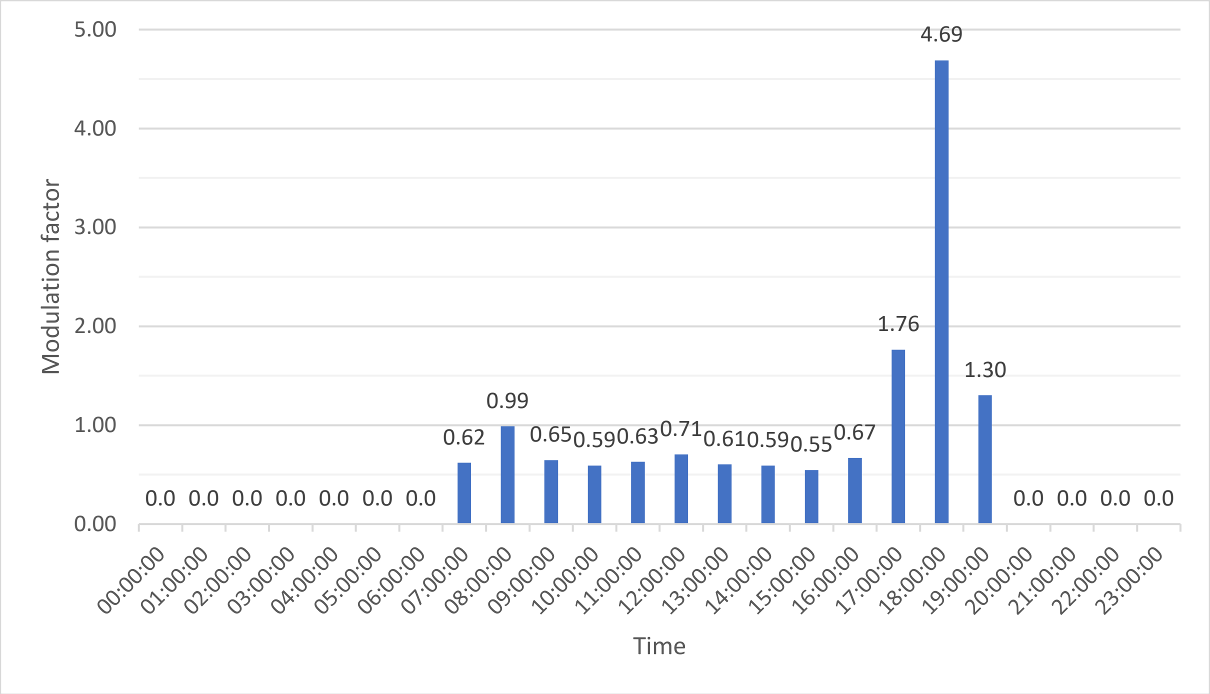




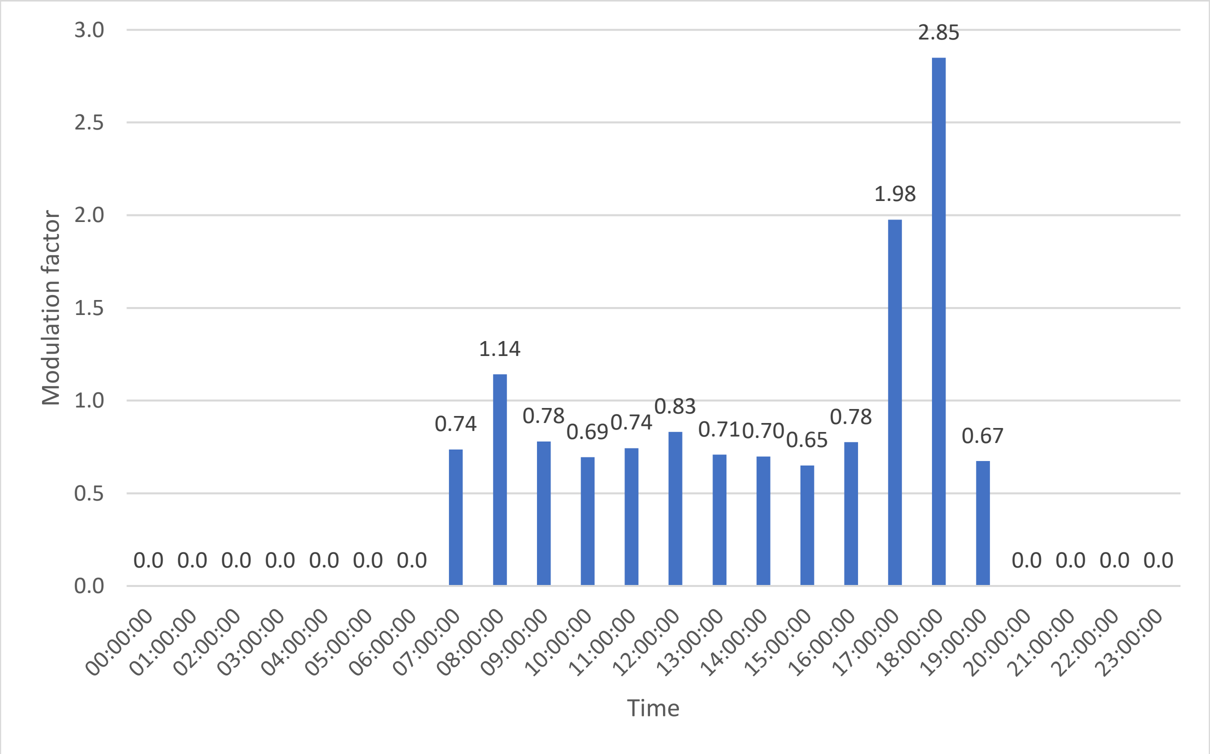

Mean time loss on bus lanes
Lost time (s)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
07:00
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
18:30
19:00
Time
baseline scenario
scenario 1
scenario 2
scenario 3
scenario 4
scenario 5

C.5 The Modulation Factors under Six Scenarios

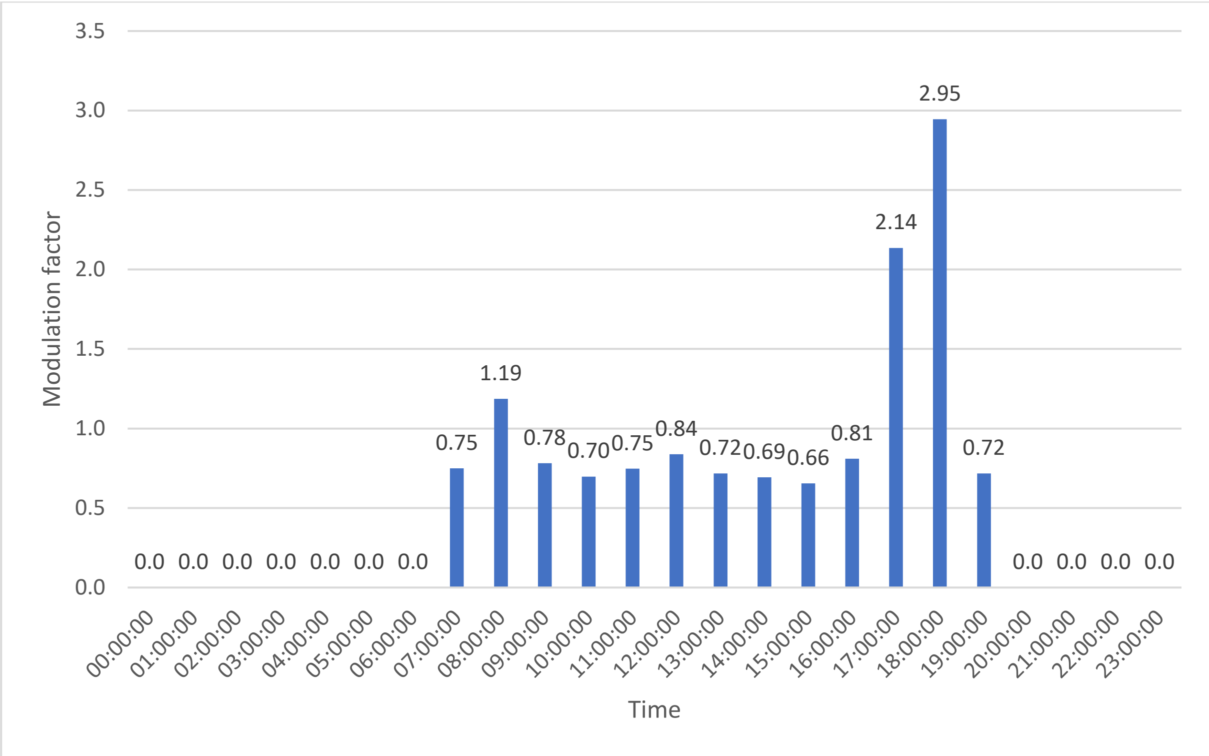
Baseline scenario



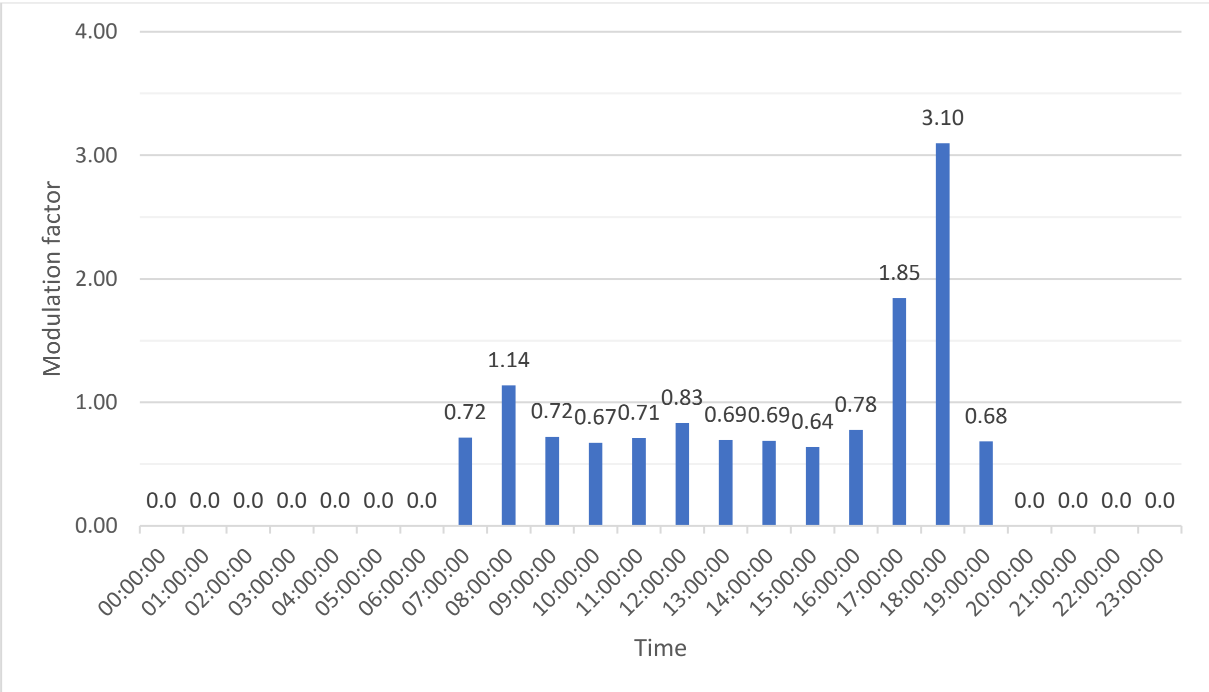
Scenario 1



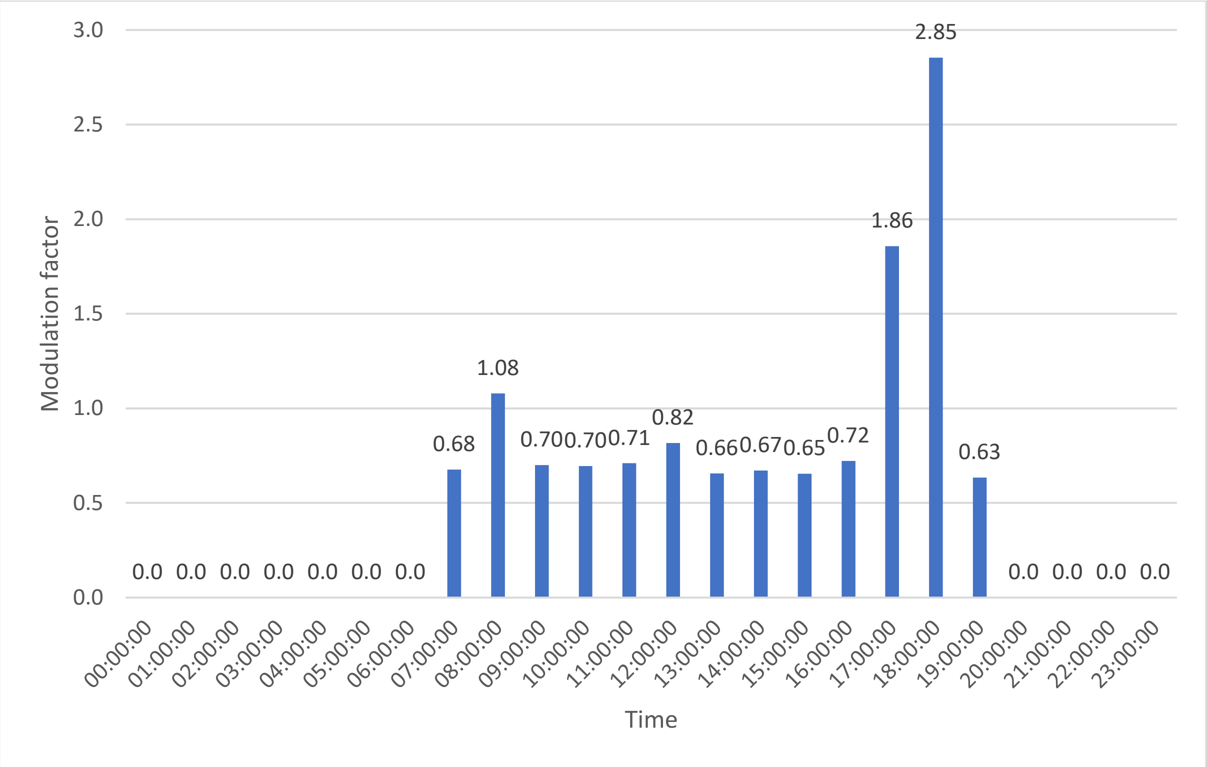
Scenario 2



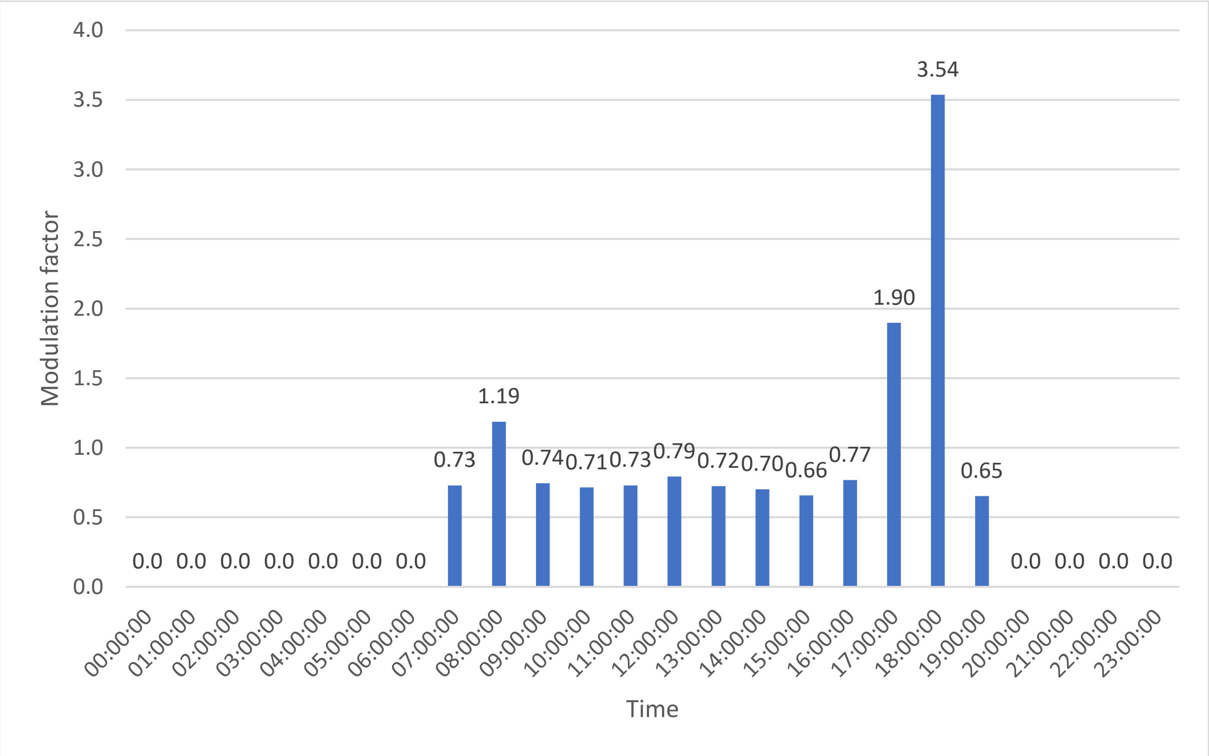
Scenario 3



Scenario 4



Scenario 5

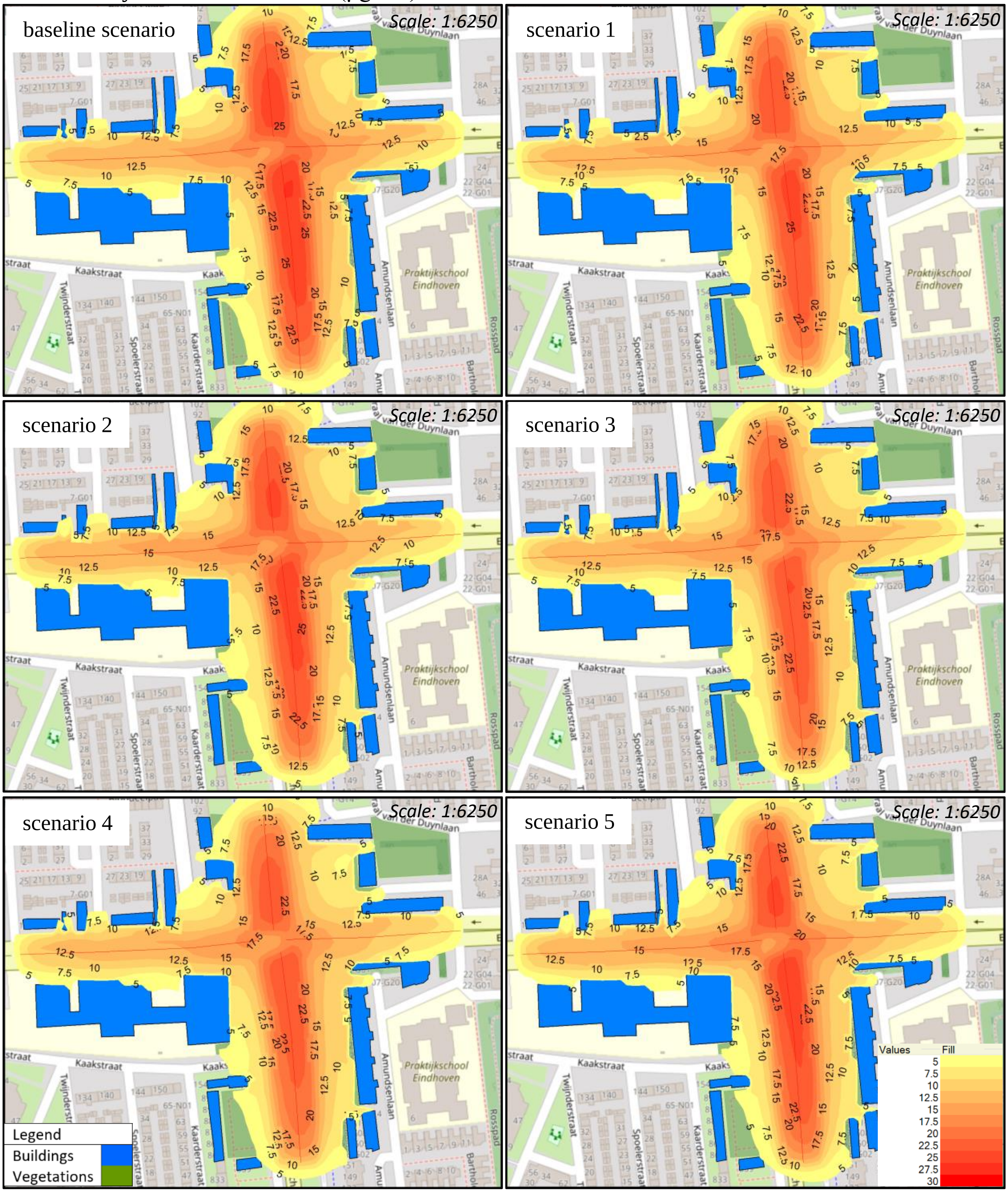


C.6 The Modelled CO Concentrations under Six Scenarios

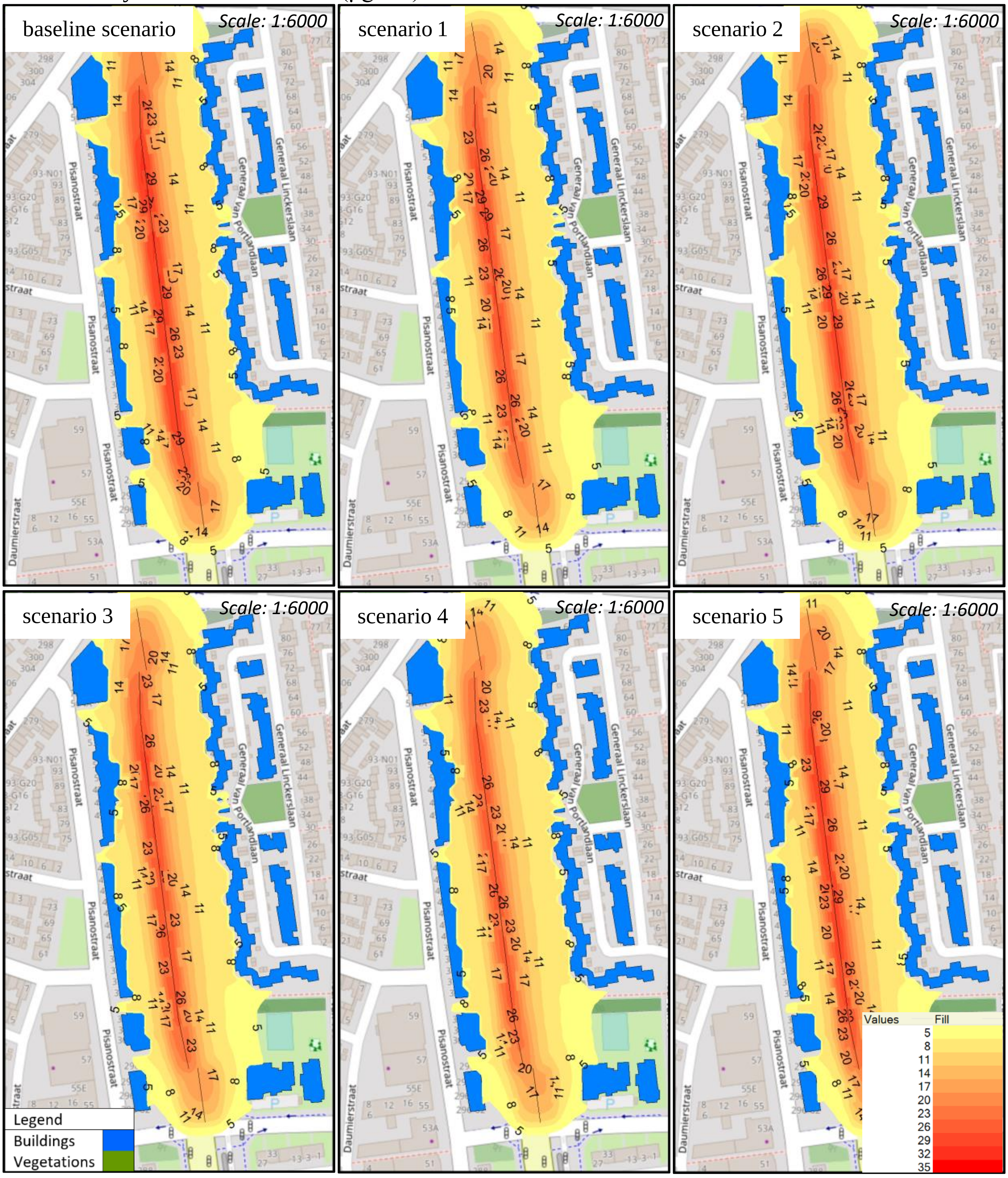
***Table 19** The max values in CO daily mean concentration maps.*

Scenario	Max value (μg/m^3)			Average (μg/m^3)
	Street i	Intersection	Street ii	
Baseline scenario	32.77	27.79	42.64	34.40
Scenario 1	30.08	25.92	41.50	32.50
Scenario 2	31.01	26.56	41.54	33.04
Scenario 3	29.65	25.16	35.29	30.03
Scenario 4	28.22	25.03	38.87	30.71
Scenario 5	31.29	26.57	40.82	32.89

The CO daily mean concentration (μg/m3) at the intersection under different scenarios.



The CO daily mean concentration (μg/m3) on street i under different scenarios.



The CO daily mean concentration (μg/m3) on street ii under different scenarios