Thesis

Assessing potential solutions to reduce congestion and travel times in a highly congested area in the city of Curitiba, Brazil

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Management summary

The city of Curitiba in Brazil has introduced sustainable transport planning with the first bus rapid transit (BRT) system in 1974, to meet its increasing demand for mobility. The BRT system is a high-quality bus-based transit system that delivers fast, comfortable and cost-effective services. This makes the system successful for implementation in developing countries. The majority of Curitiba's inhabitants use the BRT system, which amounts to 1,389,731 passengers transported, 1,226 operating buses and 14,415 trips on a business day. Curitiba has been proactive to continually improve the BRT system and its sustainability. To keep up with the growing demand of mobility, continuous bus-oriented development should be consolidated for high-performance BRT systems. At the moment, the public transportation system in the city of Curitiba is regarded as one of the most efficient of Latin America. However, the increasing demand of passenger mobility is also becoming a serious issue in the city of Curitiba. This has stimulated Curitiba's urban planners to promote a more efficient and comfortable BRT system.

Most of the public buses in the city of Curitiba operate in the context of mixed traffic conditions. Mixed traffic conditions result in long travel times, delays and congestions in some parts of the city. Accordingly, the bus system is not attracting a reasonable percentage of the travel demand within the city. To improve the attractiveness of the public buses in mixed traffic conditions, total travel times and congestions in these parts of the city should be reduced. The ultimate objective of our study is to contribute towards sustainability and efficiency in the BRT system of Curitiba. To reach this objective, our study aims to reduce congestion and travel times of buses on two streets in a highly congested area of Curitiba: the Iguaçu street and Getúlio Vargas street.

Different approaches are considered to reach the objective to improve the efficiency of the BRT system. This research investigates the various effects of deploying a bus terminal, XBLs and bus (stop) adaptions on a traffic network in terms of travel time, intersection delay, queues and average speed for buses and other vehicles on adjacent lanes. Our study aims to analyse which approach is the best to reduce congestion and travel times of buses. This gives us the following main research question:

What is the best solution to improve the bus system efficiency on the Iguaçu street & Getúlio Vargas street in the city of Curitiba in terms of congestion and travel times?

The goal of improving the bus efficiency is to reduce the average delay and total travel times of vehicles in the system, increase the overall speed of vehicles in the system and reduce the queue lengths of vehicles in the system. We use VISSIM to develop a transportation model to find the best solution.

First, we analyse the public transportation system in the city of Curitiba. This information is used as design requirements, limitations and constraints of the simulation model. Next, we analyse the bottleneck of our research. All buses come from different neighbourhoods and go to the only integration terminal in this part of the city. Since all buses drive past the same bus stops, their lines overlap causing bus bunching. Also, the Iguaçu and Getúlio Vargas streets are very crowded and buses regularly get late at the terminal. Based on literature research, we discuss existing solution approaches to reduce congestion in a traffic network. Different model interventions are developed based on the solution approaches and we figure out what data is required and available to build the simulation model. In order to build the simulation model for our network, data on the number of buses, the time and demand at different bus stops, traffic lights and number of vehicles at intersections is needed. Required data for the simulation study is partly directly available from URBS and IPPUC, and the part of the data that is not directly available needs is extracted and estimated by integrating different data sources.

In this study, different parameters are investigated in 7 simulation interventions, which are all 7 modelled for the morning peak hour from 6:30am until 7:30am (indicated by the M in intervention name) and afternoon peak hour from 5:00pm to 6:00pm (indicated by the A in intervention name). This gives us 14 situations in total (see table i). A warm-up time of 30 minutes is used to load vehicles into the model. The different simulation interventions are evaluated based on the performance parameters travel times, average speed, average delay and average queue lengths in the network. Also, all interventions are modelled for different D/C ratios to evaluate the impact of higher demands on the performance of the network.

Table i: Different parameters and interventions included in our study

Parameter / Interventions	*Vehicular volumes*	*Traffic light control*	*Buses that stop*	*Number of buses*	*Bus stop location*	*XBLs*	*Extra lane*	*Bus priority at traffic lights*
LESSBUSM				X				
LESSBUSA	X	X		X				
LESSSTOPM			X					
LESSSTOPA	X	X	X					
MOVEDSTOPM					X			
MOVEDSTOPA	X	X			X			
XBLM						X		
XBLA	X	X				X		
EXTRAXBLM						X	X	
EXTRAXBLA	X	X				X	X	
XBLPRIM						X		X
XBLPRIA	X	X				X		X
EXTRAXBLPRIM						X	X	X
EXTRAXBLPRIA	X	X				X	X	X

From the simulation results we have concluded that the XBLPRI model performed the best in terms of travel times, speed and delay for all traffic in the network. The performance of the buses significantly increases while the impact on the performance of the other vehicles in the network is minimal.

We also concluded that the average speed and average queue lengths in the network are two important KPIs that are useful in evaluating the performance of the network in the city of Curitiba. Therefore, we recommend that these two KPIs should be added to the existing ones when evaluating traffic performance by the municipality of Curitiba.

Based on the outcomes of the present study, two recommendations can be made for implementation of the XBLPRI model in the city of Curitiba. The XBL can be used by other vehicles during off-peak hours. This will help in reducing the negative impacts of XBLs at low volumes. The implementation for the XBL should avoid lanes in which the buses will turn left. This can be applied by allowing the buses that are turning left to use the other lanes instead of using the XBL.

Preface

I am proud to present you my MSc. thesis "*Assessing potential solutions to reduce congestion and travel times in a highly congested area in the city of Curitiba, Brazil*". This research marks the end of my studies at the University of Twente. The time for field research in Brazil has definitely been the most interesting and rewarding time of my studies. Although initially, the project seemed to be outside the area of Industrial engineering, in the end, I could use some skills I acquired during my studies. Also, I got the opportunity to learn some new skills and gain new experiences by conducting this research.

This research would not have been finished without the support of many people. My special thanks go to my supervisors in the city of Curitiba, Keiko Veronica Ono Fonseca and Ricardo Luders. They gave me the chance to work on this research at the Federal University of Technology – Paraná (*Portuguese: Universidade Tecnológica Federal do Paraná*, UTFPR). They were always supportive, gave me advice and challenged my ideas. Although they were busy working on their own researches and giving classes, they were always able to squeeze in some time for a meeting. Also, they helped me to get the right information and data and helped me with translations when this was necessary. Without their help I wouldn't have been able to get the right information and data myself. I would also like to thank the numerous other students and staff at UTFPR, who have introduced me to the world of programming. They always helped me out when I had questions regarding programming or using the database software. Also, they showed me around in Curitiba, introduced me to the Brazilian culture and made me feel at home. This made the experience so much better and I really enjoyed my time in Brazil.

My special thanks go also to my supervisor Peter Schuur. He was enthusiastic from the very beginning I told him I wanted to go to Curitiba in Brazil to conduct this research. Since the beginning his support and feedback was invaluable. He was always available for a (Skype) meeting, even during weekends or late in the evening because of times differences, and his guidance helped me through the rather slow start of the project. I would also like to thank the other member of the graduation committee Ipek Seyran Topan for her constructive feedback during the last part of the project.

Lastly, I would like to thank my family and friends for their support. They always believed in me, supported me and helped clearing my mind at times. This kept me going and I am very proud of what I have achieved so far. I am very grateful for all the support and advice that I have received. Thank you all.

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List of Abbreviations

BRT – *Bus Rapid Transit (p. 1)*

D/C – *Demand/Capacity (p. 7)*

GPS – *Global Positioning System (p. 20)*

HGV – *Heavy Goods Vehicle (p. 26)*

IPPUC – *Curitiba Research and Urban Planning Institute (IPPUC: Portuguese acronym for Instituto de Pesquisa e Planejamento Urbano de Curitiba) (p. 1)*

JSON – *JavaScript Object Notation (p. 20)*

KPI – *Key Performance Indicator (p. 15)*

OR – *Occupancy Rate (p. 11)*

URBS – *Urbanization Company of Curitiba (URBS: Portuguese acronym for Companhia de Urbanização de Curitiba) (p. 2)*

XBL – *Exclusive Bus Lane (p. 3)*

List of Definitions

Articulated bus: The term articulated bus refers to a city bus that consists of two chassis- and body sections that are linked by a pivoting joint. (p. 1).

Biarticulated bus: The term biarticulated bus refers to a city bus that consists of three chassis- and body sections that are linked by two pivoting joints. (p. 1).

Bus Rapid Transit (BRT): The term bus rapid transit refers to a bus-based public mass transit system that operates two-axle, articulated and biarticulated buses. Further elements of a BRT include exclusive lanes for buses, off-board fare collection at stations to enable faster embarking and disembarking, platforms on same height as the bus floor, and prioritised traffic light control. (p. 1).

C40: C40 Cities Climate Leadership Group is a group of cities around the world with the aim to reduce greenhouse gas emissions to address local and global climate risks. C40 supports cities to collaborate, share knowledge and drive sustainable action on climate change, leading the way towards a healthier and sustainable future. The city of Curitiba is a member of C40. (p. 1).

Demand/capacity (D/C) ratio: Ratio of demand to capacity in which the demand is the number of vehicles on a road and the capacity is the capacity of that road. (p. 7).

Effective green time: Effective green time is the time during which a given traffic movement or set of movements may proceed at the maximum traffic flow rate (p. 37).

Exclusive Bus Lane (XBL): The term exclusive lane refers to a lane on which only public city buses are allowed and no other (private) vehicles are permitted. (p. 3).

Integration terminal: An integration terminal is a large shared bus stop of many different bus routes with the purpose to connect the city with its neighbouring cities and its metropolitan region. Passengers have to pay the fare in advance before entering the integration terminal. (p. 5).

Key Performance Indicator (KPI): KPIs are critical indicators of progress towards an intended result. In the case of this research, towards the intended result of improving the efficiency of the BRT system.

Lost time: The time during a given phase in which traffic could be crossing the intersection, but is not. This is the period during the green interval and change intervals that is not used by traffic to cross the intersection. (p. 37).

Occupancy rate (OR): The term occupancy rate refers to the ratio of current number of passengers on a bus versus the maximal possible number of passengers that the bus can carry. This rate is expressed as a percentage. (p. 11).

Operating bus fleet: The term operating bus fleet refers to the number of buses that drive at the same time in the public bus transport system. (p. 11).

Saturation flow rate: The number of passenger cars in a dense flow of traffic for a specific intersection lane group (p. 37).

Tube station: The term tube station refers to a bus stop that enables a faster boarding and alighting to reduce the stop time by having the same height as the buses' floors and allowing the passenger to pay the fare in advance before entering the station. (p. 11).

1. Introduction

In the framework of completing my master thesis in the area of Production and Logistics Management at the University of Twente, I performed research in the city of Curitiba, Brazil into possibilities to improve the efficiency of the public transport system.

This thesis aims to improve the efficiency of the bus rapid transit system in the city of Curitiba, Brazil. Since 1965, when the Institute for Research and Urban Planning of Curitiba (IPPUC) was founded, the municipalities of the city of Curitiba have been putting effort into improving the planning of public transport in Curitiba. This chapter is divided into four sub-sections. Section 1.1 provides the motivation for focusing on the bus rapid transit system in the city of Curitiba, Brazil. Section 1.2 states the research problem, section 1.3 explains the thesis' main objectives and the key research question and section 1.4 gives a short summary and provides the outline of the thesis, including the sub-research questions. Lastly, in section 1.5 the deliverables of this thesis are mentioned.

1.1. General introduction and motivation

Today, more than fifty percent of the worlds' population lives in cities, which challenges urban planners to create good and sustainable services. Every day, many people use public transportation to move around cities. The global demand for passenger's mobility in urbanized areas is likely to double by 2050 (Little, 2018). The transportation sector contributes significantly to the greenhouse gas emissions and environmental concerns have led to shifting to a more sustainable mobility. Therefore, a further expansion of the transportation sector to meet the demand growth, must happen in a sustainable way. Public bus systems play a significant role in the urban transportation sector and offer economic and social advantages. Compared to private vehicles, less resources, road capacities and investments are required to transfer the same number of passengers. Consequently, a high-quality, efficient and effective public transport system is a fundamental element in developing cities.

The city of Curitiba is member of the network C40 Cities Climate Leadership Group (C40), an organization that aims to reduce greenhouse gas emissions (C40, 2015). C40 focuses on tackling climate change and driving urban action that reduces greenhouse gas emissions and climate risks, while increasing economic opportunities and the health and wellbeing of citizens. C40 was established in 2005 and has 96 members from all over the world that are categorised in three groups: mega cities, innovator cities and observer cities. Curitiba is classified as an innovator city which means Curitiba is a leader in environmental sustainability and an important city in the metropolitan area. The city of Curitiba also signed the C40 City Clean Bus Declaration of Intent with the commitment to reduce emissions from the transportation sector (C40, 2015). Therefore, reduction of gas emissions by public transport is important for the municipality of Curitiba. When fewer vehicles are driving on the roads, traffic congestions and gas emissions can be reduced (Stopher, 2004).

One of the forms of public transportation is the Bus Rapid Transit (BRT) system. BRT is increasingly recognised as one of the most effective solutions to cost-effective and high-quality transit services (Wright & Hook, 2007). The BRT system is a high-quality bus-based transit system that delivers fast, comfortable and cost-effective services at metro-level capacities. Thomas (2001, from Wright & Hook, 2007) defines BRT as "*A rapid mode of transportation that can combine the quality of rail transit and the flexibility of buses*". Because of this combination, the BRT system is much more reliable and faster than regular bus services. The BRT operates two-axle, articulated and biarticulated buses and includes exclusive bus lanes, an integrated network of routes and corridors, off-board fare collection, boarding on bus level and prioritized traffic light control. One of the reasons for implementation and the success of BRT systems in developing countries, is that system's ability to serve the travel needs of all inhabitants (ITDP, 2013). With the growing demand of mobility, continuous bus-oriented development should be consolidated and new standards should be set for the future of high-performance BRT systems.

The first BRT system in the world was introduced in 1973 in Ottawa, Canada. This BRT system included dedicated bus lanes through the city centre, with platformed stops. The second BRT system in the world, was the one implemented in the city of Curitiba, in 1974. Curitiba is the capital of the state Paraná, located in Southern Brazil and has approximately 1,92 million inhabitants over an area of 435 km^2 (IPPUC, 2017). The public bus transport system is operated by the governmental public transport company called Urbanization Company of Curitiba (URBS) (*URBS: Portuguese acronym for Companhia de Urbanização de Curitiba*). The majority of Curitiba's inhabitants use the BRT system, which amounts to 1,389,731 passengers transported, 1,226 operating buses and 14,415 trips on a business day (URBS, 2017). The urban planning that led to a BRT system started with a master plan in 1966 including three pillars: land use, roadways and public transit (Macedo, 2004). The public transportation system was not planned as a single entity, but in connection to the entire city. One of the aims of the master plan was to control urban growth by allowing for high densities to transport along structural axes (Macedo, 2004).

The public transportation system in the city of Curitiba is regarded as one of the most efficient of Latin America. Despite having a public transportation system that is a world- wide reference, the increasing demand of passenger mobility is a serious issue in the city. According to DENATRAN (2012), the city of Curitiba reached over 700 vehicles per 1000 inhabitants in 2010, which is the highest motorization rate of the country. This has stimulated Curitiba's urban planners to promote better and comfortable public commuting services so the number of private cars in traffic will be reduced. Also, to reduce congestion, inhabitants of Curitiba need to be stimulated to use public transport, instead of using their private car. In this thesis we consider all buses and bus lines as being part of the BRT system. Therefore, in the remainder of this thesis, we refer to BRT system for all bus related transport in the city of Curitiba.

1.2. Problem definition

Since public bus systems offer advantages, optimization of the bus system is essential (Murray, 2003). Most of the public buses in the city of Curitiba operate in the context of mixed traffic conditions (shared lanes with other vehicles). Mixed traffic conditions result in long travel times, delays and congestions in some parts of the city. Accordingly, the bus system is not attracting a reasonable percentage of the travel demand within the city. Travelers who use public transport want to travel as fast as possible between their pickup location and the final destination. This ride from pickup location to final destination can be measured in terms of total travel time. The total travel time consists of waiting time, boarding and alighting time, in-vehicle traveling time and transfer time. Besides the total travel time, the users expect reliable and comfortable rides (Cepeda et al. 2006). Therefore, to improve the attractiveness of the public buses in mixed traffic conditions, total travel times and congestions on these lines should be reduced. The congestions and delay in traffic also affect the quantity of pollutants generated by vehicles. Improvement of traffic networks therefore not only reduces travel times and congestion but also the emissions of pollutants into the environment (Tomforde et al., 2010).

A preliminary literature study revealed that building a terminal is one of the approaches that is used to reduce the overlapping of bus lines in a congested area to improve system performance. Terminals increase the possibilities of integration with other lines, which may reduce travel times and therefore has a positive impact on the quality and efficiency (minimum number of vehicles and travel times) of the public transport system. Terminals also have benefits for the region where they are implemented. The region in which the terminal is built will become part of the bus system, meaning the users only have to pay one ticket to integrate in the system. Likewise, the population of the surrounding area has the benefit that there is a real estate valuation for the region, boosting the economic development of the neighbourhood. Adding a terminal to the bus system also has the benefit of being able to use less vehicles of greater capacity which directly relates to the reduction of emissions.

However, enhancing the infrastructure of a transportation system and building new terminals to satisfy the growth of travel demand is usually expensive. Also, the impact of transfers on ridership cannot be underestimated. Transfers are often one of the main reasons people will choose not to use a system (Wright & Hook, 2007). Therefore, alternative solutions to reduce traffic congestion should be considered. Exclusive bus lanes (XBLs) are considered as an efficient and effective way to reduce urban congestion. In addition, XBLs are regarded as an effective approach to reduce air pollution and increase the efficiency of the road network. Implementation of XBLs may help to reduce the travel times and as a result the performance of the bus system will increase (Yang & Wang, 2009). When the performance of the bus system increases, drivers who face the worst congestions will take the bus instead. Therefore, the performance of transit has a large impact on reducing traffic congestion.

In contrast, buses are also considered to be a contributory factor of traffic congestion. Compared to private transport, buses require less road space per person and should therefore cause less congestion. However, excessive dwell times, inappropriate vehicle sizes and excess of vehicles result in increased congestion. If there are too many vehicles in the system, this often causes congestion near stops, where buses may have to queue in the street to wait for the boarding area to get empty.

These preliminary results strengthen the idea that traffic congestion in the city of Curitiba can be reduced by introducing a terminal or XBLs or adapt the bus stops or the number of buses in the system (see figure 1 for solution clustering). Although the municipality of Curitiba has the goal to reduce congestions in the city centre, no efforts have currently been made to involve in any research on how to reach this goal. Therefore, this research was conducted to analyse the possible benefits of implementing a terminal or XBLs, or adapt the bus stops or number of buses in the system, in order to reduce traffic congestion in a highly congested part of the city centre of Curitiba.

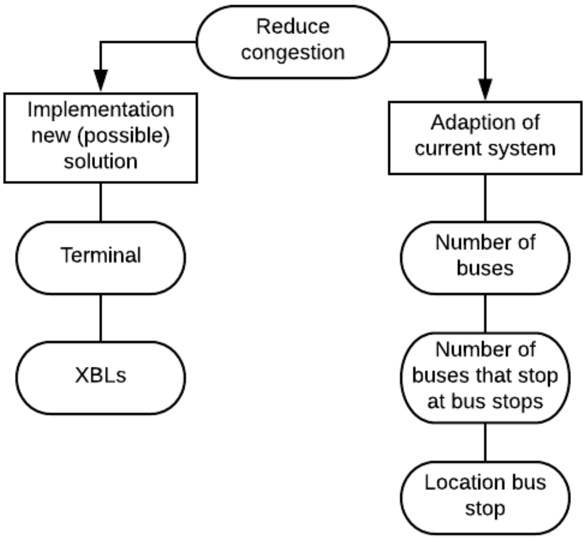


Figure 1: Cluster of possible solutions to the problem of this research

1.3. Thesis objective and main research question

The ultimate objective of our study is to contribute towards sustainability and efficiency in the bus system of Curitiba. To reach this objective, our study aims to reduce congestion and travel times of buses in a highly congested area of Curitiba. Due to the large size of the full bus network in this area, we have reduced the scope of our study to thirteen bus lines in the area called "*Água Verde*". These bus lines connect the neighbourhoods Fazendinha and Santa Quitéria with downtown Curitiba. The thirteen bus lines are chosen because the lines operate in an area with high congestion and long travel times. The following bus lines are considered during the analysis: the conventional bus lines *São Jorge*, *Portão*, *Formosa*, *Nsa. Sra. Da Luz*, *Sta. Quitéria*, *V. Izabel*, *V.Rosinha*, *Carmela Dutra* and *V. Velha* and the trunk bus lines *Fazendinha*, *Caiuá*, *Caiua/Faz/Centro* and *Cotolengo*. In figure 2 the thirteen different lines in the area of study are indicated with different colours. Also, the performance and congestion of these thirteen bus lines have an impact on the congestion of streets reaching the central bus terminal at *Praça Rui Barbosa*. The red streets in figure 2 indicate the two most congested streets in the city of Curitiba: *Iguaçu* street & *Getúlio Vargas* street. The black rectangle shows the part of the streets where all thirteen bus lines operate and consequently, contribute to the congestion on these two streets.

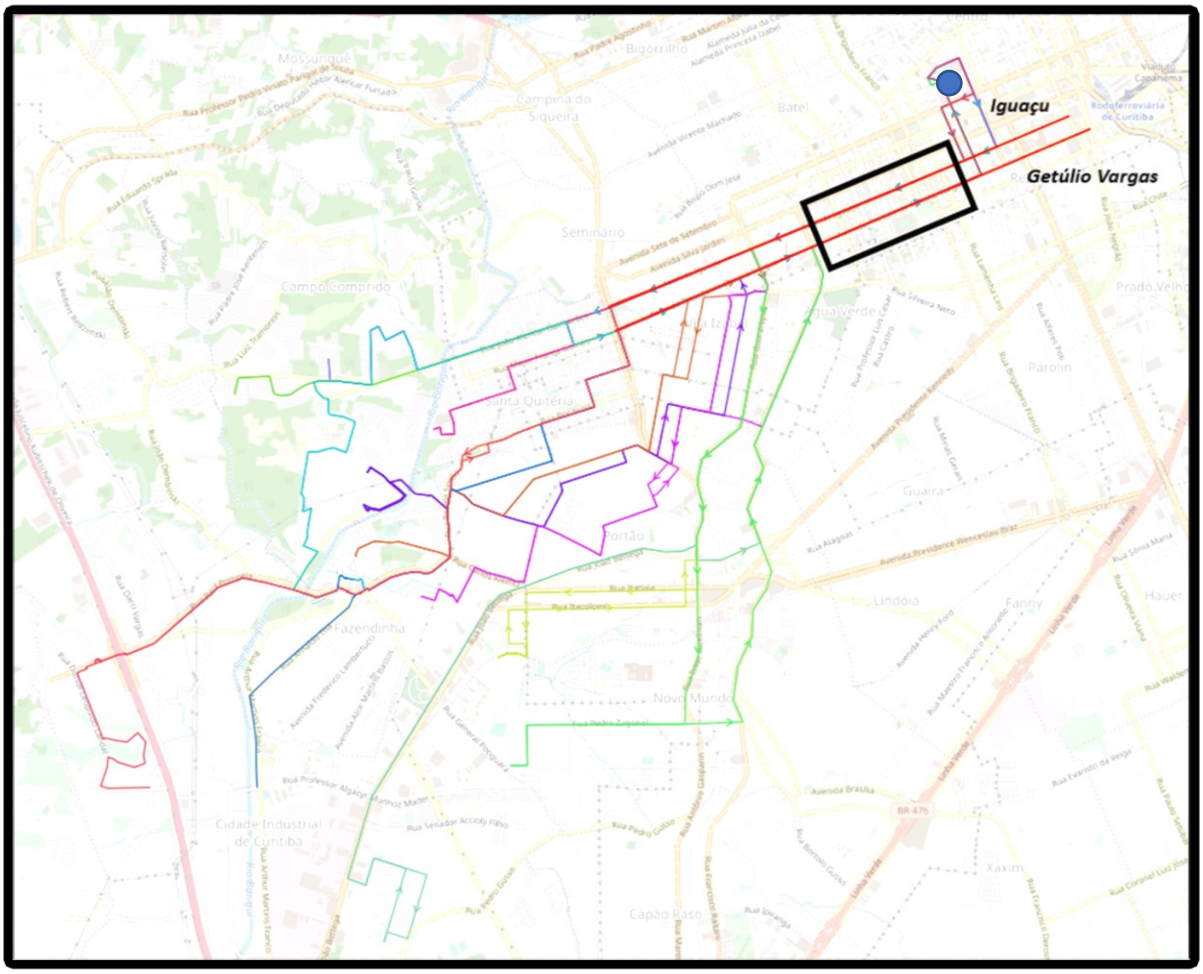


Figure 2: Congested central area in the city of Curitiba, including the thirteen bus lines that operate in this area

Different approaches that are considered to reach the objective include the implementation of a bus terminal and the usage of XBLs in the congested area to improve the performance of the bus system. Also, reduction of the number of buses, reduction of the number of buses that stop at the bus stops and moving a bus stop are considered as possible solutions to reduce the congestion and travel times of the congested area included in this study. This research attempts to address the issue of increased traffic congestion by conducting a study to evaluate the impact of these different approaches on the performance and efficiency of a part of the bus system in a highly congested area of Curitiba, while considering their possible effects on surrounding conditions. In more detail, this research investigates the various effects of deploying a bus terminal, XBLs and bus (stop) adaptions on a traffic network in terms of travel time, intersection delay, queues and average speed for buses and other vehicles on adjacent lanes. This research aims to enable comprehensive understanding of the effects of those approaches on street congestion. Also, a computational method is developed to integrate available data in order to infer necessary, missing data to evaluate the effectiveness of the approaches on the bus system.

A few possible approaches to improve bus system efficiency in the described part of the city of Curitiba have been mentioned above. The objective of this research is to analyse which approach is the best to reduce congestion and travel times of buses. This gives the following main research question:

What is the best solution to improve the bus system efficiency on the Iguaçu street & Getúlio Vargas street in the city of Curitiba in terms of congestion and travel times?

The goal of improving the bus efficiency is to reduce the average delay and total travel times of vehicles in the system, increase the overall speed of vehicles in the system and reduce the queue lengths of vehicles in the system.

By analysing and evaluating different approaches, the research aims to support decision-makers in the city of Curitiba on how to reduce congestion and travel times on those two streets. The study also aims to complement to existing scientific literature on transportation planning. The study intents to support urban planners, policy makers and investors of the city of Curitiba in policy design and future investments in the bus system. Also, this study aims to inform about the possible benefits and impacts of implementing a bus integration terminal or XBLs to reduce number of bus lines and buses in congested areas to improve performance and efficiency of the BRT system. This research attempts to further address the congestion issue by conducting a parametric study to evaluate the impact of XBLs on the performance of the urban traffic network of the city of Curitiba, and measure the effectiveness of XBLs while considering their possible effects on the surrounding traffic (private vehicle) conditions.

1.4. Thesis outline, required information and research questions

In order to solve the research problem, we follow the well-known managerial problem-solving method. This method is designed to solve action/design problems, meaning that something needs to be changed in order to reach a certain goal. Our research is clearly tackling an action problem, as we need to implement an intervention to reduce the congestion problem in the city of Curitiba. The problem-solving method lays the foundation for the structure of this report. The report is divided into six chapters, which all have (sub-) research questions. The main research questions for all chapters are visualized in figure 3.

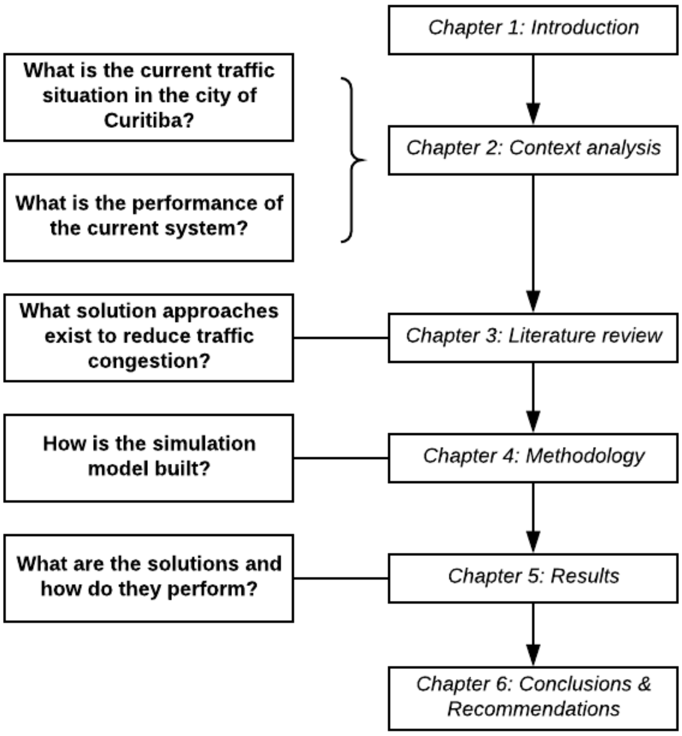


Figure 3: Thesis outline

This first introduction chapter completes the first two steps. We have established the background, context and motivation of the problem. We also determined the project goal and the scope of the project. The planning of the problem-solving process is discussed here, in this sub-chapter, and includes a discussion of the research questions and the structure of this report. The research questions are categorized as As-is questions, Bottleneck questions, Method questions and To-be questions. As-is questions are relevant to the current situation with respect to the context of the problem. Bottleneck questions deal with problems and shortcomings of the current situation. Method questions deal with the method that is used to improve the current situation. To-be questions are related to the desired state.

Chapter two describes the context and the problem of this research. First, we need to know more about the traffic situation in the city of Curitiba. Because we are looking for a congestion solution for a specific region and situation in Curitiba, the traffic and existing traffic infrastructure should be considered. This information can help as design requirements, limitations or constraints to the solution of this research. Consequently, in chapter two of this report, we want to answer the following research questions regarding the context analysis:

As-is Questions (Chapter 2)

1. What is the current traffic situation in the city of Curitiba?

a. What is the network that should be covered in this research?

To answer these questions, we firstly analyse the public transportation system in the city of Curitiba. We visit the decisionmakers of the city of Curitiba to try to understand the decision-making process that takes place before implementing new traffic and/or infrastructure related innovations.

Next, we want to find the bottleneck of our research. We want to describe the problem we are facing in this research by answering the following questions:

Bottleneck questions (Chapter 2)

2. What is the performance of the current system?

a. What KPIs are currently in place to indicate the performance of the current system?

b. What shortcomings of the current system are perceived?

To answer these questions, we talk to some inhabitants of the city of Curitiba, we take part in the BRT system by taking some buses, driving around the city centre and looking at the performance of the system. Also, we speak to employees of IPPUC and URBS who are trying to improve the current performance of the BRT system.

In chapter three, we discuss existing solution approaches that can be used to reduce congestion in a traffic network. Therefore, in chapter three of this report, we aim to answer the following research questions:

As-is questions (Chapter 3)

3. What solution approaches exist to reduce traffic congestion?

a. What approaches can be used to reduce traffic congestion in our situation?

To find existing solution approaches for traffic congestion problems, we conduct a literature review.

Chapter four presents the methodology and scope of this study. In this chapter we choose the solution approaches for our specific situation and discuss the different model interventions and demand/capacity (D/C) ratios. Next, this chapter defines the simulation model and discusses on the choices made for input and evaluation parameters. Also, the different interventions are modelled here. We aim to answer the following questions:

Method questions (Chapter 4)

4. How is the simulation model built?

a. What (traffic) data is required and available?

b. How are the different solutions evaluated?

c. What restrictions should be taken into account?

To find an answer to these questions, we first figure out what data is required for the simulation model. Next, we analyse the kind of traffic data that is available in the city of Curitiba by visiting the stakeholders of IPPUC and URBS. We choose different interventions as possible solution approaches.

Chapter five is the main section of this study and presents the results and the discussion. It evaluates the different solutions that were implemented. In this chapter we evaluate the performance of the proposed scenarios. The simulation is used to provide insight on the performance and functioning of proposed solutions in the traffic network in the city of Curitiba. Moreover, due to the large size of the full network, we are limited to simulate a smaller subnetwork. Because the simulations inputs are chosen by the user, the effect of some of these input values need to be evaluated. This leads to the following research questions:

To-be questions (Chapter 5)

5. What are the solutions and how do they perform?

a. What KPIs are useful in addition to the existing ones?

b. How sensitive are the simulation interventions to its input parameters (D/C ratios)?

c. What are the pros and cons of the different solutions?

d. What are the other benefits of the solutions next to reducing congestion?

To analyse the performance of the proposed solutions, we run simulations of all proposed interventions. Next, we perform a sensitive analysis of the input parameters of the simulation model. Lastly, we discuss which proposed solution is the best to improve the efficiency of Curitiba's BRT system.

We end the thesis by concluding the results and findings of the research in chapter six. We consider possible directions for future research and provide recommendations on the actual implementation of the proposed solution.

1.5. Deliverables

The general deliverable of conducting this research is to provide the municipality of Curitiba with a possible solution to reduce congestion and travel times in a part of the central area of the city of Curitiba.

Specifically, the deliverables of this research are:

- A simulation tool to analyse traffic congestion on Iguaçu street and Getúlio Vargas street
- A visualization of the current traffic situation on Iguaçu street and Getúlio Vargas street
- An advisory report concerning the possible solutions to reduce traffic congestion

2. Context analysis: The city of Curitiba – Case Study Area

This chapter gives an overview of the case study area. To determine to what degree the bus system efficiency can be improved, the current situation in the city of Curitiba is analysed. Section 2.1 explains how the public bus system in the city of Curitiba is organized. Section 2.2 explains how decision making regarding the bus system is done in the city of Curitiba. Section 2.3 shows the covered network of this study and section 2.4 presents the bottleneck of the research and the conclusions of this chapter.

2.1. The public transportation system of Curitiba

The population in the city of Curitiba amounts to 1,92 million people with an annual growth rate of 0,99 (IPPUC, 2019) which will result in a population peak of two million people in 2035 (IPPUC, 2019). The BRT system was implemented in the city of Curitiba in 1974 to meet the rapidly increasing demand of urban passenger mobility. Today, the BRT system of Curitiba consists of 251 bus lines transporting 1,389,731 passengers on an average business day (URBS, 2017).

Curitiba's BRT system is based on integrated use of buses in order to allow users to change among several bus lines, paying one fare ticket with fast access to their destinations. The system is based on north-south and east-west lines where express buses travel on exclusive bus roads called "*via central"*, which are flanked by local roads to gain access to surrounding activities. These exclusive bus roads give significant gains to the operational speed of the express bus lines. Adjacent to these roads there are parallel one-direction *side roads* for private cars, promoting the centre-neighbourhood and downtown-neighbourhood links (see figure 4).

Figure 4: Road system Curitiba. Showing the exclusive bus lane (red), local roads (green) and the parallel side roads for public cars on one-direction roads.

This design of fast bus lanes and slower car lanes establishes a system that structures all of Curitiba's urban planning from and to downtown. Also, there are other bus lines connecting Curitiba's neighbouring cities and there are bus lines connecting Curitiba downtown to specific neighbouring cities. All the different lines form the so-called Integrated Transport Network. The integration processes occur in integration terminals. In this way, users can choose their own route to several neighbourhoods of Curitiba. Altogether, there are fourteen cities interconnected by this Integrated Transport Network (URBS, 2019).

A bus line of the BRT system of the city of Curitiba is defined by bus stops including origin, destination and all of the intermediate stops, which must be followed sequentially according to a fixed timetable. Every bus line normally has a reverse line, going in the opposite direction. There are different kind of bus stops related to the transportation system of Curitiba. The bus stops are classified according to their infrastructure, charging method and their capacity. The three different bus stops that are part of the system are (URBS, 2019):

Regular bus stops: Regular bus stops are bus stops along the road. These bus stops just have a sign and the fares are charged inside the bus.

Integration terminals (a total of 21): Integration terminals are characterized by large infrastructure with shared bus stops to support lots of passengers and buses. Passengers are charged when they enter the terminal. The integration terminals aim to connect the city with the metropolitan region and other neighbouring areas, connecting multiple bus lines; *via rápida (English: fast lanes), linha direta (English: direct lanes)* and *canaleta (English: exclusive bus lanes).* The integration terminals make it possible to implement shorter lines to neighbourhoods in a higher frequency, reducing the travel times. These lines are called *interbairros* (*English: inter neighbourhood*) lines. A schematic model of an integration terminal can be found in figure 5.

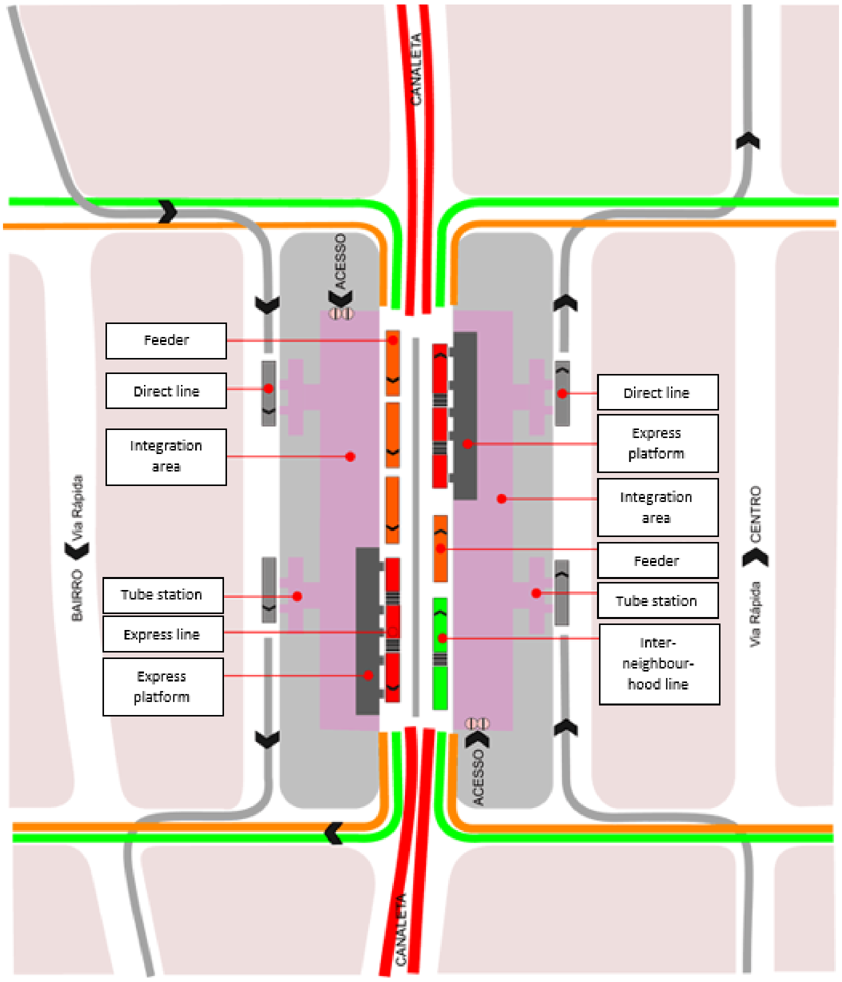


Figure 5: Schematic model of an integration terminal.

Tube stations (a total of 329): Tube stations in the city of Curitiba are not to be confused with London Underground stations, but are bus stops for the BRT system of Curitiba. The tube stations have intermediate infrastructure to support easy access to buses. The tube stations have the same purpose as integration terminals but on a smaller scale; less buses and passengers are supported compared to integration terminals. Passengers are charged when entering the tube stations. The tube stations enable faster boarding of the buses with the aim to reduce waiting times at the bus stops.

In order for the passenger to be entitled to temporary integration, the passenger must use the URBS transport card in one of the validators of the BRT System of Curitiba (bus, integration terminal or tube station). The integration system has the purpose of facilitating access to private and public destinations to the passengers of the BRT system of Curitiba, without the payment of a new tariff upon the return to the terminal. The passenger will have up to two hours to return to the terminal without paying a new ticket. The BRT fare is unique, meaning there is a fixed fare price for everyone entering the BRT system. The fare is R$4,50 (URBS, 2019) for all bus lines except for the circular centre, tourism and long-distance bus lines. An overview of all the BRT numbers can be found in table 1.

Table 1: BRT numbers 2017 (URBS, 2019)

Number	Description
1,389,731	passengers transported on a business day
628,769	paying passengers on a business day
251	bus lines
329	tube stations
21	integration terminals
1226	operating fleet buses
302,186	km travelled on a business day
14,415	trips on a business day
60.70%	tariffs paid using the transport card

The operating bus fleet of the city of Curitiba consists of up to 1226 city buses, i.e. the number of buses that serve the BRT system at the same time (URBS, 2017). The occupancy rate (OR) is expressed in a percentage of number of passengers on a bus compared to the maximum number of passengers that can be carried on the bus. The OR of the buses changes during the day, dependent on working hours and opening hours of shopping malls and public or private institutions like schools and universities. The Municipal Law 12597/08 defines that for the BRT in Curitiba, the occupation must be a maximum of six passengers per square meter.

The BRT system includes nine different bus routes that are distinguished using different colours. The different colours enable easy identification of the different buses and their routes according to the classification made by URBS. A summary of the bus routes, bus colours, capacity, number of vehicles in the operation fleet and the number of lines can be found in figure 6. More details on the different bus routes can be found in appendix A.

COMPOSIÇÃO DA FROTA 2016

RIT - REDE INTEGRADA DE TRANSPORTE

CATEGORIA DE LINHA	TIPOS DE VEÍCULO	CAPACIDADE / VEÍCULO	FROTA OPERANTE Subtotal	FROTA OPERANTE Total	QTDE LINHAS
EXPRESSO LIGEIRÃO	BIARTICULADO	250	29	29	02
EXPRESSO	BIARTICULADO	230/250	116	150	05
	ARTICULADO	170	34		
LINHA DIRETA	ARTICULADO	150	40	248	15
	PADRON	110	208		
NTERBAIRROS	ARTICULADO	140	99	111	08
	PADRON	100	2		
	HÍBRIDO	79	10		
ALIMENTADOR	ARTICULADO	140	78	449	129
	COMUM	85	341		
	MICRO ESPECIAL	70	30		
TRONCAL	ARTICULADO	140	5	87	15
	COMUM	85	73		
	MICRO ESPECIAL	70	4		
	HÍBRIDO	79	5		
CONVENCIONAL	COMUM	85	101	231	74
	HÍBRIDO	79	15		
	MICRO ESPECIAL	70	112		
	MICRO	40	3		
CIRCULAR	MICRO	40	7	7	01
TURISMO	DOUBLE-DECK	65	8	8	01
		TOTAL	1.320		250

Figure 6: Bus Route Classifications. The black box indicates the two kinds of lines that are included in this research.

Only two kinds of lines are included in this research: *Conventional* lines and *Truncal* lines. These lines are indicated by the black rectangle in figure 6. Most of the buses on these lines are the so called "*Comum"* buses with a capacity of 85 passengers.

2.2. Decision-making in the city of Curitiba

There are two main decision makers in the process of urban transportation planning in the city of Curitiba: IPPUC and URBS. Their roles and objectives related to this research are explained in the section below.

2.2.1. IPPUC

IPPUC (2019) is the institute for research and urban planning in the city of Curitiba. IPPUC has the role of coordinating the process of planning and urban monitoring of the city. All decisions regarding urban planning and infrastructure are made by IPPUC. Therefore, IPPUC plays an important role in the development of research and implementation of the BRT system of the city of Curitiba.

In order to make decisions on new urban projects or development of plans, IPPUC considers technical, operational and economical elements to access and compare alternatives. These elements are grouped into five categories: availability, performances, service level, environmental impact and costs. To enhance the attraction of potential users to the bus system, services characteristics are analysed through the following attributes (amongst others):

- *Accessibility to the vehicle*: measured by the speed of boarding and disembarking the buses, due to level of the platform, number of doors, paying system and internal arrangements.
- *Comfort*: attribute linked to the user's perception of the conditions of the trip, such as travel times and occupancy of the vehicle.
- *Regularity*: attribute linked to the continuity of the service, i.e. the guarantee of operation within a given interval.
- *Environmental pollution*: considered due to the effect caused by the emission of pollutants generated by the vehicles.

Decision-making regarding bus transportation planning and related infrastructure should also take into account other important guidelines formulated by IPPUC:

- The physical, new configuration of bus lines should allow a high capacity of the system, with the shortest route and consequently the shortest travel time and optimization of the bus fleet.
- The technology adopted should be capable of absorbing the levels of future demand with security, comfort, minimum of maintenance and reservation of capacity.
- There should be commitment to the preservation of the environment and the city centre.
- The system should be attractive and capable of promoting the bus transport system over using private cars.
- Costs of implementation should be reduced and routes and locations of terminals or stations should allow operational flexibility that might be necessary for future expansion of the system.

The process of implementing a new terminal or XBLs

Implementation of a new terminal or XBLs starts with an evaluation of the needs for this terminal or XBLs. The evaluation takes a few factors into consideration. First, there needs to be an overlap of the routes of multiple bus lines and the bus lines should have a considerable demand in terms of passengers. Next, the user benefits of a possible terminal or XLBS are evaluated. Criteria that are included to access the benefits are: faster movements, less bunching (i.e., platooning) of buses, possibility of integration with other lines and easier access to different attractions like schools, health units, warehouses or shopping areas.

For implementation of a terminal, the possibility of integration with other bus lines is considered. Also, the population around the possible terminal location is evaluated. Finally, the availability of a free area or the feasibility of expropriation of an area for the construction of a terminal is assessed. Terminals are positioned in strategic locations, to optimize the use of public transportation and allowing integration with the bus system. Strategic locations are also chosen to enhance implementation and consolidation of new planned activities and services along the new terminals. In most cases of overlapping bus lines, conventional lines might be transformed into feeders. As a result, the choice of the location for a terminal is based on the itinerary of these lines. In the ideal situation, a new terminal is implemented halfway between the served neighbourhoods and downtown. For re-routing the bus lines, this means that half of the routes will retain their original itineraries as much as possible. For new routings of bus lines, the route should be as direct as possible, aiming at reducing travel times. In most cases, a new line will be structured to serve the area between the new terminal and downtown. The size of the terminal depends on the demand to be met with growth forecast. Generally, there is a platform reserve of 30% of the area for future expanding. The used platforms are typically six-meter-wide and 84-meter-long, allowing boarding over the length of the buses.

For implementation of XBLs, travel times and congestions are considered. The number of buses, bus lines and bus stops along the considered street are taken into account. There needs to be a considerably high amount of bus activity in the area. Also, the availability of free area for an extra lane or the possible effects of an XBL on the remaining lanes are considered. In the ideal situation, XBLs are implemented without having too much impact on other traffic and congestion on the streets.

2.2.2. URBS

URBS (URBS – Urbanization of Curitiba S/A, Curitiba, Brazil, 2019) is a semi-public company and is responsible for strategic planning, strategic actions and surveillance operation involving the public transport service. URBS also manages the administration of the urban facilities throughout the city. URBS is responsible for the bus schedules, bus fleet and bus routes.

As this research includes considering changes in both strategic planning and urban planning, both IPPUC and URBS are important stakeholders.

2.3. Covered network

To determine how and to what degree the congestion and travel times can be reduced, the current situation is analysed. This section explains the current situation regarding traffic congestion and travel times in the area of Curitiba that is included in this study. This area is visualized in figure 7. Given the scope of the city centre of Curitiba, only thirteen bus lines that run between different neighbourhoods and the city centre are taken into account for this study, as mentioned before (figure 2).

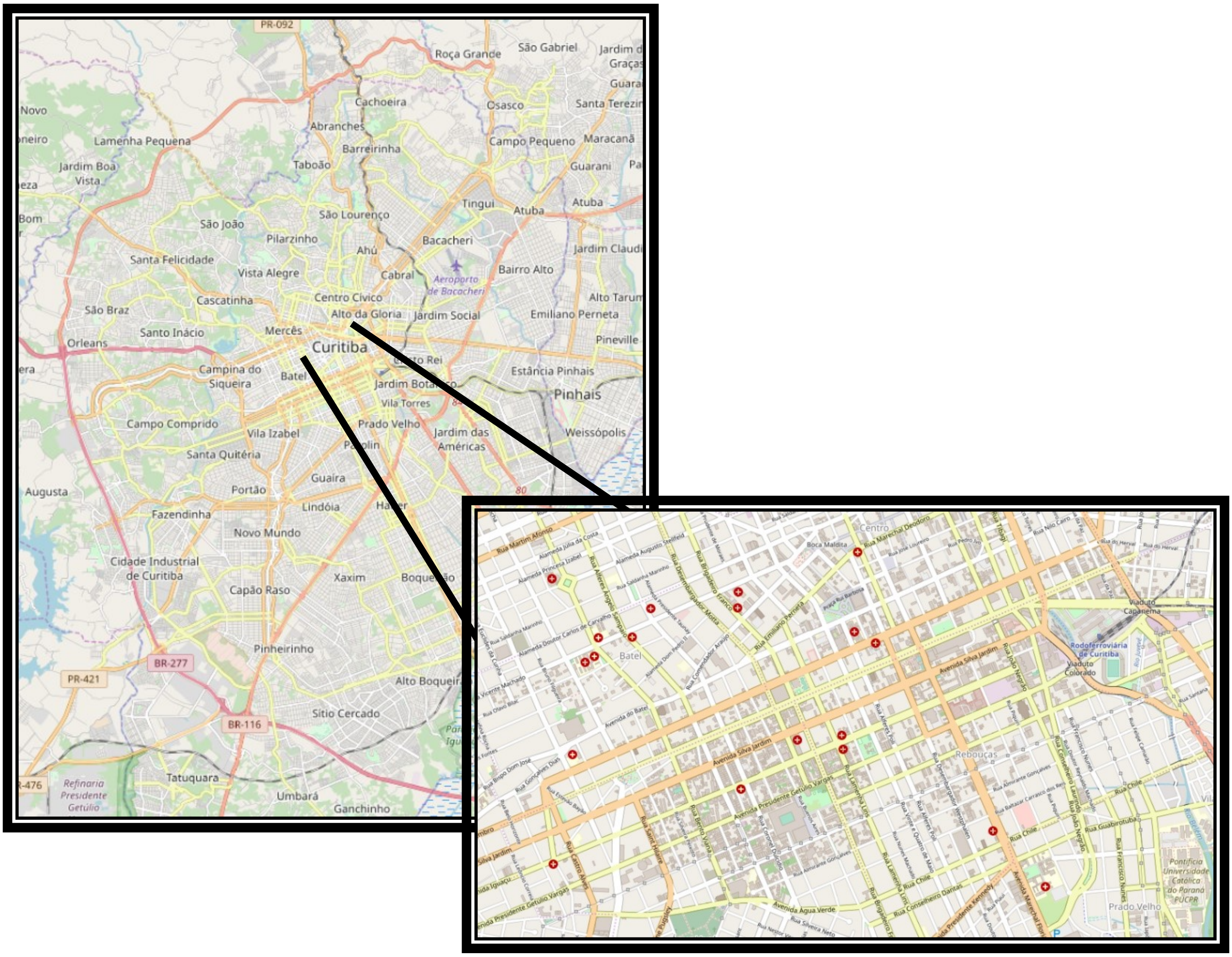


Figure 7: Study area of Curitiba, Brazil

2.4. Conclusions and bottleneck

The buses of all thirteen lines drive on both the Iguaçu street and the Getúlio Vargas street. All buses come from different neighbourhoods and are going to the terminal (indicated with the blue spot in figure 2). The lines that are included in this study, are regular bus lines which means that passengers pay the fee in the bus. There is no option for changing buses at bus stops in other directions without paying the fee again, except for at the integration terminal. This terminal is the only terminal in this area of the city centre, and therefore the only option for integration in the BRT system of the city of Curitiba. As bus stops in the city of Curitiba do not have their own bus schedules, all express and inter-neighbourhood buses stop at all bus stops they pass on their lines going to the terminal. Conventional and feeder buses stop by demand, but during rush hours they normally also stop at all bus stops on their lines. The buses of all lines are driving according to their own schedules, based on the times they leave the terminal. This means that buses can arrive at the same bus stops at the same times, when their lines start overlapping. As both the Iguaçu and Getúlio Vargas streets are very congested, buses can't overtake each other and they will keep bunching together until they arrive at the final terminal. Also, buses are regularly delayed during rush hours and get late at the terminal.

As the municipality of the city of Curitiba wants to increase the attractiveness of the bus system and make the system more efficient, bus delays and bus bunching are not desirable. Right now, the municipality of Curitiba tracks the buses that are operating so they have real-time information on the position, the delay and the speed of the buses. To access the performance of the BRT system, the municipality of Curitiba uses three key performance indicators (KPIs): travel times of buses, delays of buses and bus bunching. They have concluded that the performance of the BRT system in this small part of the system is not sufficient and also affects the performance of the BRT system in other parts of the city centre. For example, the BRT lanes at *Avenida Sete de Setembro*, of the north-south axis are two blocks away from the Iguaçu street and are regularly high congested due to congestions on the Iguaçu streets. Therefore, the bottlenecks of the system are long travel times, delayed buses and bus bunching on the Iguaçu and Getúlio Vargas streets.

3. Literature review

Evaluation of the effects of implementing XBLs on urban traffic performance has been done by many researchers. Several studies have been published on investigations and comparisons of different XBL applications and their effects on urban traffic networks. Over the last decades, computer simulation has been part of many studies to evaluate the impacts of XBLs.

The following subsections discuss implementations of XBLs and the added value of implementing a terminal.

3.1. Implementation of XBLs

XBLs are regarded as an effective approach to mitigate urban traffic congestion and reduce air pollution, as they result in higher efficiency of the road network (Tomforde et al., 2010). Bus performance in terms of travel time, delay and average speed are mostly well secured by XBLs (Yang & Wang, 2009). XBLs have been implemented in a number of cities and when XBLs are designed properly, they could reduce travel times of the buses (Cox, 1975; Rouphail, 1984; Wei & Chong, 2012). Tu et al. (2009) compared the usage of shared lanes and XBLs in a simulation. They found that bus stop operations affect capacities and speeds for vehicles in the system. When shared lanes are used, buses that stop at bus stops make vehicles on the main stream slow down and might even cause local congestions. They concluded that XBLs are always a good idea in terms of travel times for the bus but not for other vehicles on the road. They also found that when there is a lot of traffic, the travel times for all vehicles in the case of XBLs is smaller than that of all vehicles in the situation of shared lanes. Similarly, Rouphail (1984) performed a study to investigate the effect of bus priority lanes. He simulated two situations: one with XBLs and the other with no XBLs. The outcomes showed that the bus performance increased after implementation of XBLs and an increase in overall speed on the bus lane was observed.

However, XBLs can also have a negative impact on other traffic in the network. Research has shown that when XBL are implemented, performance of other vehicles decreases (Zhu, 2010; Yang & Wang, 2009). A lane taken away from the road and designated as an XBL could create more congestion on adjacent lanes for the other vehicles, particularly during peak periods. Reducing the capacities for other vehicles on the road, may cause traffic conditions to get worse when there is already high congestion. Performances of the whole traffic network only improves when XBL are implemented in case of less other vehicles on the road (Khoo & Ong, 2015).

To overcome this drawback, Viegas and LU (2004) introduced the concept of an intermittent bus lane (IBL). This system is based on the idea that opening the bus lane for other traffic when it's not used by buses, can increase the capacity. This solution provides a bus lane to reduce travel times of buses and also minimizes the negative impact of the bus lane on other traffic. Cox (1975) performed a study to evaluate XBLs and found that there was no effect on the level of service of other vehicles. Also, travel times for buses was reduced, while the speed of buses was increased. Moreover, the enhancement in level of service after implementing XBLs encouraged more commuters to use the buses. Chada and Newland (2002) published an article which states that buses receiving an early or extended green light at intersections, reduce travel times by as much as ten percent.

3.2. XBLs and signal priority

Another way of giving priority to buses is by signal priority. Bus signal priority has been used in many cities world-wide and is accepted as a way to improve bus operations, complementing bus lanes (Housell, Mcleod, Fraser & Shrestha, 2004). Implementing bus signal priority is an approach to minimizing delays to bus transportation (Daniel, Lieberman & Srinivasan, 2004). Bus signal priority is an attempt to minimize bus delays at signalized intersections by temporarily altering the traffic signal phase so that a bus receives a green light when it arrives at the traffic light. This priority can reduce bus travel times, so buses can maintain their schedules and provide better reliability in travel times (Daniel, Lieberman & Srinivasan, 2004). Although signal priority for buses can be effective for reducing bus travel times, it is not always beneficial to the overall traffic network as it can cause an increase in travel times of other vehicles in the network.

Different levels of priority can be awarded to different buses. There are two kinds of signal priority to buses, depending on the time of arrival at the traffic light (Housell, Mcleod, Fraser & Shrestha, 2004):

- A signal extension. The bus is detected on a green signal aspect, which is then extended until the bus passes the traffic light.
- A signal recall. The bus is detected on a red signal aspect, whose length is then reduced so that the desired green signal aspect comes around quicker when the bus arrives at the traffic light.

3.3. Bus stops, distances and times

Murry (2003) suggests that bus stop distances should range from 200 to 600 meters for reasonable walking accessibility. Bus stop redundancy could lead to low bus service quality. For passengers, small bus stop distances could create high accessibility, but it will also increase bus travel times and therefore reduce efficiency of the system.

As proper bus stop distances can significantly reduce travel times (Alterkawi, 2006), selection of bus stops for specific bus lines is an important objective to enhance the performance of the bus system. BRT systems with only local services have high passenger volumes but lower capacities and speed. Most of the passengers on local services will get on and off at a few common stops. Stopping at all intermediate stops adds significantly to the travel times of these passengers. Therefore, a system can benefit by introducing a service that skips intermediate stops (Wright & Hook, 2007). A system can also benefit from introducing more time between buses at the same corridor (de Sousa & Gama, 2015). Adding more time between buses will reduce bus bunching and delays, according to the research of Verbich (2016).

The number of stops to be skipped obviously depends on the demand profile of the passengers. It is possible that a system introduces different limited-stops routes in order to reduce the travel times for a large number of passengers. In this case, some routes can skip only a few stops when other lines might skip half of the total number of stops. The main advantages of limited-stop services are: time savings, reduction of congestion at stops that have been skipped (as well as the buses that stop at those stops). Sometimes it is possible to adjust the service to better meet the demand by having some bus routes turn around before reaching the final destinations. In this way, the same corridor can host several routes of varying lengths (Wright & Hook, 2007).

3.4. Implementation of integration terminals

Any public transportation infrastructure development project should begin with the recognition of a need to meet the present or growing demand (Farkas, 2009). As identified by IPPUC, in the city of Curitiba this is based on the overlap of multiple bus lines. All thirteen lines that are part of this research, share the same bus stops on the Iguaçu and Getúlio Vargas street. So, it can be concluded that the need of a solution, such as the implementation of a new terminal, is there.

In most BRT systems, integration terminals are the trip origin for an express service where demand is consolidated (Wright & Hook, 2017). According to Wright & Hook (2017), significant efficiency gains can be achieved along a corridor when a limited-stop service is added. Usage of a limited-stop services will improve the average speed and capacity of the system. To realize the combination of both regular and limited-stop services, the implementation of an integration terminal along the corridor is necessary.

The selection of an appropriate location for an integration terminal requires precise evaluation from different perspectives. According to Farkas (2009) this can be done using factor analysis, consisting of two steps: site screening and site evaluation. The site screening step includes the identification of the candidate sites and the site evaluation step includes the examination of each candidate site to find the most optimal one (Farkas, 2009).

3.5. Assessment and transport simulators

Because XBLs could negatively affect traffic conditions for other vehicles, the surrounding traffic environment and the effects of the possible XBLs should be taken into account when evaluating the traffic performance. The success of XBL can be measured by the improvement of the network performance which can be simulated using transport simulators (Noori, 2013). For our work, the microsimulation is appropriate considering that the performance of a relatively small traffic network should be verified. The use of simulation is well suited to this optimization work since the test of implementing a terminal or a bus lane is not simple to perform in practice and it could generate many unwanted side effects.

Noori (2013) analyses the performance of several existing micro-simulators on a traffic related problem. In his work, Open Street Map is used as well as data obtained from traffic sensors. Some examples of the simulators that are assessed in his work are: SUMO, VEINS, VISSIM, STRAW, PARAMICS and CityMob. For our study, a few aspects are important: 1) Integration with use of digital maps, 2) simulation which is close to reality, 3) possibility of obtaining statistical measures to evaluate the performance of the system.

3.6. Conclusions

From the research of Noori (2013), it can be concluded that VISSIM works really well for small traffic network evaluations. Therefore, VISSIM is chosen as the traffic simulation model to evaluate possible solutions of our research.

This chapter has given insights into factors that influence traffic performance in small networks. It has been found that usage of XBLs can secure bus performances in terms of travel time, delay and average speed. However, XBLs can also negatively influence the performance of other vehicles in het network. Traffic light priority is also found to be effective for reducing bus travel times, but it’s not always beneficially to the overall performance of the traffic network as it can cause an increase in travel times of other vehicles in the network. Travel times can also be reduced by proper bus stop distances. Stopping at all intermediate stops adds significantly to the travel times of these passengers. Therefore, a system can benefit from a service that skips intermediate stops or adds more time between buses at the same corridor.

As the goal of our research is to increase the overall performance of the network by reducing travel times and delays and increasing the speed, the impact of all of these factors on the network performance is considered in the simulation model.

4. Methodology

Section 4.1 recaps the goals of this study. Section 4.2 discusses the required data that is necessary to reach these goals and section 4.3 presents the data that is available for this study and it describes how the data for this study is collected. The simulation model, including the parameters and evaluation criteria is discussed in section 4.4. Section 4.5 describes the different simulation interventions and in section 4.6 the parametric study is discussed. Section 4.7 describes the evaluation parameters of this study and the last sub-section of this chapter summarizes the findings and conclusions of this chapter.

4.1. Goals of this study

The goal of this study is to evaluate possible solutions to reduce traffic congestion and travel times of a congested area in the city of Curitiba. Proposed possible solutions to this problem were implementation of a new integration terminal and implementation of XBLs.

The literature review has given insights that simulation of the traffic network, using VISSIM might be a good approach to evaluate the impact of XBLs. VISSIM simulation aims to evaluate the impact on congestion for different interventions, including implementation of XBLs and changing the headways and bus stops for different bus lines. A factor analysis can be used to evaluate candidate locations for a new integration terminal. The municipality of Curitiba is more interested in the possible implementation of XBLs than the building of a new integration terminal, and therefore the main focus of the remainder of this research will be on the impact of XBLs.

4.2. Required data

To find the best location for a new integration terminal, we need information on the decision-making and conditions for the building process of new terminals. For example, we need to know what the minimum sizes for a bus terminal are, and what percentage of space needs to be reserved for further expansion. Also, we need to know which areas can be used for integration terminals (i.e., public spaces/free ground etc.).

In order to simulate part of the traffic network in the city of Curitiba, data is needed for the input of the simulator. Necessary data for VISSIM to be able to evaluate traffic performance includes data from the number of buses per hour and the time or demand at different bus stops, traffic lights data and flow data of the different intersections. To be able to simulate the traffic network in the city of Curitiba as accurately as possible, we need data on the number of cars, motors, trucks and buses in the network. Also, we need to know the traffic light programs of all traffic lights that are part of the model. We need to know the number of buses present in the network and for all buses we need to know when they arrive at the bus stops, how many passengers are boarding and alighting the buses at these bus stops and how long the buses stop at each bus stop. When all this data is collected or estimated, we can start building the simulation model.

4.3. Available data and data collection

To evaluate possible terminal locations, data is required on the lay-out and sizes of the terminal, the costs and build permits. The city of Curitiba couldn’t provide all of this information and therefore, only a factor analysis can be conducted. The methodology of the factor analysis is described in appendix B.

Required data for the simulation study is partly directly available from URBS, and the part of the data that is not directly available needs to be extracted and estimated by integrating different data sources. URBS provided us with data on the location of the buses, the times of boarding of passengers and the locations of all bus stops of the traffic network. The available data is gathered from URBS over a period of a month, in October 2017. This month is a good representation of the average traffic and buses in the system of the city of Curitiba. The different data sources we used in this study are described below in section 4.3.2. URBS did not have any data available on the buses' stop time or the number of passengers boarding and alighting at each bus stop. We tried to estimate this data by crossing some other data sources. The heuristics we used to do this are described in section 4.3.3.

4.3.1. Transport data sources

Due to the large number of sensors and devices installed on buses and terminals, data is generated every day. In most cities, and also in Curitiba three different data sources are available regarding bus systems: routes and schedules for bus lines, automatic vehicle locations and automatic fare collection data. This data consists of bus Global Navigation Satellite System (GNSS), vehicle and line information and passenger boarding information and is collected by different systems with different objectives. For example: Automatic Fare Collection (AFC) systems are used to record the share of city passengers, recording the passenger card id, bus route and vehicle. Automatic Vehicle Location (AVL) systems focus on the bus trajectories to assess routes with predefined trajectory shapes, recording bus routes and vehicles including times series of Global Positioning System (GPS) data.

AFC systems collect data from boarding of passengers. There are two types of AFC systems: flat fare and distance-based fare. For the flat-fare systems, passengers are required to tap their smart cards over a card reader when they enter the bus, but they don't need to tap it again when they leave the bus. For distance-based systems, passengers have to tap their smartcards when they enter and leave the buses. The flat-fare systems are the most common and these systems are also used in the city of Curitiba. The AFC data was collected from a database containing information on user cards. Information on the use of transportation cards was obtained through a dedicated link, only shared with URBS partners. This information is only shared on request (privately) because of sensitive information. Each record contains a timestamp, card id and vehicle id.

AVL systems normally track the position of public transport vehicles by using GPS data. GPS devices on buses send data to a server that generates a real-time view of the location of the buses and creates a historical record of the bus movement. This data typically includes a timestamp, the vehicle id and geographical coordinates. AVL data was obtained from the database of URBS.

4.3.2. Heuristic for estimation of bus stop times and number of boarding/alighting passengers

AVL data is used in this study to extract the time at which the buses are at a specific bus stop, as the buses only have a scheduled time to leave the terminals and no scheduled times to be at the intermediate stops. This AVL data contains the vehicle location for every 20 seconds and all data is separated into JavaScript Object Notation (JSON) format files. The AVL data was then integrated and analysed with the GPS location of the different bus stops of the lines to identify at which times, buses from specific bus lines were at specific bus stops. For this estimation it is necessary to find the minimum distance between a bus location and the stop location and extract the corresponding time. This is the time considered for the bus to be at the closest bus stop. *For example: Bus A is driving along Iguaçu street and stopping at bus stop number 1. However, the GPS locations of bus A (AVL data) and bus stop 1 are never exactly the same. Therefore, we need to find the minimum difference between the GPS location of bus A (AVL data) and the GPS location of bus stop 1, in order to find the exact time at which bus A was at bus stop 1. This exact time can also be extracted from the AVL data, as it stores both the GPS location and the time bus A was at this location in the json files. The time at which bus A was at the GPS location which is the closest to the GPS location of bus stop 1 is taken as the time that bus A was at bus stop 1 to pick up and deliver passengers.*

The results from this heuristic can also be used to calculate the travel times of a bus between two (or more) bus stops. To do so, the time difference between the time at which a bus is at bus stop 1 and the time at which this bus is at bus stop 2, is calculated.

If one wants to know the boarding location of passengers in a city, it will be necessary to merge the data from the above systems. Given the amount of data and the diversity of their source and nature it becomes hard to integrate and analyse the data. Station entrances with the smart card are challenging for this research, as there is a registration of the card, but no route or vehicle assigned to it. This study aims to integrate AFC and AVL data in order to analyse the passenger's origin (bus stop locations) and time for each passenger's boarding record. With passenger's origin and times, different analyses can be performed, for instance: bus and bus stop crowding estimation, which can assist urban planners in their choices for implementing a terminal or change the number of buses and lines in a specific area.

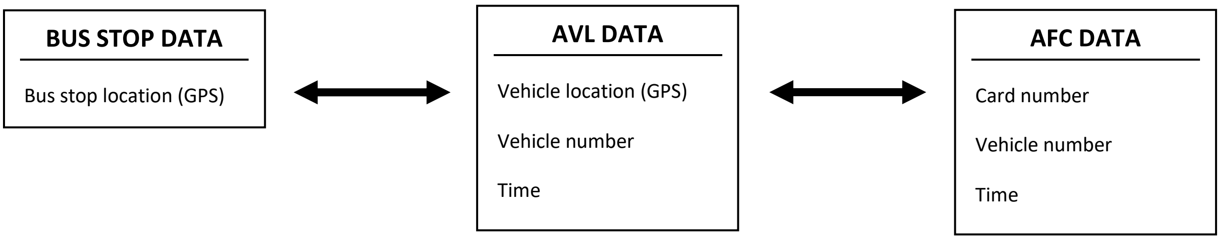


Figure 8: Integrating bus stop, AVL & AFC data

The database of the user cards only has the information on the number of the card, the bus (line) on which the card was validated and the timing of this validation. The geolocation information is not part of this and in order to identify or estimate the starting point of passengers, it is necessary to cross the information of the bus card database with the database containing the positions of buses in the network. Basically, it is necessary to find the closed bus to the time and location at which the passenger validated his card (ZHAO, 2004). Once the GPS position of the card is identified, it can be identified which is the nearest bus station covering the line in question. This bus stop is considered for boarding.

Integrating AFC and AVL data to find the locations of passengers entering the bus, demands matching the boarding records of user cards to the bus trip data. This means, identifying for each passenger in the AFC data what the location of that specific bus in the AVL data was. To integrate the data, a script was made in Python to cross data between vehicle location and bus stops combined with the user card information to extract the demand of passengers per bus stop, per bus line. This challenge was approached by 1) reading the user card data, 2) matching the vehicle number for AVL and AFC data, 3) matching the boarding records to the stop that has the minimum time difference and the minimum distance between GPS locations. *For example: Passenger X uses his card on bus Y at time 9:00. However, the bus stop for this boarding passenger X is unknown. Therefore, we need to find out where bus Y was at time 9:00 on the day of boarding. Because the GPS location of the buses in the city of Curitiba is sent to the data base every few seconds, it is possible that there is no record of the GPS location of bus Y at 9:00 exactly. To be able to extract the location of bus Y, we need to find the minimum time difference between the time passenger X validated his card and the time the GPS location of bus Y was extracted. When this minimum time difference is found, we need to find the closest bus stop to the GPS location of bus Y at the closest time to 9:00. This bus stop is taken as the boarding bus stop of passenger X. Remark: Due to transmission faults it is possible that there is no available data. In this case, an error can be detected by either finding a bus too far from the passenger or finding no bus at the current locations and/or time.*

QGIS enables the creation of heat maps through kernel maps. The term kernel map refers to a statistical method of estimation of curves of density. The demand of users at bus stops of the included lines of this research is visualized using this method. The heat maps were generated from the demand that was calculated by crossing the data from the database as explained above. The demand points along the bus lines that were found using this heuristic can be found in figure 9 (left). Figure 9 also presents the density of the demand at each bus stop (right).

Figure 9: Demand points along the bus routes (left: all demand points, right: heat map of the number of demand points)

A limitation in this data is that there are no records of passengers leaving the buses. Most bus transportation systems around the world have validation only at the entrance of the bus system, which is also the case in the city of Curitiba. This means that users do not validate their transport cards when they leave the system. Therefore, there is no direct information available on destinations of the passengers. As a consequence, some hypotheses had to be taken in order to estimate the final destination of each passenger. To be able to predict the destination of all passengers in the system, a few assumptions had to be made, and for this study we made the following assumptions:

> *1. There is no private mode of transport (car, motorcycle, bicycle, etc.) used between two consecutive uses of the card on the day;*
>
> *2. When a passenger uses his card multiple times on the same day, the final destination of the last trip of the passenger is the same bus stop as where the passenger boarded on his first trip that day.*

In this approach, only passengers that used the card twice on a day are included. In case the passengers used the card exactly twice during the day (which would be the most simple and obvious), it is assumed that: the user uses the card a first time in the day at the bus stop where he enters the system, descending at the bus stop where he would use the card for the second time. For the cases in which a passenger only uses the transportation card once, the final destination of the passenger is assumed to be the final stop on that line. However, the script that was made in Python, including these steps, did only show a few records of a second card validation on the same day. This only gave us a few destination records for the passengers and not enough to create an origin-destination matrix. Therefore, exact origin-destination information was not available for this study and only the number of boarding passengers were estimated by integrating the AFC and AVL data.

4.3.3. Traffic light data

There are several types of traffic lights in use around the world. One of them is the traffic lights that work with fixed time. These are the ones that are used the most in the city of Curitiba. The fixed time traffic lights use phase or state sequences which represent every possible movement of vehicles at a given intersection. Figure 10 illustrates the concept of phases presenting a cross of two avenues with four phases to differentiate the various possible motions (F01, F02, P01 and P02). There are also times of transition between the phases, which are the times of yellow lights and all-red lights; see the colour scheme at the right of the figure (illustrating the green, yellow, red and flashing red lights respectively). The duration of a complete sequence of phases is called cycle time. Another important parameter that a fixed time traffic light uses is the set time or offset, which is the moment of the start of a cycle in relation to a central time reference (FHWA, 2008). This central time is important to synchronize several crossings creating a green wave. In the figure, the times for each part of the cycle are also given. The transitions and (cycle-) times are given for different time frames during the day.

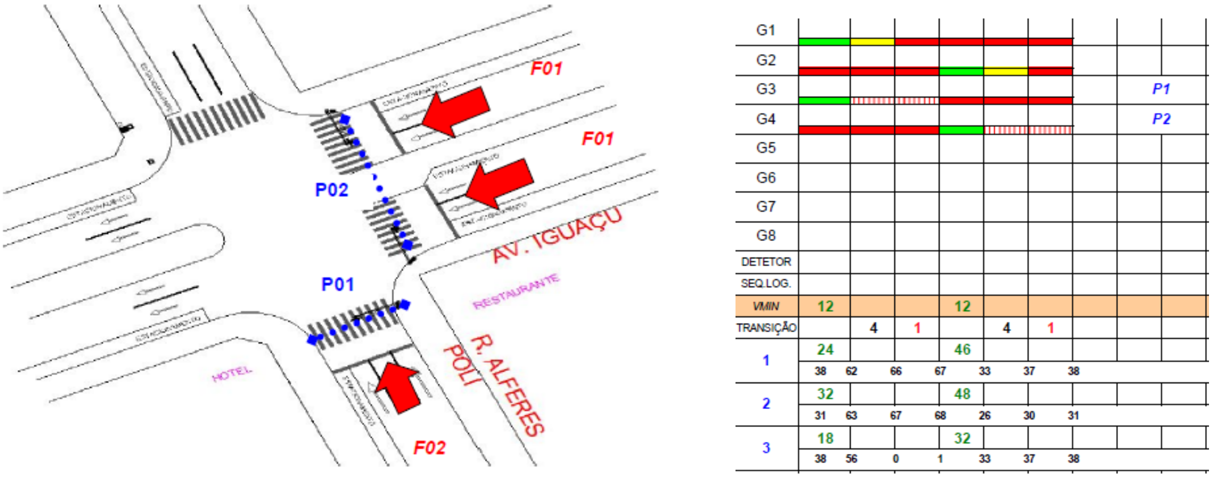


Figure 10: Fixed traffic light phases of one of the traffic light programs used in this study (picture provided by URBS).

Traffic lights timing control in the city of Curitiba is currently carried out by the Integrated Monitoring System (SIM) installed at URBS. This control centre has access to several cameras installed in the main intersections of the city. The city is divided into 33 different semantic regions which have independent timing programs, automatically triggered according to the time of the day. The signal has different timing depending on the time of the day. The signal timing for each of the stages can be seen in the table of figure 10 (right). This table shows the cycle times of the four different groups of traffic lights in the same phase. The group G1 belongs to flow F01 in figure 10 (left), group G2 belongs to flow F02, group G3 belongs to flow P01 and group G4 belongs to flow P02. The P flows are passengers flows and are not considered in our research. In the upper part of the table in figure 10 (right), the times of all colour transitions are displayed. *For example: for G1 the first column is a green light which takes 24 seconds. The second column for G1 is yellow light which takes 4 seconds etc. There are different transition times for different parts of the day. The whole cycle length is the total of all phases of the cycle, which for transition 1 is: 24+4+1+46+4+1 = 80 seconds.*

Figure 11 shows the region that is included in this study. The grey squares indicate traffic lights at the intersections. Because the distances between the traffic lights are short, the arrivals of vehicles are influenced by the control decisions of adjacent traffic lights. The traditional way of coordinating the traffic lights in such a situation, is using the offset. Firstly, all traffic lights in the area are set to operate with a common cycle time. This cycle time reflects the traffic condition at the most congested intersection. Next, all intersections are set to an offset at the beginning of their control cycles. For this offset, a value is chosen that reflects the expected travel time between the two intersections.

This way of traffic control is used in this area of Curitiba. All intersections that are included in this study have the same traffic light programs. This means the transitions are the same for all traffic lights groups at all intersections. Cycle times and times for the groups differ per time interval of the day. Cycle times for all traffic lights are the same, they only have a different value for the offset. The traffic light data is used as an input for the simulation study.

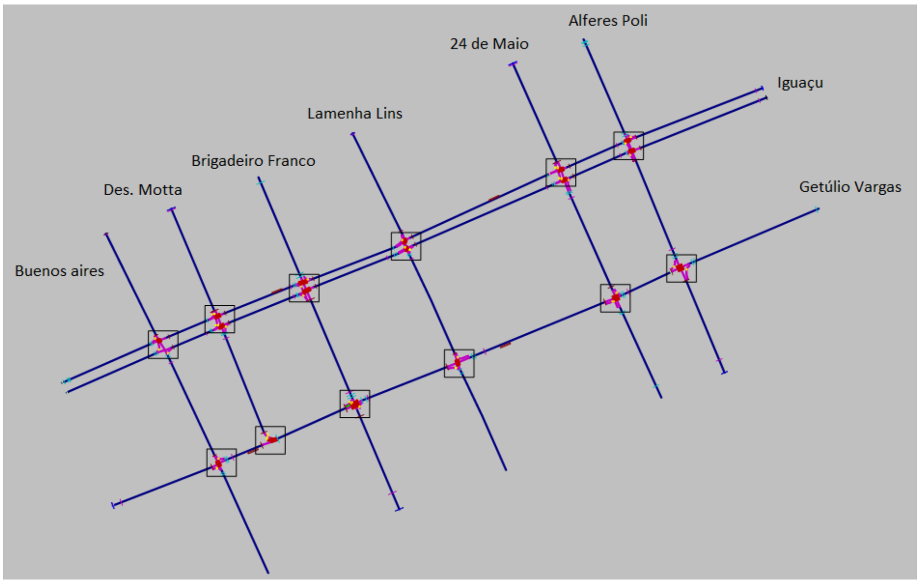


Figure 11: Traffic lights and intersections that are part of this study

4.3.4. Traffic flow data

In 2012 IPPUC carried out a research to count traffic flows at different intersections around the city centre. Unfortunately, this is the most up to date data of traffic flows they could provide for this study. Therefore, the flow data from these documents is adjusted with a growth factor to estimate the traffic flow numbers for the year of this study. The growth factor is also provided by IPPUC, and the traffic numbers are calculated, using linear rate. The annual growth rate provided by IPPUC is 1,37% per year and this value is used for our calculations. The calculated intersection flows with growth factor are taken as an input for the simulation study.

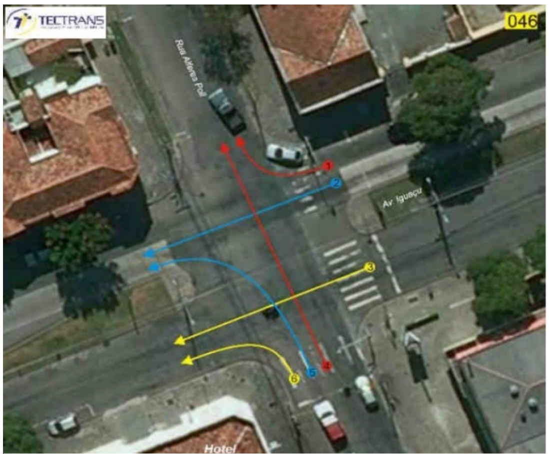


Figure 12: Traffic flows of one of the intersections considered in this study (left) and an example of traffic volumes for different vehicle types (right)

The traffic flows per intersection that are included in this study, are similar to the traffic flows that are illustrated in figure 12. The different arrows indicate different traffic flows. Similar colours have the same destination. For all intersections, the vehicle counts of all traffic flows in 2012 were provided by IPPUC (table 2).

Table 2: Vehicle counts of the traffic flows of an intersection

Faixa Horária	Automóvel	Ônibus	Caminhão	Moto	Bicicleta
06:30 - 06:45	8	0	0	1	0
06:45 - 07:00	20	0	0	0	0
07:00 - 07:15	29	0	0	1	0
07:15 - 07:30	30	0	1	2	0
07:30 - 07:45	30	0	0	4	0
07:45 - 08:00	34	0	0	3	0
08:00 - 08:15	13	0	0	0	0
08:15 - 08:30	26	0	0	2	0
08:30 - 08:45	12	1	0	1	0
08:45 - 09:00	26	0	1	0	0

4.4. Simulation model

VISSIM micro-simulation software was used to model the implementation of an XBL and evaluate its impact under different traffic conditions. VISSIM can be used to analyse urban traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals and transit stops. In addition to that, VISSIM calculates important data such as volume, queue length, delay time and network performance (California Department of Transportation, 2002).

VISSIM can model public transportation in mixed traffic conditions or on an exclusive bus lane. Also, bus volumes and bus headways of the buses on an XBL can be modelled and customized using VISSIM. During a simulation run, VISSIM can evaluate travel times when measurement sections are defined in the model (California Department of Transportation, 2002). VISSIM also has a user-programmable traffic signal controller to customize the behaviour of the traffic lights in the model. All in all, these features make VISSIM suitable for the simulation of the proposed solutions in our study. The main purpose of the VISSIM model is to simulate the traffic situation along the corridor as realistic as possible. To achieve this, it is necessary to define a set of parameters and variables in the model. The following sub-sections describe the setup of the experiments used in VISSIM, including model assumptions and model performance, and the traffic input data.

4.4.1. Model setup

To build a realistic model, there needs to be geometrical accuracy between the model and the real situation to correctly define geometrical elements of the traffic network. To model part of the traffic network of the city of Curitiba, a scaled map is used as a background for the simulation model. This scaled map also contributes to the visualisation of the model. In this case a Google Earth map of the area has been used as the background map (see figure 13).

Figure 13: Background map simulation model

To model the roads, the so-called links are placed on the roads shown on the background map. These links all represent one road segment, and for each link the properties can be edited (figure 14). The columns ‘count’ and ‘index’ show the number of lanes for the road. In figure 14, the ‘motta’ street is street number 14 in the model and has 4 lanes. The vehicles on this road behave like vehicles in an urban area. The ‘display type’ and ‘level’ that can be defined in the model have an influence on the appearance of the road in the VISSIM model.

The first important parameters that are defined in our model are the number of lanes and the width of the lanes. The width of all lanes in our model is three meters. Also, for some of the interventions that are modelled, the parameter ‘blocked vehicle classes’ is enabled. This parameter is used to close one or more lanes for specific vehicle classes. This affects the behaviour of specific vehicles as follows: changing to this lane is not allowed and vehicles are not allowed to enter the lane. The other parameters (columns in figure 14) can be used to indicate whether vehicles can change lanes from left to right or right to left.

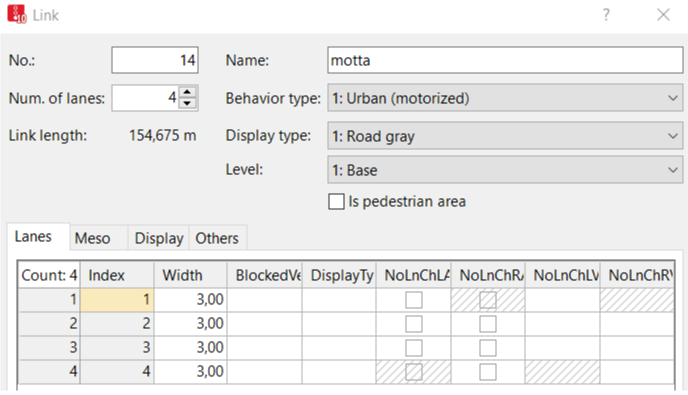


Figure 14: Link properties

4.4.2. Vehicle compositions

The vehicle composition (table 3) represents the mix of vehicle types that are added to the model. It consists of a list of vehicle types for which a flow percentage and a speed distribution are assigned. In a vehicle composition the following parameters can be defined:

Table 3: Vehicle compositions

Count: 3	VehType	DesSpeedDistr	RelFlow
1	100: Car	50: 50 km/h	342,000
2	200: HGV	50: 50 km/h	8,000
3	610: Bike Man	50: 50 km/h	24,000

- **Vehicle type**: Defines the vehicle type (car, bus, heavy goods vehicle (HGV) or bike).
- **Desired speed**: Definition of the speed distribution of this vehicle type.
- **Relative flow**: The relative percentage (proportion) of this vehicle type.

The relative flows of the different vehicle types for all links are different and therefore the vehicle composition is adjusted for every link in the simulation network. For each type of vehicle, the desired speed needs to be defined. In order to simulate the vehicles behaviour as realistic as possible, the simulation model implements all the speed limit signs of the network, which is 50km/h.

4.4.3. Vehicle input

Vehicle inputs have to be defined at the starting points of network entering streets. Traffic volumes are defined for each link in vehicles per hour. Vehicles enter the link according to a Poisson distribution (PTV AG, 2011), based on the vehicle inputs as shown in figure 15. If the defined traffic volume exceeds the link capacity the vehicles ‘wait’ outside the network until there is space on the link.

The traffic volumes for the different vehicle types on the network entering streets, are added to the model as traffic inputs. The traffic volumes for the morning (6:30-7:30) and afternoon (17:00-18:00) peak hours and the streets, are shown in figure 15.

Count: 9	No	Name	Link	Volume(0)	VehComp(0)
1	1		37: iguacu	379,0	1: Iguacu 1
2	2		38: iguacu	409,0	2: Iguacu 2
3	3		27: 24 maio	841,0	3: 24 maio
4	4		34: alferes poli	903,0	8: alferes poli
5	5		5: lamenha lins	383,0	4: lamenha lins
6	6		14: motta	631,0	5: desembargo
7	7		9: buenos aires	298,0	6: buenos aires
8	8		2: vargas	1532,0	7: vargas
9	9		22: franco	917,0	9: franco

Count: 9	No	Name	Link	Volume(0)	VehComp(0)
1	1		37: iguacu	736,0	1: Iguacu 1
2	2		38: iguacu	645,0	2: Iguacu 2
3	3		27: 24 maio	1642,0	3: 24 maio
4	4		34: alferes poli	1254,0	8: alferes poli
5	5		5: lamenha lins	461,0	4: lamenha lins
6	6		14: motta	1009,0	5: desembargo
7	7		9: buenos aires	355,0	6: buenos aires
8	8		2: vargas	1804,0	7: vargas
9	9		22: franco	1354,0	9: franco

Figure 15:Traffic volumes morning peak (left) and afternoon peak (right)

The traffic volumes were added to the model. These volumes will remain constant for all interventions. The volumes are adjusted for all interventions with different D/C ratios. For each intervention there is also a D/C ratio based on a growth scenario that includes expected traffic volumes in 20 years. For this traffic volumes, a growth factor is considered (as explained in chapter 4.3.4 Intersection flow data). It should be noted that the percentage of each type of vehicle has been calculated based on the actual data for the peak hours, obtained from IPPUC, (see section 4.3.4). This data included peak hour traffic volumes of different kinds of vehicles: cars, motors, bikes, buses and trucks (see section 4.3.4, figure 12).

4.4.4. Vehicle routes

Vehicles that are added as inputs to the model, can have different destinations. Possible routes are defined by sequences of links. The vehicles start at the network entering streets, which is the first routing decision point. From each routing decision point, the vehicle can have multiple destination points. Once a vehicle has passed a routing decision point it will follow one of the defined routes until it has reached the destination point. The static routing decision uses a static percentage for each destination. Percentages are defined in relative flows of the input (PTV AG, 2011). These relative flows are calculated based on the vehicle counts of the traffic flows that were provided by IPPUC, as explained in section 4.3.4.

Table 4: Example routing decisions

Count: 2	VehRoutDec	No	Name	DestLink	DestPos	RelFlow(0)
1	6	1		39: vargas	6,165	837,000
2	6	2		36: alferes poli	8,904	779,000

After the definition of all destinations per routing decision it is necessary to define the route properties. The main property to be defined is the relative flow from the routing decision point to each destination point. The last column of table 4 shows one of the routing decisions used in our model and shows the relative flow for each destination. For this specific situation, this means that all vehicles which go across this street are going to be divided like this: 837 vehicles go to the (Getúlio) Vargas street and 779 vehicles go to the Alferes Poli street. The related vehicle routes are shown in figure 16.

Figure 16: Example vehicle routes

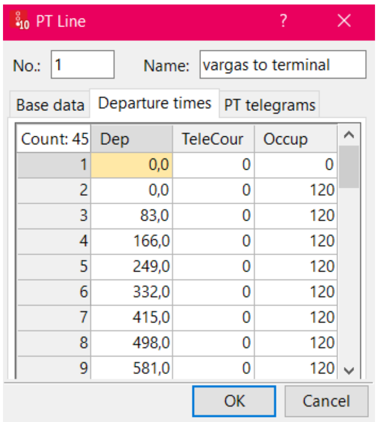
Vehicles enter the link according to a Poisson distribution , routing decisions are at every intersection

4.4.5. Bus lines and stops

All public transport lines have to be defined separately in the model from entry link to destination link. For all public transport lines, the vehicle type has to be chosen, as well as the desired speed. In our model the vehicles are buses and the desired speed is 50 km/h, which is the speed limit in the area. In our study area, there are ten different bus routes and all ten are modelled in VISSIM (see figure 17).

Count: 10	No	Name	EntryLink	DestLink	DestPos	EntTmOffset	VehType	DesSpeedDistr
1	1	vargas to terminal	2: vargas	35: alferes poli	142,573	0,0	300: Bus	50: 50 km/h
2	2	terminal to iguacu	27: 24 maio	4: iguacu	134,883	0,0	300: Bus	50: 50 km/h
3	3	iguacu straight	37: iguacu	4: iguacu	127,779	0,0	300: Bus	50: 50 km/h
4	4	desembargo to iguacu	14: motta	4: iguacu	129,655	0,0	300: Bus	50: 50 km/h
5	5	lamenhalins to iguacu	5: lamenha lins	4: iguacu	126,681	0,0	300: Bus	50: 50 km/h
6	6	alferespoli to terminal	34: alferes poli	35: alferes poli	141,010	0,0	300: Bus	50: 50 km/h
7	7	iguacu to terminal	37: iguacu	35: alferes poli	137,087	0,0	300: Bus	50: 50 km/h
8	8	terminal to other streets	27: 24 maio	32: 24 maio	121,643	0,0	300: Bus	50: 50 km/h
9	9	franco bus	22: franco	18: franco	144,102	0,0	300: Bus	50: 50 km/h
10	10	vargas straight	2: vargas	39: vargas	193,316	0,0	300: Bus	50: 50 km/h

Figure 17: Bus routes



Count: 45	Dep	TeleCour	Occup
1	0,0	0	0
2	0,0	0	120
3	83,0	0	120
4	166,0	0	120
5	249,0	0	120
6	332,0	0	120
7	415,0	0	120
8	498,0	0	120
9	581,0	0	120

Figure 18: Example departure times bus line Vargas to terminal

For all bus lines, it has to be defined whether the buses on this line stop at the bus stops they are passing on their routes. When the bus stop is activated, all buses on that bus line will stop at the bus stop. To add buses to the lines, departure times for all buses should be defined in the model (see example in figure 18).

Count: 4	No	Name	Lane	Pos	Length	PedsAsPass
1	1	stop 110211	24 - 1	46,022	15,000	☐
2	2	stop 110210	15 - 1	34,197	15,000	☐
3	3	stop 110208	26 - 1	76,917	15,000	☐
4	4	stop110209	10 - 1	20,403	15,000	☐

Figure 19: Definition of bus stops

As our study area includes four bus stops, the bus stops have to be defined in the simulation model. For each stop, it is necessary to define the length of the bus stop (see figure 19). All bus stops in our research have a length of fifteen meters. It is possible to set boarding volumes for all bus stops in the model. As we don't have the origin-destination matrixes of all boarding and alighting passengers of our lines and at our bus stops, we choose a dwell-time distribution in VISSIM for estimating the time each bus spends at the bus stop. It has been chosen to use a normal distribution defined by a mean value and a standard deviation. Also, times for opening and closing of the doors of the bus can be adjusted here. We choose three seconds for opening and closing of the bus doors, as this time was recorded when doing field research in the city of Curitiba.

4.4.6. Conflict areas

A conflict area is the place in the model where two links overlap. Conflict areas need to be modelled for all conflicting movements that might occur, especially permissive turns. Also, intersections under congested conditions should be coded. For each conflict area, it is necessary to select which of the conflicting links has priority (i.e. right of way). The standard setting for the conflict area is that all vehicles yield. However, there are other ways to manage the conflict areas depending on the colours:

Figure 20: Conflict area

- Road in green: main road (priority)
- Road in red: minor road (yield)
- Road in yellow: all vehicles yield

In figure 20, an example of a conflict area from the simulation model of our study is given. This example shows two streets that are both one-way streets (see directions in figure 20). Traffic on the second (from left) lane that arrives from the west can either make a left turn or go straight. This is a conflict area because vehicles that are waiting to make a turn could block the vehicles that want to go straight. For this lane, the conflict area is adjusted to ‘green’ (priority) for all traffic going straight. Vehicles that want to take the left turn have to wait. The whole intersection is coded to ‘red’ (yield), so no traffic will block the intersection when there is a traffic jam.

Defining conflict areas was necessary in our model to avoid unexpected driving behaviour on conflicting lanes. If this conflict area wasn’t coded as shown in figure 20, the vehicles in the network would try to overtake each other in order to continue driving, causing unexpected and unwanted behaviour of vehicles in our model.

4.4.7. Simulation settings

In this study, a simulation period length of 1 hour was used to analyse the interventions and D/C ratios. To get more realistic results, the network used 30 minutes of warm-up time to load vehicles into the network. Because the system starts empty, it takes time for the system to reach a stable state and the performance during the beginning of the simulation does not represent the real situation. We reduce the impact of this bias by introducing a warm-up time and discard the performance measurements made during this period. The simulation model is split up in time intervals of 30 minutes (1800 seconds) and during the 30-minute warm-up period, no statistics are gathered. The simulation period starts at two different times for the two peak hours considered in this study: from 6:30 am to 7:30 am and from 5:00 pm to 6:00 pm.

Each micro-simulation run presents a random seed, meaning each modelled intervention runs 10 times, for 10 different seeds, to account for the randomness of traffic volumes in VISSIM. This is required for ensuring the validity of the results. By considering the average performance over multiple runs we eliminate possible bias caused by the specific arrival pattern of vehicles that could occur within one run.

4.4.8. Model assumptions

Making relevant assumptions is necessary to make the development of the simulation and different interventions feasible. Urban traffic systems are very complex, with a lot of different dynamics. The assumptions aim to make modelling the situation simpler and still keep the simulation close to the situation in reality. The model is based on the following assumptions:

- *Driving behaviour of vehicles is created at each intersection. Therefore, it can happen that one car drives a circle as the routing decision at an intersection can choose a road the vehicle has already been.*
- *Turn fractions are fixed at each intersection, based on the routing decisions.*

- *Percentages of different vehicles in the network are the same as obtained from the data of URBS.*
- *Vehicles can only see 250 meter and 4 cars.*
- *Vehicles keep a stand-still distance of 0.5 meter from other vehicles.*
- *Vehicles can't change lanes between the two Iguaçu streets.*
- *There are no parking spots.*
- *Vehicles enter the links according to a Poisson distribution.*
- *Routing decisions are at every intersection.*
- *Vehicles don't drive faster than 50 km/h.*
- *Buses have a constant inter-arrival time.*
- *Stop times of buses are according to a normal distribution.*
- *No intersections are blocked by vehicles.*

4.4.9. Data collection points, vehicle travel time measurements and queue counters

In order to collect data at a specific road segment and during a specific time interval, the feature data collection is used (figure 21). Data collection points in VISSIM can be placed anywhere in the model and the points only collect data at the specific location and time where the vehicles cross the data collection points. Travel times can also be measured over a road segment. The feature vehicle travel time measurements in VISSIM is used for this (figure 22). In order to measure the vehicle travel times, measurement points are placed at the beginning and ending of a road segment over which the travel times should be calculated. The data collection points and vehicle travel time measurement points in our model were placed on the Iguaçu and Getúlio Vargas streets to measure travel times on these streets as these are relevant for the evaluation of the interventions. Vehicle travel time measurement points were also placed at the bus stops to evaluate the travel times of the buses in our model between the two bus stops. From the AVL data we received from URBS, we calculated the average travel time of the buses between the bus stops on the Iguaçu and Getúlio Vargas streets. The travel times of the buses in the model are used to verify if the simulation model represents the actual situation in the centre of Curitiba. Also, the travel times are evaluated to compare the results of the different simulation interventions. Lastly, queue counters were placed at all intersections of the model (figure 23). Queue counters collect data at the specific location and time from which the vehicles form a queue. All vehicles that are part of the queue from that point until the end of the road segment are counted.

Data Collection Points

Select layout...

Count: 14	No	Name	Lane	Pos
1	1	iguacu 1	26 - 1	0,500
2	2	iguacu 2	4 - 1	137,500
3	3	iguacu 3	4 - 2	137,500
4	4	iguacu 4	26 - 2	0,500
5	5	iguacu 5	25 - 1	1,500
6	6	iguacu 6	25 - 2	1,500
7	7	iguacu 7	3 - 1	137,500
8	8	iguacu 8	3 - 2	137,500
9	9	vargas 1	2 - 3	1,000
10	10	vargas2	2 - 2	1,000
11	11	vargas 3	2 - 1	1,000
12	13	vargas 4	33 - 2	77,500
13	14	vargas 5	33 - 1	77,500
14	78	vargas 6	33 - 3	77,500

Figure 21: Data collection points

Vehicle Travel Time Measurements

Select layout... <Single List>

Count: 5	No	Name	StartLink	StartPos	EndLink	EndPos	Dist
1	1	vargas	2: vargas	1,000	33: vargas	77,500	838,48
2	2	iguacu 1	26: iguacu	0,500	4: iguacu	137,500	735,76
3	3	iguacu 2	25: iguacu	1,500	3: iguacu	137,500	735,91
4	4	bus stop iguacu	26: iguacu	91,951	10: iguacu	20,274	313,23
5	5	bus stop vargas	15: vargas	49,253	24: vargas	46,049	365,01

Figure 22: Vehicle travel time measurements

Queue Counters

Select layout...

Count: 1	No	Name	Link	Pos
1	1		37: iguacu	188,000
2	2		38: iguacu	188,700
3	3		30: iguacu	82,000
4	4		31: iguacu	81,000
5	5		26: iguacu	210,000
6	6		25: iguacu	211,500
7	7		19: iguacu	124,000
8	8		20: iguacu	124,800
9	9		10: iguacu	106,000
10	10		11: iguacu	106,400
11	11		7: iguacu	62,000
12	12		8: iguacu	62,000
13	13		2: vargas	147,500
14	14		15: vargas	56,000
15	15		16: vargas	105,000
16	16		1: vargas	128,500
17	17		24: vargas	204,000
18	18		33: vargas	78,500

Figure 23: Queue counters

4.5. Simulation interventions

In this study, we simulated eight different interventions for which we evaluated the performance. The parameters considered for the different interventions are described in section 4.5.1. Each intervention is evaluated for two peak hour scenarios and different D/C ratios. A description of the modelled interventions and peak hour scenarios and D/C ratios is given in section 4.5.2.

4.5.1. Parameters considered for the simulation interventions

Different parameters play a role in the performance evaluation of the simulation interventions. From our literature review, we have learned that usage of XBLs plays a role in the performance of travel networks. XBLs are designed to provide a dedicated lane for buses on a road. This dedicated lane could reduce travel times and delay amongst buses. However, XBLs can also have a negative impact on the other traffic in the road network. Therefore, evaluation of the effects of implementation of XBLs should be considered and other possible solutions to improve the traffic performance of our network should be evaluated as well. Also, XBLs could be implemented in our network by changing one of the lanes to an XBL or by adding an extra exclusive lane for buses. Next to usage of XBLs, the number of buses that stop at bus stops, bus headways and bus stop locations affect the performance of a traffic network. To reduce the travel times of buses and to reduce their delays, bus priority at traffic lights (on XBLs) could be implemented. This bus priority can have a big influence on normal traffic in the network and therefore is also an important parameter to consider in our model interventions. This gives us the following list of parameters, that we are going to set in our simulation model:

- *Vehicular volumes*
- *Traffic light control*
- *Number of buses that stop*
- *Number of buses in the system (bus headways)*
- *Bus stop location*
- *XBLs*
- *Extra lane*
- *Bus priority at traffic lights*

Table 5: Traffic parameters

Traffic parameters	**Definition**
Vehicular volumes	Different vehicle (car, truck and bike) inputs in the system
Traffic light control	Different traffic light control; different cycle lengths and green light periods
Buses that stop	Different numbers of buses will stop at the bus stops
Number of buses	Average time between two buses/ number of buses per time interval in the system
Bus stop location	Bus stop location with respect to the intersection
XBLs	Presence or absence of XBLs in the system
Extra lane	Presence or absence of an extra lane in the system
Bus priority at traffic lights	Presence or absence of bus priority at traffic lights on the XBLs

Each of these traffic parameters are varied individually to evaluate the effect on the implement of XBLs on the road segment. As shown in table 5 different parameters were considered in the analyses of the traffic performance and XBLs. The following sections describe the interventions for the experiments.

4.5.2. Description of the simulation interventions

A zero-measurement of a simulation scenario that represents the current situation is evaluated first. Next, eight different interventions are evaluated in this study. To find the best solution to reduce congestion and travel times on the Iguaçu and Getúlio Vargas streets, it has been chosen to model and compare different interventions including less buses, less buses that stop at the bus stops, moving a bus stop, and XBLs factor to evaluate the impacts of the interventions. In one of the interventions, the effect of the bus stop was studied through one experiment that considered a difference between the bus stop at the beginning of the block of the end of the block. The bus headway interventions were used to assess the performance of the bus lines during peak hours and to assess the delay on the road segment. Two different bus headways (varying the number of buses in the system) were examined. XBLs were evaluated individually by varying the traffic parameters described in the section above. To be able to see the effect of the individual parameters, the model was adjusted for one parameter, keeping all the other parameters fixed. Default values of the traffic parameters are used for the analyses unless otherwise specified. The interventions that are included in our study are described below.

Scenario 0: The first scenario is the zero-measurement which illustrates the traffic network as it currently is in the city of Curitiba. This is the simulation model of the current situation to evaluate its current performance. The data gathered from this model is used to compare the results of all other interventions and scenarios on possible improvements regarding congestion and travel times.

In the other seven interventions, one or a combination of the traffic parameters of table 5 is taken into account and evaluated in the model. To make the relation between the different interventions and parameters clear, the interventions and the parameters that are evaluated in the model interventions are given in table 6 below. Also, all interventions are given a name that indicates the main parameter that has been adjusted. In the remainder of this report, we will refer to the names as shown in table 6.

Table 6: Parameters included in the interventions

Parameter / **Interventions**	***Vehicular volumes***	***Traffic light control***	***Buses that stop***	***Number of buses***	***Bus stop location***	***XBLs***	***Extra lane***	***Bus priority at traffic lights***
LESSBUSM				X				
LESSBUSA	X	X		X				
LESSSTOPM			X					
LESSSTOPA	X	X	X					
MOVEDSTOPM					X			
MOVEDSTOPA	X	X			X			
XBLM						X		
XBLA	X	X				X		
EXTRAXBLM						X	X	
EXTRAXBLA	X	X				X	X	
XBLPRIM						X		X
XBLPRIA	X	X				X		X
EXTRAXBLPRIM						X	X	X
EXTRAXBLPRIA	X	X				X	X	X

LESSBUS: For these interventions, less buses are modelled. We chose to reduce the number of buses to 66% by adapting the departure times of the buses.

LESSSTOP: In these interventions, the number of buses that stop at a bus stop are reduced. The number of buses in the system stay the same. We chose to let the buses stop at only one of the two bus stops they pass on the streets. Half of the buses stop at the first bus stop and half of the buses stop at the second bus stop. In the city of Curitiba, all buses stop at all bus stops. However, this option is modelled to see whether it would be a good option for the municipality of Curitiba to not let all buses stop at all bus stops along their lines.

MOVEDSTOP: We observed that one bus stop was placed in a very inconvenient place, right in front of the stopping lights, causing long queues. Therefore, we chose to move this stop a little further away from the traffic lights in these two interventions.

XBL: In these interventions, one of the lanes of the Iguacu and Getúlio Vargas streets is replaced by an XBL. Only the remaining number of lanes are available for other vehicles.

XBLPRI: These interventions have one lane replaced by an XBL (similar to XBL) and signal priority for buses. The buses ignore traffic lights and all other traffic in the system gives them priority.

EXTRAXBL: In these interventions, an extra XBL has been added to the Iguaçu and Getúlio Vargas streets. This means that those streets have one extra lane, for buses only. For other vehicles nothing changes, they still have access to the same number of lanes compared to the initial situation. For this intervention, it means that the roads need to have space for an extra lane. Next to the current roads, there are parking spaces and for this simulation intervention it has been assumed that these parking spaces can be removed to make an extra lane.

EXTRAXBLPRI: For these interventions, traffic light priority has been added to an extra XBL (similar to EXTRAXBL).

4.5.3. Peak hour scenarios and D/C ratios

All interventions are modelled for two different peak hours (morning and afternoon). The last M and A in the names as shown in table 6, refer to the morning peak or afternoon peak. The traffic light control is different for both peak hours. This means that the traffic light input of the model should be programmed separately for both the morning and the afternoon peak hour. Also, there is a difference in vehicular volumes between the morning peak and the afternoon peak. In the afternoon peak simulations, the vehicular volumes and traffic light control are adjusted compared to the morning peak simulations. All other parameters and inputs are the same in both simulation interventions.

The effects of the different interventions that are explained in section 4.5.2 are influenced by the number of vehicles in the network. This makes that vehicular volumes are an important parameter to consider while modelling our interventions. Therefore, the performance of all interventions is examined for different vehicular volumes. The base scenarios for both peak hours are therefore evaluated using different vehicular volumes. Different demand/capacity (D/C) ratios are evaluated for all interventions for both peak hours. The D/C ratios are the same, but the related vehicular volumes are different because of different base volumes. One of the D/C ratios that is considered includes the vehicular volumes that are predicted for the year 2040. This growth scenario is taken into account as URBS and IPPUC want to consider possible solutions for the longer term (20 years from now). To calculate the vehicular volumes for the growth scenario, an annual growth rate provided by IPPUC of 1,37% is considered. Different D/C ratios are considered to evaluate the impacts of the proposed interventions in the future. More information on the D/C ratios is given in section 4.6.5 below.

4.6. Parametric study

In this section, the results of the conducted parametric study are presented. To be able to set up the model as described earlier, we need to know the number of vehicles that we need to add to our model so that it closely represents the current situation. Therefore, vehicle data from URBS was used to calculate the number of private vehicles in the system. To estimate the number of public buses that need to be added to our model, we used Python and Excel to extract relevant information on the number of buses within our time frames from the data provided by URBS. To be able to evaluate the D/C ratios of our model, we calculated the intersection flow rates and capacity of all the relevant intersections in our model. Results are described below.

4.6.1. Vehicle input

The annual growth rate provided by IPPUC is 1,37% per year. This value is used to calculate the approximate number of vehicles in the current network in the city of Curitiba, as vehicular volumes were only given for 2012. Also, the growth factor scenario for the prediction of the number of vehicles in the network in 20 years is calculated using this annual growth rate.

The new number of vehicles in the network are calculated using the following equation:

$$(1)\ \ Vehicular\ volume = Number\ of\ vehicles\ in\ 2012 * 1{,}0137^{N}$$

Where:

Vehicular volume = Number of vehicles that are predicted for the year 2012+N

Number of vehicles in 2012 = Number of vehicles in 2012 that were provided by IPPUC

N = Number of years from 2012

This equation is used to calculate vehicular volumes by substituting n=8 for the current situation analysis (0 measurement) and by substituting n=12 for the growth scenario of the traffic situation in 20 years. The vehicular volumes are used as the vehicle inputs for our model in VISSIM (see figure 24).

Vehicle Inputs / Vehicle Volumes By Time Interval

Select layout... Vehicle volumes by

Count: 9	No	Name	Link	Volume(0)	VehComp(0)
1	1		37: iguacu	417,0	1: Iguacu 1
2	2		38: iguacu	449,0	2: Iguacu 2
3	3		27: 24 maio	925,0	3: 24 maio
4	4		34: alferes poli	993,0	8: alferes poli
5	5		5: lamenha lins	421,0	4: lamenha lins
6	6		14: motta	693,0	5: desembargo
7	7		9: buenos aires	328,0	6: buenos aires
8	8		2: vargas	1685,0	7: vargas
9	9		22: franco	1009,0	9: franco

Figure 24: Vehicular volumes used as the input for VISSIM

4.6.2. Number of buses

Before being able to evaluate the impact of reducing the number of buses, the number of buses that stop or the implementation of XBLs, we need to know the number of buses that need to be added to our model. Therefore, we extracted the number of buses during our peak hours at the four different bus stops. Table 7 shows the number of buses for the 13 lines at each bus stop for the peak hours that are considered in this research. However, next to these 13 lines that were assigned to be included in this research, we observed that there are more buses running on the Iguaçu and Getúlio Vargas streets. Therefore, we also analysed how many buses in total are traveling on these streets (table 7). The results on these number of buses in the system are added to our simulation model in VISSIM. Figure 25 shows the locations of the bus stops. An example of a more detailed overview of the number of buses at a bus stop, as analysed in Excel, is given in figure 26.

Table 7: Number of buses at the bus stops, during both peak hours

Number of bus stop	**#buses morning peak (13 lines)**	**#buses morning peak (total)**	**#buses afternoon peak (13 lines)**	**#buses afternoon peak (total)**
110208	*31*	*85*	*33*	*91*
110209	*30*	*85*	*32*	*91*
110210	*25*	*87*	*25*	*61*
110211	*32*	*83*	*32*	*60*

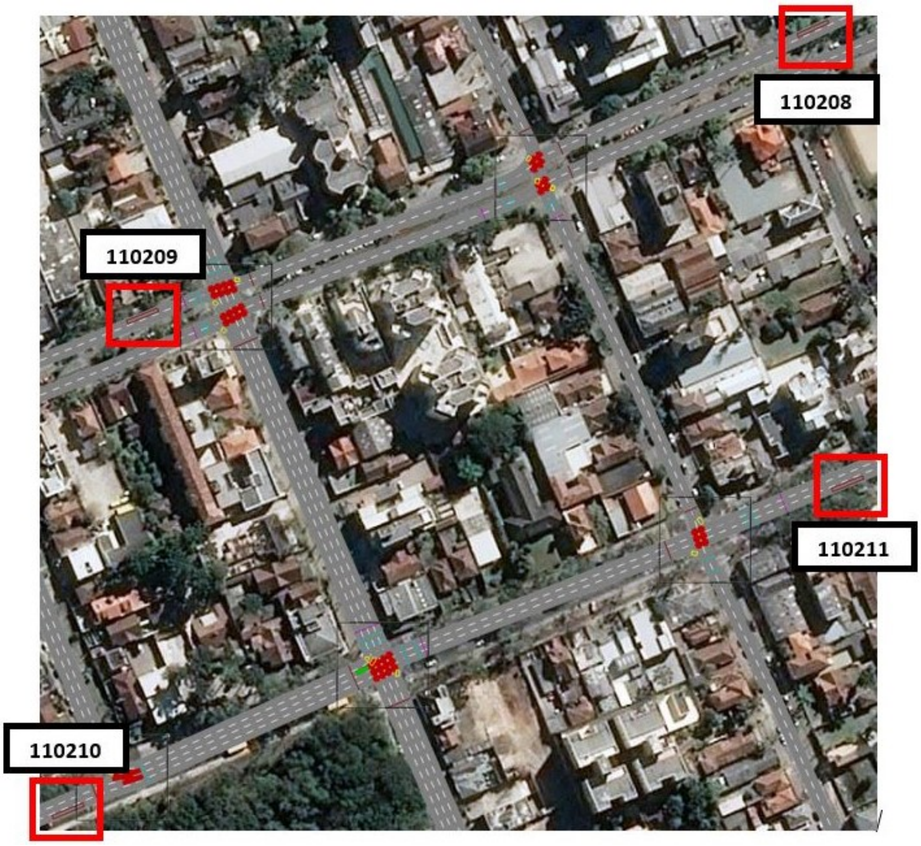


Figure 25: Location and numbers bus stops

Bus line	Date	LONG	LAT	Bus stop number	Seconds	Bus number
670	4-10-2017 06:32	-25.443.793	-49.273.635	110208	23575	HN604
778	4-10-2017 06:37	-25.443.343	-49.272.576	110208	23826	HN607
673	4-10-2017 06:37	-25.442.276	-49.271.885	110208	23842	HN611
703	4-10-2017 06:37	-25.443.066	-4.927.169	110208	23864	HN614
703	4-10-2017 06:38	-25.443.821	-49.273.473	110208	23900	HN615
762	4-10-2017 06:42	-2.544.317	-49.272.018	110208	24146	HN617
701	4-10-2017 06:42	-25.442.851	-4.927.168	110208	24159	JC002
701	4-10-2017 06:43	-25.443.188	-4.927.203	110208	24187	JC003
701	4-10-2017 06:43	-25.443.758	-49.273.506	110208	24206	JC004
674	4-10-2017 06:47	-2.544.219	-49.271.905	110208	24472	JC006
674	4-10-2017 06:48	-2.544.374	-49.273.315	110208	24521	JC010
777	4-10-2017 06:50	-25.443.421	-49.272.681	110208	24640	JC011
777	4-10-2017 06:50	-2.544.351	-49.272.915	110208	24644	JC013
760	4-10-2017 06:56	-25.442.831	-492.717	110208	24962	JC301
701	4-10-2017 06:59	-2.544.307	-49.271.745	110208	25148	JC304
670	4-10-2017 07:00	-25.443.528	-49.272.893	110208	25247	JC307
778	4-10-2017 07:02	-25.443.501	-492.728	110208	25366	JC309
674	4-10-2017 07:07	-25.442.356	-4.927.184	110208	25662	JC310
701	4-10-2017 07:09	-25.442.096	-4.927.196	110208	25746	JC311
673	4-10-2017 07:09	-25.443.295	-49.272.403	110208	25778	JC312
703	4-10-2017 07:09	-25.443.286	-49.272.321	110208	25792	JC601
703	4-10-2017 07:10	-25.443.541	-49.272.926	110208	25815	JC603
777	4-10-2017 07:13	-25.443.545	-4.927.292	110208	25984	JC851
671	4-10-2017 07:16	-25.443.483	-49.271.805	110208	26215	JC852
703	4-10-2017 07:18	-25.443.146	-49.271.961	110208	26298	JC854
703	4-10-2017 07:18	-25.443.346	-492.725	110208	26305	JC855
760	4-10-2017 07:18	-25.443.823	-49.273.708	110208	26337	JC860
701	4-10-2017 07:19	-25.442.985	-49.271.611	110208	26391	JC863
703	4-10-2017 07:24	-25.442.431	-49.271.846	110208	26642	LC012
703	4-10-2017 07:24	-2.544.351	-49.272.821	110208	26693	LC019
674	4-10-2017 07:28	-25.443.881	-49.273.875	110208	26884	LC022

Figure 26 Analysis number of buses between 6:30-7:30 at bus stop 110208 in Excel

4.6.3. Average travel times between bus stops on Iguaçu and Getúlio Vargas streets

In order to evaluate the impact of our interventions on the travel times of the buses, we need to know the current average travel times or average speed of the buses. Because we don't have any data on the average speed or travel times on the Iguaçu and Getúlio Vargas streets, we can't compare the results of our interventions to the current situation. Therefore, we used the average travel times between the bus stops on the Iguaçu and Getúlio Vargas as a benchmark to compare the results of our interventions with. To calculate the average travel times of the buses between the bus stops in our study area, we extracted the bus stop locations and the times at which the buses were at these locations from our AVL data. Next, we calculated the time difference between the times the buses were at the two bus stops. We did this for different buses to get an average travel time. The average travel times between the bus stops of both streets are shown in table 8.

Table 8: Average travel times between bus stops

	Average travel time 110208-110209, Iguaçu (sec)	**Average travel time 110210-110211, Getúlio Vargas (sec)**
Morning peak	68.7	76.7
Afternoon peak	65.2	78.7

4.6.4. Lane capacities and saturation flow rates

To evaluate low, moderate and high congestions on the streets, we chose to evaluate different D/C ratios. These ratios represent different growth scenarios. For this study it has been chosen to model four different D/C ratios: 0.5, 0.75, 0.85 and 1. The D/C ratios are based on the street capacities, which are calculated for the traffic flow on the Iguaçu and Getúlio Vargas streets and the streets which were used for the traffic inputs of the simulation model. The capacities of the streets were calculated using the following formula (Highway Capacity Manual, 2000):

$$(2)\ C = \left(\frac{g}{C}\right) * S$$

Where:

C = street capacity, total capacity of all lanes (vehicles/hour)

g = effective green time for the phase (seconds)

C = cycle length (seconds)

S = saturation flow rate (vehicles/hour)

By substituting the value of each parameter in the formula, the capacity was calculated. The effective green time for the phase is the time during which a given traffic movement may proceed at the saturation flow rate. Each time a movement is started and stopped, when traffic lights change colour, two lost times are experienced. At the beginning of a movement, vehicles at the beginning of the queue experience start-up losses which results in movements proceeding at less than the saturation flow rate. These start-up losses are called start-up lost time. At the beginning of the yellow light, some vehicles still cross the intersection for a short period of time. This is called an extensive of the effective green. At the end of the movement, a part of the change and clearance interval is not used for vehicle movements and this is called the clearance lost time. The total lost time for the phase is the sum of the start-up and clearance lost times. Research has shown that the start-up lost times and the extension of effective green times are both about 2 seconds. The total lost time is then equal to the clearance lost time and, in this case, the effective green time is also equal to the duration of the green light (Highway Capacity Manual, 2000). Therefore, in our calculations we used the duration of the green lights as the effective green times. The cycle lengths are 80 seconds for the morning peak and 90 seconds for the afternoon peak.

The saturation flow rate depends on different factors such as, the number of lanes, the lane width, parking activities and heavy vehicles (Highway Capacity Manual, 2000). Therefore, there is no fixed value for the saturation flow rates of cars crossing an intersection. To calculate the saturation flow rate of each lane, the following formula was used (adapted for our research from Highway Capacity Manual, 2000):

(3) $S = NS_0 f_w f_{hv} f_g f_p f_{bb} f_a f_{lpb} f_{rpb}$

Where:

S *= saturation flow rate for lane group (vehicles/hour)*

N *= number of lanes in lane group*

S_0 *= base saturation flow (vehicles/hour/lane)*

f_w *= adjustment factor for lane width*

f_{hv} *= adjustment factor for heavy vehicles*

f_g *= adjustment factor for approach grade*

f_p *= adjustment factor for existence of parking activity*

f_{bb} *= adjustment factor for blocking effect of buses that stop within intersection area*

f_a *= adjustment factor for area type*

f_{lpb} *= adjustment factor for left-turn movements*

f_{rpb} *= adjustment factor for right-turn movements*

A base saturation flow rate S_0 of 1700 vehicles per hour is chosen because research has found that this is the average saturation flow rate of a lane in urban traffic situations (Highway Capacity Manual, 2000). The formulas for the adjustment factors from the Highway Capacity Manual are used for our study (figure 29).

The adjustment factor for lane width accounts for the negative impact of narrow lanes on the saturation flow rate. Standard lane widths are 3.6m, the lane widths of the lanes in our study are 3 m and therefore the saturation flow rate needs to be adjusted. The adjustment for heavy vehicles considers the additional space that is occupied by vehicles with more than four tires compared with passenger cars. For the peak hours considered in our study, the percentage of heavy vehicles was calculated for each intersection. This percentage is used to calculate the adjustment factor.

The adjustment for grade accounts for the effect of elevation profile on the speed of the vehicles. Therefore, the gradients of all intersections were gathered from Google Maps, using a 'bike path' which shows the gradient of the route (figure 27).

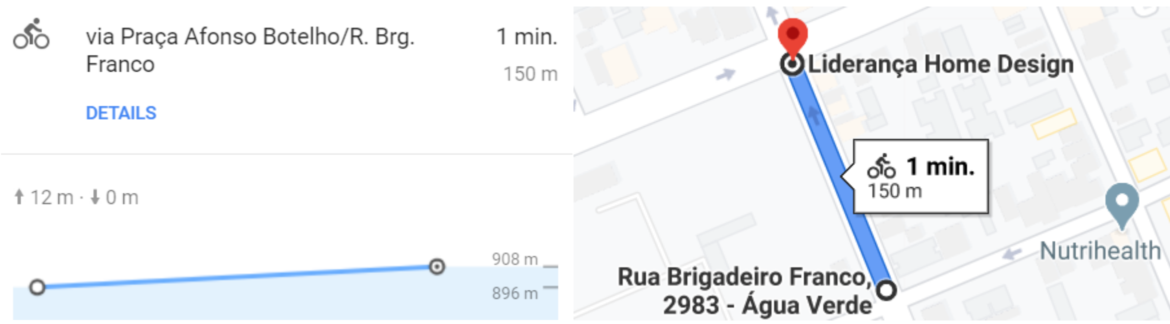


Figure 27: Gradient of streets

The parking adjustment factor accounts for the effect of a parking lane on the flow of vehicles by vehicles moving into and out of parking spaces. Because no data was available on the number of cars going in and out of the parking spots, the adjustment factor is calculated using $N_m = 0$. The bus blockage adjustment factor accounts for the impacts of buses that stop within 75m of the stop line. The area type adjustment factor accounts for characteristics of a central business district, like frequent parking manoeuvres, vehicle blockages, taxi and bus activity. The area of this study definitely has these characteristics, so therefore this adjustment factor is considered for calculating the saturation flow. The adjustment factor is estimated as being 0,9 in the Highway Capacity Manual (2000). The right-turn and left-turn (movement) adjustment factors account for flow reductions that are caused by turning movements. In our study, the adjustment factors for right turns and left turns were estimated using a value of P_{lt} and P_{rt} of 25%.

Example intersection Iguaçu - Buenos Aires (see also table 9 for values):

N = 2

S_0 = 1700 vehicles/hour/lane

f_w = 1 + (3.0 – 3.6)/9 = 0,9333

f_{hv} = 100/ (100+1,03(2-1)) = 0,9898

f_g = 1- (0,22/200) = 0,9989

f_p = 0,9475 (fixed value because we don't know the parking manoeuvres)

f_{bb} = 1 (because there are no buses stopping within 75m from the intersection)

f_a = 0,9 (because of characteristics of a central business district)

f_{lpb} = 1 (because there are no turns)

f_{rpb} = 1 (because there are not turns)

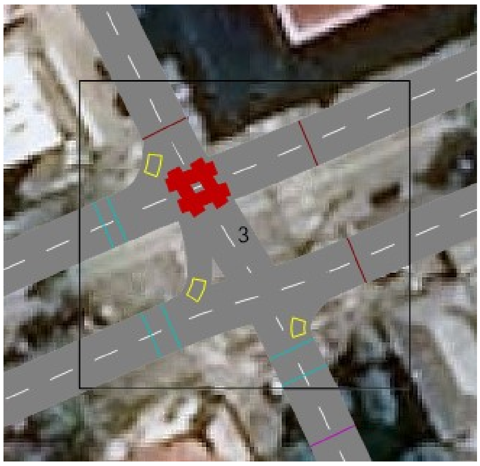


Figure 28: Intersection Iguaçu - Buenos Aires

$$S = NS_0 f_w f_{hv} f_g f_p f_{bb} f_a f_{lpb} f_{rpb}$$
$$= 2 * 1700 * 0{,}9333 * 0{,}9898 * 0{,}9989 * 0{,}9475 * 1 * 0{,}9 * 1 * 1$$
$$= 2675\ vehicles/hour$$

To calculate the saturation flow rate of a lane with left and/or right turns, the f_{lpb} and f_{rpb} are calculated and added to the calculation. The total saturation flow rate is the saturation flow rate of all lanes together.

Factor	Formula	Definition of Variables
Lane width	$f_w = 1 + \frac{(W - 3.6)}{9}$	W = lane width (m)
Heavy vehicles	$f_{HV} = \frac{100}{100 + \% HV(E_T - 1)}$	% HV = % heavy vehicles for lane group volume
Grade	$f_g = 1 - \frac{\% G}{200}$	% G = % grade on a lane group approach
Parking	$f_p = \frac{N - 0.1 - \frac{18N_m}{3600}}{N}$	N = number of lanes in lane group N_m = number of parking maneuvers/h
Bus blockage	$f_{bb} = \frac{N - \frac{14.4N_B}{3600}}{N}$	N = number of lanes in lane group N_B = number of buses stopping/h
Type of area	f_a = 0.900 in CBD f_a = 1.000 in all other areas	
Left turns	Protected phasing: Exclusive lane: $f_{LT} = 0.95$ Shared lane: $f_{LT} = \frac{1}{1.0 + 0.05P_{LT}}$	P_{LT} = proportion of LTs in lane group
Right turns	Exclusive lane: $f_{RT} = 0.85$ Shared lane: $f_{RT} = 1.0 - (0.15)P_{RT}$ Single lane: $f_{RT} = 1.0 - (0.135)P_{RT}$	P_{RT} = proportion of RTs in lane group

Figure 29: Adjustment factors for saturation flow rate. E_T in formula for heavy vehicles = 2.0, (Highway Capacity Manual, 2000).

It has been chosen to calculate the saturation flow rates of the main streets of our study: Iguaçu and Getúlio Vargas. Because we want to calculate the D/C ratios for the traffic inputs of our study, the saturation flow rates were also calculated for the intersections of which the traffic input lanes were part. To calculate the saturation flow rates of all intersections, the adjustment factors were also calculated for all intersections. The results are shown in table 9. *Remark: Iguaçu represents the right three lanes, and Iguaçu 2 the left 2 lanes (two parallel streets).*

Table 9: Adjustment factors

Intersection	Name	Lane width factor	Left turns factor	Right turns factor	Bus block factor
3 (iguacu)	buenos aires	0,9333			1,0000
16	motta	0,9333			0,8360
7	franco	0,9333		0,9625	1,0000
9	lamenha lins	0,9333			0,8400
12	maio	0,9333			1,0000
14	alferes poli	0,9333		0,9625	1,0000
15 (getulio vargas)	buenos aires	0,9333		0,9625	1,0000
6	motta	0,9333			0,8907
8	franco	0,9333	0,9877		1,0000
10	lamenha lins	0,9333		0,9625	0,8880
11	maio	0,9333		0,9625	1,0000
13	alferes poli	0,9333	0,9877		1,0000
3 (iguacu 2)	buenos aires	0,9333	0,9877		1,0000
16	motta	0,9333	0,9877		1,0000
7	franco	0,9333			1,0000
9	lamenha lins	0,9333	0,9877		1,0000
12	maio	0,9333	0,9877		1,0000
14	alferes poli	0,9333			1,0000

Type of area factor	Number of lanes	Heavy vehicles factor morning	Heavy vehicles factor afternoon	Parking factor
0,9	2	0,9898	0,9941	0,9475
0,9	2	0,9877	0,9887	0,9475
0,9	2	0,9819	0,9895	0,9475
0,9	2	0,9793	0,9815	0,9475
0,9	2	0,9937	0,9962	0,9475
0,9	2	0,9821	0,9848	0,9475
0,9	3	0,9907	0,9659	0,9650
0,9	3	1,0000	1,0000	0,9650
0,9	4	1,0000	1,0000	0,9738
0,9	3	0,9909	0,9715	0,9650
0,9	3	0,9898	0,9697	0,9650
0,9	3	0,9917	0,9839	0,9650
0,9	2	0,9860	0,9942	0,9475
0,9	2	0,9851	0,9959	0,9475
0,9	2	0,9771	0,9878	0,9475
0,9	2	0,9817	0,9965	0,9475
0,9	2	0,9833	0,9865	0,9475
0,9	2	0,9663	0,9883	0,9475

Using these adjustment factors, the saturation flow rates for the intersections were calculated, using formula 3 from section 4.6.4. The outcomes were then substituted into formula 2 from section 4.6.4 to calculate the capacity of all intersections. The results are shown in table 10 and 11 for the Iguaçu and Getúlio Vargas streets. In table 12 and 13, the saturation flow rates are given for the streets for which the vehicle input is defined in our simulation model.

Table 10: Total saturation flows

Intersection	Name	Total saturation flow intersection morning	Total saturation flow intersection afternoon
3 iguacu	buenos aires	5318	5362
16	motta	4872	4902
7	franco	5250	5297
9	lamenha lins	4862	4888
12	maio	5339	5349
14	alferes poli	5207	5278
15 vargas	buenos aires	4046	3957
6	motta	3678	3678
8	franco	5526	4167
10	lamenha lins	3604	3538
11	maio	3990	3972
13	alferes poli	4075	4050

Table 11: Intersection capacities

Number of intersection	Intersection capacity morning	Intersection capacity afternoon
3	3390,46	3693,80
16	2131,34	2341,92
7	1968,86	2001,07
9	2674,30	2715,49
12	2936,29	2852,84
14	1562,08	1642,00
15	2275,91	2022,25
6	1839,01	1675,54
8	2694,15	1990,88
10	2207,52	2358,36
11	2094,96	1853,41
13	1833,60	1575,19

Table 12: Total saturation flows traffic inputs

Input flow	Total saturation flow intersection morning	Total saturation flow intersection afternoon
maio	5682	5699
alferes poli	4248	4235
lamenha lins	2883	2854
motta	5661	5692
buenos aires	2883	2883
franco	5647	5632

Table 13: Input flows capacities

Input flow	Capacity morning	Capacity afternoon
maio	1846,73	1899,52
alferes poli	1805,43	2117,47
lamenha lins	937,07	951,30
motta	2476,74	2340,18
buenos aires	684,78	576,66
franco	2188,32	2315,45

4.6.5. Different D/C ratios

Different D/C ratios are used as an input for our model to evaluate the effects of our interventions for growth scenarios in the future. We have chosen to evaluate the following D/C ratios for our interventions: 0.5, 0.75, 0.85 and 1. To compare and evaluate the results of the D/C ratios with the current situation and our growth scenario, we also want to know the D/C ratio of our base and growth scenario. To calculate these D/C ratios we used the number of vehicles that were used as the input for our model. Results are given in table 14 for the morning peak and in table 15 for the afternoon peak.

Table 14: D/C ratios now and in 20 years, morning peak

Scenario morning peak / Input flow	(Base scenario)	(Growth scenario, 20 years)
Iguaçu	0.61	0.78
Getúlio Vargas	0.78	1.01
Maio	0.52	0.67
Alferes Poli	0.58	0.76
Lamenha Lins	0.45	0.59
Motta	0.28	0.37
Buenos Aires	0.48	0.63
Franco	0.50	0.64

Table 15: D/C ratios now and in 20 years, afternoon peak

Scenario Afternoon peak / Input flow	(Base scenario)	(Growth scenario, 20 years)
Iguaçu	0.98	1.27
Getúlio Vargas	1.01	1.32
Maio	0.96	1.26
Alferes Poli	0.80	1.04
Lamenha Lins	0.53	0.70
Motta	0.47	0.62
Buenos Aires	0.68	0.89
Franco	0.67	0.87

As can be seen in table 14 and 15, in the growth scenario the demand exceeds capacity (when D/C =1) on the Getúlio Vargas during the morning peak and on the Getúlio Vargas, Iguaçu, Maio and Alferes Poli streets during the afternoon peak. Also, the demand in the current situation during the afternoon peak on the Getúlio Vargas street is equal to the capacity of the street. On the Iguaçu and Maio streets, the D/C ratio is also almost 1, which means that demand is almost equal to capacity.

Based on the D/C ratios and the different intersection capacities that are calculated for all intersections of the Iguaçu and Getúlio Vargas streets (table 12) and input streets (table 13) in our model, vehicular volumes are calculated for our simulation scenarios. These vehicular volumes are used as the input for our simulation model to model the growth scenarios for the different D/C ratios. All vehicular volumes that are calculated and used as an input for our model can be seen in table 16 for the morning peak and in table 17 for the afternoon peak.

Table 16: Vehicular volumes for D/C ratios, morning peak (vehicles per hour)

D/C ratio Input flow (vehicles per hour)	0.5	0.75	0.85	1
Iguaçu	781	1172	1328	1562
Getúlio Vargas	1138	1707	1935	2276
Maio	924	1385	1570	1847
Alferes Poli	903	1354	1534	1805
Lamenha Lins	469	703	796	937
Motta	1239	1858	2105	2477
Buenos Aires	343	514	582	685
Franco	1094	1641	1860	2188

Table 17: Vehicular volumes for D/C ratios, afternoon peak (vehicles per hour)

D/C ratio Input flow (vehicle per hour)	0.5	0.75	0.85	1
Iguaçu	821	1232	1396	1642
Getúlio Vargas	1011	1517	1719	2022
Maio	950	1425	1615	1900
Alferes Poli	1059	1588	1799	2117
Lamenha Lins	476	713	808	951
Motta	1170	1755	1989	2340
Buenos Aires	289	433	490	577
Franco	1158	1736	1968	2315

4.7. Traffic performance evaluation

One of the important objectives of implementing the different interventions is to enhance the systems performance in terms of reduction of travel times and increased efficiency of bus lines. A successful intervention would result in improvements in bus performance such as reductions in bus travel time and delay, and increases in bus speed. In addition to investigating the effect of the different interventions on bus performance, traffic performance of other vehicles will be evaluated as well. Performance of general traffic, may be affected as different interventions are implemented. Without considering the effect on private vehicles in the model, the interventions could result in excessive delays and queues and may even create a more complicated situation. To evaluate the traffic performance of the different interventions, a few parameters are discussed:

Travel times: The goal of our research is to reduce the travel times of the buses on Iguaçu and Getúlio Vargas streets. Therefore, the travel times of traffic in our model is the most important parameter to evaluate the performance of the system. In our VISSIM model, data collection points were added on both streets to store the travel time data of the traffic in the model.

Speed: When travel times are shorter, the average speed of the vehicles will increase. This makes the speed another important parameter to discuss in the analyses of the different interventions.

D/C ratio: This is the ratio of the demand at an intersection to the capacity of an intersection. The D/C ratio assesses the suitability of an intervention to manage a given traffic volume. When the degree of saturation exceeds a certain value, queues will be formed and delays will start to increase.

Delay: The delay is an important parameter to evaluate on the performance of different interventions. There are two kinds of delays; control delay and geometric delay. Control delay is the time that a driver spends decelerating for a queue, queueing and accelerating out of the queue (Highway Capacity Manual, 2000). The Highway Capacity Manual (2000) uses the control delay to define the service level of a transportation facility. The geometric delay can be defined as the additional time that a single vehicle with no conflicting flows spends on slowing down to a lower speed, proceeding through the intersection and accelerating back to normal speed.

Queue length: The length of queues formed at intersections is a measure that evaluates the suitability of the intervention on reducing travel times. Queues will have a negative impact on the reduction of travel times.

4.8. Conclusions of the methodology

Findings in chapter 3 already revealed that modelling the traffic network using VISSIM is a good approach to evaluate possible solutions of our research. Also, possible factors that influence traffic performance were found.

This chapter built on these findings to find the necessary data to model the traffic network. As data is needed for the input of the traffic simulator, we gathered available data from URBS on the location of the buses, the times of boarding of passengers and the locations of all bus stops of the traffic network. This data was used to build the bus lines and stops in our VISSIM model. Based on the data, we developed a heat map with the passenger demand points along the bus routes. Next, we used traffic light data and traffic flow data for the modelling of traffic lights and vehicle routes in the VISSIM simulation model. Also, the traffic network was built using Google Maps as a background to locate streets and crossings. Vehicle inputs were based on the traffic volumes provided by URBS.

Based on the discussed literature on possible factors to improve the performance of a traffic network, we developed a list of parameters to set in our simulation model and we developed different simulation interventions. The 0 measurement was developed based on the current situation. Next, 7 interventions were developed based on a difference in simulation parameters: LESSBUS, LESSSTOP, MOVEDSTOP, XBL, XBLPRI, EXTRAXBL and EXTRAXBLPRI. Simulation parameters that were used to describe the interventions are the number of buses that stop, the number of buses in the network, the bus stop location, usage of XBLs, an extra lane and bus priority at traffic lights. The interventions were also modelled for different peak hours (morning and afternoon) and for different D/C ratios. Then, we developed a parametric study to be able to set up the model. To be able to evaluate different D/C ratios of our model, we calculated the intersection flow rates and capacity of all the relevant intersections in our model. Based on the calculations, we could calculate the vehicular volumes for different D/C ratios. These vehicular volumes are used as an input for the VISSIM models of the different interventions. Based on the findings in chapter 3 and the calculations done in this chapter, five parameters are chosen to evaluate the traffic performance of the different interventions: travel times, speed, D/C ratio, delay and queue length.

The next chapter analyses the performance of the current system and the performance of the different interventions. It also discusses the sensitivity of the three interventions with the best performance to a difference in D/C ratios, the difference between the Getúlio Vargas and Iguaçu streets and a possible growth scenario in 20 years.

5. Results

In this chapter, the results of our simulation scenarios are given. In the first sub-section the current performance of the system in the city of Curitiba is analysed. Also, the performance of this model is verified against the real system performance. Next, in section 5.2, the performance analyses of the different intervention for the current situation are discussed. Each simulation intervention is analysed individually to study the impact of the interventions on the network performance in terms of travel times, delay, speed and queues for the buses and regular traffic. In section 5.3, a sensitivity analysis is conducted on the three models that perform best. Section 5.4 highlights the performance differences between the two streets that are tackled in this study; Getúlio Vargas and Iguaçu. In section 5.5, the growth scenario in 20 years is discussed and section 5.6 summarizes the conclusions of this chapter.

Based on expert opinion, all simulation scenarios run 10 times, for 10 different seeds with a warm-up period of 30 minutes.

5.1. Current system performance

The first scenario that was simulated was the system as it is today (indicated as scenario 0 in chapter 4), with the current design and D/C ratios. This scenario simulation was used as a base measurement to compare the results of all the different interventions based on travel times, speed, delays and queues. It was also used to validate the representation of the model with the real-life situation as it is today.

As explained in section 4.6.5, simulations are done for different D/C ratios. Also, the current situation is simulated using different D/C ratios. This is done to compare how an increase in demand (more traffic) would influence the current situation in terms of travel times, speed, delays and queues. Four different D/C ratios are simulated: 0.5, 0.75, 0.85 and 1. The results of these simulations are plot in a graph to see the effect of different demands on the evaluation parameters: travel times, speed, delays and queues. The goal of our research is to reduce the travel times of the buses in our network in such a way that the whole network is affected as less as possible. The average travel times of all vehicles gives a good enough representation of the impact of our interventions on the average travel times, of all vehicles in our network. This is also the case for the average speed and the average delays of the vehicles in our network. We are not interested in the differences in performance of different kinds of vehicles in the network. Therefore, we only evaluate and compare the travel times, speed and delays of all traffic in our network and the travel times, speed and delays of the buses in our network.

5.1.1. Verification and validation

Verification and validation of the simulation model was an ongoing process during the whole model building. It was possible to verify the built network with the connectors, detectors, routs and signal heads in the model, as well as the behaviour of the traffic in the model. All inputs to the model, as explained in chapter 4, needed to be verified in order to make sure the modification resulted in the intended behaviour of traffic in the model.

The model behaviour was verified by looking at the simulation in VISSIM. By studying the simulation in VISSIM graphically, it was possible to determine intended or unintended behaviour of the vehicles in het network. For example, it was possible to determine whether a vehicle stopped in front of a stopping light or whether a bus stopped at the bus stop. When studying the simulation while running the model, behaviour not consistent with field observations or intentions were discovered and corrected.

As already explained in chapter 4.6.3, we calculated the average travel times of the buses between the bus stops on the Getúlio Vargas and Iguaçu streets. These calculations were based on the available data from URBS. To validate our model, we calculated the travel times of the buses between the same bus stops in our simulation model in VISSIM and compared them to the travel times that were calculated based on the data. The results of the calculations of the average travel times of the buses in our simulation are shown in table 18. In table 19, the percentual differences are shown between the average travel times based on the data and the average travel times based on the simulation model. The travel time differences are only a few seconds for both streets for the morning peak and for the travel times during the afternoon peak on the Getúlio Vargas street. For the afternoon peak on the Iguaçu street the difference in travel times is 8.8 seconds which is a difference of 13.49% compared to the travel times that were calculated based on the data source.

Table 18: Average travel times between bus stops in simulation

	Average travel time 110208-110209, Iguaçu (in seconds)	**Average travel time 110210-110211, Getúlio Vargas (in seconds)**
Morning peak	67.4	73.3
Afternoon peak	56.4	77.1

Table 19: Difference between calculated travel times of buses based on data and based on simulation

	Difference travel time 110208-110209, Iguaçu between data source and simulation in seconds (percentage)	**Difference travel time 110210-110211, Getúlio Vargas between data source and simulation in seconds (percentage)**
Morning peak	-1.3 (1.89%)	-3.4 (4.43%)
Afternoon peak	-8.8 (13.49%)	-1.6 (2.03%)

5.1.2. Average travel times in the current system

Figure 30 represent the average travel times of all traffic on the Getúlio Vargas and Iguaçu street in our simulation model. As can be seen in the figure, the average travel times are much longer on the Getúlio Vargas street, compared to the Iguaçu street for both peak hours. It can also be seen that on average travel times are longer during the afternoon peak hour than during the morning peak hour. When comparing the travel times of the different vehicles, it can be seen that the travel times of the buses are much longer than the average travel times of all vehicles.

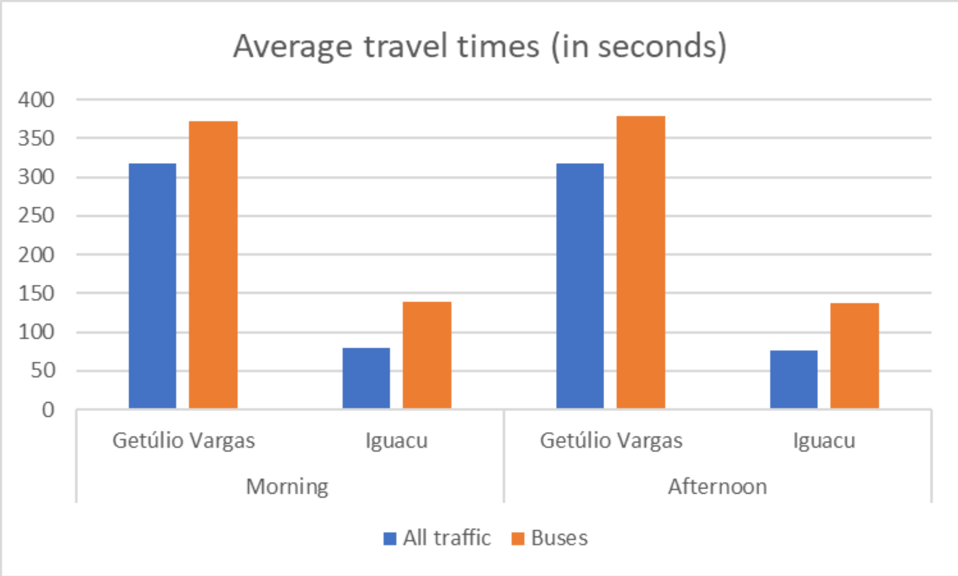


Figure 30: Average travel times of all traffic and buses on Getúlio Vargas and Iguaçu street during morning and afternoon peak hours

Table 20: Average travel times in the network for the current situation

Average travel times in seconds		All traffic	Buses
Morning	**Getúlio Vargas**	295.48	357.32
	Iguacu	74.39	146.34
Afternoon	**Getúlio Vargas**	319.97	393.68
	Iguacu	76.69	131.32

As can be seen in figure 30 and table 20 there is a difference between the travel times on the Getúlio Vargas and Iguaçu streets during the morning and afternoon peaks. Also, travel times of buses are longer than the average travel times of all traffic in the network. To evaluate the effect of the number of vehicles in the network on the travel times of all traffic in the network, the current situation has been modelled for different D/C ratios. The results of these simulations are shown in table 21. For more details, the D/C ratios and related average travel times are illustrated in appendix C.

Table 21: Average travel times (in seconds) in the network for the current situation for different D/C ratios

Average travel times in seconds		D/C ratio	All traffic	Buses
Morning	**Getúlio Vargas**	**0.5**	75.41	200.16
		0.75	86.35	405.19
		0.85	103.08	447.94
		1	313.22	417.70
	Iguacu	**0.5**	62.73	143.24
		0.75	92.80	154.08
		0.85	86.95	191.67
		1	466.33	427.52
Afternoon	**Getúlio Vargas**	**0.5**	191.93	231.97
		0.75	365.27	414.67
		0.85	390.34	428.98
		1	403.17	460.91
	Iguacu	**0.5**	73.95	122.92
		0.75	81.23	144.52
		0.85	87.44	141.29
		1	153.36	226.18

From table 21, it can be established that when the D/C ratio on the Getúlio Vargas street decreases during the morning peak, travel times also significantly decrease. The lower the D/C ratio, the greater the positive impact on travel times. If the D/C ratio increases to 0.75 and higher, the travel times do not increase that much anymore. On the Iguaçu street, the effect of the D/C ratios on the travel times is different. Higher D/C ratios until 0.85 only have a slight increase in travel times as a result. From a D/C ratio of 0.85 and higher, the travel times increase by over 400% for all traffic and for more than 200% for the buses. This indicates that little differences in D/C ratios to the current situation don't have as much impact on the travel times as a slight increase in D/C ratios above 0.85. The longest travel times are modelled for a situation where the D/C ratios are 1 (see table 21). For the afternoon peak hour, the results look similar. For the Getúlio Vargas street, travel times are reaching a steady state after a D/C ratio of 0.75. For the Iguaçu street, travel times start increasing significantly when D/C ratios are higher than 0.85.

This analysis coincides with findings that were made during field observations. It was observed on the Getúlio Vargas street that during peak hours travel times were much longer than during other times of the day. On the Iguaçu street it was observed that travel times more or less stay the same during the whole day. Also, the Getúlio Vargas street always seemed more crowded than the Iguaçu street. This might be an explanation for why travel times for the Iguacu street do not change much until D/C ratios of 0.85; The Iguaçu street is still further away from reaching its capacity. The analysis results are also in line with the D/C ratio of the current situation; the D/C ratio on the Getúlio Vargas street is much higher than the D/C ratio on the Iguaçu street.

5.1.3. Average speed in the current system

Another measure we use to evaluate the performance of the network, is the speed of the vehicles. The speed limit of the streets in the network is 50km/h. In VISSIM, the average speed in the network is calculated based on the average speed of all vehicles in the network from when they enter the network until they leave the network, including possible stops. Because we don't have this information about the current real-life situation, we calculate the average speed of the simulation scenario that represents the real-life situation to compare this average speed to the average speed of all other simulated interventions.

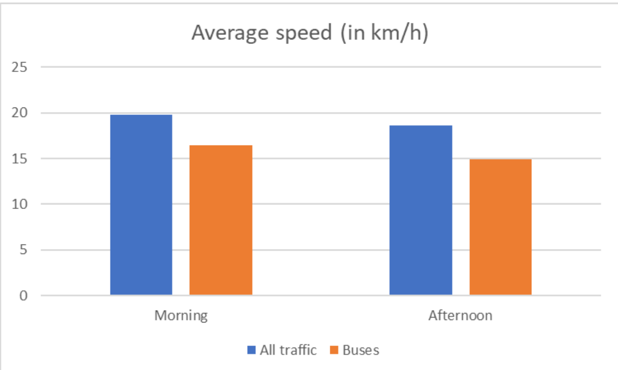


Figure 31: Average speed in the network, during morning and afternoon peaks

The average speed of all traffic and the buses in our network is shown in figure 31. It can be seen that the average speed of the buses is lower than the average speed of all traffic in the network. Also, there is a difference between the average speed of all vehicles during the morning and afternoon peak hours.

The average speed of all traffic is lower during the afternoon peak, compared to the morning peak. Also, the average speed of the buses is lower than the average speed of all traffic in the network. Right now, in the current situation, the average speed of all traffic during the morning peak is around 20km/h. The average speed of the buses during the morning peak is a little lower, around 16 km/h (table 22).

Table 22: Average speeds in the network for the current situation

Average speed in km/h	All traffic	Buses
Morning	20.23	15.68
Afternoon	18.53	13.82

As can be seen in table 23, the speed increases for lower D/C ratios. When D/C ratios are higher than 0.75 the average speed decreases less drastically and it seems to reach a steady state. The average speed from this point on is lower than 10km/h. During the afternoon peak hour, the average speed for both all the traffic and the buses, is lower than during the morning peak hour. For more details on the speed for different D/C ratios, see the figures in appendix C.

Table 23: Average speeds in the network for the current situation for different D/C ratios

Average speed in km/h	D/C ratio	All traffic	Buses
Morning	**0.5**	25.97	20.78
	0.75	10.96	10.18
	0.85	9.88	8.72
	1	7.24	6.74
Afternoon	**0.5**	23.79	18.84
	0.75	12.75	9.00
	0.85	10.53	8.94
	1	9.34	7.84

5.1.3. Average delay in the current system

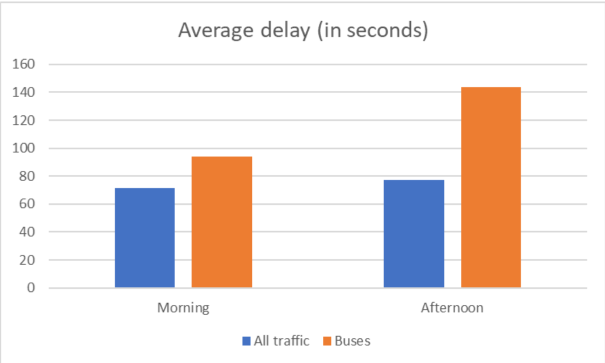


Figure 32: Average delay of vehicles in the simulation network

The average delay is also one of the measures we consider for the evaluation of our interventions on the performance of the network. The average delay of the vehicles in the network is the average time (in seconds) that the vehicles are not driving on their preferred speed, which is in our case the 50km/h speed limit of the streets in our network. Figure 32 shows the average delay during both the morning and afternoon peak for all traffic in our network and for the buses separately. It can be seen that the average delay during the afternoon is longer than during the morning. Also, it can be seen that buses drive longer than average under their desired speed compared to the all traffic. The average delays in the network for the morning and afternoon peak are shown in table 24.

Table 24: Average delay in the network for the current situation

Average delay in seconds	All traffic	Buses
Morning	68.86	100.96
Afternoon	77.39	121.51

Table 25 present the average delay of all traffic and buses during the morning peak for the current situation and for different D/C ratios. The table shows that higher D/C ratios will cause longer delays. However, when D/C ratios are higher than 0.75 the increase ratio of the delay is less than for lower D/C ratios. This is the same for the situation during the afternoon peak. Delays are a little higher already for both all traffic and the buses during the afternoon peak, compared to the morning peak. For more details, see the figures in appendix C.

Table 25: Average delay in the network for the current situation for different D/C ratios

Average delay in seconds	D/C ratio	All traffic	Buses
Morning	**0.5**	44.49	66.47
	0.75	149.93	164.82
	0.85	164.87	193.75
	1	220.53	252.32
Afternoon	**0.5**	52.37	77.19
	0.75	124.58	191.29
	0.85	153.78	188.79
	1	171.01	216.24

5.1.4. Average queue lengths in the current system

The last parameter we consider during our analysis of the different simulation interventions is the queue length of the queues at all intersections of the network. Therefore, we need to know how long the queues are in the network model of the current situation. In our simulation model, we calculated the average queue lengths at all intersections. The results are shown in figure 33 (morning and afternoon peaks).

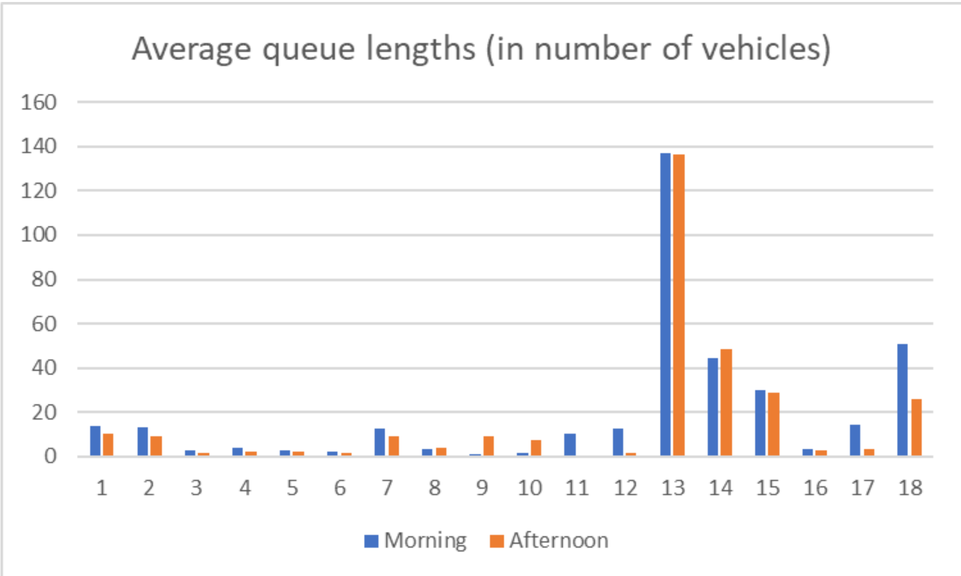


Figure 33: Average queue lengths in number of vehicles (vertical axis) for both morning peak and afternoon peak for all 18 intersections in the network (horizontal axis)

It can be seen that average queue lengths differ per intersection. There is a huge difference between the queue lengths of intersection 13 (longest queues) and the queue lengths of intersection 10 (shortest queues). Also, there are slight differences between the queue lengths at each intersection between the two different peak hours. From observations it wasn't expected that intersection 13 would have been the intersection with the longest queues. However, from the results of the simulation it is not really surprising, as intersection 13 is the first intersection for the input flow of the network that is inserted on the Getúlio Vargas street. The numbers for the input flow on this street are relatively high and the link before the intersection is only short. Also, the vehicles in the network need some time to disperse and therefore queues are most likely higher for this intersection.

Figure 34 shows all the intersections of the network and their numbers (1-12 for the iguacu street and 13-18 for the getulio vargas street). Analysing the queues at each intersection is one way of measuring the congestion on these two streets. Total queue lengths are given in table 26.

Table 26: Total queue length in the network for the current situation

	Total queue length in number of vehicles
Morning	305.83
Afternoon	350.81

Figure 34: Numbers of the different intersections in the network

Figures 35 and 36 present the average queue lenghts in meters of all intersections in the network, during both the morning and afternoon peaks. When looking at the graphs in figure 35 and 36, it can be seen that there is a difference between the queues during the morning peak and the afternoon peak for different D/C ratios. During both peak hours there are different intersections that have longer queues.

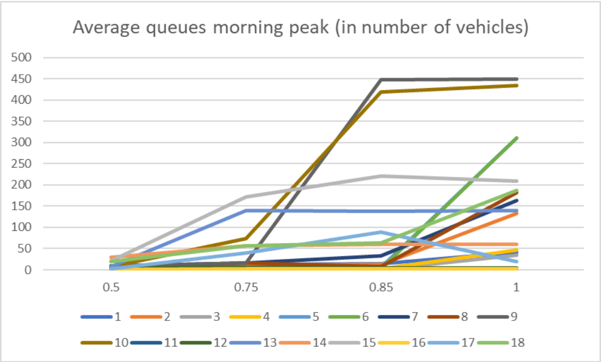


Figure 35: Average queues morning peak

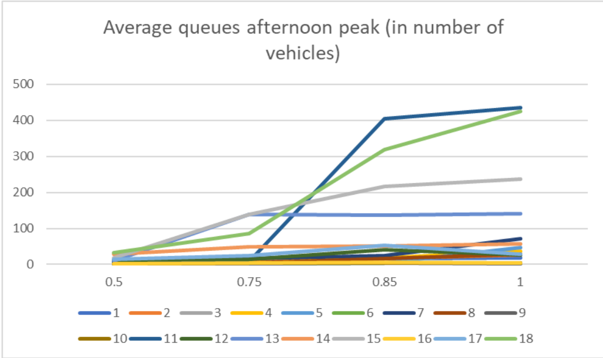


Figure 36: Average queues afternoon peak

5.1.5. Discussion about network performance of the current situation

Based on the results of the previous paragraphs it can be concluded that travel times for the Getúlio Vargas street are in general longer during the afternoon peak hour, compared to the morning peak hour. Also, travel times are longer for buses. For the right lanes of the Iguaçu street this is not the case. On this street, the travel times are longer during the morning peak hour. On the left lanes of the Iguaçu street, the travel times are more or less the same during the morning and afternoon peak hours. A D/C ratio of less than 0.75 will have a big positive impact on the travel times on the Getúlio Vargas street; the lower the D/C ratio, the shorter the travel times are. For the Iguaçu street, travel times will become much longer when the D/C ratio reaches 0.85 or higher.

The results of the average speed show that the average speed in the network is higher during the morning peak than during the afternoon peak. Also, it can be concluded that the buses have a lower average speed compared to all other traffic in the network. From a D/C ratio from 0.5 until 0.75, a small difference in D/C ratio has a big impact on the speed of the traffic, for both morning and afternoon peaks and for all traffic. When the D/C ratio is higher than 0.75, the speed is not decreasing as much anymore but the speed at that point is really low (below 10km/h).

The average delay of all traffic in the network is longer during the afternoon peak hour, compared to the morning peak hour. Also, the average delay reaches a point from which the average delay is growing less rapidly, this is at a D/C ratio of 0.75.

There are 18 intersections considered in this research, which all have different queue lengths during the morning and afternoon peak hour. For some intersections, the queue lengths are really long for higher D/C ratios. It can be seen that there is a shift in congestion between the morning and afternoon peak hours, as different intersections have the longer queue lengths between those two peak hours. Also, the queue lengths are increasing more when the D/C ratio is higher than 0.75.

Based on all results, it can be concluded that lower D/C ratios have a big positive impact on the results of all evaluation parameters of the current network in the city of Curitiba. It can also be concluded that higher D/C ratios as a result of traffic growth will have big negative impacts on the congestion in this network. The impacts are different for both streets; the Getúlio Vargas street is closer to its capacity and only D/C ratios lower than 0.75 have positive impacts on the performance of this street. Therefore, there is only limited space for further improvement of the travel times on this road without changing structural properties of the street as an extra lane or traffic light optimization or priority. Special attention should be paid to the intersections 11, 13, 14 and 18 which present long queues in the current traffic situation. On the other hand, Iguaçu street seems not so close to its capacity. There is some space for increasing traffic numbers, which won’t have a big influence on the performance of the street until a D/C ratio of 0.85. In order to reduce the impacts of traffic growth in this network, different interventions are modelled and evaluated.

For a quick overview, all the performance indicators for the current situation scenario and their values are shown in table 27.

Table 27: Overview performance indicators scenario 0

KPI	Morning		Afternoon	
	All traffic	Buses	All traffic	Buses
Travel times (average both streets)	184.94	251.83	198.33	262.5
Speed	20.23	15.68	18.53	13.82
Delay	68.86	100.96	77.39	121.51
Queue length	305.83	-	350.81	-

5.2. Performance of the different interventions

In this section, we compare the results of all seven different interventions to the normal current situation and each other, to see which three interventions score best in terms of travel times, delays, speed and queue lengths in the network. More detailed results of all interventions can be found in appendix D.

First, we have a look into the total travel times of all traffic and buses in the network. To be able to say something about the performance of the intervention on the whole network, we want to find the intervention that leads to the shortest travel times in the network for both streets. Therefore, we added the travel times of both streets together and we visualized this total travel times in figure 37.

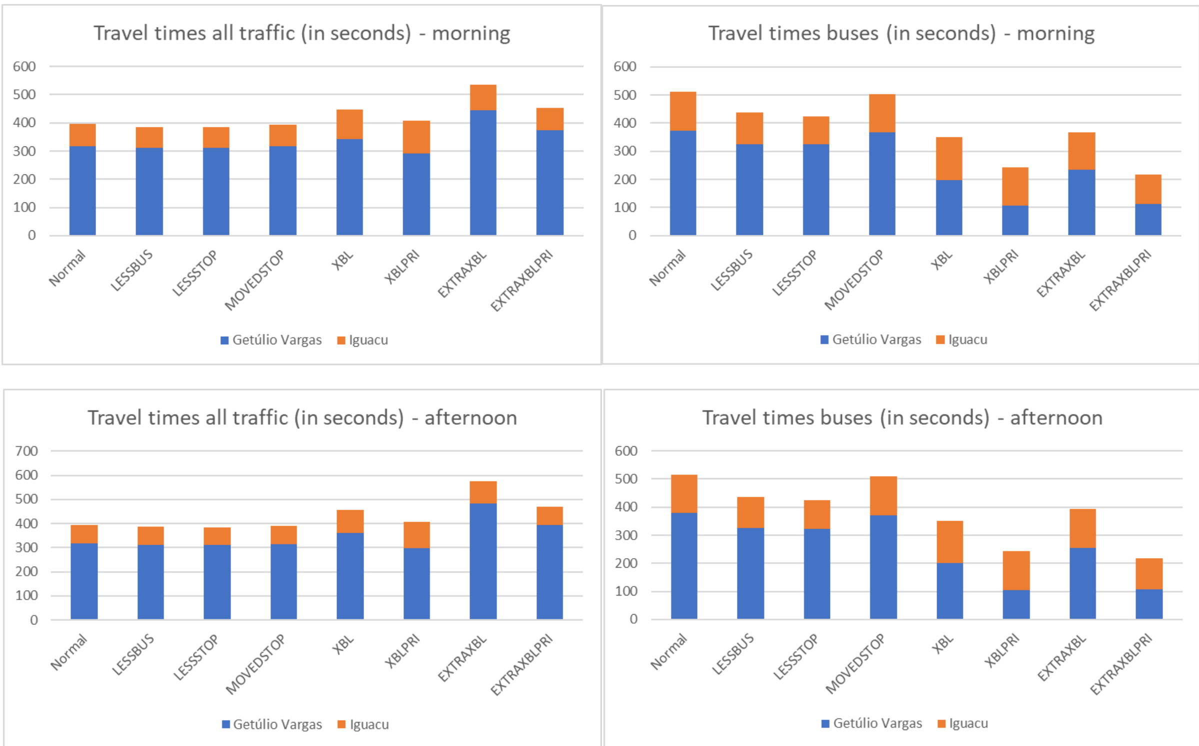


Figure 37: Travel times for all traffic during morning and afternoon peak (upper and lower left) and travel times for buses during morning and afternoon peak (upper and lower right)

When looking at the results in figure 37, it can be seen that the LESSBUS and LESSSTOP interventions score best for all traffic in the network in terms of travel times as travel times are a little shorter than in the current situation. The EXTRAXBL intervention scores worst. For this intervention, travel times have become much longer. When looking at the results for the buses in the network (right side of figure 37), the results are a bit more diverse. In all interventions, travel times are shorter than in the normal situation. Only for the MOVEDSTOP intervention, the difference is nihil. It can also be seen that the travel times of the buses decrease a lot on the Getúlio Vargas street when XBLs are implemented. The EXTRAXBLPRI and XBLPRI interventions give the best results in terms of travel times for the buses in the network.

The graph of figure 38 shows the average delay in the network during the morning peak. It can be seen that XBLPRI has on average the smallest delay, for both all traffic and buses in the network. Secondly, the normal XBL model scores best. The results of the afternoon peak hour look different (figure 39), but the smallest delay is also in the XBLPRI model. The biggest difference between the two figures is between the average delays of the EXTRAXBL and EXTRAXBLPRI models. The EXTRAXBLPRI model scores third best on lowest travel times during the morning peak hour, but during the afternoon peak hour the EXTRAXBLPRI model scores worst on average delays in the network (figures 38 & 39).

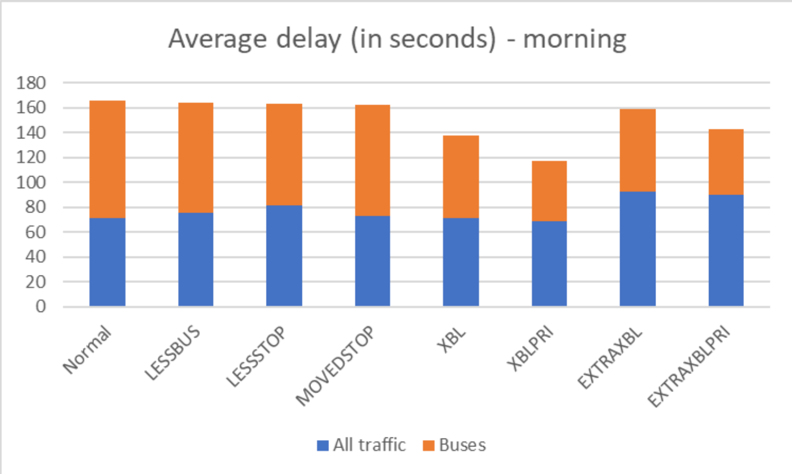


Figure 38: Average delay during the morning peak hour

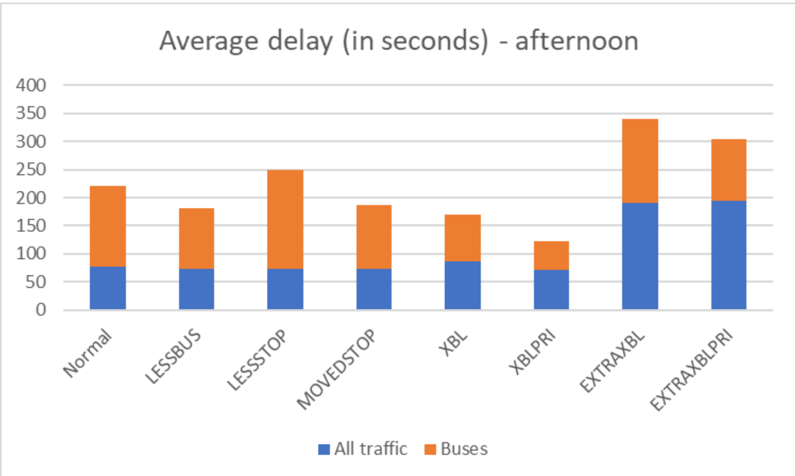


Figure 39: Average delay during the afternoon peak hour

The average speed in the morning network, is the highest for all traffic in the XBLPRI model. Also, when looking only at the buses, the buses have the highest speed in this model. The model in which the buses have the second highest speed is the EXTRAXBLPRI. When looking only at the average speed of all traffic, the normal XBL model scores second best on highest speed. These results can be seen in figure 40. For the afternoon peak hour, the XBLPRI also scores best in terms of average speed. For both all traffic and buses only, this model results in the highest average speed. Surprising is that the LESSBUS model scores third best on highest average speed in the model, after the XBL intervention. This is different compared to the morning peak hour. The EXTRAXBLPRI model that scored second best during the morning peak, scores second worst during the afternoon peak hour (see figure 41).

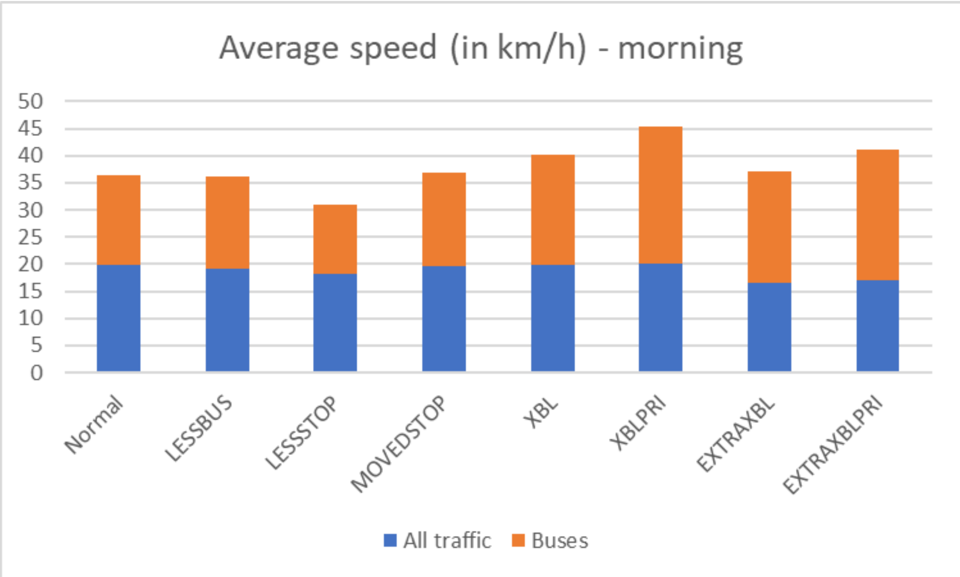


Figure 40: Average speed during the morning peak hour

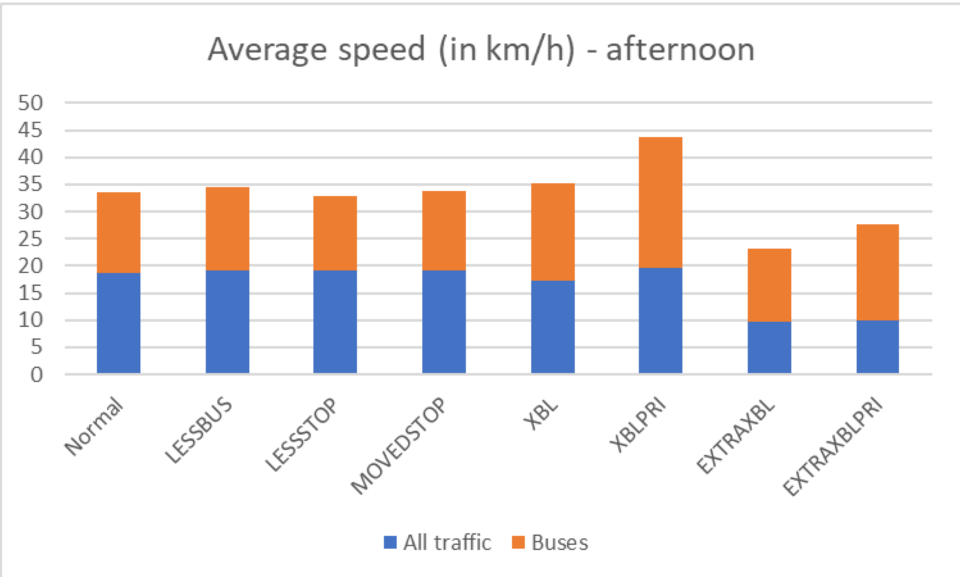


Figure 41: Average speed during the afternoon peak hour

In figure 42 and 43 the total queue lengths in the network for all models are showed for the morning peak and afternoon peak respectively. For the morning peak, it can be seen that the lengths of the queues for the first six models lay really close to each other. Only for the EXTRAXBL and EXTRAXBLPRI models, the queues in the network are longer. For the afternoon peak, queues are shorter on average. Especially the queues for the EXTRAXBL and EXTRAXBLPRI models are much shorter during the afternoon peak hour compared to the morning peak hour.

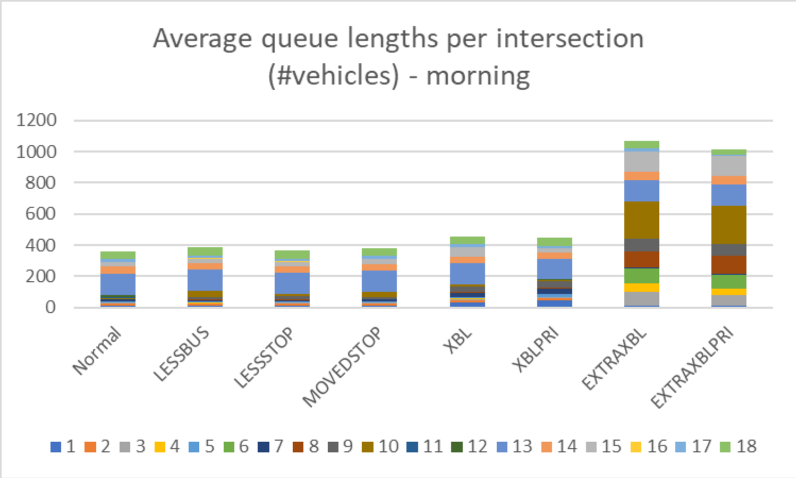


Figure 42: Average queue lengths per intersection during the morning peak hour

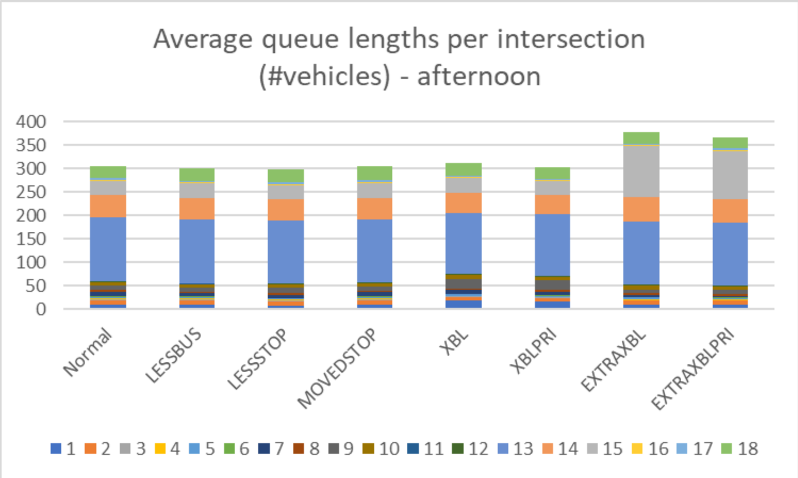


Figure 43: Average queue lengths per intersection during the afternoon peak hour

To get an overall idea of the performance of all models for the current situation, we summarized the results of all performance indicators for all models. In table 28, all numeric results are shown for all simulation models for all traffic. The numeric results are an average of the morning and afternoon peaks to make it easier to compare the performance of the different interventions. The numeric results are also calculated for the buses only, these results can be seen in table 30. Percentual improvements are calculated as well, for all simulation models compared to the current situation. Green numbers indicate an improvement in performance and orange numbers indicate a performance decrease. The percentual improvements are shown in table 29, for all traffic in the network and in table 31 for only the buses in the network.

Table 28: Average results on performance parameters for all interventions for all traffic, current situation

Performance parameter	Normal	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	197.72	193.53	192.62	196.63	225.35	203.44	278.15	230.75
Speed (km/h)	19.22	19.22	18.63	19.37	18.57	19.86	13.17	13.44
Delay (s)	74.52	74.61	77.50	73.66	78.88	69.95	141.84	142.31
Queue length (#)	332.97	342.34	331.63	343.35	381.62	376.91	723.65	690.60

Table 29: Percentual improvement for all models, compared to current situation (all traffic)

Performance parameter	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	-2.12	-2.58	-0.55	13.97	2.90	40.68	16.71
Speed (km/h)	-0.03	-3.05	0.76	-3.38	3.35	-31.48	-30.06
Delay (s)	0.12	3.99	-1.15	5.85	-6.14	90.33	90.96
Queue length (#)	2.81	-0.40	3.12	14.61	13.20	117.33	107.41

Table 30: Average results on performance parameters for all interventions for all buses, current situation

Performance parameter	Normal	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	256.57	218.56	212.18	253.07	175.76	121.67	190.47	108.78
Speed (km/h)	15.71	16.16	13.28	15.97	19.08	24.70	16.91	20.89
Delay (s)	119.03	97.89	129.17	100.74	75.21	49.57	107.91	80.62

Table 31: Percentual improvement for all models, compared to current situation (all buses)

Performance parameter	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	-14.81	-17.30	-1.36	-31.50	-52.58	-25.76	-57.60
Speed (km/h)	2.82	-15.45	1.63	21.44	57.19	7.65	32.96
Delay (s)	-17.75	8.52	-15.36	-36.81	-58.36	-9.34	-32.27

Table 29 illustrates that the performance of the network for all traffic is worse for some of the interventions that are introduced in our study. Especially the EXTRAXBLPRI scores are relatively bad, compared to the current situation. For this model, there is a decrease in performance for all performance indicators. The same counts for the EXTRAXBL model, only percentual decreases are lower here than for the EXTRAXBLPRI model. Also, the normal XBL model does not show any improvements in performance compared to the current situation. The LESSBUS, LESSSTOP and MOVEDSTOP interventions have an improvement in travel times as a result. The LESSSTOP intervention also improves the queue lengths compared to the normal situation and the MOVEDSTOP intervention has a higher speed and a smaller delay compared to the normal situation. When looking only at the results of the buses in the network, it can be seen in table 31 that all interventions improve the performance of the buses compared to the current situation. Only the speed and delay performance indicators scored worse than in the normal situation for the LESSSTOP intervention. Highest percentual improvements are for the XBLPRI model.

All interventions are ranked for all performance indicators to find an intervention that performs overall as the best solution for the current situation problem in the city of Curitiba (ranking from 1-7 where 1 is the best solution and 7 is the worst solution). Rankings for all interventions are given in table 32 and

33. Based on the interests of stakeholders of this study, URBS and IPPUC, the travel times and queue lengths are given a weight 2 in calculating the total scores for the overall performances of the interventions. The final ranking of the interventions is calculated by adding the two total scores of all traffic and buses. This calculation gives 35, 36, 41, 41, 24, 59 and 44 points respectively for all interventions. Because better solutions are awarded with lower rankings, the interventions with the least points are the best. This are XBLPRI (1), LESSBUS (2) and LESSSTOP (3). In the next paragraph, these interventions are analysed for different D/C ratios.

Table 32: Ranking of all traffic performances

Performance parameter	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	2.00	1.00	3.00	5.00	4.00	7.00	6.00
Speed (km/h)	3.00	4.00	2.00	5.00	1.00	7.00	6.00
Delay (s)	3.00	4.00	2.00	5.00	1.00	6.00	7.00
Queue length (#)	2.00	1.00	3.00	5.00	4.00	7.00	6.00
TOTAL SCORE:	**14**	**12**	**16**	**30**	**18**	**41**	**37**

Table 33: Ranking of buses performances

Performance parameter	LESSBUS	LESSSTOP	MOVEDSTOP	XBL	XBLPRI	EXTRAXBL	EXTRAXBLPRI
Travel time (s)	6.00	5.00	7.00	3.00	2.00	4.00	1.00
Speed (km/h)	5.00	7.00	6.00	3.00	1.00	4.00	2.00
Delay (s)	4.00	7.00	5.00	2.00	1.00	6.00	3.00
TOTAL SCORE:	**21**	**24**	**25**	**11**	**6**	**18**	**7**

5.3. Different D/C ratios for 3 best solutions

The XBLPRI, LESSBUS and LESSSTOP interventions are found to be the best solution for the current traffic congestion problem in the city of Curitiba. To find the most robust solution, the three interventions are analysed for four different D/C ratios: 0.5, 0.75, 0.85 and 1. Results are given in figures for the morning peak hour. Trends are similar for the afternoon peak hour and these results can be found in appendix E.

5.3.1. XBLPRI

In figure 44, the travel times, speed, delay and total queue length of the XBLPRI model during the morning peak are shown. It can be seen that the travel times of all traffic increase the most from a DC of 0.5 to a D/C of 0.75. For D/C ratios higher than 0.75, there is still an increase in travel times but in smaller steps. The travel times of buses has a peak at a D/C ratio of 0.75. This is unexpected and maybe has to do with a huge number of passengers that were boarding a bus in that simulation. The graph of the speed of the traffic in the network shows the same trend for both all traffic and buses in the network. It can be seen that the speed of buses is higher than the speed of all traffic. When looking at the delay of the traffic, there is a huge increase in delayed seconds from a D/C ratio of 0.5-0.75. From that point on, the delay for all traffic in the network stays more or less the same, with a little increase at a D/C ratio of 1. For buses the delay also increase a lot between D/C ratios of 0.85-1. It seems like some buses have been waiting in front of a bus stop, which has caused a higher delay. Total queue lengths increase the most from a D/C ratio of 0.5-0.75 and the least between a D/C of 0.75-0.85.

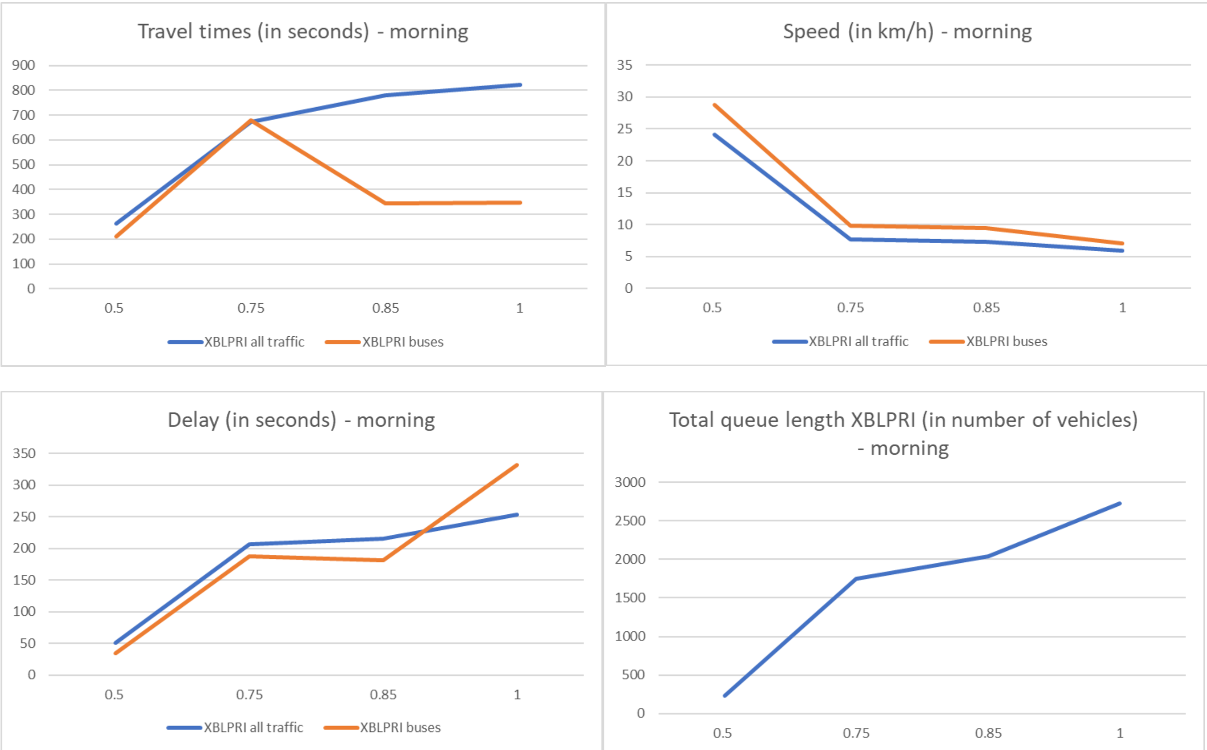


Figure 44: Performance XBLPRI (morning) for different D/C ratios

5.3.2. LESSBUS

The intervention that scored second best on the performance indicators is the LESSBUS model. In figures 45, the performance of the model on travel times, speed, delay and queue lengths is shown for the morning peak and afternoon peak respectively. When looking at figure 45, it can be seen that the travel time increases most between D/C ratios of 0.5-0.75. From 0.75-0.85, the travel times stay the same and after a D/C ratio of 0.85, they increase again. The pattern is the same for both all traffic and buses in the model. The speed of the traffic in the network drops significantly between D/C ratios of 0.5-0.75. After a D/C ratio of 0.75, the speed remains quite constant. Also, the delay in the network increases the most between D/C ratios of 0.5-0.75. However, the total queue length in the network increases linear from a D/C ratio of 0.5-1.

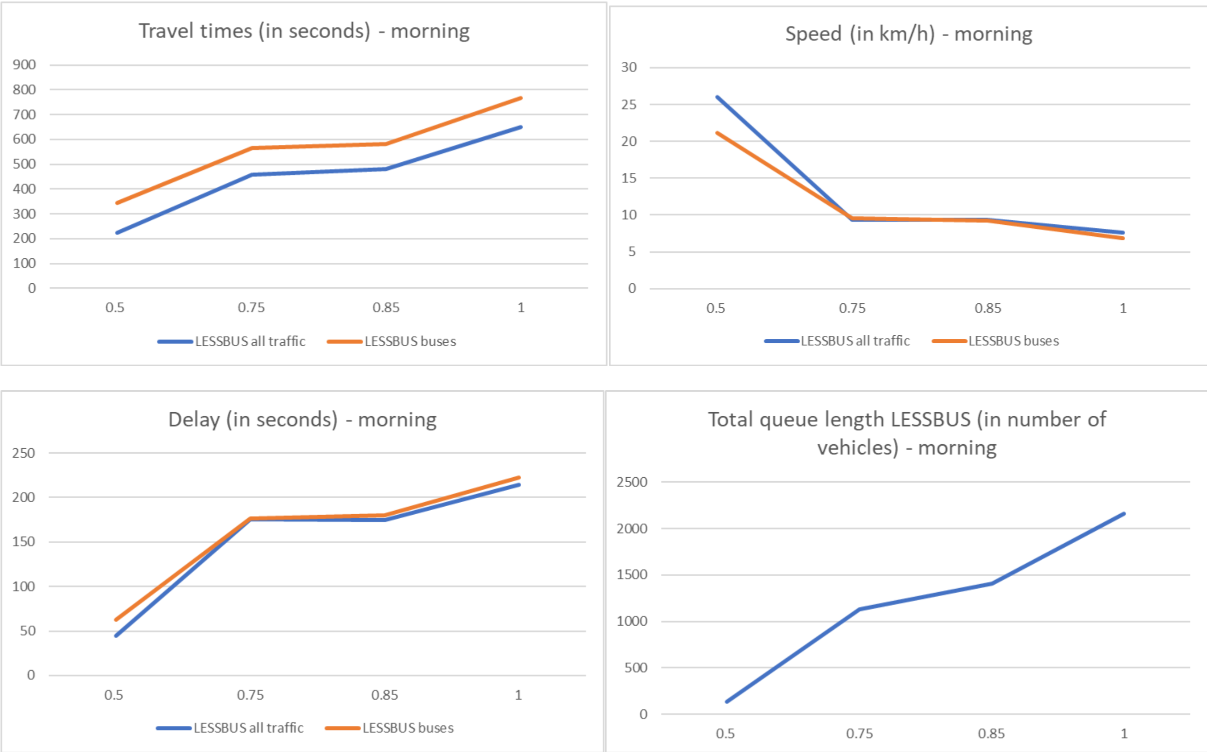


Figure 45: Performance LESSBUS (morning) for different D/C ratios (horizontal axis)

5.3.3. LESSSTOP

The last intervention that is analysed for different D/C ratios is the LESSTOP intervention. The results from this D/C analysis are shown in figure 46. It can be seen that for all D/C ratios, the buses have longer travel times than the average vehicles in the network. The speed of all traffic in the network significantly drops from a D/C ratio of 0.5 until 0.75. After a D/C of 0.75, the speed reaches a steady state and doesn’t change much more. The delay in the network also increases the most from D/C ratios of 0.5-0.75. For a D/C of 0.85, the delay for all traffic in the network is a little longer than the delay for the buses. For a D/C ratio of 1, this is the opposite. When looking at the last graph of figure 46, it can be seen that also the total queue length increases the most between D/C ratios of 0.5 and 0.75. Between 0.75 and 0.85, the total queue length drops a little bit and for D/C ratios above 0.85, the queue length increases again.

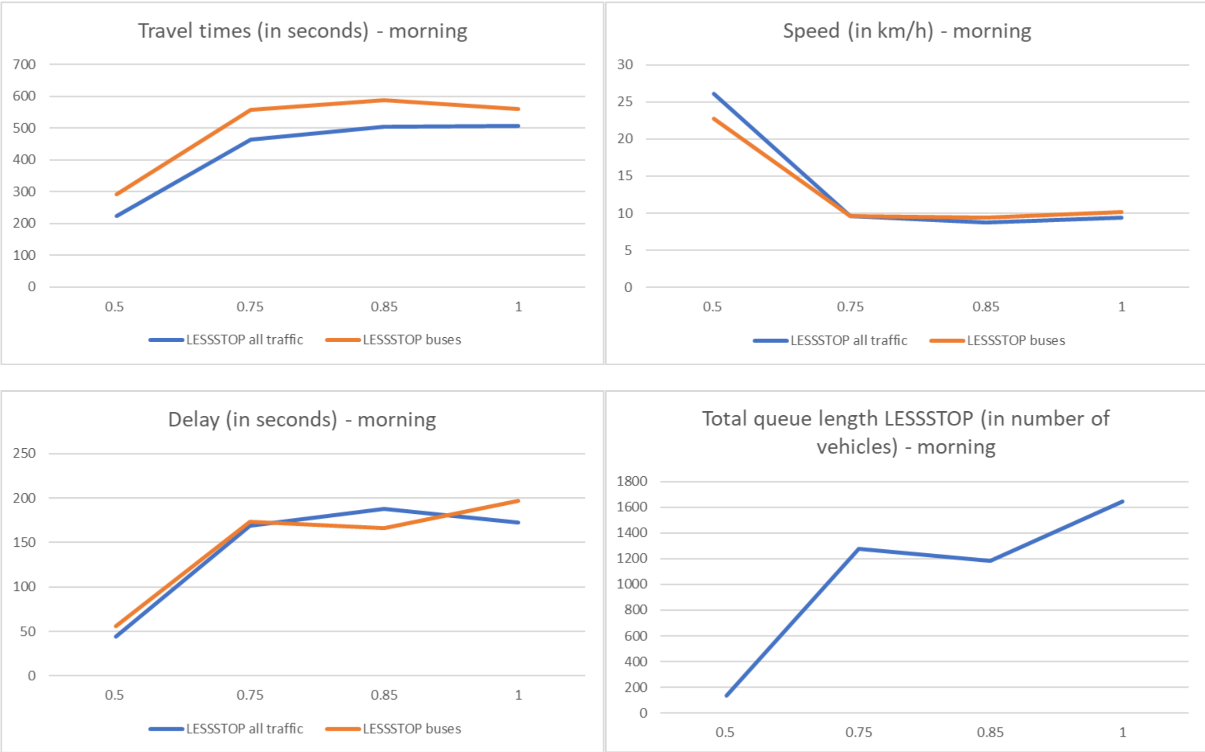


Figure 46: Performance LESSSTOP (morning) for different D/C ratios (horizontal axis)

From the results of the D/C analysis of all three interventions, it can be concluded that the performance of the models is most sensitive to an increase in D/C ratios between 0.5 and 0.75. Between these two D/C ratios, the travel times, speed, delay and queues in the network were influenced the most. To validate these observations, a sensitivity analysis is done for all three models, on the four performance indicators. Results are discussed in the section below.

5.3.4. Sensitivity analysis

Table 34 shows the results of the sensitivity analysis that we have conducted on the three different interventions. For all performance indicators, it has been analysed what the percentual improvement or decrease is when the D/C ratios increase from 0.5 to 0.75, from 0.75 to 0.85 and from 0.85 to 1. The grew highlighted values indicate percentual differences that are higher than 25. It can be observed from the table that a change in D/C ratio from 0.5 to 0.75 has the most influence on the performance indicators of the model. From this it can be concluded that all three models are the most sensitive to a raise in D/C value from 0.5 till 0.75

When looking at the models individually, the LESSSTOP model has 4 other situations in which the percentual difference is more than 25. This is the case for the queue length when D/C ratios increase from 0.85 till 1 during the morning peak hour, and when D/C ratios increase from 0.75-0.85 and 0.85-1 during the afternoon peak hour. The last percentual difference that is bigger than 25 is when the D/C ratio raises from 0.75 till 0.85, for the delay of all traffic in the network during the afternoon peak hour. The LESSBUS model is more sensitive to a change in D/C ratio from 0.85-1 during the morning peak, than the other two models. This is indicated by the four grey boxes in table 34. For the travel times of all traffic and buses in the network, for the speed of the buses and for the queue length in the network, the percentual difference is more than 25. This is also the case for the queue length during the afternoon peak, when the D/C ratio changes from 0.75 to 0.85. Lastly, when looking at the results of the XBLPRI, the results are a little more spread. There are 5 situation in which the performance of the network is changed by more than 25%: for the travel times of the buses when D/C ratios increase from

0.75-0.85, for the delay of the buses between D/Cs of 0.85-1 and for the queue length in the network for a change in D/C ratios between 0.85-1, all during the morning peak hour. During the afternoon peak hour, performance changes are more than 25% for the speed of the buses and for the delay of the buses when D/C ratios increase from 0.85 to 1 (all can be seen in table 34).

Table 34: Sensitivity analysis.

The table shows the sensitivity of the 4 performance indicators separately for buses and all traffic in the network. Also, a distinction is made between the morning and afternoon models. The second row of the table indicates the two D/C ratios for which the sensitivity analysis has been done. For example: 0.5-0.75 means the sensitivity of the performance indicator when the D/C ratio raises from 0.5 to 0.75 etc.

		Morning			Afternoon		
	LESSSTOP	**0.5-0.75**	**0.75-0.85**	**0.85-1**	**0.5-0.75**	**0.75-0.85**	**0.85-1**
Travel times	*All traffic*	106,58	8,70	0,86	71,70	6,97	6,19
	Buses	91,20	5,20	-4,68	71,32	4,83	5,08
Speed	*All traffic*	-62,93	-9,70	7,36	-47,82	-19,52	-8,98
	Buses	-57,41	-3,10	8,00	-61,02	2,98	18,78
Delay	*All traffic*	282,01	10,99	-8,00	153,02	26,47	8,72
	Buses	210,56	-4,04	18,47	247,95	-7,52	-2,82
Queue length		847,53	-7,30	38,79	266,13	110,91	33,30
		Morning			Afternoon		
	LESSBUS	**0.5-0.75**	**0.75-0.85**	**0.85-1**	**0.5-0.75**	**0.75-0.85**	**0.85-1**
Travel times	*All traffic*	105,43	4,88	35,49	67,82	2,11	9,33
	Buses	64,58	2,93	32,20	54,04	0,39	8,87
Speed	*All traffic*	-64,28	-0,14	-18,72	-52,02	-10,14	-13,84
	Buses	-54,92	-3,31	-26,41	-53,06	-6,37	5,61
Delay	*All traffic*	296,98	-0,67	22,83	177,73	12,10	14,84
	Buses	179,50	2,43	23,38	143,31	3,60	-6,29
Queue length		742,25	24,09	53,76	556,05	34,20	23,23
		Morning			Afternoon		
	XBLPRI	**0.5-0.75**	**0.75-0.85**	**0.85-1**	**0.5-0.75**	**0.75-0.85**	**0.85-1**
Travel times	*All traffic*	154,42	15,97	5,65	160,34	6,03	0,13
	Buses	219,67	-49,04	0,80	41,05	2,82	0,42
Speed	*All traffic*	-68,33	-4,57	-18,40	-57,49	-7,24	-7,96
	Buses	-65,85	-4,44	-24,40	-58,81	-14,18	-27,68
Delay	*All traffic*	304,52	4,12	17,66	195,48	6,82	8,13
	Buses	431,86	-3,05	83,17	290,98	6,28	39,92
Queue length		665,22	16,14	34,00	1315,85	18,60	17,55

During the morning peak, the XBLPRI model is the least sensitive to changes in D/C ratio for the queue length. However, for the afternoon peak this is the opposite and the LESSSTOP model is the least sensitive. The XBLPRI model is the most sensitive to changes in the D/C ratio for the delay, speed and travel times in the network. Percentual differences are the highest for this model for both all traffic and buses in the network.

5.4. Difference Iguaçu and Getúlio Vargas streets

While analysing the results of the different interventions, we noticed there are some big differences between the impact of the interventions on travel times on the Iguacu and Getúlio Vargas streets. Therefore, we have chosen to analyse the performance in terms of travel times for both streets individually. To do so, we first summarized the travel times for the normal situation and all interventions in a graph (figure 47). This is done for all traffic and buses individually for both peak hours. Next, we summarized the travel times of the three analysed interventions for different D/C ratios. This is also done for both the morning peak and afternoon peak and is visualized in four graphs (figure 48); travel times on the Iguaçu and Getúlio Vargas street for both all traffic and buses in the network separately. For the analysis, the average travel times between the morning and afternoon peaks are used as an input for the graphs.

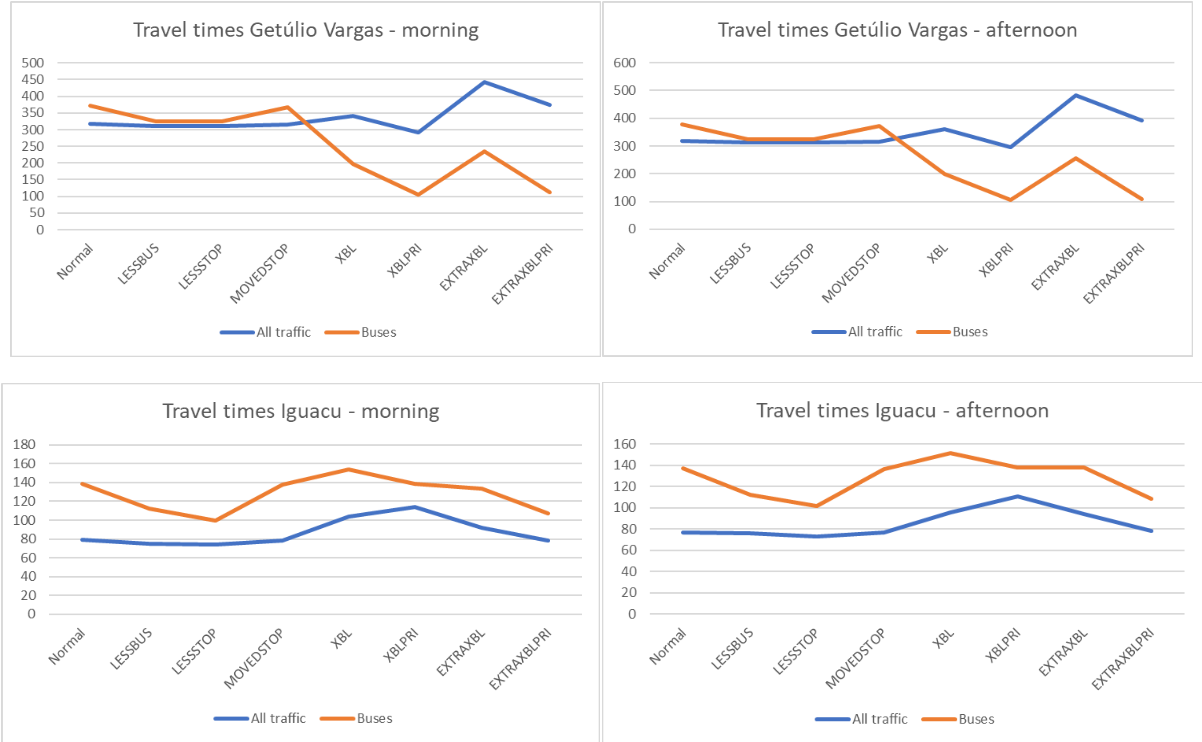


Figure 47: Difference between travel times on Iguaçu and Getúlio Vargas for all interventions

In figure 47, in the left upper corner, it can be seen that for the current situation the XBLPRI scenario works best for all traffic and buses on the Getúlio Vargas street. For all traffic in the network the differences between different models are small, but for buses the XBLPRI performs significantly better than most of the other models. A similar pattern can be seen for the afternoon (upper right corner of figure 47). For the Iguaçu street, the models show different results. The travel times for all traffic are quite similar between the normal situation and the LESSBUS, LESSSTOP and MOVEDSTOP models. For the buses in the network, the shortest travel times are in the LESSSTOP and EXTRAXBLPRI models. Again, the pattern looks similar for the afternoon peak on the Iguaçu street (see figure 47).

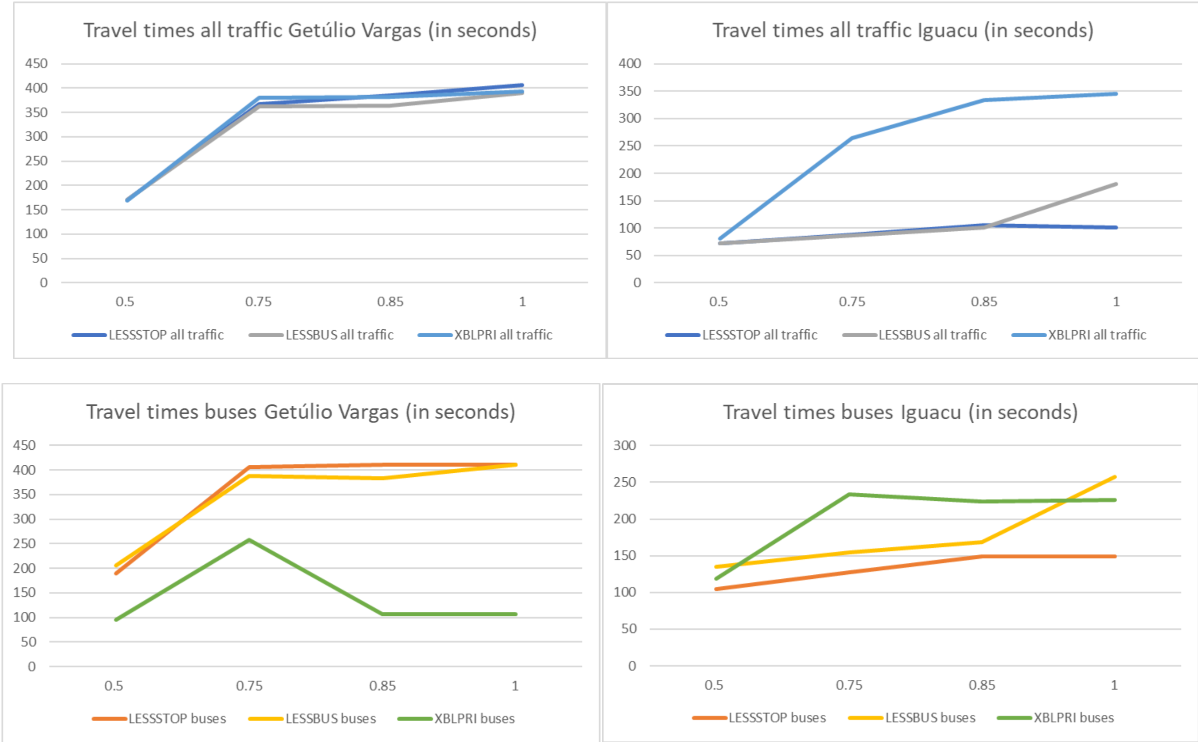


Figure 48: Difference between travel times on Iguaçu and Getúlio Vargas for different D/C ratios (horizontal axis)

The interventions that have been modelled for different D/C ratios are also analysed on travel times for the Iguaçu and Getúlio Vargas streets. The results of this analysis are shown in figure 48. For the travel times on the Iguaçu street (upper left corner of figure 48) it can be seen that the travel times of all three interventions are really close to each other for all D/C ratios. The LESSBUS intervention performs a little better than the other two models for all traffic in the network. When looking at the travel times for all traffic on the Iguaçu street (upper right corner of figure 48), it can be seen that the LESSSTOP models performs best until a D/C ratio of 0.85 and the XBLPRI model perform best until a D/C ratio of 1. When looking only at the buses in the network (lower two graphs in figure 48), it can be seen that the XBLPRI model scores best for all D/C ratios for the travel times of the buses on the Getúlio Vargas street. For the buses on the Iguaçu street, the LESSSTOP model performs best for all D/C ratios.

5.5. Growth scenario in 20 years

When looking at the sensitivity analysis of section 5.4, it can be seen that the XBLPRI intervention is very sensitive to increasing D/C ratios for all performance indicators. The municipality of Curitiba wants to know the most robust solution for the congestion problem in the city and therefore we need to compare the D/C ratios that were calculated in section 4.6.5 with the D/C ratios that were modelled for the three best interventions. From this comparison we can predict how the intervention would function in 20 years from now.

From our calculations in section 4.6.5 of the D/C ratios for a growth scenario in 20 years, we found that during the morning peak the D/C ratio on Iguaçu and Getúlio Vargas raise to 0.78 and 1.01 (above capacity) respectively. For the afternoon peak hour, the D/C ratios grow even more. For 6 out of the 8 streets we analysed, the D/C ratios raise above 0.75; 0.87 on Franco, 0.89 on Buenos Aires, 1.04 on Alferes Poli, 1.26 on Maio, 1.27 on Iguacu and 1.32 on Getúlio Vargas.

When looking at all the results, the LESSSTOP model seems to be the best solution for the current situation and for all D/C ratios until 1 on the Iguacu street. When D/C ratios are growing above 1, it's hard to predict which model would give the best performance results in the network. On the Getúlio

Vargas street, the XBLPRI model seems to be the best solution in terms of travel times. But this model is also the most sensitive to a change in D/C ratios. As it is predicted that D/C ratios raise above 1 on the Getúlio Vargas street during the next 20 years, this might not be the most robust solution for the long term. Although the EXTRAXBLPRI model hasn't been analysed for different D/C ratios, this model might be a good alternative for the Getúlio Vargas street to be able to manage the growing demand of vehicles on the street. This is discussed in chapter 6.

5.6. Conclusions of the results

From section 5.3 it can be seen that different interventions score better for different performance indicators of the network in the current situation. For all traffic in het network, the LESSSTOP model resulted in the lowest travel times and queue lengths in the model. The XBLPRI scored best on the performance indicators speed and delay. LESSSTOP also scored relatively high on the performance indicators. For the buses in the network, the XBLPRI scored best on the performance indicators speed and delay and the EXTRAXBLPRI model scored best on travel times.

For the three best interventions we found in our study, we only simulated the models for D/C ratios of 0.75, 0.85 and 1. Therefore, we shortly recap the results of the models with high D/C ratios to be able to say something about the performance of the models when D/C ratios are even higher. From sections 5.4 and 5.5 we concluded that the XBLPRI, LESSBUS, and LESSSTOP are the interventions with the best improvement compared to the current situation. For buses in the XBLPRI model, travel times drastically decrease. However, for all other traffic in the model, travel times become longer because there is one lane less to drive on. Especially on the Iguaçu street, the effect is big and travel times start to increase after a D/C ratio of 0.5 with a peak of almost 400 seconds when the D/C ratio is 1. When looking at the D/C ratios of the growth scenario, it is most likely that this model is not going to be able to handle the increasing number of vehicles. For the LESSBUS model, travel times for buses are much lower compared to the normal situation. This is the case for both Iguaçu and Getúlio Vargas. Even for D/C ratios close to 1, the travel times are still realistic and there are no enormous queues on the streets. A similar situation is identified for the LESSSTOP model. Here, travel times are much lower on the Iguacu street. Again, traffic still looks normal and there are no traffic jams. When comparing the LESSBUS and LESSSTOP models, the LESSSTOP model performs better on the Iguacu street, but scores worst on the Getúlio Vargas street. The LESSSTOP model seems to be the best solution for the current situation and for all D/C ratios until 1 on the Iguacu street. On the Getúlio Vargas street, the XBLPRI model seems to be the best solution in terms of travel times.

6. Discussion & conclusion

This section provides the discussion and conclusion of our research. We give answers on the research questions formulated in section 1.4.

6.1. Discussion

In general, the buses travel times increases when the D/C ratios increase for mixed traffic conditions (LESSBUS, LESSSTOP, MOVEDSTOP). When considering XBLs, the buses travel times stay more or less the same as they have a constant travel time regardless of the level of congestion on the main road. It can be seen that for higher D/C ratios the other vehicles in the road face heavy congestion in the XBL and XBLPRI models. The more traffic on the road, the greater the impact of XBLs on other traffic as well. From this it can be said that the implementation of the XBL has a negative impact on the other vehicles' travel time in adjacent lanes, especially at high D/C ratios when the network reaches its capacity (D/C ratio of 1). This is because the capacity of the road is reduced for other traffic after taking one lane for implementation of the XBL. Similar to the travel times, the buses delays increase with the increase in D/C ratios in the mixed traffic conditions for the LESSBUS, LESSSTOP and MOVEDSTOP models. For the XBL interventions, delays are almost constant. For lower traffic volumes, the delay doesn't have much impact on other traffic. The bus delay increases with the increase in traffic volumes. For higher D/C ratios, bus delays are higher too. The effect of the XBL on the delay of all vehicles is very small for D/C ratios of 0.75 or less because the network operates at a low traffic volume. However, for higher volumes the effect of the XBL is clear as the delays have increased drastically. At high capacity, other vehicles have difficulties changing lanes because the roads are fully congested. In mixed traffic conditions, the average speed of the buses along the main road decreases as the demand increases. The effect of the XBL on the average speed of the buses is very obvious as the buses maintain a constant speed along the whole XBL because there is no interaction between the buses and other vehicles. This indicates the importance of XBL to improve the performance of the buses' average speed at level of congestions/high D/C ratios. The average speed of the other vehicles, in mixed traffic condition, experiences a significant drop at high traffic volumes because other traffic has less space on the road then before due to the implemented XBL. This is because vehicles move from one lane to another and try to overtake each other to reach their destination and the available road space for other vehicles is way less than before. This also results in higher delays for other vehicles in the network. The EXTRAXBL and EXTRAXBLPRI models should overcome these results as there is the same number of lanes available for regular traffic and there is an extra XBL available for buses only.

XBLPRI was one of the best solutions according to our simulation model. However, there are some limitations regarding the bus priority of this model. In the model it was simulated that all buses had priority and all other vehicles had to wait. Because this was not modelled with the traffic lights, the other vehicles only stopped for the bus passing and continued driving right after. In the real situation, there needs to be some traffic light modification that might result in less green time for vehicles of other directions. This might negatively influence the performance parameters as discussed in this study. This is also the case for the EXTRAXBLPRI model.

Many buses in the network can lead to buses occupying bus stops for each other which might cause delays due to congestion. Also, buses have to wait before they can stop at the bus stop, which increases the buses travel times. The LESSBUS intervention reduced the number of buses in the system and a positive effect on travel times could be seen. Because of less bus bunching in this model, buses don't have to wait in front of a bus stop which reduces the travel times of buses in the network. By reducing the number of buses and also the number of buses that stop at the bus stops (LESSSTOP intervention), the overcapacity might be reduced but is not entirely eliminated. In the LESSSTOP model where there are less buses that stop at the bus stops, less other vehicles have to wait behind the bus to continue driving. This can explain why the average travel times in these models are shorter than in the normal situation. However, buses can get delayed at another part in the network after which they enter the specific network of our study around the same time. This can still result in buses that have to stop at the same bus stop in the same time frame. The total travel times of the buses are less in the LESSSTOP model because when all buses in het network skip two bus stops, there is no or less waiting time at these bus stops as they can just overtake the buses that are picking up passengers.

The MOVEDSTOP simulation only influences the results on the Getúlio Vargas street, as the stop is moved along this street. It can be seen that this movement has a positive effect on the performance indicators of the network as the travel times are shorter, the speed higher and the delay shorter compared to the normal situation.

For D/C ratios of 0.75 or less, the interventions were expected to have almost no effect on the vehicles in the network as the network is operating below its capacity, thus allowing vehicles to freely move around the network. However, sensitivity analysis has showed that between D/C ratios of 0.5 and 0.75, the effect of demand is greater on the different performance indicators. One explanation could be that the network actually has a lower capacity than the one calculated in this study. It might be possible that when D/C ratios change from 0.5 to 0.75, that vehicles have to wait longer in front of stopping lights or for turns which also causes traffic congestion. For D/C ratios above 0.75, it seems like the network is fully congested and the vehicles are trapped in traffic congestion as most of the performance indicators do not change values much anymore. When travel times, speed, delay and queues in the network remain constant this shows that a traffic network is reaching capacity and more delays or queues are almost not possible. For D/C ratios of 1 until 0.75, there is only small improvement possible in the performance of the network when D/C ratios drop. Only for the models that include an XBL, the performance indicators for the buses stay the same. This shows the effectiveness of the XBL in improving the travel times for the buses when the network reaches capacity.

During field observations, it was observed that there are more queues during the morning peak hour, compared to the afternoon peak hour. This is in line with the results from the simulation. In general, there is more congestion during the morning peak hour for all models. However, differences are only small in most cases. Small differences between the two peak hours make it more feasible to choose one intervention to improve the current traffic congestion during both peak hours.

Looking at the VISSIM software and the modelling part of the different intervention, there are a few discussion points regarding the outcomes of this study. First, when the network is too congested the vehicles that are waiting to enter the network are not feasible in the network. This means that these vehicles are also not taken into account for calculations of travel times, speed, delay and queues in the network. Also, for the travel times on the Iguaçu and Getúlio Vargas street this is a limiting factor. All vehicles that not passed the second sensor are not taken into account for the travel time calculations. When vehicles are stuck in a traffic jam, they won't be able to pass the second sensor and this will influence the results.

For the modelling of the interventions for different D/C ratios, all model inputs are given the same D/C ratio. In the current situation, the demand of vehicles is different on different streets. This means that not all vehicle inputs are increased with the same percentage of vehicles compared to the situation right now. That is one of the reasons that the morning and afternoon peak hours look similar. It's also an explanation for the differences we see between the trends of the results of the current situation models and the models that are analysed for different D/C ratios. Lastly, in real life vehicles can switch lanes between the right and left Iguaçu streets. In this model, the streets are modelled as different inputs so the effect on the other Iguaçu street is not simulated.

6.2. Conclusions

The reason for conducting this research is to find a solution to improve the bus efficiency, in terms of congestion and travel times, on the Iguaçu street and Getúlio Vargas street in the city of Curitiba. Curitiba implemented the second BRT system in the world and the system is regarded as one of the most efficient of Latin America. The increasing motorization has stimulated Curitiba's urban planners to promote better and more comfortable public transport services by reducing congestion and travel times. Today, 251 bus lines transport 1,389,731 passengers on an average business day over 9 different routes. Given the scope of the BRT system of the city of Curitiba, only thirteen bus lines that run on the Iguacu and Getúlio Vargas streets between different neighbourhoods and the city centre are taken into account for this study.

These thirteen lines are chosen because the municipality of Curitiba has concluded that the performance of the BRT system in this small part of the city is not sufficient and negatively affects the performance of the BRT system in other parts of the city. All buses come from different neighbourhoods and go to the only integration terminal in this part of the city. Since all buses drive past the same bus stops, their lines overlap causing bus bunching. Also, the Iguaçu and Getúlio Vargas streets are very crowded and buses regularly get late at the terminal. To access the performance of the BRT system, the municipality of Curitiba uses three key performance indicators (KPIs): travel times of buses, delays of buses and bus bunching. We conclude that these three KPIs are also the bottlenecks of the system.

We found different possible interventions to reduce the impact of these bottlenecks on the performance of the BRT system. XBLs are commonly used as bus priority strategies to improve bus system performance. In this study, the impact of XBLs on traffic network performance was investigated, next to a couple of other interventions. These interventions include the implementation of a bus terminal, the reduction of the number of buses, the reduction of the number of bus stops and moving of a bus stop.

From the literature we conclude that simulation using VISSIM, a micro-simulation model, is the best approach to tackle our problem and to evaluate the impact of the different interventions on the performance and efficiency of the network that is included in the scope of our research. VISSIM was utilized to model the impact of adding different interventions under different traffic conditions (vehicle inputs and traffic light control), on the performance of all buses and all traffic in the network. For the selection of an appropriate terminal location, factor analysis consisting of site screening and site evaluation is a suitable approach.

In order to build the simulation model for our network, data on the number of buses, the time and demand at different bus stops, traffic lights and number of vehicles at intersections is needed. Required data for the simulation study is partly directly available from URBS and IPPUC, and the part of the data that is not directly available needs to be extracted and estimated by integrating different data sources. Data from both AVL and AFC systems are used in our study to extract input data for our model on the number of buses and the times and demand at bus stops. Traffic light data and vehicle numbers were obtained from URBS and used as an input for the model. To build a realistic model, there needs to be geometrical accuracy between the model and the real situation to correctly define geometrical elements of the traffic network. To model part of the traffic network of the city of Curitiba, a scaled map is used as a background for the simulation model and all traffic elements are built on top. Vehicle routes were based on the turning volumes obtained by URBS and inserted in the simulation model. The different bus routes in the network are identified and departure times for all buses are defined in the model. Simulation runs are done for 2 peak hours: from 6:30 am to 7:30 am and from 5:00 pm to 6:00 pm. A warm-up time of 30 minutes was used to load vehicles into the model. The different simulation interventions are evaluated based on the performance parameters travel times, average speed, average delay and average queue lengths in the network. Also, all interventions are modelled for different D/C ratios to evaluate the impact of higher demands on the performance of the network. A parametric study is conduced to compare the results of the simulation model with the real-life situation in the city of Curitiba. There are some restrictions that can influence the results of the simulation study. The restrictions are discussed in more detail in section 6.1 below.

From the simulation results we have concluded that the XBLPRI model performed the best in terms of travel times, speed and delay for all traffic in the network. The LESSBUS model resulted in the shortest queue lengths in the network for all traffic and scored second best on the other performance indicators. The LESSSTOP and MOVEDSTOP models also had a relatively high performance compared to the other simulation models. When looking only at the buses in the network, the EXTRAXBLPRI model scores best on shortest travel times for buses in the network, followed by the XBLPRI and XBL models. On speed and delay, the XBLPRI scores best, followed by EXTRAXBLPRI and XBL. It can be concluded, that the buses have a much higher performance when XBLs are introduced to the network. In that case the travel times for buses significantly drops, as well as the delays and the average speed of the buses significantly increases. Overall, the XBLPRI model performs best for all traffic in the network; the performance of the buses significantly increases while the performance of the other vehicles in the network is not too much negatively influenced. We also concluded that average speed and average queue lengths in the network are two important KPIs that are useful in evaluating the performance of the network in the city of Curitiba. Therefore, we recommend that these two KPIs should be added to the existing ones when evaluating traffic performance by the municipality of Curitiba.

When looking at the different interventions and the simulation results, it can be concluded that the LESSBUS, LESSSTOP and XBLPRI models perform the best in terms of travel times, speed, delay and queue lengths. These three interventions have been analysed for different D/C ratios. A sensitivity analysis has shown that the XBLPRI model is the most sensitive to the number of vehicles in the network. All three interventions are most sensitive for changes in D/C ratios between 0.5-0.75. A small change in D/C ratio between these values has a huge change in performance as a result. Obviously, when D/C ratios get higher, the travel times, speed, delay and queues in the network get worse as more traffic reduces the ability to freely move in the system. In the LESSBUS model, the number of buses in the model is reduced which causes less bus bunching at bus stops. This has shorter travel times and less delay in the network as a result. However, this also means that there are less buses driving the routes and buses would be more packed when picking up the same amount of people. This can be a bottleneck during peak hours when a lot of people have to get on the bus and the buses get too full. The LESSSTOP model also has shorter travel times and less delays as a result. Again, there is less waiting of buses at bus stops because they only stop at one of the two bus stops, they pass. One con of the LESSSTOP model is that not all buses stop at all bus stops, so people might have to walk further to get on the right bus. Also, waiting times at bus stops will become longer in this situation. Next to reducing congestion, the LESSBUS and LESSSTOP models can reduce costs when less buses are needed on these routes. Also, when less buses stop at the bus stops, they will arrive earlier at the terminal and during the day one bus can drive more rounds, so there would be a higher frequency of buses. The XBLPRI model has the advantage that the buses always have priority and therefore have much shorter travel times than the buses in mixed traffic. This will hopefully attract more people to use the public transportation system in the city of Curitiba, so pollution in the city centre can be reduced when less people use private vehicles.

Having concluded this, we can answer the main objective of this study:

Find the best solution to improve the bus system efficiency on the Iguaçu street and Getúlio Vargas street in the city of Curitiba in terms of congestion and travel times.

From our study we can conclude that implementing an XBL with traffic light priority is for the coming years the best option for the municipality of Curitiba. Distinction can be made between the Iguaçu and Getúlio Vargas streets as we have seen that the performance of these streets is different for different D/C ratios. On the long term, performance differences between the two streets might become smaller when vehicular volumes on the Iguaçu street are growing. When this happens, the volumes on both streets reach their capacity and other vehicles have to use the XBL to increase their performance in the network.

The XBL was found to be effective at D/C ratios higher than 0.75. Because the travel times for buses are lower than the average travel time of all vehicles in the network, which indicates the effectiveness of the XBL to save travel times for passengers at high congestions. At lower D/C ratios, the travel times for the buses are higher than the travel times of the other vehicles so there's no need to operate XBL. However, on the Iguacu street, an XBL at higher D/C ratios negatively influences the performance of other traffic in the network as there is not enough road space left for other vehicles. The LESSSTOP model seems to be a good solution to reduce congestion on the Iguacu street. This model has less congestion as a result and buses that come from different neighbourhoods can still pick up people from there and arrive faster at the terminal when they pass some stops close to the city centre. When the buses arrive when the street is fully congested already, this intervention does not have any advantage anymore. Therefore, a better solution for the future seems to be the EXTRAXBLPRI model. In this model there is enough space for the current traffic and buses can reduce their travel times because of traffic light priority.

The EXTRAXBLPRI model adds an extra XBL to the current traffic situation, and this has an enormous positive effect on the travel times of buses in the network. There is a continuous flow of buses, they don't have to wait anywhere except for at the bus stops. For normal traffic on the Iguaçu street, travel times have also decreased compared to the normal situation. On the Getúlio Vargas street, the performance of the traffic is a little less than expected. As discussed before, this has probably to do with the turning of vehicles over the XBL in combination with the traffic light signals.

When the EXTRAXBLPRI model can be optimized with a new signal control and more effective turns, this solution would probably be the best in terms of travel times.

6.3. Restrictions and limitations of the study

Several restrictions might have an effect on the results from the simulation study. The input data used in the simulation study is constructed based on several different data sets. Therefore, some insecurity about the quality of the data may exist. As mentioned in chapter X, some of the data is provided by URBS, other data is provided by IPPUC and some of the data is predicted based on field observations. The differences in origin, but also time frames make it difficult to know if the data is entirely comparable regarding travel times and number of vehicles in the network. The data set containing the traffic numbers is measured by hand, at several times and days by only a few people. Since no advanced equipment was used to measure the traffic numbers, human errors might have occurred during these measures. Traffic numbers were not available for the same days for all streets which could have led to inconsistencies between traffic numbers used as an input for the simulation model. There were also some intersections for which no turning volumes or traffic numbers were available, so these numbers had to be predicted. Also, the data used in this study is a few years old. More actual data would probably have been better to use. Nevertheless, the number were adjusted with a growth factor and the data was considered good enough to use in this study.

As with all simulation models, the simulated behaviour is not a complete representation of the real traffic network. The vehicle behaviour in the network is correct when looking at origins, destinations and routes but the way they drive is not entirely correct. From field observations it has been observed that vehicles move lanes more often, creating more traffic jams in real life than are present in the simulation model. In the simulation software, it was not possible to simulate motorbikes. Therefore, they were simulated in the model as normal bikes. This did not have a great impact on the simulation results, as all parameters were adjusted for a motorbike (e.g. speed, breaking and speeding), but it could have had a small effect. Also, most of the motorbikes try to pass other vehicles in traffic jams or they stop between cars when waiting for the stopping lights. In the simulation model this is not simulated and all motorbikes wait behind other vehicles. Since pedestrians are not simulated, the vehicles in the model never wait for pedestrians at intersections. Of course, our simulation model only simulates a small section of the entire traffic network in the city of Curitiba. Simulating more roads would have made the simulation model to big and complicated. However, other roads and traffic situation can have an influence on the vehicle behaviour in the simulated part of the network. This makes that some behaviour might not totally represent the traffic behaviour in the real situation.

6.4. Recommendations and future research

Based on the outcomes of the present study, the following recommendations can be made:

- The application of an XBL can be based on time. In other words, the XBL can be used by other vehicles during off-peak hours. This will help in reducing the negative impacts of XBLs at low volumes. Traffic light control should be adapted for this; only priority for buses on the XBL and not for regular traffic.

- The implementation for the XBL should avoid lanes in which the buses will turn left. This can be applied by allowing the buses that are turning left to use the other lanes instead of using the XBL. The longer travel times and delays for buses will most likely be reduced with this as buses can easier turn left, they don't have to wait for other vehicles anymore and take a huge turn from the rightest lane to one of the left lanes. This will also positively influence the weird driving behaviours of other vehicles in het network as they won't have to overtake or wait for the bus.

Based on the results of our study, we also have some recommendations for future research:

- Combination of transit signal priority for buses on (shared) XBLs, in combination with detectors at all intersections, to study the impact of prioritized XBLs on traffic network performance.

- Implementing a dynamic traffic assignment instead of a static traffic assignment for vehicle routing in the simulation model.

- Investigating the effect of the location of bus stops on the performance of the network, especially at intersections when buses take a turn.

- Optimizing the traffic light signals for different D/C ratios while considering the volume of all streets at an intersection.

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Appendix A: Bus routes and classifications

Table 35: Bus routes and classifications

Route	Description	Bus
Expresso Ligeirão (Super Express)	Operates blue biarticulated buses that drive on exclusive bus lanes, where no other vehicles are permitted. These buses stop exclusively at integration terminals and tube stations.	
Expresso (Express)	Operates red biarticulated and articulated buses that drive on exclusive bus lanes. The difference with the super express buses is that there are more stops included on the route.	
Linha Direta (Direct Lines)	Operates with silver, two-axle and articulated buses. The bus routes have stops at tube stations on average every three km. The direct lines are complementary lines, mainly for the express lines and inter-neighbourhood lines which only stops at a few tube stations.	
Interbairros (Inter-Neighbourhood)	Operates green articulated and two-axle buses that drive on roads outside the city centre to connect neighbouring districts with each other and with integration terminals.	
Alimentador (Feeder)	Operates orange mini, two-axle and articulated buses that link terminals and neighbourhoods. These bus routes aim to feed the super express and express buses.	
Troncal (Trunk)	Operates yellow mini, two-axle and articulated buses that connect the terminals to the city centre.	
Convencional (Regular)	Operates yellow mini and two-axle buses that connect surrounding neighbourhoods to the city centre without connections to integration terminals.	

Circular Centro (Downtown Circular)	Operates white mini city buses that circle around the downtown area to carry passengers quickly around the city centre.	
Linha Turismo (Tourism Route)	Operates green tourist double-decker buses that drive only on one route along the main city attractions.	

Appendix B: Factor analysis for location of possible new bus terminal

Our study tries to find a good zone for the location of a new bus terminal from a set of candidate locations. As indicated in the work of Farkas (2009), site selection typically involves two steps: 1) site screening and 2) site evaluation. In the first step, possible candidate locations are 'screened', which means just choosing a few locations where it is feasible to build the new terminal. During the second step these candidate locations are evaluated.

For the municipality of Curitiba customer satisfaction is very important as they want to increase usage of the bus system in the city centre. If it's not convenient or easy to walk to a BRT station, then customers will be discouraged from using the system. Mapping the quality of pedestrian facilities around the BRT station is a basic first step to identify barriers and difficulties faced by the customer. The different factors are defined respective to the preferences for the city of Curitiba. By considering the condition and preferences of the city of Curitiba in which the problem is investigated, the most important factors that we have selected in order to locate the bus terminals locations are:

- Accessible to public buildings
- Accessible to health facilities
- Accessible to schools
- Close to existing user demand
- Close to existing bus stops
- Close to existing bus routes
- Close to other bus lines
- Minimize disruption and avoid topographic challenges

We categorized these factors in five different categories: 1) Proximity to other facilities, 2) Proximity to users, 3) Reduction of traffic impact, 4) Access to public transportation services and the 5) Environmental impact (see table 36).

Table 36: Categories and factors

Category	Weight	Factor	Weight	Ranges five-point scale
Proximity to other facilities	10	1 Accessible to public buildings	8	1 = 0 buildings within 250m 3 = 1 buildings within 250m 5 = 2-3 buildings within 250m
		2 Accessible to health facilities	8	1 = 0 buildings within 250m 5 = 1 buildings within 250m
		3 Accessible to schools	10	1 = 0 buildings within 250m 3 = 1 buildings within 250m 5 = 2 buildings within 250m
Proximity to users	10	4 Close to existing user demand	10	1 = 0-500m 2 = 500-1000m 3 = 1000-1500m 4 = 1500-2000m 5 = 2000-2500m
		5 Close to existing bus stops	8	1 = <4 stops within 250m 3 = 4-6 stops within 250m 5 = >6 stops within 250m
Reduce traffic Impact	25	6 Close to existing bus lines of study area	25	1 = >2 lines within 250m 3 = 1-2 lines within 250m 5 = 0 lines within 250m
Access to public transportation services	20	7 Close to other bus lines	20	1 = 0-5 lines within 250m 2 = 5-10 lines within 250m 3 = 10-15 lines within 250m 4 = 15-20 lines within 250m 5 = 20-25 lines within 250m
Environmental impact	25	8 Minimize disruption and avoid topographic challenges	25	1 = topographic challenges 2 = disruption of green and parking spots 3 = disruption of green 4 = small free space available

				5 = free space is available (including growth)

All five categories and eight factors are given a weight. Weights are obtained by discussing on what the most important categories and factors are for placing a terminal in the city of Curitiba. Evaluating candidate locations is done based on a five points scale. For each factor, the ranges for the five-point scale are set. The ranges of the five-point scale can be seen in table 3. The rating indicates how well the candidate location satisfies the particular factor. The five-points scale used is as follows: 5 = excellent; 4 = good; 3 = satisfactory; 2 = below average; 1 = poor. Next, all candidate locations are analysed and given points based on the five-point scale. Most of the candidate locations are analysed on the facilities within 250m around the area. Research (Federal Highway Administration, 2013) has found that people are willing to walk up to 400m to a bus stop when the bus stop is in a safe area. People prefer to walk more over walking through an unsafe area and take unnecessary risks. However, we chose to use a distance of 250m in a safe area for our analysis.

By considering the points and the weights of each criterion and factor, relative importance of each candidate location is specified. Next, the different candidate locations are given a score based on all different factors. The candidate locations with the best total score is considered as the best location to build the new terminal. *For example: Location A scores 1, 2, 3, 4, 5, 4, 3 and 2 points respectively on factors 1 until 8. The calculation of the total score on the different factors would then be the score times the weight of the factor times the weight of the category divided by the weights of all categories: ((1x8 + 2x8 + 3x10) x 10 + (4x10 + 5x8) x10 + (4x25) x 25 + (3x20) x 20 + (2x25) x 25)/(25+20+25+10+10) = 69,89.*

For our study, a database management program was used to visualize the possible terminal candidate locations. PostGresSQL is an open and free object-relational database management program based on Structured Query Language (SQL). PostGIS is an extension to PostgresSQL that enables geographical objects. PostGIS allows integration of SQL queries to directly include conditions linked to the geographical positions of objects. To work with georeferenced database management programs, Geographic Information Systems (GIS) can be of great value. In this work, QGIS (from https://qgis.org) was used. Through the connection of this program to the PostgreSQL or PostGIS database, it is possible to create fast and easily composed visualization of several layers as the location of bus stops and the routes of bus lines on the city map. The QGIS visualization tool was used with the objective to apply a geofencing around the proposed grid and to use the available datasets to locate the grid point that was closed to these facilities.

Because the municipality of Curitiba didn't screen any possible locations for the terminal yet, this study placed a grid in QGIS on the beginning of the congested area (where all bus lines merge together) to find possible terminal locations. All grid points were considered as possible terminal locations (see figure 49).

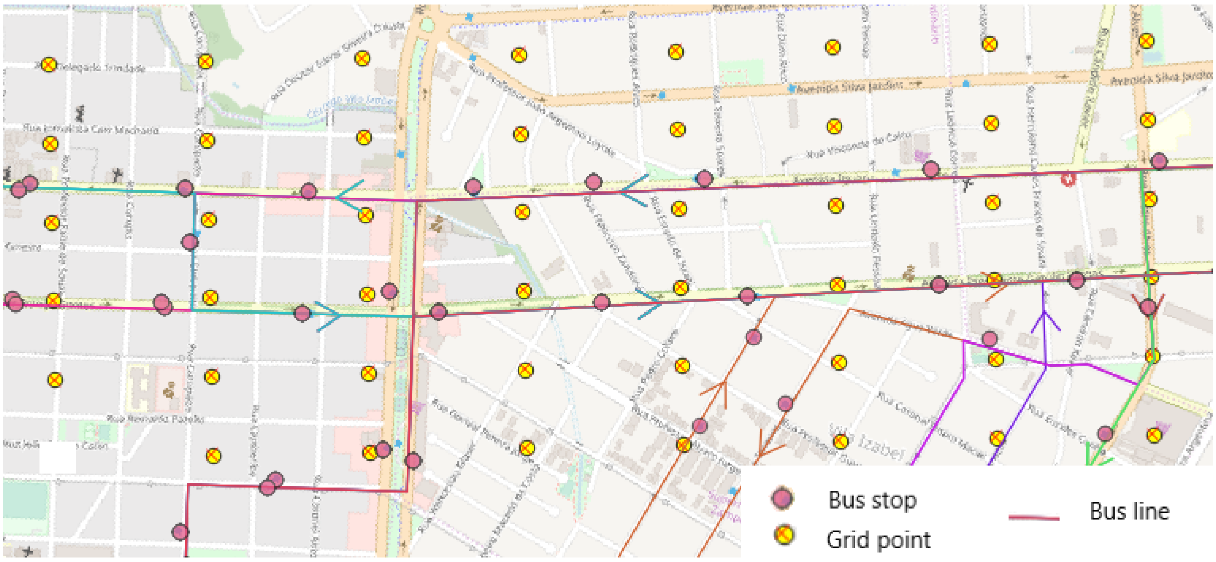


Figure 49: Grid points for possible terminal locations

Next, the grid points were evaluated on space. If there was a free area available around the grid point, the point was considered as a possible terminal location. If there was no free area available around the grid point, the point was removed and not considered as an option. Evaluating all grid points on space, this gave us 17 possible locations for the terminal (figure 50). These 17 locations are evaluated on the factors of the different categories, as can be seen in table 37.

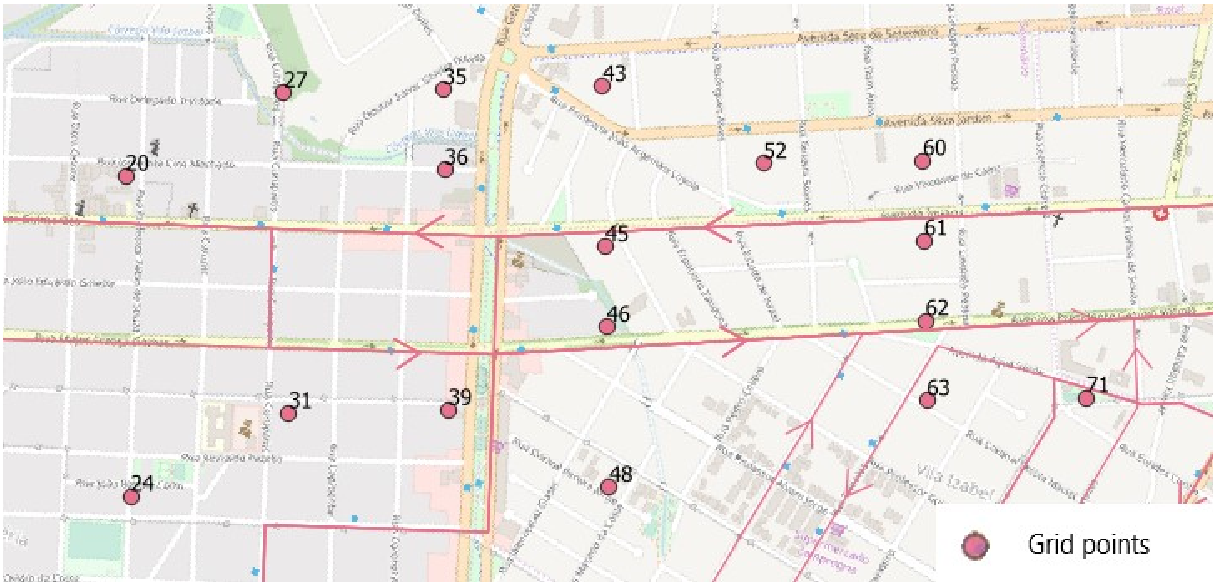


Figure 50: Final grid points that are considered as possible new terminal locations

The integration of the intermediary input GIS layers produced intermediary results, such as the relation of bus lines, bus stops and facilities to the different grid points. A distance of 250m around grid points is considered as the coverage area to evaluate proximity to health facilities, schools, users, bus stops, bus routes and bus lines. This coverage is defined in the GIS map to determine ranges and points for the five-point scale as defined in table 3.

Results of factor analysis for evaluating possible bus-terminal locations

The results of the scoring of possible terminal locations can be found in table 37. All grid points are evaluated on the different factors that are described in the section above. The scores, based on the five-point scale, are given in table 37.

For selecting candidate locations for the terminals, the factors with the highest weights should be selected as major priorities. The final score point of each terminal location was calculated as the sum of the points for each factor. Only the 5 best locations for a possible terminal are considered as options for the municipality of Curitiba. Total scores for candidate locations can be found in table 38.

Table 37: Factor analysis possible terminal locations

Option	**Terminal candidate location (grid point number)**	**Accessible to public buildings**	**Accessible to health facilities**	**Accessible to schools**	**Close to existing user demand**	**Close to existing bus stops**	**Close to existing bus routes**	**Close to other bus lines**	**Minimize disruption and avoid topographic challenges**
1	**20**	1	1	3	2	3	3	1	5
2	**24**	5	1	5	2	2	1	1	5
3	**27**	3	1	5	1	2	3	2	3
4	**31**	3	1	5	2	4	3	2	2
5	**35**	1	1	1	1	1	3	3	2
6	**36**	3	1	1	1	2	1	3	2
7	**39**	5	1	1	4	4	3	3	3
8	**43**	1	1	3	1	2	3	4	5
9	**45**	3	5	3	3	3	5	3	5
10	**46**	5	5	1	3	3	5	3	5
11	**48**	5	1	3	2	2	1	3	1
12	**52**	1	1	3	2	2	3	3	1
13	**60**	3	5	1	3	2	3	3	2
14	**61**	3	5	1	5	3	5	2	5
15	**62**	5	5	1	4	3	5	3	3
16	**63**	3	1	1	3	4	3	3	2
17	**71**	3	1	1	3	4	3	5	3

Table 38: Total scores of the factor analysis

Terminal candidate location	**Total Score**	**Ranking**
20	310	8
24	304	10
27	298	12
31	299	11
35	229	15
36	203	17
39	340	7
43	352	6
45	**458**	**1**
46	**454**	**2**
48	224	16
52	242	14
60	305	9
61	**438**	**3**
62	**414**	**4**
63	289	13
71	**354**	**5**

Grid location 45, 46, 61, 62 and 71 belong to the top five candidate locations with the maximum points. Therefore, these grid points are the most suitable locations for building a new terminal (for locations see figure 50).

Appendix C: Current situation for different D/C ratios

The results of the D/C simulations of the morning peak hour are shown in figure 51 for all traffic and for the buses. These figures illustrate the different D/C ratios and the related average travel times of all traffic and buses (separately) on the Getúlio Vargas and Iguaçu streets.

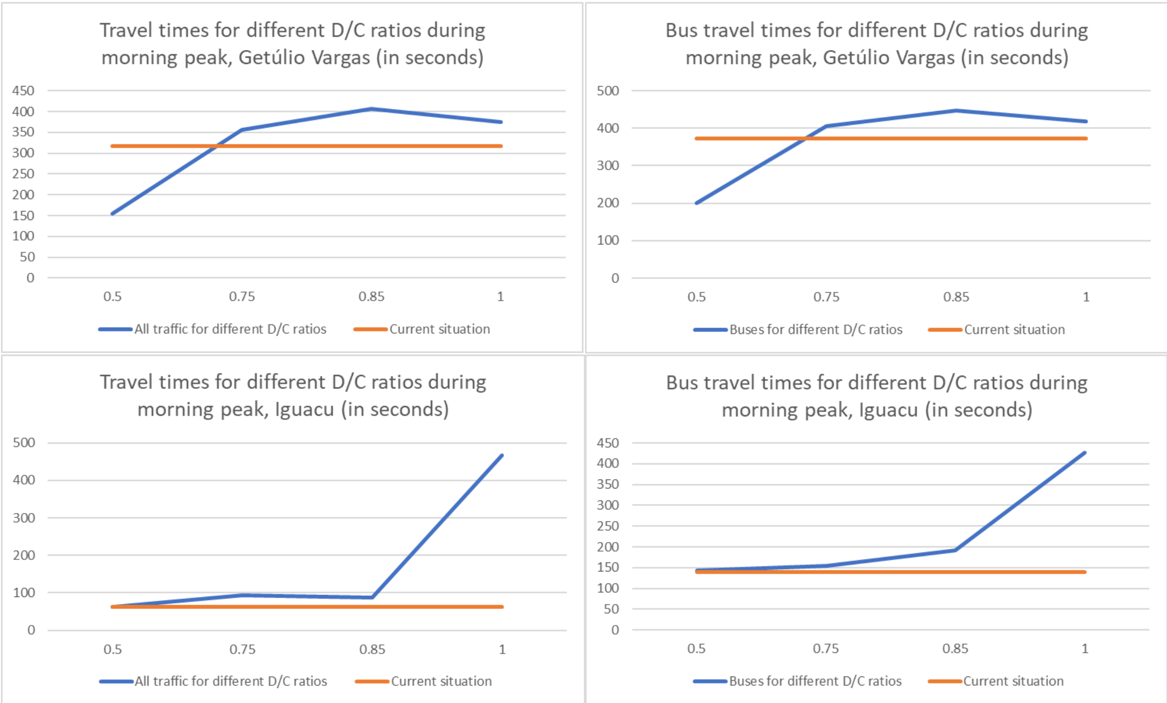
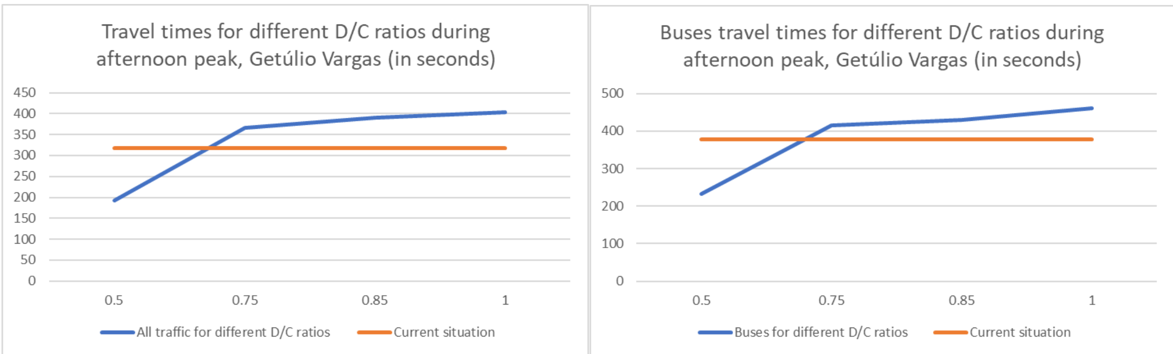


Figure 51: Travel times (vertical axis) for different D/C ratios (horizontal axis), for the current situation during the morning peak hour

For the afternoon peak hour, the results look similar. The only difference between the morning and afternoon peaks is that the current travel times for the afternoon peak are higher (see figure 52).



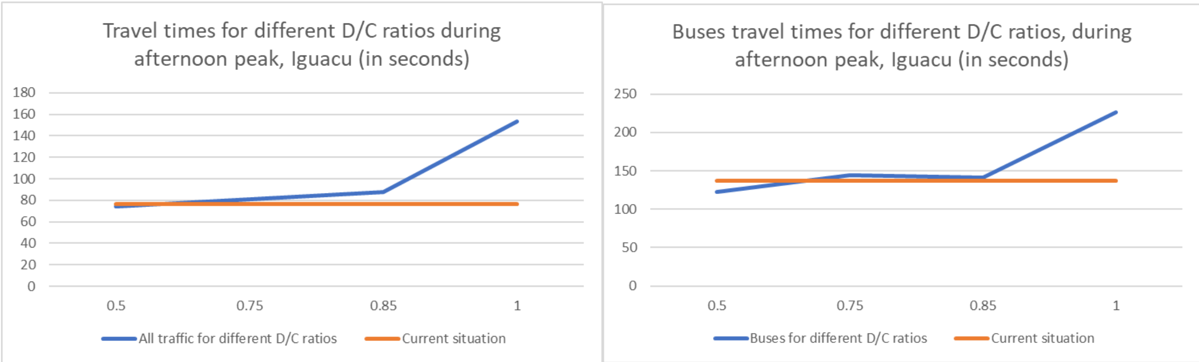


Figure 52: Travel times (vertical axis) for different D/C ratios (horizontal axis), for the current situation during the afternoon peak hour

The average speed in the network for different D/C ratios is given in figure 53.

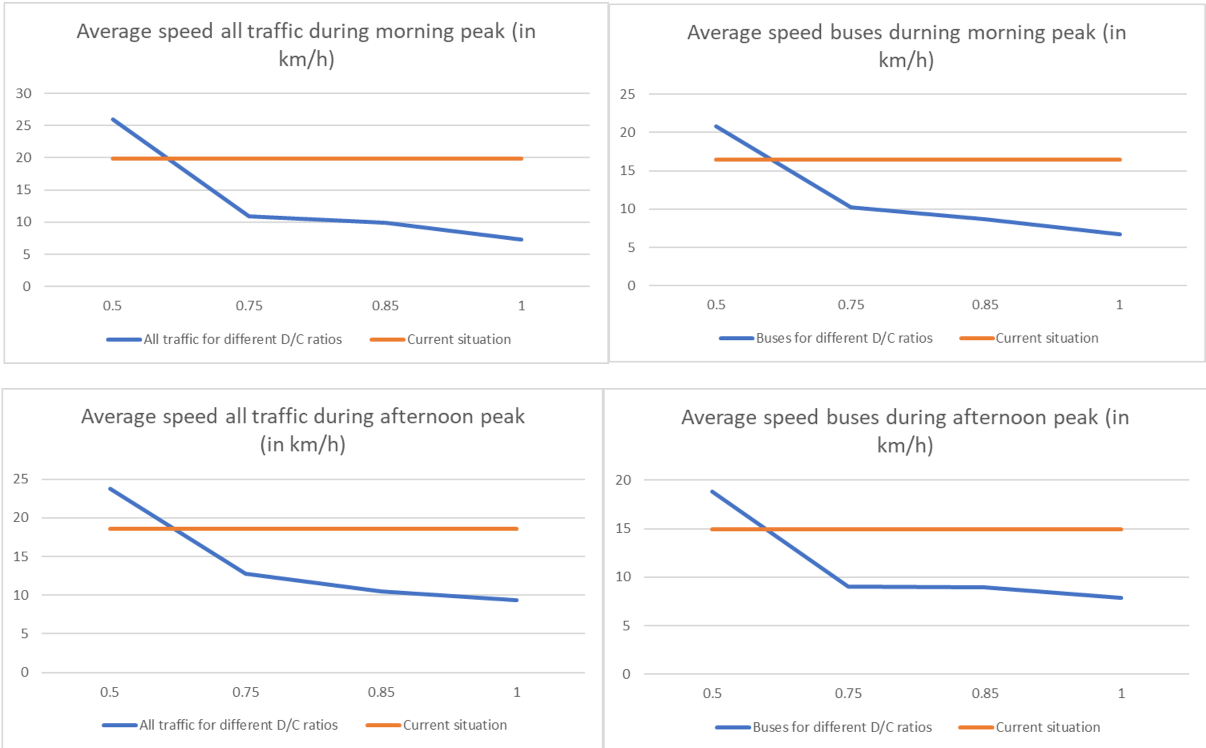


Figure 53: Average speed (vertical axis) during the morning peak and afternoon peak for different D/C ratios (horizontal axis)

The average delay in the current situation network for different D/C ratios is given in figure 54.

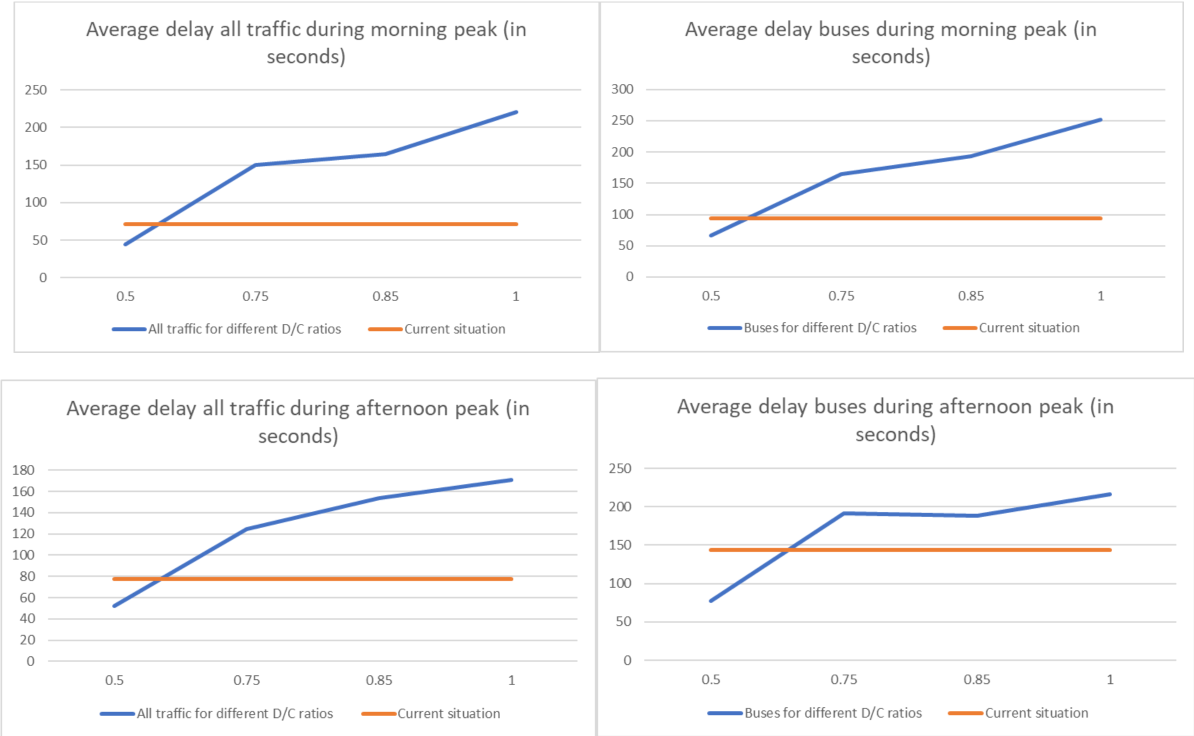


Figure 54: Average delay (vertical axis) of buses during the afternoon peak hour for different D/C ratios (horizontal axis)

Appendix D: Comparing the different interventions for the current situation

Here, we have summarized the results of all models for the current situation. The interventions are compared with the normal situation for all performance indicators. Results are presented in graphs for travel times, delay, speed and queue lengths for both the morning and afternoon peak hours.

LESSBUS

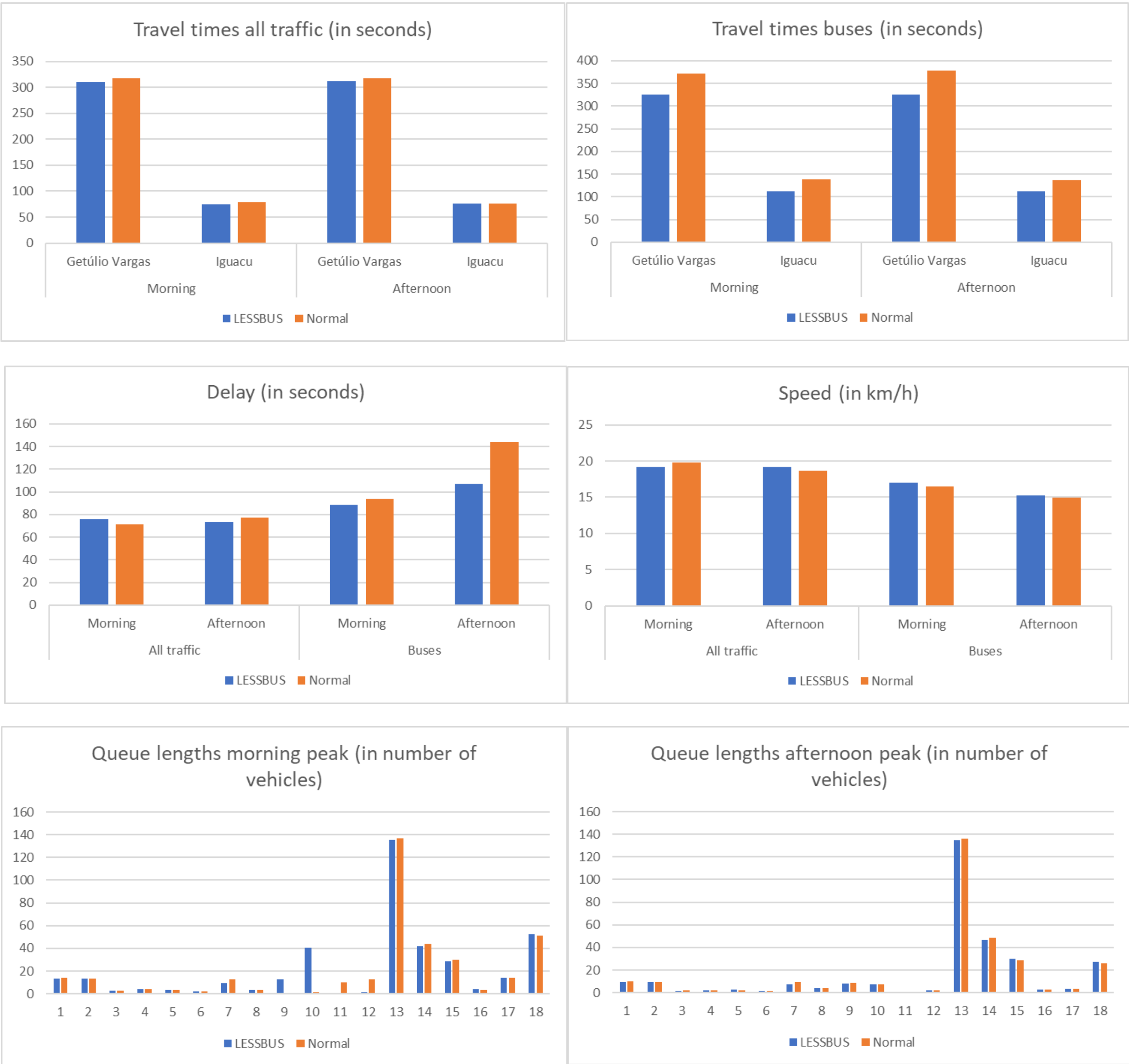


Figure 55: Queue lengths during the morning peak hour, LESSBUS intervention

LESSSTOP

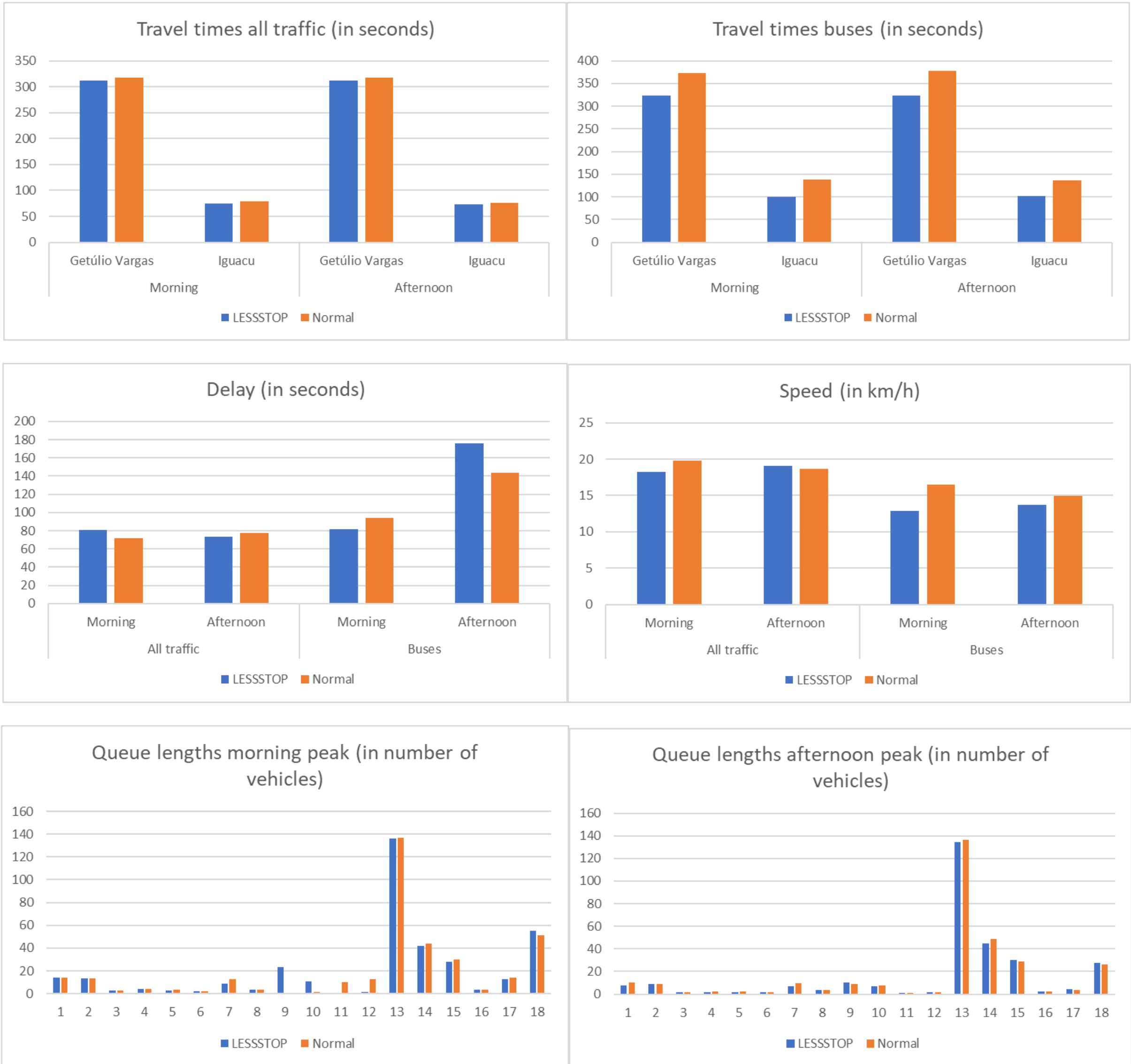


Figure 56: Queue lengths during the afternoon peak hour, LESSSTOP intervention

MOVED STOP

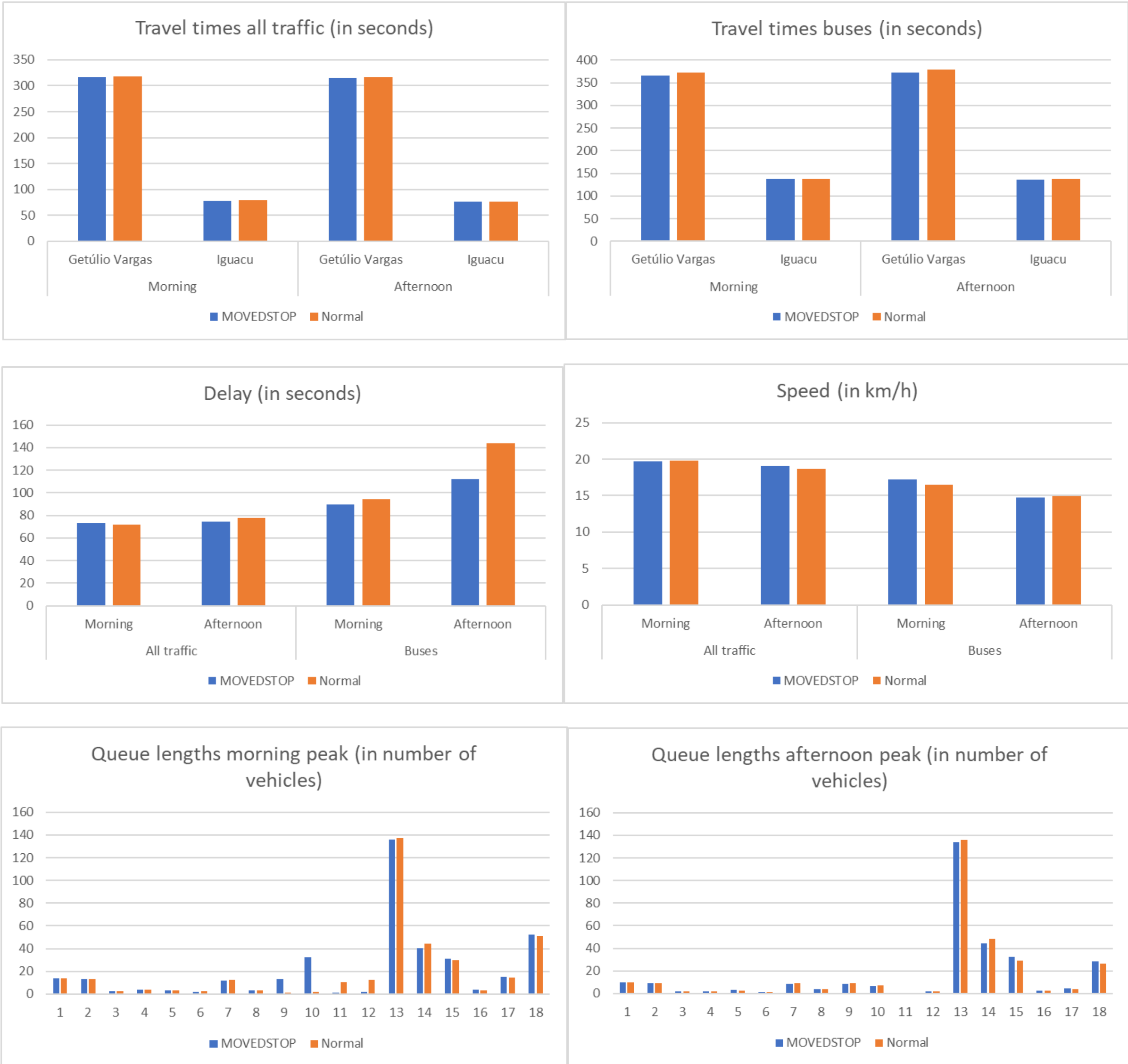


Figure 57: Queue lengths during the afternoon peak hour, MOVEDSTOP intervention

XBL

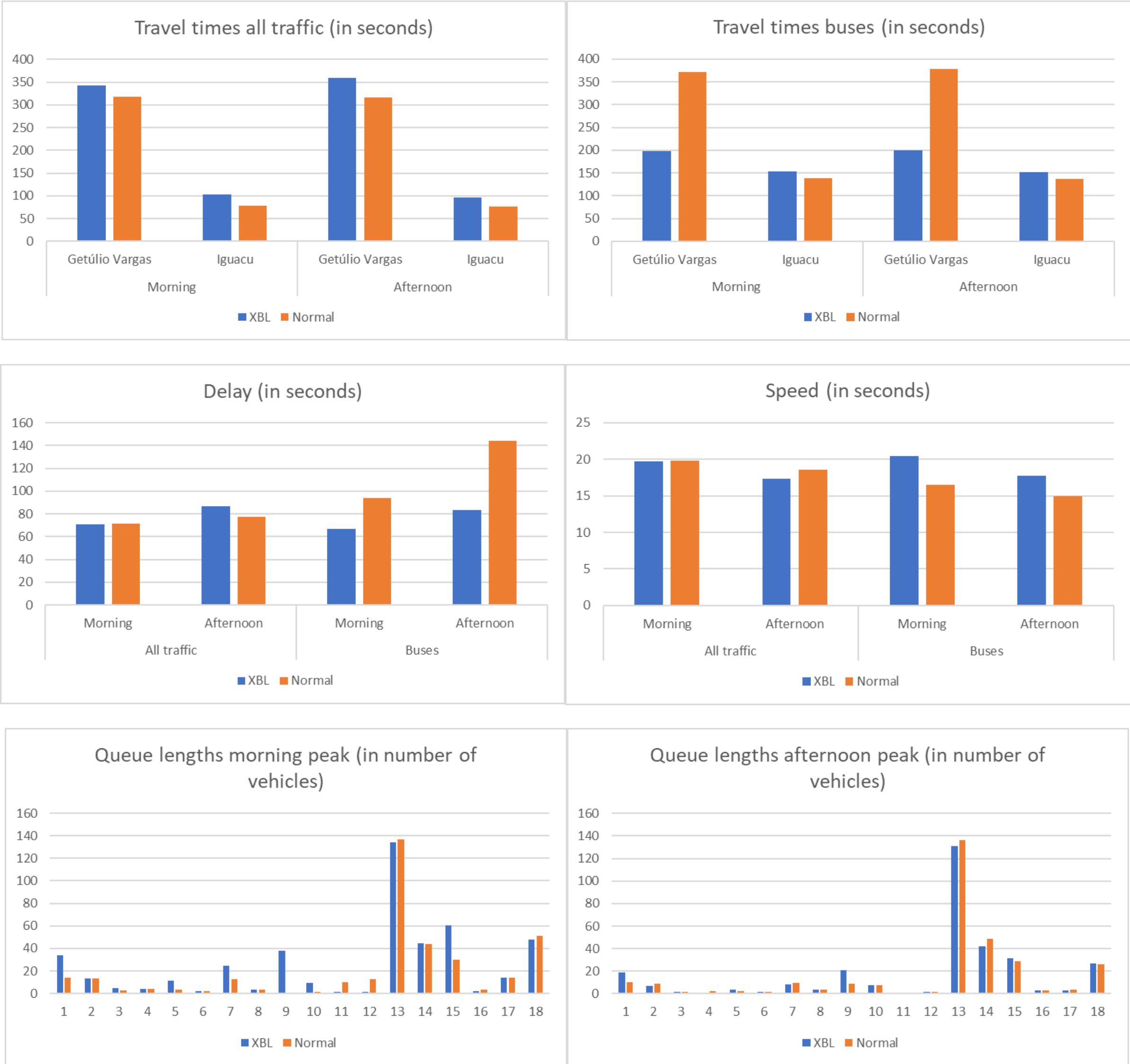


Figure 58: Queue lengths during the afternoon peak hour, XBL intervention

XBLPRI

Figure 59: Queue lengths during the afternoon peak hour, XBLPRI intervention

EXTRAXBL

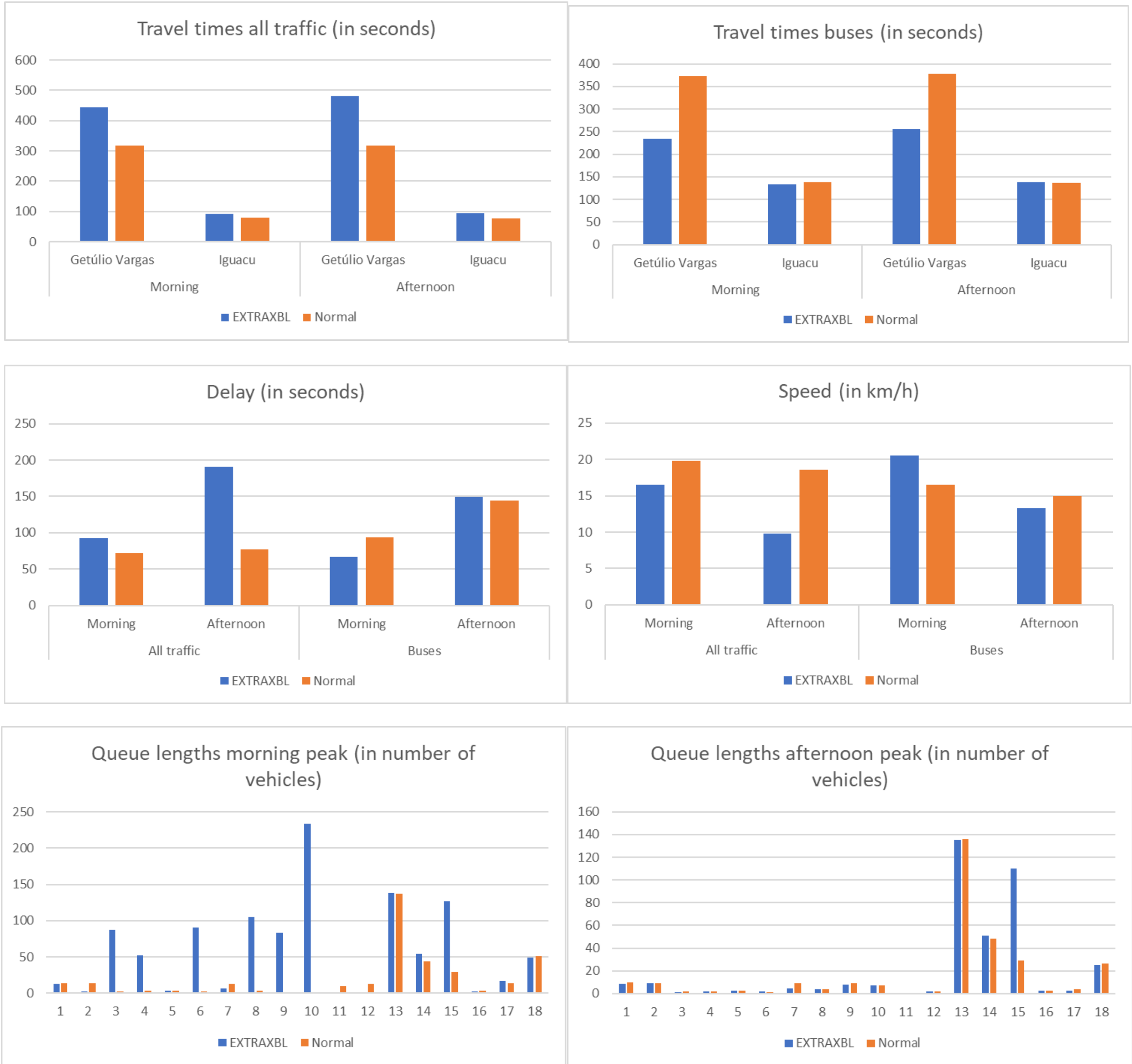


Figure 60: Queue lengths afternoon peak hour EXTRAXBL intervention

EXTRAXBLPRI

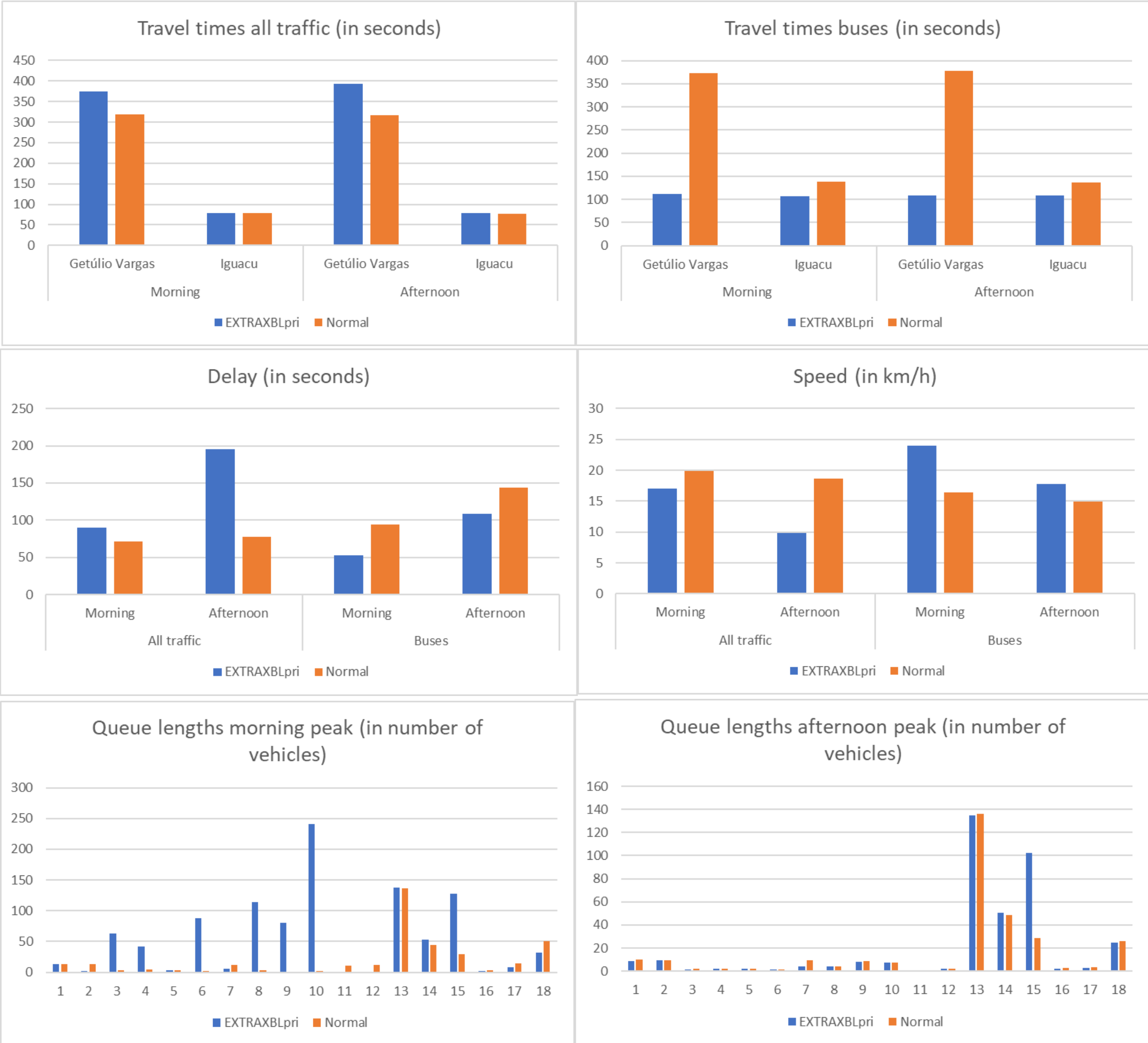


Figure 61: Queue lengths during the afternoon peak hour, EXTRAXBLPRI intervention

Appendix E: Results afternoon peak hour for XBLPRI, LESSBUS and LESSSTOP

The results of the afternoon peak hours for all performance indicators and for different D/C ratios are presented here for three interventions: XBLPRI, LESSBUS and LESSSTOP.

XBLPRI

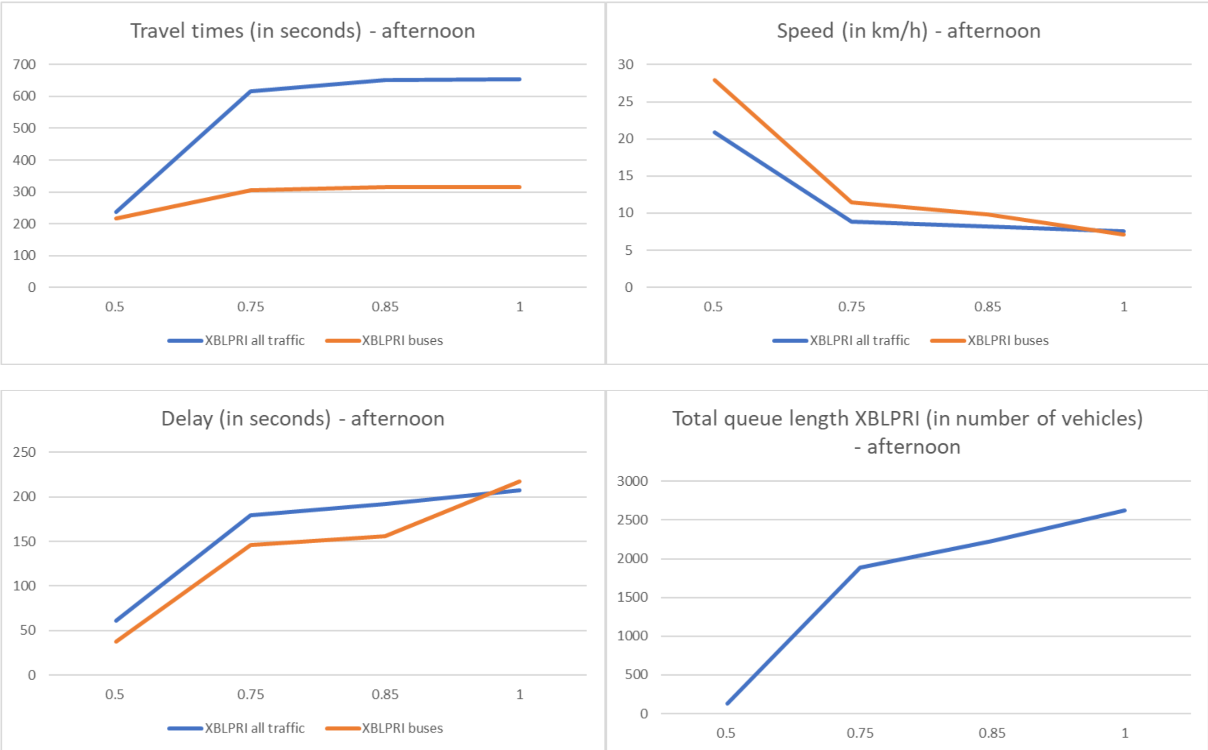


Figure 62: Performance XBLPRI (afternoon) for different D/C ratios

LESSBUS

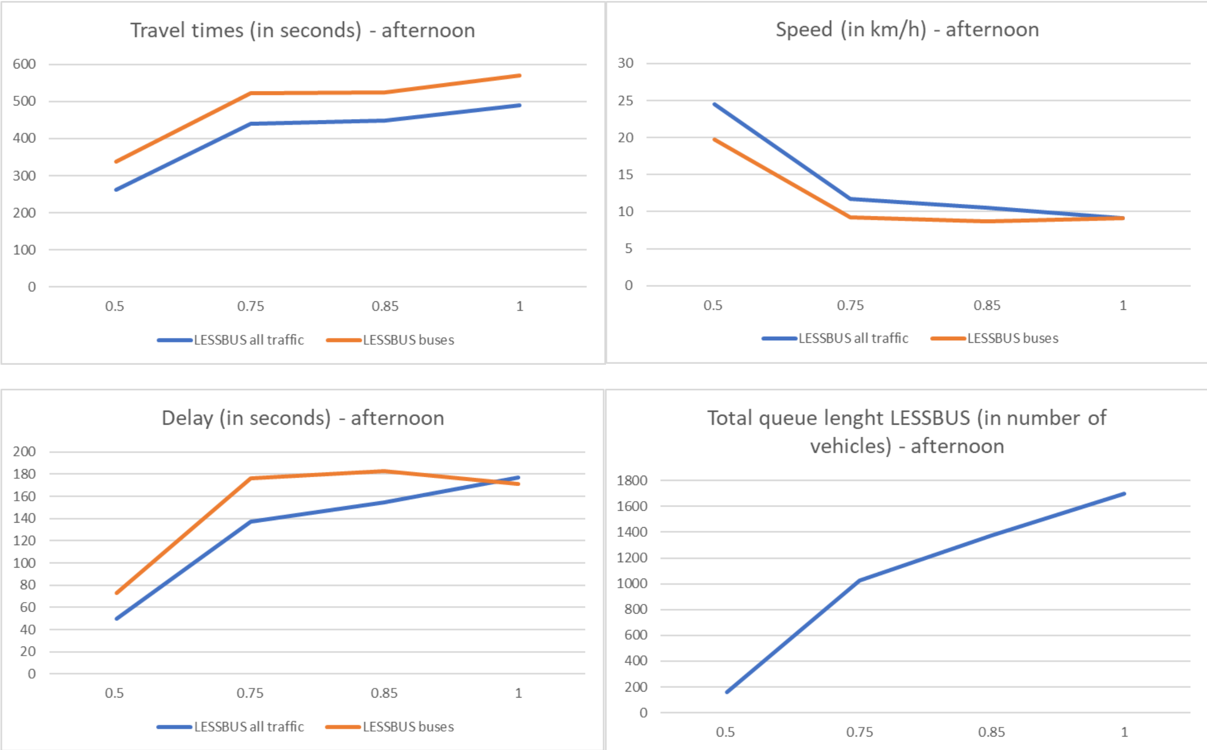


Figure 63: Performance LESSBUS (afternoon) for different D/C ratios (horizontal axis)

LESSSTOP

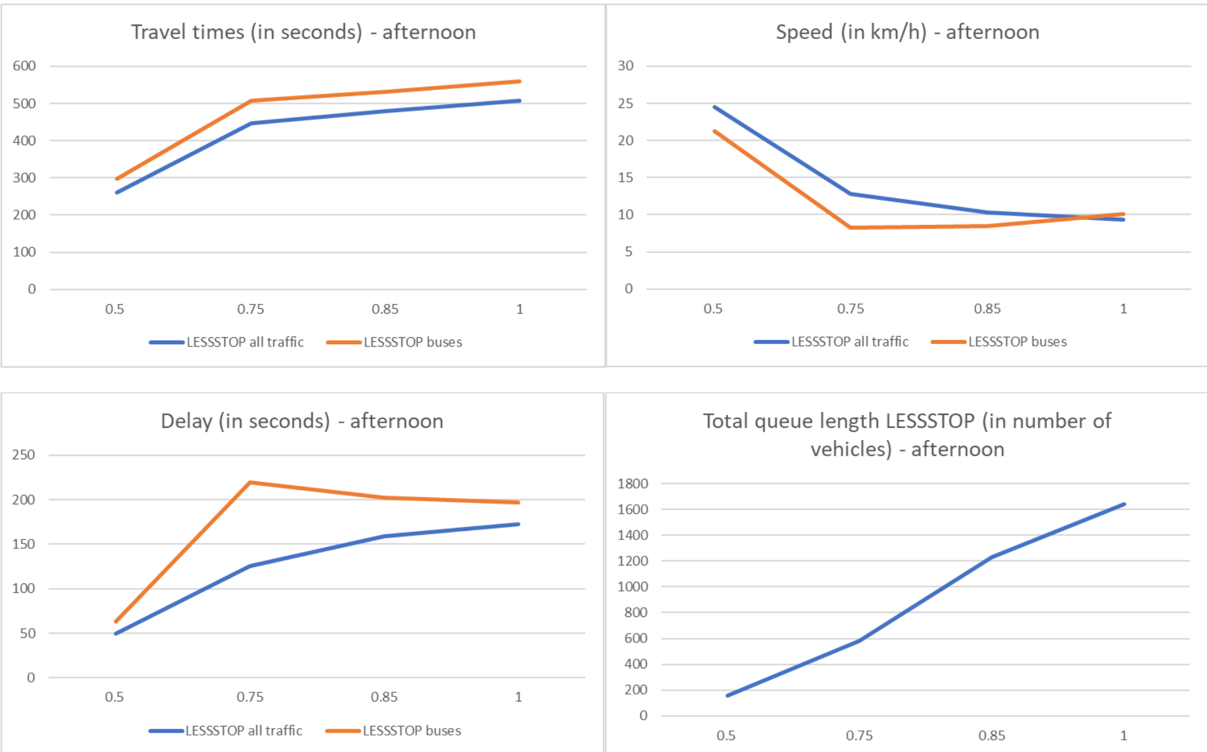


Figure 64: Performance LESSSTOP (afternoon) for different D/C ratios (horizontal axis)