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Bus Rapid Transit, Safety, and Roundabouts

Evaluation of design solutions for roundabouts with Bus Rapid Transit based on safety and level of service of all modes

TU Delft

MANNVIT

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By

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in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering – Transport and Planning
at the Delft University of Technology,
to be defended publicly on Wednesday August 31, 2022.

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Preface

This thesis marks the end of my studies at TU Delft, where for the past two years I have been following the master programme of Transport and Planning. These past years have been very educational, challenging, and enjoyable.

Since 2016, I have been interested in the Borgarlinan project and followed that project as well as learning more about BRT systems and other public transport systems. I have also found roundabouts very cool for years and being able to combine these two interests into a thesis topic is fantastic. This was a long and challenging process but enjoy is the feeling that is the strongest overall regarding this thesis.

This project would not have been possible and this enjoyable if not for all the people around me.

First, I would like to thank everyone at Mannvit for being welcoming, and open from the beginning about helping me with my thesis and brainstorming with me about potential topics. I especially want to thank my company supervisor, Albert. Thank you for all your help, supervision, and guidance throughout this whole process.

I also want to thank my graduation committee at TU Delft, Niels van Oort, Haneen Farah, and Rob van Nes. Thank you all for your support, supervision, guidance, time, and valuable feedback.

I want to give special thanks to my family. Thank you for always supporting me in everything I do and always wanting to listen to all my explanations of what I was doing at the moment and about my progress.

Thank you to all my friends. My friends in the Netherlands, Florida, and Iceland, and my friends from the thesis room at the TU. Thank you for all the enjoyable moments both outside and during my study hours. Thank you for keeping me motivated and encouraging me to keep going and working well, while also spending time with me outside of school.

I am very proud of this work, and I look forward to the next chapter in my life.

Guðrún Birta Hafsteinsdóttir
Delft, August 2022

Summary

Introduction

Bus Rapid Transit (BRT) is a high-quality bus service concept that has designated lanes, priority on intersections, off-board fare collection and fast and frequent service which leads to that BRT provides a fast, reliable, accessible, and comfortable service that is comparable to light rail and metro services. The popularity of BRT has been growing rapidly worldwide over the past 20 years, where more and more cities and countries add BRT to their public transport system.

Roundabouts are also often seen in many cities and have become a popular option for an intersection design. Roundabouts are considered to be one of the safest types of intersections when it comes to car traffic while also improving the traffic flow of the intersection. Furthermore, roundabouts have much fewer conflict points and less severe crashes than conventional X-intersections, and the speed of cars is lower.

It is likely that in some cities a BRT route will go through a roundabout, because of the popularity and number of roundabouts already built in many cities. To keep the priority of BRT and keep the safety effects of a roundabout, the evaluation of roundabouts with BRT based on safety and level of service (performance) of all modes is investigated.

Some countries have already developed and built solutions for roundabouts with BRT, where the solutions can range from the buses driving in mixed traffic, to be given a full priority and can pass through the intersection on an exclusive bus lane that goes through the centre island of the roundabout. These types of solutions are often called throughabouts. However, few guidelines have been developed about what types of solutions work for roundabouts with BRT. Additionally, there seems to be a disagreement between different countries on the effectiveness and the safety of roundabouts with BRT. Where some countries have a negative experience and see more accidents at roundabouts with BRT, but other countries have a positive experience with these roundabouts as well as they see an increase in the safety and performance of throughabouts.

This thesis aims to reduce this research gap and develop a methodology that evaluates different design solutions of roundabouts with BRT based on the safety and level of service of all modes. This leads to the main research question:

> *How can roundabouts with different priority configurations for Bus Rapid Transit be evaluated and compared based on safety and performance of all modes and which alternative proves to be the most optimal?*

Methods

The methods used to answer the main and sub research questions are firstly literature review, where different solutions, evaluation studies, and guidelines of roundabouts with BRT are investigated from different countries. Secondly, an evaluation method is chosen to evaluate and compare the different design solutions. To evaluate the design solutions based on safety, traffic performance, and costs, a multicriteria analysis (MCA) is chosen as an evaluation method.

Thirdly, a microsimulation in VISSIM is used to model the intersection and the different designs considered. Output such as total intersection throughput, travel time, and variation in travel time can be collected directly from the VISSIM model which are then used as criteria in the MCA. To evaluate the safety, the Surrogate Safety Assessment Model (SSAM) by the Federal Highway Administration (FHWA) is used. SSAM can calculate the number of conflicts and identify the types of conflicts by using the trajectory files from the VISSIM output, and thresholds of TTC and PET that are defined. Where TTC is Time-to-Collision, which is the time until two vehicles will collide if they continue their current trajectory and speed, and PET is Post Encroachment Time, which is the time between when the first vehicle leaves a conflict area until the second vehicle enters that area. The TTC and PET thresholds that are used for

the calculations are 1.5s and 5s, respectively, for conflicts between vehicles, and 2.7s and 8s, respectively, for conflicts between active mode users and vehicles.

These methods help with developing the evaluation methodology. This methodology is tested and illustrated by using a case study. The case study also helps with comparing and evaluating different designs and shows which design solution proves to be the most optimal.

The evaluation methodology consists of choosing alternative design solutions, evaluation criteria and method, and modelling the design solutions in VISSIM. Each design is run for 10 simulation runs in VISSIM to get the average and standard deviation of the traffic performance parameters collected. The performance parameters are total throughput, travel time, and variation in travel time. This is done because of stochasticity in the model which varies the exact volume of vehicles in the model each run, resulting in a more realistic output. In addition to the traffic performance parameters, the trajectory of each vehicle is recorded. These trajectories are used as an input into SSAM, where the number and types of conflict are calculated. To evaluate and compare the design solutions, MCA is used. The VISSIM and SSAM output is used as an input for the MCA evaluation. Multiple stakeholders are considered in the MCA to investigate if the most optimal solution or if the ranking of the design solutions changes depending on different views and goals. Therefore, weight sets are made based on the views of each stakeholder. The stakeholders considered for the case study are the municipality or Reykjavík, the road authority Icelandic Road and Coastal Administration (IRCA), and the public transport authority Strætó bs. The municipality's main focus is on the safety of active mode users and also the access to public transport and active modes. The IRCA's main focus is on the safety and making sure that all modes are easily accessible. The main goals of Strætó bs. is to improve the bus services and make public transport the number one mode for commuting. This leads to the results of the MCA, where the designs can be compared and are evaluated based on the chosen criteria, which are throughput, travel time, variation in travel time, number of conflicts per type of vehicle – vehicle conflicts, number of conflicts for active mode user – vehicle conflicts, and costs.

Main findings

A case study of a roundabout called Melatorg in Reykjavík, Iceland, is used to test and illustrate the evaluation methodology that is developed in this thesis. This roundabout is a two-lane roundabout that is located close to the University of Iceland, the National and University Library, and the National Museum in the centre of Reykjavík. Figure 1 shows a map of the roundabout and its surroundings. A BRT route with an exclusive lane is planned to go through the intersection on the road that lies on the NE - SW axis, called Sudurgata. Four lines are planned to use this route through the roundabout, where three of them are BRT lines, and one a regular bus line. This means that there are exclusive lanes for these buses on Sudurgata. During the peak hours of the day, the frequency of these lines is the same for all lines, 8 buses per hour per line per direction, leading to that there are 64 buses driving through the roundabout along Sudurgata per hour. The crossing road of Sudurgata, lying on the SE – NW axis, is one of the main roads in Reykjavík called Hringbraut.

Figure 1 Map of Melatorg

Based on the literature review, three design solutions are chosen to be used as design alternatives that will be compared and evaluated in the research. Design solution 1 give the least priority to the BRT of the designs. Figure 2 shows this design solution. It is a conventional roundabout where the buses that are on the exclusive lane merge with mixed traffic before the intersection and drive through the roundabout in mixed traffic, and then can enter its exclusive lane again after the intersection. This design is chosen as a design solution alternative because it is close to the current roundabout design of Melatorg, and it shows an alternative that does not give the buses priority through the intersection.

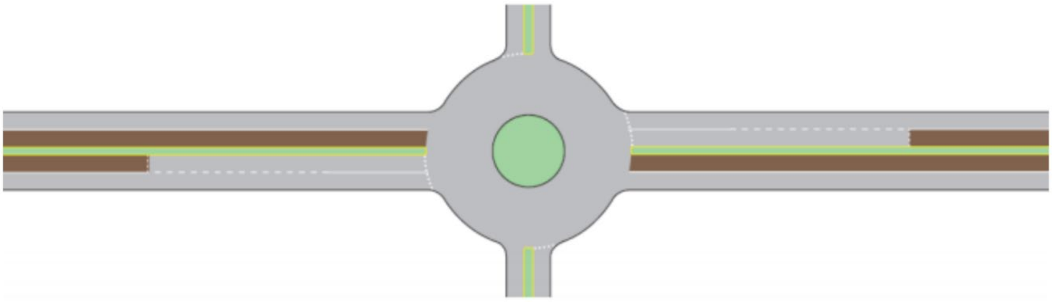


Figure 2 Roundabout solution for mixed traffic conditions

Design solutions 2 and 3 are both throughabout designs where the configuration of the signals for the yielding traffic is different between the designs and can be seen in Figure 3. The throughabout solutions are chosen because the literature review showed that they are beneficial, and they are used in multiple countries already. Design solution 2 is a throughabout with traffic signals for entering traffic, as shown in Figure 3 (left). Design solution 2 is chosen because it gives full priority to the buses and it is fully regulated, similar to a signalized X-intersection. Design solution 3 is also a throughabout but the traffic signals are located inside the circulatory road of the roundabout and only stops the flow of vehicles that are in conflict with the buses and is shown in Figure 3 (right). Design 3 is chosen because it gives full priority to the buses, while also only stopping the conflicting flows, possibly leading to a better overall flow through the intersection. This design solution is a version between the first two solutions.

Figure 3 Throughabout with traffic signals for entering traffic (left) and throughabout with traffic signals for conflicting traffic (right)

These designs are modelled in VISSIM where the vehicle trajectories are used for safety calculations in SSAM and the output of throughput, travel time, and variation in travel time is used as input in the MCA evaluation.

The results of the MCA show that design solution 3: Traffic signals for conflicting traffic scores the highest for all stakeholders. Design solution 2: Traffic signals for entering traffic scores the next highest, and design solution 1: Mixed traffic conditions scores the lowest, as seen in Table 1. The table also shows that design solution 3 scores highest in both traffic performance and safety. This indicates that a throughabout with traffic signals for conflicting traffic is the most optimal solution for roundabouts with BRT.

Table 1 Main results of the MCA

	Municipality			Road authority			Public transport authority		
Design solutions	1	2	3	1	2	3	1	2	3
Throughput	0.10	0.00	0.07	0.13	0.00	0.09	0.07	0.00	0.05
Travel time	0.04	0.05	0.08	0.07	0.04	0.10	0.11	0.19	0.26
Variation in travel time	0.03	0.06	0.08	0.06	0.07	0.09	0.10	0.22	0.24
Vehicle conflicts	0.12	0.09	0.14	0.10	0.08	0.12	0.05	0.04	0.06
Active mode conflicts	0.00	0.36	0.36	0.00	0.30	0.30	0.00	0.10	0.10
Costs	0.10	0.00	0.02	0.10	0.00	0.02	0.10	0.00	0.02
Total	0.39	0.56	0.74	0.46	0.49	0.72	0.44	0.54	0.72

Sensitivity analysis is performed to test if the results of the evaluation are sensitive to changes in factors that are chosen from assumptions made in the VISSIM model, safety calculations, and the MCA. The input parameters to the VISSIM model that are varied are the frequency and punctuality of buses. These parameters are chosen because they are thought to be the most important, as when the frequency of the buses is changed, the total time used to give them priority changes as well and that can affect the performance of the whole intersection. The punctuality is also thought to be important because if the buses are not on time, they are likely to bunch, which also affects the performance of the intersection where the buses are given priority. The results of the sensitivity analysis show that the exact values for each criterion changed slightly when these inputs are changed, but the order of design solutions from best to worst is the same for all variations of the inputs tested. Therefore, it is unlikely that the results of the evaluation will change as the frequency or punctuality of buses is changed.

Sensitivity analysis for the safety calculations is also performed, where the TTC and PET thresholds are varied. The TTC thresholds for each conflict group (vehicle – vehicle and active mode – vehicle conflicts) is changed by +/-0.5s where values both below and above the assumed threshold are tested. The assumed PET value is tested with these three TTC values, and then again with a PET threshold that is 1.5s lower than the assumed threshold. This results in that as the TTC and PET are varied, the exact numbers of conflict change slightly, however, the order of the best to worst design solution stays generally constant and therefore it is unlikely that the changing of TTC or PET will have an effect on the MCA results.

Sensitivity analysis is also performed on the weights of the MCA. The stakeholder analysis also acts as a sensitivity analysis, but because of high subjectivity of MCA, more theoretical weight sets are tested as well to see how the results are affected. First, all the weights are set to be equal, then the weight of each criterion, one at a time, is multiplied by 2 and then 4. These tests result in that design solution 3 always ranks as the best solution. However, the order of designs 1 and 2 change when the weights of the criteria of travel time for public transport, variation in travel time for public transport, or the number of conflicts between active mode users and vehicles have weights that are 4 times higher than the rest of the criteria. This means that the exact order and scores of designs 1 and 2 might switch places when these criteria are weighted much higher than the others, but design solution 3 is always rated the best.

The sensitivity analysis, therefore, result in that the result from the evaluation methodology is robust, which means that the solution is not likely to change even if the assumptions in the VISSIM model, safety calculations, or MCA weights are changed.

Conclusions and recommendations

The results of the thesis show that the most optimal design solution for a roundabout intersection where BRT is being added is a throughabout with traffic signals for conflicting traffic, or design solution 3. This is because the evaluation resulted in that this design solution scored the highest overall score for all stakeholders. Additionally, the MCA showed that design solution 3, a throughabout with traffic signals for conflicting traffic is both the safest and best performing design solution. The results indicate that design solution 3 would also be the most optimal design for other cases where BRT goes through a roundabout, even if they differ from the case of Melatorg. This is because at Melatorg the BRT route crosses a main road, leading to that the main flows of the intersection are stopped when a bus passes through the intersection. However, it is more common that a BRT route goes along the main road, leading to that a throughabout with traffic signals for conflicting traffic (design solution 3) will perform even better in those cases. Throughabouts improve the performance of buses while also keeping the safety benefits of roundabouts. This means that throughabouts can help with this change in making environmentally friendly modes more attractive and possibly reduce car uses by providing more priority to the buses and safer and more comfortable environment for these modes.

This thesis aims to address the research gaps of limited guidelines of roundabouts with BRT and the disagreement that seems to be between countries on the effectiveness of roundabouts with BRT. To address these gaps an evaluation methodology that uses methods such as MCA, microsimulation, and safety calculations to compare and evaluate different design solutions of roundabouts with BRT based on safety and performance is developed and the most optimal design solution is found out of three roundabout design solutions. This evaluation methodology can help with deciding between different roundabout or intersection designs, which can be used in guidelines or as a methodology to make a decision on the most optimal design. Additionally, this thesis shows that the most optimal design solution is a throughabout with traffic signals for conflicting traffic, and shows that this design solution is very effective, both in terms of the performance and safety of all users compared to other roundabout designs. However, this thesis did not compare throughabouts with traffic signals for conflicting traffic to conventional signalized intersections. Therefore, this research gap is only partially solved, and it is recommended to compare throughabouts to other types of intersection design to determine its full effectiveness.

One of the major limitations encountered in the research was the modelling of active mode users and a limited number of active mode users and crossings at Melatorg. One of the limitations of the VISSIM model is that VISSIM is not able to model active mode users as pedestrians and record their trajectory. Since the trajectory of the users is needed for the safety calculations, the active mode users are modelled as vehicles. This leads to that the behaviour of the active mode users is not as realistic as it could be and therefore limits the VISSIM model. Additionally, the number of active mode users at the intersection is limited, and there are only crossings at two of the roads at the intersection investigated. This can lead to that the effects on the performance of active modes from changing the priority of BRT are not fully shown. These limitations limit the information that can be gained on the active mode user side of the evaluation. Therefore, it is recommended to investigate these further.

A recommendation for an authority or a consultant wanting to add a BRT route to a road where there are two-lane roundabouts is to use throughabout with traffic signals for conflicting traffic. Furthermore, if a roundabout is smaller, has low traffic volume, or the total frequency of buses passing through the intersection is relatively low, the option of adding a throughabout with yielding signs, warning signs, or warning lights and bells might be a good solution as well, but further investigation is recommended. It is also recommended to look into comparing throughabouts that have traffic signals for conflicting traffic to other types of intersection designs, such as signalized X-intersections.

Terms and Abbreviations

AADT: Average annual daily traffic. The total volume of vehicles that drive on a road or a road segment on an average day for the whole year, where the total yearly traffic volume is divided by 365.

Active mode users: Active modes refer to transport modes such as walking, cycling, e-step scooters, moped scooters, skateboarding, etc. Active mode user is a term that describes everyone that is travelling by an active mode. In some reports these users are also called vulnerable road users, as they do not have the protection of a vehicle when travelling.

Active modes crossing: A regular pedestrian crossing. However, in this thesis all active mode users share a path and therefore a pedestrian crossing is referred as active mode crossing to include all modes using the crossing.

Bus: Overall term for all types of buses considered in this thesis. It can be split into two types: **regular buses**, which are 12m buses that drive less frequently outside of rush hours and their routes are more in neighbourhood areas, and **BRT vehicles**, which are 18m long buses that have a high frequency service, have routes that include mostly exclusive lanes and serve the major bus routes of the network. Both types of buses can drive both on exclusive lanes and in mixed traffic.

Bus Rapid Transit (BRT) and Buses with High Level of Service (BHLS): BRT is a high-quality bus service that provides a fast, reliable, accessible and comfortable service that is comparable to light rail and metro services (Borgarlinan.is, n.d.; ITDP, 2022; National BRT Institute, n.d.; Van der Meijs, 2015). BRT has designated lanes, priority on intersections, off-board fare collection and fast and frequent service, however, BRT can also have less demand and have some corridors that are in mixed traffic, especially in Europe. This version of BRT is called BRT light or BHLS. While both BRT and BHLS systems can include exclusive bus lanes, priority on intersections, and high frequency, BHLS systems tend to focus more on the passenger experience and BRT systems tend to focus more on mass transit (Finn et al., 2011; Hidalgo & Gutiérrez, 2013). For the purposes of this thesis, the term Bus Rapid Transit (BRT) will be used as a synonym describing both types of systems.

Conflict: A noticeable situation where two or more road users are approaching each other that could result in a crash if their speed and path does not change (Gettman, Pu, Sayed, Shelby, & Energy, 2008).

Conventional intersection (or roundabout): Regular T- or X- intersections which could be signalized or not, or a roundabout with mixed traffic. In the thesis different types of intersections are discussed. Intersections that do not have any priority public transport and are only for mixed traffic are referred as conventional intersections in the thesis.

Exclusive lane: Exclusive lanes are lanes that are dedicated to only buses. Exclusive lanes are often separated from mixed traffic.

Surrogate Safety Assessment Model (SSAM): SSAM is a model by the Federal Highway Administration (FHWA) which can calculate the number and types of conflicts between vehicles, or vehicle objects. The conflicts are calculated from the trajectories of each vehicle from the VISSIM simulation, the Time-to-Collision (TTC) threshold and Post Encroachment Time (PET) threshold (FHWA, 2021).

Throughabout: A roundabout with an exclusive bus lane that goes through the centre island of the roundabout (Zakeri & Choupani, 2021). Throughabouts can also be called continuous median roundabouts (Aakre & Aakre, 2017).

Throughput: The number of users in the VISSIM simulation that go through the intersection and arrive at their destination during the data collection period, which is one hour. The throughput is also the flow of the intersection, indicated as veh/h which also includes the active mode users that pass through the intersection in an hour.

Table of Contents

1. Introduction

The objective of the chapter is to introduce the topic of the thesis and its background. Additionally, the objective of the chapter is to discuss the purpose of the research, state the problem, and present the research questions.
Chapter 1.1 introduces the concept of Bus Rapid Transit in chapter 1.1.1, in addition to the background of roundabouts and their costs and benefits in chapter 1.1.2. Chapter 1.1.3 introduces the concept of roundabouts with BRT. Chapter 1.2 is split up in chapter 1.2.1 which defines the problem and chapter 1.2.2 which discusses the purpose and objective of the research and the research questions. Chapter 1.3 explains the setup of the rest of the thesis.

1.1 Background

Public transport and roundabouts are a common sight in many cities and countries all over the world. Many cities in the world were built up as car-oriented cities and had little space allocated for active modes and public transport (Vuchic, 2005). However, cities today are rethinking the designs of the network and making the cities more for the people, by giving more access to other modes than the car, such as public transport (Gemeente Rotterdam, 2020; Reykjavíkurborg, 2021). Bus Rapid Transit (BRT) is one type of a high-quality bus service, which has been growing in popularity for over 20 years because of its advantages (BRT Data, 2021; Van der Meijs, 2015). The growth of BRT, its advantages, challenges and background are further introduced in chapter 1.1.1.
Roundabouts have been, and still are, a popular option for an intersection design because roundabouts are much safer, have higher capacity, and smoother traffic flow than conventional X – intersections (Dijkstra, 2005; Gruden, Otković, & Šraml, 2022; SWOV, 2022). The safety and other benefits of roundabouts along with their disadvantages are further introduced in chapter 1.1.2.
Since BRT systems are being added to already built-up areas, where many intersections on their route can be roundabouts, there is a need for investigating if there are solutions which

could work where BRT vehicles drive through roundabouts or if intersections where BRT vehicles drive through should be changed to signalized intersections. Some cities throughout the world have come up with solutions for BRT in roundabouts, which is further introduced in chapter 1.1.3.

1.1.1 Bus Rapid Transit

The popularity of public transport has grown in previous years due to increasing population, increasing car traffic and more factors. Public transportation is a wide concept as there are many types of it. The types can be split into fast and slow modes. One type of fast public transportation is Bus Rapid Transit (BRT). BRT is a high-quality bus service concept that has designated lanes, priority on intersections, off-board fare collection and fast and frequent service which leads to that BRT provides a fast, reliable, accessible and comfortable service that is comparable to light rail and metro services (Borgarlinan.is, n.d.; ITDP, 2022; National BRT Institute, n.d.; Van der Meijs, 2015). BRT is a less expensive option to light rail due to low investment costs. This reason, along with flexibility, reliability, speed, impact, and fast implementation might be one of the reasons why there is a steep increase in the number of cities that have added a BRT network to their cities over the past 20 years (Figure 4) (BRT Data, 2021; Nikitas & Karlsson, 2015). Figure 4 shows the growth of BRT systems in cities all over the world, and as of 2020, a total of 181 cities have implemented BRT systems (BRT Data, 2021).

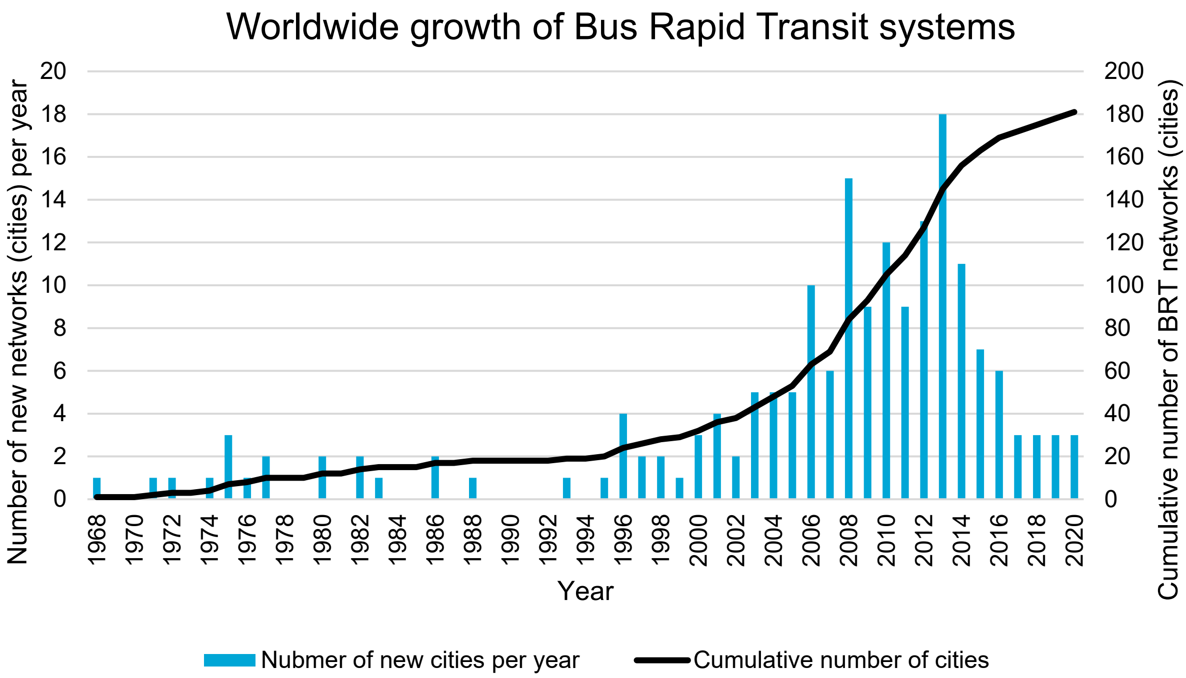


Figure 4 Worldwide growth of Bus Rapid Transit systems (BRT Data, 2021)

The first BRT system was built in Curitiba, Brazil and BRT systems were popular in South America and Europe, for the first years (BRT Data, 2021; Nikitas & Karlsson, 2015). In 2020, BRT systems in Europe and South America consist of more than 50% of BRT systems in the world (BRT Data, 2021). The first BRT system in Asia was built in 1998 and the first BRT system in Africa was built ten years later, in 2008 (BRT Data, 2021). There is, however, a slight difference between BRT systems in Europe, and in South America and Asia. In Europe, it is more common to use the term Buses with High Level of Service (BHLS) which is sometimes called BRT Light, rather than BRT, especially amongst researchers and practitioners (Finn, Heddebaut, & Rabuel, 2010; Hidalgo & Gutiérrez, 2013). While both BRT and BHLS systems can include exclusive bus lanes, have priority on intersections, and high frequency, they differ in a way that BHLS systems tend to focus more on the passenger experience whereas BRT systems tend to focus more on mass transit (Finn et al., 2011; Finn et al., 2010; Hidalgo & Gutiérrez, 2013). Therefore, it can be inferred that systems in Europe (BHLS) tend to have corridors where the buses drive in mixed traffic and sometimes use regular sized buses, as it is less used for mass transit and has a lower demand, but the passenger experience of a fast and reliable bus system is still available. On the other hand, systems in South America tend to be on completely exclusive lanes or busways, which sometimes are grade separated, and use long articulated buses (Hidalgo & Gutiérrez, 2013). For a bus system to be considered BRT, it must have certain characteristics, such as that the buses are mostly on exclusive lanes, the stations are nice, have off-board fare collection, good information, the stops are spaced on average 300-400 m apart in cities, and the service is frequent and reliable (ITDP, 2022; Vuchic, 2005). To help with making BRT systems, the Institute for Transportation and Development Policy (ITDP), a worldwide institute, has made a BRT Planning Guide, and many countries use this guide as a base for their BRT guidelines and systems (ITDP, 2017; Mannvit, 2019). The ITDP also has a standard that rates BRT systems, and for the system to be considered a BRT network, it has to have a certain number of points from this standard (ITDP, 2022; Mannvit, 2019). The BRT Standard's scorecard is based on six categories (ITDP, 2022).

- *The BRT Basics:* This category is based on the dedicated right of way and the type of alignment, as well as off-board fare collection, intersection solutions and level boarding.
- *Service planning*: This category is based on how well the service is planned, were factors such as if the service has multiple routes, the hours of operation and demand profile of the service are observed.
- *Infrastructure:* This category focuses on passing lanes at stations, distance to stops from intersections, and minimizing emissions from the buses.
- *Stations:* This category looks at the distance between stations, the number of doors on the buses, the safety and comfortability of the stations along with other factors related to the stations.
- *Communications:* This category focuses on how information is given to the passengers and the branding.
- *Access and integration:* This category includes universal access, access for pedestrians and their safety, secure bicycle parking and cycle lanes, along with integration with other public transport.

Based on these categories, the BRT systems can be ranked in either gold, silver, or bronze levels, depending on how high they score according to the standard (ITDP, 2022). Systems that are considered BHLS or BRT Light might score as a bronze level or as a basic BRT according to the standard, for instance. Despite these differences between BRT and BHLS, the systems have a lot of similarities and therefore, for the purposes of this thesis, the term Bus Rapid Transit (BRT) will be used as a synonym describing both types of systems.

BRT systems have many advantages. One advantage is the low-to-moderate cost of implementation. Because BRT is a bus service, i.e., rubber-tire buses, the investment costs are lower than rail-based systems (Hidalgo & Gutiérrez, 2013; Vuchic, 2005). This means that the buses can operate on already built roads, either in mixed traffic or on designated lanes, whereas rail-based systems need a new and different infrastructure and possibly more priority (for metro systems) which requires more investment costs and time. Another advantage of BRT is that while it is a bus service, it has some qualities of light rail and metro services and has a better service than a regular bus system (Hidalgo & Gutiérrez, 2013; Van der Meijs, 2015; Vuchic, 2005). The stops of a BRT service are further apart than for a regular bus service and has designated lanes, making the service fast, comfortable, and reliable (ITDP, 2022; VSÓ Ráðgjöf, 2019). Public transport passengers are more willing to travel further to a stop if the service has higher frequency, which lowers the waiting time, and if their trip is more direct

or to avoid transfers (Brand, Hoogendoorn, Oort, & Schalkwijk, 2017; Ministerie van Infrastructuur en Waterstaat, 2016; Rijsman et al., 2019). The distance between stops should not be too long and has to be optimised so that the buses can gain some speed between stops and that walking time to stations is not too long (ITDP, 2017). An ideal distance between stops in cities is 300 – 450 m but might be more (ITDP, 2017; Rijsman et al., 2019; Vuchic, 2005). By placing the stops further apart, the average speed of the bus service increases as the buses stop less often, and can gain speed between the stops (Brand et al., 2017; Vuchic, 2005).
There are also some disadvantages to BRT systems as well. A disadvantage of a BRT system is that the quality of the service and its reliability can easily decrease, especially if it is in mixed traffic (ITDP, 2017; VSÓ Ráðgjöf, 2019). This would occur for example in a situation where the BRT would not have designated lanes in areas where much traffic congestion arises. Additionally, the quality of the BRT service would decrease if the buses would have to stop in many places that are not bus stops, for example at intersections or in traffic. These factors would decrease the quality of the BRT service and it would become more similar to a regular bus service system.

This chapter concludes that BRT is a fast-growing type of public transport all over the world, as indicated in Figure 4. BRT systems have many advantages over a regular bus system and has many similar features to light-rail systems. However, one of the main challenges for BRT systems is that the level of service can easily be decreased, for example if the reliability and speed is decreased due to low priority at intersections.

1.1.2 Roundabouts

Roundabouts are considered to be one of the safest types of intersections when it comes to car traffic (Dijkstra, 2005; Gruden et al., 2022; SWOV, 2022). Studies have shown that by changing a conventional intersection to a roundabout significantly improves both safety and traffic flow (Dijkstra, 2005). What makes roundabouts so much safer than conventional T- or X- intersections is that the number of conflict points are reduced from 32 to 8 for a single lane roundabout and to 24 for a double lane roundabout, as seen in Figure 5 (Hallgrímsdóttir, Ottósson, & Hafsteinsdóttir, 2019). Furthermore, roundabouts have less severe crashes than conventional intersections and the speed of the cars is lower (SWOV, 2022).

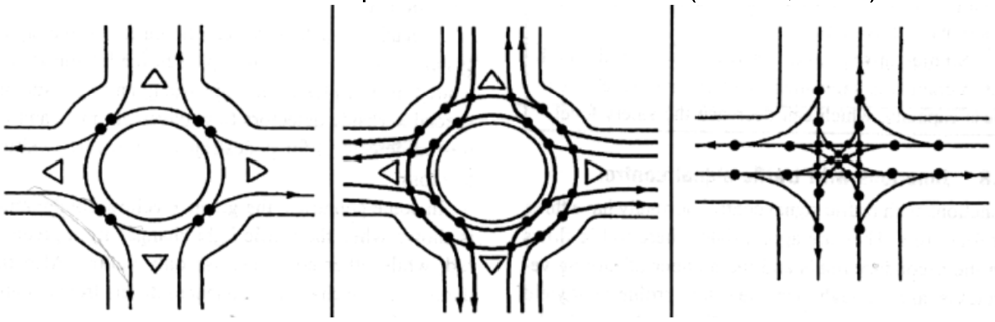


Figure 5 Conflict points on a single lane roundabout (left), on a double lane roundabout (centre), on a X-intersection (right) (Hallgrímsdóttir et al., 2019)

However, roundabouts have mostly only been researched on vehicle traffic and safety. Some studies have been performed on bicycle safety in roundabouts and about the design of roundabouts that is safer for cyclists but the focus on pedestrian safety in roundabouts has been very limited. Nevertheless, the safety and behaviour of active mode users has gained interest in the previous years (Gruden et al., 2022). Gruden et al. (2022) mention that even though roundabouts are considered more safe than conventional signalized intersections, pedestrians often perceive roundabouts as less safe and thus, it is important to research this further and include pedestrians and cyclists in the evaluation process of the safety of roundabouts.

Roundabouts have been a popular choice for intersection designs for many years in urban areas. The increase in popularity of roundabouts is due to the safety benefits of the roundabout compared to a conventional intersection, where there are fewer and less severe conflict points, traffic is slower, and the traffic flow is smoother (Dijkstra, 2005; SWOV, 2022). The smoother traffic flow also results in that sometimes roundabouts have higher capacity than conventional X- intersections. Furthermore, with smoother traffic, less CO_2 is emitted to the atmosphere, which happens when cars are idling at a red light. One of the major goals for countries all over the world is to reduce CO_2 emissions and other greenhouse gases, making the roundabout a good option for an intersection design. However, a disadvantage of roundabouts is that they are not always favourable. For instance, in a situation where the flow on the main street is much heavier than the flow on the minor street, it can be very difficult for the cars from the minor street to get into the roundabout, whereas if the intersection was signalized, the cars on the minor street would always get their turn, and more frequently (Hallgrímsdóttir et al., 2019).

Roundabout designs can differ slightly per country, and many countries have their own standards or guidelines for roundabout designs. Kennedy (2007) compared the guidelines for roundabout designs of multiple countries all over the world. Kennedy found that there is a difference in the size of the roundabouts based on countries, where roundabout designs in Germany, France, and the Netherlands are smaller and have a tighter geometry than the roundabout designs in Sweden, Denmark, and Norway (Kennedy, 2007). The smaller geometry leads to lower speeds in the roundabouts and are used for reasons of road safety (Hallgrímsdóttir et al., 2019; Kennedy, 2007). Roundabout designs in countries such as the United Kingdom, Australia and the United States are however more focused on increased capacity of the roundabouts and therefore also have larger designs and more wider turns and geometry (Kennedy, 2007). These types of designs are not recommended in Germany, France, or the Netherlands as they tend to lead to higher speeds in the roundabouts (Kennedy, 2007). However, guidelines for roundabouts with BRT are limited. This thesis aims to gain more information about possible roundabout solutions where BRT drives through the roundabouts by comparing the effectiveness of three design solutions. The designs considered are further discussed in chapter 5.4.

1.1.3 Bus Rapid Transit in Roundabouts

In cities that have Bus Rapid Transit (BRT) systems, the BRT routes sometimes go through intersections that are roundabouts. Number of cities have developed solutions for getting the BRT vehicles through the roundabout, while still giving priority to the buses, as seen in Figure 6. This type of design can also be seen for other priority public transport in cities, such as trams.

Figure 6 BRT solution with an exclusive lane through the centre island of a roundabout (ITDP, 2017)

The BRT Planning Guide by ITDP suggests several ways how roundabouts with BRT can be designed. The solutions suggested are all kinds of solutions, ranging from where the bus merges into traffic before the roundabout, to a signalized roundabout, to where the bus has an exclusive lane through the roundabout and can have full priority though the roundabout, controlled by signals, as shown in Figure 6 (ITDP, 2017). These design solutions will be described in more detail in chapter 3.1.2.
There are cities all over the world that have designed intersections as roundabouts that have public transport (bus, BRT, or tram) lanes through the centre of the roundabout. There are also other solutions that still give the public transport some priority through the roundabout, which will be mentioned in chapter 3.1.2. These kinds of design solutions can for example be seen in France, Indonesia, the Netherlands, Norway, and Sweden (ITDP, 2017; Mannvit, 2019; VSÓ Ráðgjöf, 2019). The decision if an intersection should be a roundabout or a signalized intersection might depend on traffic volume, where if a roundabout would be at capacity, then it might be better to design the intersection as a signalized intersection. The decision might also depend on the space available, as BRT routes are usually being built in an already built-up city and space might be limited, then the size of the intersection is a controlling factor in the decision-making process.

This thesis investigates how buses (BRT vehicles) can travel through roundabouts, as roundabouts are often used as a solution for a safe intersection, as discussed in chapter 1.1.2. Multiple countries have developed solutions for roundabouts with BRT, which are discussed in this chapter (1.1.3). However, few research gaps regarding BRT and safety in roundabouts have been found. One of the main research gaps is that there are few guidelines on these solutions and there seems to be a disagreement about the effectiveness of design solutions of roundabouts with BRT between some countries. This research gap is further discussed in chapter 3.3.

1.2 Problem definition and research questions

Limited number of guidelines for roundabouts with BRT have been made and often they are vague and therefore it is needed to investigate how designs can be evaluated and what designs are better than other. Additionally, there is a disagreement between guidelines and the attitude between different countries about the effectiveness of roundabouts with BRT. To add to the knowledge about roundabouts with BRT and their effectiveness, this thesis aims to develop a methodology that can be used to evaluate and compare different roundabout designs that can give an indication of which of the designs are better or worse compared to the design alternatives studied.
Nowadays, more cities are changing their focus from the private car to more environmentally friendly modes such as active mode and public transport and giving more access and priority to these modes. BRT is one of the solutions to make public transport more attractive as its service is better than for a regular bus, and it can be compared to modes such as light rail (Vuchic, 2005). This chapter further investigates this change in road user hierarchy, and the problem of limited knowledge about the effectiveness of roundabout designs with BRT.

1.2.1 Problem definition

In today's society, planners, engineers and politicians are trying to increase the usage of other, more environmentally friendly modes, such as public transportation and active modes (walking, biking, e-scooters, etc.). In order to increase the usage of these modes, and decrease the use of the private car, these other modes have to become more attractive, which can occur by giving the facilities, and infrastructure more space along with giving more priority to those modes.

Many cities around the world have been built as private car-oriented cities where the focus is on car traffic. Nowadays, many cities are rethinking their city's design and trying to reduce the usage of the private car. One way to do that is to change the road user hierarchy, where

before, the car was the most important mode and at the top of the hierarchy but now pedestrians are at the top, followed by cyclists, then public transport and cars are at the bottom, as showed in Figure 7 (Department of Transport, 2022; Gemeente Rotterdam, 2020). By changing the road user hierarchy, the city becomes safer and more accessible for active mode users, as the car is now a guest in zones where there are many active mode users, such as residential and recreational areas and city centres (Gemeente Rotterdam, 2020). Furthermore, modes that are more environmentally friendly, such as active modes and public transport, become more attractive and are more competitive to the car.
The Department for Transport in the UK added a new Hierarchy of Road Users in The Highway Code in early 2022 (Department of Transport, 2022). There they note that the road users that are at the most risk and can suffer the most damage, i.e. active mode users, are at the top of the hierarchy, and the road users that can cause the most damage and have lowest risk, i.e. cars and trucks, are at the bottom (Department of Transport, 2022). Other cities and countries have also started to use this type of road user hierarchy. In the Reykjavík Municipal plan for 2024 (Iceland) this hierarchy is also mentioned (Reykjavíkurborg, 2021). Rotterdam (the Netherlands) has implemented this road user hierarchy in their city planning and mobility approach. They focus on reducing unnecessary road traffic in residential areas, reducing through traffic in residential areas and in the city centre, and building more and higher quality spaces for pedestrians and cyclists (Gemeente Rotterdam, 2020).

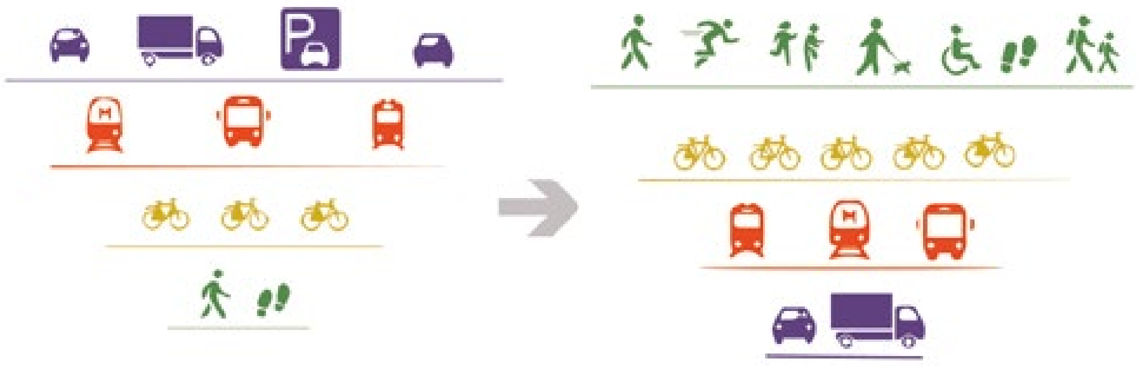


Figure 7 Change in Road user hierarchy (Gemeente Rotterdam, 2020)

Previously, the common practice was to mainly focus on the car performance (flow and capacity) and safety when designing roundabouts. Less attention has been spent on the active mode users and their safety when evaluating different roundabout designs. Some research has been done on cyclists and their safety in roundabouts and even less about pedestrians. Research about BRT in roundabouts is also limited.

With this new road user hierarchy, road corridors and intersections are being redesigned to allocate more space, accessibility and safety for active modes and public transport, while limiting the space for cars. Therefore, cities might be adding more or better public transport to their network services, for example BRT services. However, because of few and vague guidelines and unclear effectiveness about BRT solutions in roundabouts, this thesis aims to gain more knowledge on different design solutions and their effectiveness compared to each other by developing an evaluation methodology that can evaluate and compare different design solutions.

1.2.2 Research objective and research questions

The objective of this thesis is to develop a methodology that evaluates design solutions of roundabouts with a priority public transport service (BRT). The methodology will evaluate and compare the designs based on safety and the performance of all modes that are using the intersection. Other criteria such as costs are also considered when evaluating the different designs. This evaluation methodology will also show which of the design solutions proves to be the most optimal.

Given this objective, the following research question is proposed:

How can roundabouts with different priority configurations for Bus Rapid Transit be evaluated and compared based on safety and performance of all modes and which alternative proves to be the most optimal?

This research question will lead to an evaluation methodology that can be used to evaluate new designs, redesigns, or different alternative designs for a roundabout intersection. The methodology can then give an indication of the best design of the alternatives that are being investigated.

To answer the main research question, first it is important to look at the design solutions of roundabouts with BRT that have already been built, in addition to investigating if there are some guidelines, both limited and more detailed, available in other countries and seeing what they are doing with roundabouts with BRT, buses, or trams. Therefore, the following sub-question is proposed:

a. *What design solutions or guidelines on the safety and roundabouts with BRT have been developed in different countries?*

To know about criteria used in roundabout designs with BRT, it needs to be investigated what types of designs have been built. Therefore, the first sub-question of sub-question a is proposed:

i. What types of design solutions have been found for roundabouts with BRT?

Additionally, as mentioned in chapter 1.2.1, these roundabouts are usually in built up areas, or city centres, where there are numbers of active mode users as well. With the new road user hierarchy, more attention is paid to active mode users and their priority and safety. With better access for active mode users, it can also be expected that their numbers will increase, therefore it is important to include active mode users in the evaluation. To include them it is important to know more about their safety and what factors affect their safety at roundabouts. Therefore, the following sub-question to sub-question a is proposed:

ii. What factors affect the safety of active mode users in roundabouts?

When sub-question a has been answered, that information gives insights into what has been developed in other countries, which indicates what design alternatives can be investigated further, and what factors are important in safe designs for all modes, especially active modes. To evaluate and compare the designs a methodology can be developed, which helps answer the main research question. To develop the methodology, the criteria, and methods on how these design solutions can be evaluated have to be investigated. Therefore, sub-question b is proposed:

b. *What criteria can be used to evaluate the roundabout design solutions and how can they be evaluated?*

The criteria used to evaluate the performance and safety of the designs could either be qualitative or quantitative, or both and therefore it is important to investigate different evaluation methods. Therefore, the first sub-question of sub-question b is proposed:

i. What evaluation methods are available for the possible criteria used?

When evaluating both safety and performance, the criteria for that might be specific. By using the information from sub-question a, it can be indicated what types of designs are preferred or safer for BRT and active mode users. But the approaches on how to evaluate the safety and performance are still not known. Therefore, the next two sub-questions of sub-question b are proposed:

ii. How is the safety of all modes evaluated at roundabouts?
iii. How can the traffic performance and the performance of public transport be evaluated at roundabouts?

In evaluations such as this one, multiple stakeholders with different views on the importance of a criterion can be considered. Therefore, the fourth sub-question of sub-question b is proposed:

iv. What stakeholders can be considered in the evaluation and what weight sets should be used for each stakeholder?

These four sub-questions of sub-question b will help answering that question and will set up the answer to the main research question. However, sub-question b only sets up a theoretical methodology, but to test and illustrate the methodology, a case study can be used. The case study can help with finalising the answer to the main research question by testing if the methodology works and finding which alternative proves to be the most optimal. Therefore, sub-question c is proposed:

c. *How does this methodology work in a case study at the roundabout Melatorg in Reykjavík, Iceland?*

All these sub-questions the lead back to answering the main research question of how the designs can be evaluated and compared based on safety of all modes and traffic performance.

1.3 Thesis setup

The remainder of the thesis is set up in the following way. Chapter 2 describes the methods used to answer the research questions. Chapter 3 contains the literature review which aims to answer sub-question a. Chapter 4 describes the evaluation methodology, and discusses the criteria used in the evaluation, stakeholders, and the weight sets. Additionally, chapter 4 aims to answer sub-question b. Chapter 5 introduces the case study of Melatorg in Reykjavík, Iceland in addition to the three design solutions considered and the simulation model inputs. Chapter 6 shows the results of the case study, both from the simulations and the evaluation methodology. Additionally, chapter 6 discusses the sensitivity analysis performed to test the sensitivity of the simulation model, safety calculations, and evaluation method. Chapter 7 includes the refection of the impacts of the main assumptions and the research methods, and limitations of the research. Finally, chapter 8 includes the conclusions and recommendations of the thesis.

2. Research methods

This chapter discusses the different methods that are used to answer the research questions stated in chapter 1.2.2. Sub-question a is about what has been used in other countries as criteria and how safety and roundabout design can be evaluated for all modes present. Literature review is used to answer this question and will be explained in more detail in chapter 3.

Sub-question b is about what criteria can be used to evaluate different roundabout designs and how the methodology can be set up. To answer this question, the potential criteria used to evaluate the designs have to be decided. These criteria are discussed further in chapter 4.2. These criteria are used to evaluate the designs, by also using an evaluation method which is discussed in chapter 2.1. By using the selected criteria in the evaluation method, the multiple design solutions considered can be compared. The values for the criteria can be collected from a simulation of the intersection and the different design solutions. Some values need, however, further calculations before used as criteria values. Chapter 2.2 discusses possible simulation software and calculation methods to get the criteria values.

When the methodology has been set up by defining the criteria, evaluation methods and design solutions, the methodology is tested by using a case study. This answers sub-question c, and the case study is further introduced in chapter 5.

2.1 Evaluating and comparing designs

There are multiple ways to compare and evaluate different alternatives. Most of the time, these ways are either monetary based or non-monetary based. One of very common monetary based approach is Cost and Benefit Analysis (CBA), and then Multicriteria Analysis (MCA) for non-monetary analysis[1]. This chapter will compare these two methods, discuss pros and cons

[1] Lecture slides from lecture by A. van Binsbergen on the topic of Multi Criteria (Decision) Analysis in the course of CIE5817 Assessment of Transport Infrastructure and Systems

for each method and decide which method is more appropriate for the continuation if this research. Identifying the evaluation method used answers the first sub-question of sub-question b.

2.1.1 Cost and benefit analysis

Cost and Benefit analysis (CBA) is a monetary based analysis where the costs are compared to the benefits of a project or an alternative. CBA can be used to compare multiple alternatives, where usually one of the alternatives is a reference case of a current or 'no change' case (Annema, Mouter, & Razaei, 2015; Dodgson, Spackman, Pearman, & Phillips, 2009; Wee, Annema, & Banister, 2012). For each alternative, all the costs and benefits for all actors are found, and the net present value is computed (Dodgson et al., 2009; Wee et al., 2012). The CBA results in one aggregated value that shows the impacts of the alternative (Annema et al., 2015; Dodgson et al., 2009). This value is also easily understood as it is presented in a familiar scale, money (Dodgson et al., 2009). To find the best alternative, either the difference of the benefits and the costs (B-C) or the benefit-to-cost ratio (B/C) is computed (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). An advantage of CBA is that it is based on the societal willingness to pay and willingness to accept compensation, and all actors should be included in the CBA, while MCA is based on the views and goals of stakeholders and other decision makers, that might have different preferences than the citizens (Annema et al., 2015; Wee et al., 2012). However, there are few downsides to CBA. The first downside mentioned is that the decisions of CBA might be based on assumptions and uncertain things, which can lead to that the final outcome is over or underestimated which limits the accuracy of the method (Wee et al., 2012). To mitigate that, a sensitivity analysis is recommended, where for instance different interest rates can be used to compute different net present values (Wee et al., 2012). Another downside to CBA is that it is not possible or realistic to value all effects in monetary terms (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). Often it is difficult to put some factors into monetary terms, such as value of life, value of time, environmental effects, and safety and health effects (Dodgson et al., 2009). Monetizing these factors can be done, and there are some general values for these, but often it is not wanted to monetize these factors. However, it is possible to perform CBA where the most important factors are monetized and the things that cannot be monetized are still included in the decision process, by for instance combining CBA and MCA (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). Furthermore, a downside to CBA is that generally, it does not take the interaction between impacts into account and can have equity problems (Dodgson et al., 2009; Wee et al., 2012). For example, people might feel more strongly about a project that negatively affects both the environment and society, while the CBA might then underestimate this combination by placing two separate values on each effect (Dodgson et al., 2009). Additionally, since the CBA results in a one value, the distribution between winners and losers is not visible, so even if an alternative shows the most benefits, it might be that for some of the losers that there is no compensation (Wee et al., 2012).

2.1.2 Multicriteria analysis

Multicriteria analysis (MCA) is a non-monetary based analysis. MCA is more flexible and comprehensive than CBA (Dodgson et al., 2009). Additionally, MCA can bring more structure and openness to the analysis than CBA (Dodgson et al., 2009).
Similar to CBA, MCA can take values from many factors, or criteria, and aggregate it to a single score (Annema et al., 2015; Dodgson et al., 2009). Multiple alternative can be compared with MCA, and their scores can be used to rank the alternatives (Dodgson et al., 2009; Wee et al., 2012). Similar to CBA, often a reference case is used in the MCA ranking to see if alternatives are better or worse than that reference, which is often the current situation or a 'no change' situation (Annema et al., 2015). An advantage of MCA over CBA is that it can include criteria that is qualitative and quantitative, while CBA can only include quantitative criteria, which means that it can compare multiple types of factors and aggregate it into a single score (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). Before combining

the criteria into a final score, weights are used for each criterion, which show what criterion is the most important and so on (Wee et al., 2012). These weights are based on the views and goals of stakeholders and decision makers (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). These weights can be found by getting them directly from the stakeholders, or by using previous works, sources, or literature to derive the appropriate weights (Wee et al., 2012). However, since the weights are mainly decided by the decision maker, MCA is subjective and easy to manipulate by choosing weights to favour one alternative over another, which is a limitation to the method (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). However, the choices of the weights should be transparent and made explicit, which would limit the manipulation factor of the limitation (Wee et al., 2012). Furthermore, sensitivity analysis is recommended to mitigate factors such as subjectivity of the MCA (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). The sensitivity analysis can be performed by considering multiple stakeholders and using multiple weight sets (Annema et al., 2015; Wee et al., 2012). This could, however, lead to that the ranking order of the alternatives is not always the same, but it could show some patterns that lead to a justified decision (Wee et al., 2012).

Another downside of MCA is that it does not avoid double counting (Annema et al., 2015; Wee et al., 2012). Some criteria could be related to each other, and measure the same thing, such as speed and travel time. But in MCA there is nothing that makes sure that both are not included in the evaluation (Annema et al., 2015; Wee et al., 2012). This limitation can be mitigated by only including one of the criteria that is related to each other.

2.1.3 Conclusions

The differences between CBA and MCA are often smaller than is commonly thought (Wee et al., 2012). Both methods are usually compared to a reference case, result in a single, understandable value, but both can also be manipulated to a desired outcome (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). This limitation can be minimised by sensitivity analysis for instance, however, these methods are a good tool to examine the pros and cons of alternatives and use them as a way to justify decisions (Wee et al., 2012).

One of the main advantages MCA has over CBA is that it can include both qualitative and quantitative criteria, while CBA can only include quantitative criteria that has been changed to monetary terms (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012).

The main goal of this research is to investigate the level of service and safety of different roundabout designs. This means that the criteria used in the analysis will mainly be traffic performance indicators, such as travel time, and safety indicators. As safety and other factors are often difficult to monetize and the costs of the design solutions considered in not known in monetary terms and will only be included in the analysis in a qualitative way, the most appropriate method to use for this research is MCA. The limitations of MCA are mitigated by performing sensitivity analysis by considering multiple stakeholders and testing different weight sets for the analysis and the double counting is minimised by only including one criterion of the criteria that is known to be correlated.

2.2 Microsimulation and Safety Calculations

The main goal of this research is to answer the question of how different roundabout designs with BRT can be evaluated and compared based on safety and traffic performance. As explained in the beginning of this chapter, both multicriteria analysis (MCA) and simulation are used to help answer this question with the addition of a case study. The main criteria used for the MCA are traffic performance indicators, safety indicators, and costs. When evaluating and comparing different design solutions for one intersection, collecting real data and investigating the effects of multiple design solutions for one intersection is not possible, and therefore a good method to investigate the effects of different designs is simulation.

The criteria that is relevant to collect for evaluation on an intersection with MCA are for example the throughput of the intersection, travel times, speed, queue lengths, the number of conflicts and more. It is also important to be able to distinguish some of these factors for each mode and/or direction. The criteria considered for this thesis is further discussed in chapter 4.2.

There are few different types of simulation, macrosimulation, microsimulation, and meso-simulation (Azlan & Rohani, 2018; Knoop et al., 2020). The two most common types of simulation are macro and microsimulations. Macrosimulation is appropriate to use when the focus is more on a network level, such as change in routes, as macrosimulations are less detailed and is expressed in more aggregated terms than microsimulation (Azlan & Rohani, 2018). Microsimulation is appropriate to use when a small part of the network is being investigated, such as one intersection or a corridor, where the characteristics and behaviour of individual vehicles or different vehicle types can be investigated (Azlan & Rohani, 2018).

Since this research focuses only on the changes of a design of one intersection, microsimulation is more appropriate. Outputs from microsimulation can be, for example, the traffic performance indicators of throughput (or flow), travel time, speed, queue lengths, trajectories, density and more (Azlan & Rohani, 2018; Knoop et al., 2020). These indicators can be used to calculate safety effects of the intersection. For this research, criteria such as throughput, travel time, and number of conflicts which are calculated from the vehicle trajectories are used as criteria in the MCA. Therefore, microsimulation is used as a simulation method for this research.

2.2.1 Simulation software

There are multiple simulation software available that do microsimulation and evaluations of intersections. An example of these microsimulation software are AIMSUN, VISSIM, and Paramics.

The simulation software used in this research is used to model different design solutions of roundabouts where BRT drives through. Therefore, the simulation software has to be able to model multiple modes. Additionally, the output that is needed from the model is throughput, travel time, and the vehicle trajectories that can be used for the safety calculations (chapter 2.2.2).

AIMSUN and VISSIM can do very similar simulation and analysis, and therefore very similar to each other. Both software are known and used worldwide. Both AIMSUN and VISSIM can model an intersection, even a small network, and they can also model multimodal traffic, where cars, public transport, and active mode users can have their own behaviour patterns (AIMSUN, n.d.; PTV Group, n.d.). Paramics is a slightly different simulation software compared to AIMSUN and VISSIM. It can also simulate intersections and small networks and has 3D features that work well for showing the model, however, Paramics seems to mainly only model vehicular traffic (cars, trucks, buses) and not active modes (Paramics Microsimulation, n.d.).

Based on this, either AIMSUN or VISSIM are more suitable for this research, as they model active modes as well as other vehicular modes.

2.2.2 Safety calculations

As the research focuses also on the safety of the design solutions, the microsimulation can record the vehicle trajectories from the simulation which can be used to calculate the number of conflicts that can occur at that design solution. The number of conflicts that occur during a time period can help indicate the safety effects of the intersection. The Surrogate Safety Assessment Model (SSAM) by the Federal Highway Administration (FHWA) is used to evaluate the types of collisions, the Time-To-Collision (TTC) and Post Encroachment Time (PET) for vehicles (FHWA, 2021).

Table 2 Surrogate safety measures and types of conflicts that can be calculated using SSAM

Type of surrogate safety measure	**Explanation**
Types of conflict	SSAM defines three types of conflicts between vehicles which are based on the angle of the potential conflict, or link and lane locations of the vehicles (Gettman et al., 2008). The three types of conflict are crossing conflicts, which are when the collision angle is between 180° and 85°, lane-changing conflict, where the collision angle is between 85° and 30°, and rear end conflicts, where the collision angle is between 30° and 0° (Gettman et al., 2008).
TTC	The time until two vehicles would collide with each other if they continue their current trajectories and speed (Gettman et al., 2008). A TTC threshold is defined in SSAM which defines the minimum time that is needed to avoid a collision, for two vehicles, this threshold is usually 1.5s (Gettman et al., 2008; Wu, Radwan, & Abou-Senna, 2016).
PET	The time from when the first vehicle leaves a conflict area (which is the area that two conflicting vehicles occupy) until the second vehicle enters that area (Gettman et al., 2008). PET also has a threshold, like TTC, where a collision would occur if the time of the PET is lower than this threshold, which is usually 5s, for a conflict between two vehicles (Gettman et al., 2008; Wu et al., 2016).
Deceleration rate	The initial deceleration rate of a vehicle, where a higher deceleration rate would indicate higher probability of a collision (Gettman & Head, 2003).
Maximum speed	The maximum speed of the two vehicles involved in the potential conflict (Gettman & Head, 2003). A higher maximum speed indicates a more severe collision (Gettman & Head, 2003).
Difference in speed	The maximum relative speed of the two vehicles involved in the potential conflict (Gettman & Head, 2003). A higher difference in speed between the vehicles indicated a more severe collision (Gettman & Head, 2003).

Common practice has been to measure the safety effects by investigating crashes before and after changes of an intersection (Ghanim & Shaaban, 2019; Muley, Ghanim, & Kharbeche, 2018). However, this method is a bit counterintuitive, to have to observe the crashes to reduce the crashes. Microsimulations can help with this problem. Microsimulation is commonly used for analysing the performance of traffic networks while it is less common practice to use microsimulation as a technique to assess safety performance (Muley et al., 2018). Additionally, microsimulations can test multiple alternatives and their safety effects can be compared. By using microsimulation for safety evaluations enables engineers and technicians to evaluate dangerous intersections without having to obtain the crash data (Ghanim & Shaaban, 2019). SSAM can be used along with few microsimulation software, such as VISSIM and AIMSUN (FHWA, 2021). SSAM can take the trajectories from the microsimulation software and calculate and summarize five surrogate safety measures and three conflict types, as explained in Table 2 (Wu et al., 2016). The surrogate safety measures that can be calculated are Time-To-Collision (TTC), Post Encroachment Time (PET), deceleration rate, maximum speed, and the difference in speed (Wu et al., 2016). The three types of conflict are rear – end conflict, lane-changing conflict, and crossing conflict, where the types of conflict depends on the angle the conflicting vehicles, as explained further in chapter 4.1.2 (Wu et al., 2016). For this research, the types of conflicts, TTC and PET are used to calculate the number of conflicts.

2.2.3 Conclusions

There are multiple types of simulation software available for an analysis of an intersection. Few of those simulation software work with SSAM where their output can be directly used as an input for SSAM. For this research, there are few requirements that the simulation software has to fulfil. The software must:

- Be able to work with SSAM. All the simulation software considered can work with SSAM.
- Be able to simulate multiple modes. The intersection considered has cars, trucks, buses, BRT buses, pedestrians, cyclists, and e-scooter users, and the software must be able to differentiate between these modes and show their different behaviours.

With these requirements, Paramics can be eliminated as a potential software, because of the limited modes that it can model.

When deciding on what software to use, the availability of the software, the knowledge of the software, and the availability of helping material to learn how the software works is considered. Table 3 shows the three simulation software considered, and the requirements needed and helps decide which software to use.

Table 3 Comparison of each simulation software considered and the requirements for this research

Requirements	**AIMSUN**	**VISSIM**	**Paramics**
Works with SSAM	YES	YES	YES
Multimodal simulation	YES	YES	NO
Availability of software	NO	YES	NO

From the table, PTV VISSIM is chosen as the simulation software that is used in this research. VISSIM is able to model multiple modes and their interaction as well. VISSIM is also available through TU Delft and tutorials and help are easily accessible. Additionally, VISSIM is the most optimal microsimulation software to use to evaluate safety of an intersection since it can, among other things, provide output that can be directly be put into the SSAM (Terentyev, Andreev, Anikin, Morozova, & Shemyakin, 2020).

3. Literature review

The aim of this chapter is to answer part of sub-question a. Where solutions or guidelines on the safety and roundabouts with BRT from different countries are investigated. Sub-question a is divided into two sub-sub-questions.

The first sub-question of sub-question a is about what types of design solutions are out there for roundabouts with BRT. The answer to this question can indicate what has been done in other countries and will help in answering sub-question a. Additionally, the answer to this question helps with deciding the design alternatives which are investigated further and used in the case study. Chapter 3.1 discusses more about BRT in roundabouts.

Since BRT lines are usually in urban areas, there are also active mode users around that area. Furthermore, with better public transport, there are more people walking or cycling, for example for access or egress, or because other modes than the car are made more available and attractive. Because of this, it is likely that there will be active mode users around when designing intersections with BRT, especially in denser areas such as city centres. Therefore, the next sub-question of sub-question a asks specifically about designs that are safe for active mode users and what factors affect their safety at roundabouts. Chapter 3.2 discusses more about the safety of active mode users in roundabouts.

When the answers for the safety of active mode users and used roundabout designs have been found, sub-question a can be answered which leads on to the next sub-question of the evaluation criteria.

Literature review is used as a method to answer these questions because a literature review can help establish what information and methods exist and can help in answering the main research question. The results of the literature review can also help with deciding what criteria to consider for the multicriteria analysis (MCA) and the simulation setup.

To search for literature, the search methodology used was to use key words, which are listed in Table 4, to search in multiple search engines, such as Google Scholar, Scopus, SWOV, and World Transit Research. The key words or their synonyms and similar words were used to search the search engines. Either the key words were used by themselves, sentences were created from one or more key words, or Boolean logic operators such as AND, OR, and NOT were used. Additionally, snowballing techniques were used to find further literature. In addition to these searching methods, some literature was found by suggestions of supervisors.

Table 4 Key words for literature search

Main key word	**Synonyms**
Roundabout	Intersection
Bus Rapid Transit	BRT Bus Tram
Safety	
Evaluate	Assess
SSAM	Surrogate safety measures Surrogate safety assessment model
VISSIM	
Pedestrian	Cyclists/ Cycle Active modes

3.1 Bus Rapid Transit in roundabouts

As introduced in Chapter 1.1.3, some countries and cities have built solutions where BRT lines go through roundabouts. This sub chapter discusses about the safety of having exclusive lanes for BRT, different existing roundabout design solutions, and the effectiveness of roundabouts with BRT.

3.1.1 Safety of exclusive lanes for public transport

BRT systems are usually designed on exclusive lanes, but also sometimes as a part of mixed traffic for part of the route or a limited length. It is recommended to have the buses drive on a separate lane from other modes, both for reasons of safety and effectiveness (speed, reliability) (VSÓ Ráðgjöf, 2019). Separating bicycle lanes from the car lanes also improves safety of the cyclists, which is described further in Chapter 3.2.1. Additionally, designing good and accessible infrastructure for pedestrians and cyclists that connects to the BRT network both improves accessibility for the passengers and increases safety (VSÓ Ráðgjöf, 2019). Tzouras, Farah, Papadimitriou, van Oort, and Hagenzieker (2020) performed a stated survey amongst tram drivers in Athens, Greece on perceived safety and driving stress. Their results showed that the factors that influenced driving stress were the alignment type, and the existence and type of pedestrian crossings (Tzouras et al., 2020). The drivers experienced less stress when the alignment was exclusive or semi exclusive compared to tram/pedestrian malls and driving in mixed traffic (Tzouras et al., 2020). This aligns with other studies Tzouras et al. (2020) mentioned and also the report by VSÓ Ráðgjöf (2019). This leads to that separating the buses from other modes is both safer and less stressful than having the buses drive in mixed traffic.

It is important to design small and simple intersections when (re)designing intersections. Models have shown that by adding one lane to an intersection, increases severe accidents linearly by 17% (VSÓ Ráðgjöf, 2019). Therefore, it is key to consider multiple alternatives for intersections when changing the design, for example when adding a BRT line. Furthermore, intersections where traffic crosses the bus lanes are less safe than intersections where only right turns are allowed (Duduta, Adriazola, Hidalgo, Lindau, & Jaffe, 2012; VSÓ Ráðgjöf, 2019). By turning a X- intersection into two signalized T- intersections and continuing the median on the main street, as shown in Figure 8, increases safety (Duduta et al., 2012; VSÓ Ráðgjöf, 2019). If BRT crosses a main road or a road with high traffic volume, and it is wanted to have a X- or T- intersection, it is recommended to have it signalized (VSÓ Ráðgjöf, 2019). A disadvantage of having a signalized intersection with priority for BRT in a case like this could be that the main road might get less priority, as well as cyclists (VSÓ Ráðgjöf, 2019).

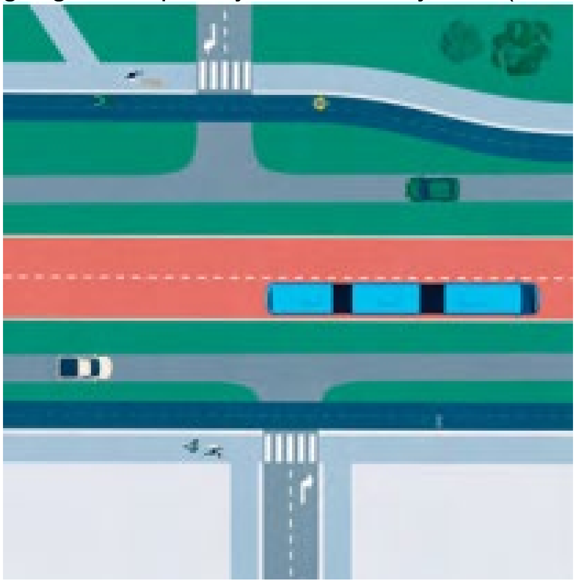


Figure 8 Two T- intersections where only right turns are allowed (1. lota forsendur og frumdrög, 2021)

Although this type of intersection is the safest option, it is unrealistic to change all intersections along a corridor to this type of intersections. Duduta et al. (2012) recommend however, to change some X- intersections to this type to eliminate left turns over the bus lane and this design will improve the traffic flow on these corridors. But this does not automatically indicate that the other intersections where left turns are allowed should be a signalized X- intersection, where roundabouts might still be a safer option.

At intersections, the accessibility and safety of active mode users must also be considered. Adding audible and visible warning systems for pedestrians and other active mode users at crossings with BRT or other priority public transport increases the safety of the active mode users (Tzouras et al., 2020). Active mode users can be less aware of the risk of an accident with a tram or BRT vehicle at a crossing and therefore, important to add some measures such as warning bells, light signals, or an offset crossing to make these users more aware of the risk of a priority public transport vehicle on an exclusive lane.

The following list includes the main findings in this section.

- Separate lanes for public transport are safer than having BRT driving in mixed traffic or pedestrian streets, it also reduces the stress of the drivers.
- It is important and safer to keep intersections small and simple.
- It is safer when cars don’t have to cross the BRT lanes, especially left turns.
- It is important to include warning systems for active mode users and make them more aware of their surroundings.

3.1.2 Roundabouts with BRT designs

Many countries have come up with solutions for roundabout designs that have a priority public transport route (tram, BRT, bus) going through them. There are many types of design solutions that give different level of priority to the buses. The BRT Planning Guide by ITDP (2017) has several suggestions of design solutions which are shown in detail in the chapter. This chapter shows few different design solutions, each in its own sub chapter and are ordered depending on the priority the buses get, from mixed traffic to full priority.

Buses in mixed traffic

A solution that gives the least priority to the buses is to have the buses drive through the roundabout or intersection in mixed traffic. This is designed in a way that the exclusive bus lane ends before the intersection, where the bus would merge with traffic and cross the intersection or roundabout with mixed traffic (Frøyland, Ristesund, & Simonsen, 2014; ITDP, 2017; VSÓ Ráðgjöf, 2019). Shortly after the intersection, the bus could enter the exclusive bus lane again. Figure 9 shows an example of this type of solution. This solution is, however, considered worse than other roundabout solutions, where the buses get more priority, because the level of service of the BRT decreases, along with the comfort of passengers (VSÓ Ráðgjöf, 2019).

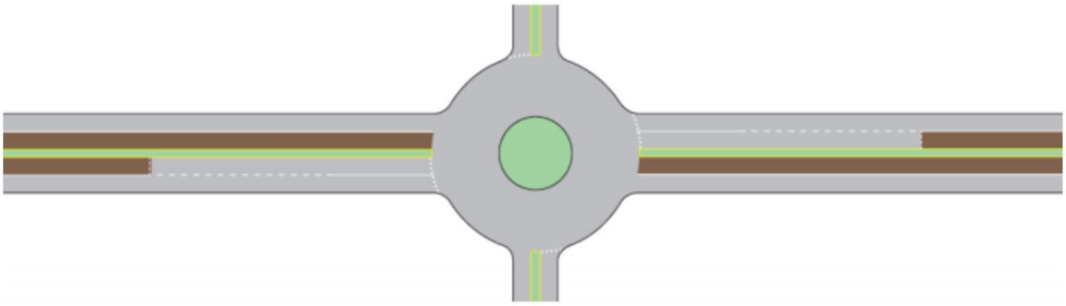


Figure 9 Buses drive in mixed traffic through the roundabout (VSÓ Ráðgjöf, 2019)

Bus lane in roundabouts

Another suggested solution is where there is an exclusive lane for the buses inside the circulatory road of the roundabout, as seen in Figure 10 (ITDP, 2017). In this solution, the buses would cross the circulating traffic both when entering and exiting the roundabout which can be controlled by signalization on not (ITDP, 2017). This solution, compared to full priority, can decrease the comfort of passengers, and might decrease the performance of the service, similarly to the previous solution, especially if not controlled with signals. Additionally, this solution might be problematic because an extra lane inside the roundabout has to be added and the space available might be limited.

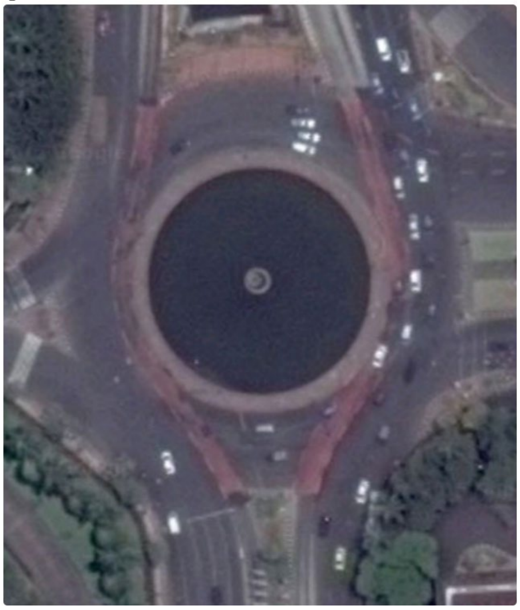


Figure 10 Roundabout with bus lanes. TransJarkata corridor, Indonesia (ITDP, 2017)

Bus lane through centre island

Another solution of a roundabout, with full priority for the public transport, is a roundabout where the bus lane goes though the centre island (Figure 11). This type of design both increases the speed of buses and increases the comfort for the passengers as the bus does not have to turn and drive around the central island of the roundabout like car traffic, because of the exclusive bus lanes through the centre island (ITDP, 2017; Nikitas & Karlsson, 2015). This solution, sometimes called continuous median roundabouts or throughabouts, has been seen in multiple countries and some studies have been performed, where the effectiveness and safety of these types of roundabout designs is researched. Zakeri and Choupani (2021) performed a microsimulation study on evaluating the effects of throughabouts on cars and public transport (BRT). In their study, they compare the design of the throughabout with standard roundabouts and intersections in Iran. Their results showed that the throughabout design improved travel time for both private and public transport and kept the traffic flowing at all volumes (Zakeri & Choupani, 2021). Their results also showed that a throughabout provided higher capacity than a standard roundabout or intersection design, and a signalized throughabout had even higher capacity than when unsignalized (Zakeri & Choupani, 2021). Zakeri and Choupani (2021) concluded that throughabouts can be very beneficial in a situation where BRT demand is high and where it needs to be prioritized. However, at signalized throughabouts with bus priority, where there is heavy traffic or the bus lanes cross he main road, the special signalling for the buses can cause delays and reduce the capacity though the intersection because there will be many signal callings from the buses (Frøyland et al., 2014; VSÓ Ráðgjöf, 2019).

Figure 11 Picture of a throughabout on N196 in Aalsmeer, Netherlands. Picture from Google Maps Street view.

There are multiple ways this solution of throughabouts can be designed. The two most used solutions in practice are either where there are traffic signals at all entries of the roundabout (Figure 12 (left)), or where there are traffic signals only for the traffic crossing the bus lane (Figure 12 (right)). These two types of signalized throughabouts are discussed in more detail in the next two sections.

Figure 12 Two solutions for throughabouts with traffic signals for entering traffic (left) and traffic signals for conflicting traffic (right)

Signals for entering traffic

Solutions as shown in Figure 12 (left), that have signals for all entering traffic have been designed and built for example in Stavanger, Norway. Bråtveit (2016) investigated one of these roundabouts at Hillevågsveien, shown in Figure 13. Figure 13 also shows how the signalization for entering traffic is at that roundabout. The entering traffic lights for the cars have yellow and red lights and are kept turned off when no bus is approaching, and the yielding sign is valid, as at a normal roundabout. At the same time, the bus has a stop signal when no bus is approaching (Frøyland et al., 2014). When a bus approaches the roundabout, the traffic signals for cars turn on (yellow, then red) and the bus can proceed and gets priority though the intersection (Frøyland et al., 2014). At the intersection investigated, there were a lot of red-light crossing and much delay for cars, which could partly be due to that there is also a bus stop located close to the intersection causing the traffic light for entering traffic to turn red while the bus might still have to stop at the bus stop (Bråtveit, 2016). Bråtveit (2016) investigated multiple alternative solutions to try to reduce the delays and the number of red-light crossings, one of the solutions that he recommended was a roundabout design where users of the roundabout would not have to be disrupted unnecessarily, i.e., only the traffic that is in conflict with the bus should be disrupted.

Figure 13 Roundabout on Hillevågsveien in Stavanger, Norway. Picture from google maps street view.

Signals for traffic in conflict with the bus

Aakre and Aakre (2017) performed a microsimulation of the same roundabout as Bråtveit (2016) but as a throughabout with yielding signs for the cars inside the roundabout. Therefore, only vehicles that are crossing the bus lane in the centre have to yield to the approaching bus, as if there were lights for the conflicting traffic. Their study resulted in that the throughabout has higher capacity than when there are signals for all entering traffic, which results in lower delays and more reliable travel times for all movements and vehicle types (Aakre & Aakre, 2017). There are multiple ways this signalling or warning for drivers when a bus is approaching can be implemented. Aakre and Aakre (2017) used yielding signs in their microsimulation. Having yielding signs or traffic signals for the cars that are crossing the bus lane might have an effect on the final result, because with yielding signs the flow might be smoother, but the safety might decrease whereas with traffic lights, all cars have to stop and wait which might affect the travel time and throughput but is safer because then the drivers are warned when a bus is arriving.

A roundabout in Delft, the Netherlands at Delflandplein (Figure 14) has lights that turn red when a bus or a tram is approaching to warn drivers, cyclists, and pedestrians of the approaching bus and that they should stop. Additionally, there are warning bells that sound when the light turns red. This type of solution can also be seen in other places in the Netherlands. Another solutions can be seen in Oslo, Norway, where tram roundabouts are sometimes equipped with LED-lights that warn the drivers that are in conflict with the tram when the tram is approaching (Giæver & Tveit, 2006). The LED lights might be a solution that results in a throughput or flow similar to a yielding sign but might increase the safety because of the visible warning of the approaching bus.

Figure 14 Roundabout at Delflandplein in Delft, the Netherlands. Picture from google maps, street view.

Other intersection solutions

Roundabouts are not the only alternative to signalized or other conventional T- or X-intersections. Norwegians have designed an additional solution of an intersection with BRT called "Kryss uten Kryss" or intersection without intersection (VSÓ Ráðgjöf, 2019). This intersection has signalized U-turns shortly after the intersection and no left turns are allowed at the intersection itself, eliminating crossings of the BRT lanes at the intersection (Figure 15). This solution has increased safety for all road users compared to signalized intersections and roundabouts (VSÓ Ráðgjöf, 2019).

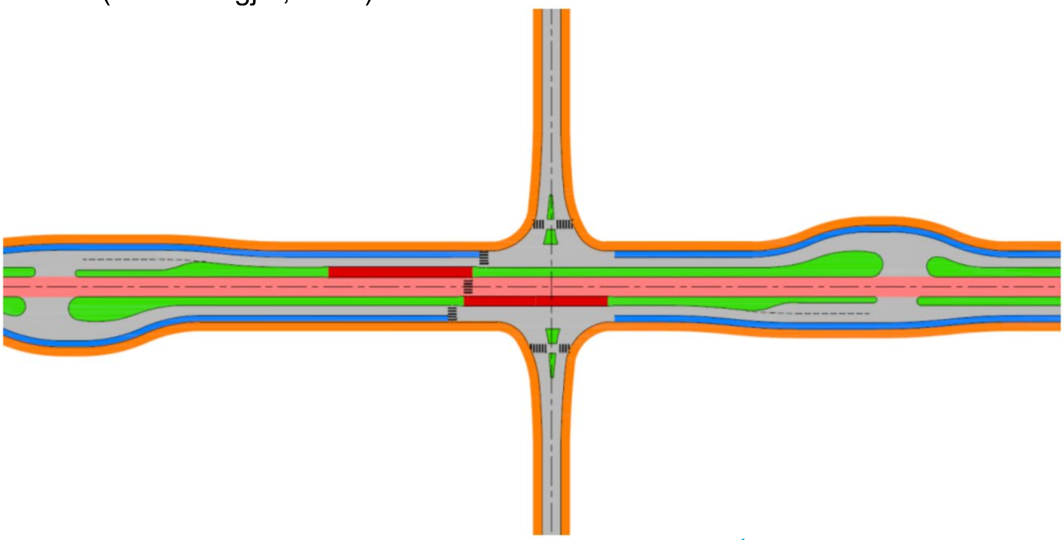


Figure 15 Intersection without intersection solution (VSÓ Ráðgjöf, 2019)

Conclusions

This thesis' focus is to look at alternative solutions for roundabout designs with BRT. There are multiple solutions on how to design a roundabout with BRT, where both the geometrical design of the roundabout and bus lanes are different but also the yielding or stop rules for the users of the roundabout to give priority to the bus. These designs might all have different results of traffic performance and safety of all road users, and would have to be tested by using, for instance, a microsimulation to know the effects and differences between each design. Additionally, conditions of each intersection might be different, which means that the best roundabout design might differ between different intersections as well.

For the purpose of this research only three design types are considered, buses in mixed traffic, throughabout with traffic signals for entering traffic, and throughabouts with traffic signals for conflicting traffic. These designs are chosen because the mixed design solution is a solution that is close to the current design. The throughabout designs are chosen because of the literature discussed in this chapter that indicated that they are beneficial and that these designs can be seen in multiple places over the world. Chapter 5.4 further discusses the reasons behind the selections of these designs.

3.1.3 Effectiveness of roundabouts with BRT

When considering roundabouts with BRT, there seems to be a disagreement between some countries of the use of these roundabouts, especially when it comes to the safety of the intersection (VSÓ Ráðgjöf, 2019). In France, signalized throughabouts showed higher accident rates than conventional signalized intersections, and therefore, signalized intersections are preferred. In line with this experience in France, in Denmark it is suggested to change current roundabouts to signalized intersections where BRT is planned to drive through (VSÓ Ráðgjöf, 2019). On the other hand, Norwegian guidelines have three versions of designs of roundabouts with BRT lanes through the centre island (throughabouts), and it seems that there is a positive experience with throughabouts (VSÓ Ráðgjöf, 2019). The first version has traffic lights for all entering traffic, as was explained in section 3.1.2 and showed in Figure 12 (left) (VSÓ Ráðgjöf, 2019). The second design has the circulating traffic stop for the bus when in conflict with the buses which is similar to the design where there are traffic lights for the conflicting traffic, as shown in Figure 12 (right), and the third design is signalled like the second design but the cycle paths are separated from the car traffic (VSÓ Ráðgjöf, 2019). A review of these three versions resulted in that the solution of a throughabout with traffic signals for conflicting traffic, versions two and three, are not recommended because they are considered too complex and safety is not ensured (VSÓ Ráðgjöf, 2019). The second version was not good for pedestrians and cyclists and the third version had too many conflict points which decreases the safety (VSÓ Ráðgjöf, 2019). It is therefore recommended in Norway to use the first version of placing traffic signals for all entering traffic and make sure that bus stops are in a bit distance from the intersection (VSÓ Ráðgjöf, 2019). Dutch guidelines also mention roundabouts with public transport. Their guidelines include that at roundabouts where public transport, such as buses and trams, has priority, the priority of the public transport at roundabouts can be controlled or given by for example tracks that run through the roundabout and/ or traffic lights (CROW, 2015). Indicating that the public transport vehicles can be given priority by lanes through the roundabout and/ or with traffic signals. As mentioned in chapter 3.1.2, multiple places in the Netherlands already have roundabouts which are throughabouts where there are traffic signals for conflicting traffic, both that seem new and older. Therefore, it can be assumed that they have a positive experience with these types of designs.

Bråtveit (2016) investigated a throughabout with BRT in Stavanger, Norway that had traffic signals for all entering traffic (as explained in section 3.1.2), where all entering traffic would get a red light when a bus is approaching to give priority to the bus through the intersection. This solution was causing an extra delay for the cars and led to many red light crossings (Bråtveit, 2016). Because of this, Bråtveit (2016) investigated alternative solutions to try to reduce the number of red light crossings. An alternative solution suggested by Bråtveit (2016) is to design the roundabout in a way that car traffic, and cyclists only have to yield to the buses if they cross the bus lane and therefore, traffic will not be disrupted unnecessarily. Aakre and Aakre (2017) further investigated the suggestion of Bråtveit (2016) where they performed microsimulations for different solutions for the roundabout and investigated the change in delays. Aakre and Aakre (2017) mention that microsimulations are a great tool with a large potential for transit priority in roundabouts in addition to, that microsimulations can help in significantly reducing delays and emissions. One of their simulations was a throughabout design where there are yielding signs for the cars inside the roundabout, and thus only the cars that are in conflict with the buses have to yield (Aakre & Aakre, 2017). This resulted in that this roundabout design has higher throughput, which results in lower delays and more reliable travel times for all movements and vehicle types, compared to the design where there are traffic lights on all entering traffic that give priority to the buses (Aakre & Aakre, 2017).

Giæver and Tveit (2006) investigated multiple roundabouts and accessibility of public transport and make recommendations of improvement of a roundabout with trams in Oslo, Norway. They mention examples of different versions for roundabouts with trams and/or buses in Norway and other countries. Roundabouts generally have a low accident rate, as most crashes at a roundabout are material damage. In Oslo, the accident rate at an average roundabout is 0.07 personal injury accidents per million vehicles (Giæver & Tveit, 2006). Roundabouts with trams, however, have significantly higher accident rate. They mention that the main reason for this might be because tram roundabouts are not the average roundabout in Oslo and also that the location of roundabouts with trams are located in the city centre where there are higher volumes of pedestrians and complex traffic situations (Giæver & Tveit, 2006). Furthermore, they also mention that it is not unlikely that the trams are also contributing to higher accident rates (Giæver & Tveit, 2006). The tram roundabouts in Oslo are equipped with LED-lights for the circulating traffic that warn the drivers that are in conflict with the tram when it is approaching (Giæver & Tveit, 2006).
In Trondheim, Bergen, and Stavanger (Norway) are roundabouts where buses have priority. Traffic authorities and bus companies in those cities have shown a positive attitude toward roundabouts with a central lane for buses (Giæver & Tveit, 2006). In Gothenburg and Molndal (Sweden), are roundabouts with trams where the conflicts are controlled with traffic signals (Giæver & Tveit, 2006). In Melbourne (Australia) is also a similar system at one roundabout (Giæver & Tveit, 2006). Additionally, Zakeri and Choupani (2021) performed a research in Iran. Their study resulted in that throughabouts have better traffic flows than conventional roundabouts and that throughabouts reduced the number of injury accidents by approximately 50% over a 5-year period, compared to a conventional roundabout (Zakeri & Choupani, 2021). They concluded that changing a roundabout to a throughabout where BRT demand is high and needs to be prioritised is very beneficial (Zakeri & Choupani, 2021).
Norway and other countries seem to have an interest in a solution such as a throughabout as it gives priority to the buses and/or trams in a safe way and can reduce both queues and time delays for car traffic while being favourable for the buses as well.

Conclusions

There is a disagreement between some countries on the effectiveness and safety effects of roundabouts with BRT, and especially when there is an exclusive BRT lane though the centre island of the roundabout. Table 5 summarises the different views and the overall attitude which are inferred from research or views from the country's guidelines, road authority, and/ or the public transport operators in the countries. The table shows that France and Denmark have a negative attitude towards throughabouts, as they have experienced more accidents at throughabouts than at signalized intersections and therefore do not recommend them. On the other hand, Norway, Iran, and the Netherlands show positive views towards throughabouts, where they see increase in safety and overall happiness of the road authority and the bus companies in multiple cities.

Table 5 Summary of different attitude between countries on the effectiveness of roundabouts with BRT

Country/ Country of research	**Views/ Attitude/ Research on safety and effectiveness**	**Overall attitude**
France	More accidents at signalized throughabouts than signalized intersections (VSÓ Ráðgjöf, 2019).	Negative
Denmark	Do not recommend having a roundabout with BRT (VSÓ Ráðgjöf, 2019). Recommend changing to signalized intersections when implementing BRT (VSÓ Ráðgjöf, 2019).	Negative
Norway	Have 3 designs of roundabouts with BRT in their guidelines – all signalized throughabouts (VSÓ Ráðgjöf, 2019). Signals for entering traffic preferred due to more complexity and conflict points for signals for only those that are in conflict with the bus (Duduta et al., 2012; VSÓ Ráðgjöf, 2019). Overall positive attitude with traffic authorities and bus companies where there is a roundabout with BRT (Giæver & Tveit, 2006).	Positive
Iran	Throughabouts reduce injury accidents and crashes by 50% over 5-years compared to conventional roundabouts and signalized intersections (Zakeri & Choupani, 2021).	Positive
The Netherlands	Guidelines suggest when public transport has priority at roundabouts to give the required priority by adding exclusive lanes and/or signals (CROW, 2015).	Positive

3.2 Active mode users' safety in roundabouts

Often, BRT lines are located inside cities. This means that in many areas where BRT lines are, active mode users are also present, especially in city centre areas. For this reason, the safety and accessibility of active mode users has to be considered.

Roundabouts are generally considered a safer intersection than conventional T- or X-intersections due to fewer conflict points, simpler and less severe conflicts, and lower speeds (Gruden et al., 2022). However, roundabouts are not necessarily safer for pedestrians and other active mode users, as the crossings are usually not signalized (Gruden et al., 2022).

Many studies have showed that roundabouts are much safer than conventional intersections (Dijkstra, 2005). By changing a X-intersection to a roundabout decreased cyclist casualties by about 60% and car casualties reduces by about 75% (Dijkstra, 2005). However, these studies focused mainly on traffic flow and road safety and not the safety of active mode users such as cyclists and pedestrians. In previous years, some studies have been performed on the safety of cyclists in roundabouts, but even less studies have focused on pedestrian safety in roundabouts.

3.2.1 Safety of cyclists in roundabouts

Several analyses have been performed on the safety of cyclists in roundabouts. The main results from studies show that the safest infrastructure design for cyclists is to have a separate cycle path outside of the circulatory road of the roundabout (Dijkstra, 2005; Høye, 2017; Jensen, 2017; Kennedy, 2007; Poudel & Singleton, 2021). In roundabouts where the cycle path is a part of the road, as a cycle lane or where cyclists share the lane with cars, there is a significantly higher risk of a collision with a car (Dijkstra, 2005; Høye, 2017; Poudel &

Singleton, 2021). The number of casualties of cyclists are about the same for roundabouts where the cyclists share a lane with cars and where there is a cycle lane (Dijkstra, 2005). When the cyclists are on the circulating road, sharing the road with the cars, the most common crash occurs when a driver that is entering the roundabout fails to see the cyclist that is in the roundabout and therefore, does not yield, leading to a crash (Høye, 2017; Poudel & Singleton, 2021).
By giving cars priority when exiting and entering the roundabout is safer for cyclists (Dijkstra, 2005; Høye, 2017; Jensen, 2017; Poudel & Singleton, 2021). At a roundabout where there is a cycle path, separated from the car lane, the cyclists cross the exiting and entering links of the roundabout at a similar place as pedestrians. Dijkstra (2005); Høye (2017); Jensen (2017); Poudel and Singleton (2021) show that when cyclists have to yield to cars at these crossings, fewer crashes occur between cars and cyclists.
The design of the roundabout and cycle path is also important, as the safety of pedestrians and cyclists largely depend on the design of the roundabout (Høye, 2017). Jensen (2017) mentions that roundabouts with central islands that are 20-40m in diameter are safer for cyclists than larger or smaller islands. Poudel and Singleton (2021) mention that roundabouts with a separate cycle path are more comfortable for the cyclists. Additionally, the direction of the cyclists' route is important. When there are two way cycle paths, the risk of an accident between a car and cyclist is higher at an entrance or an exit (Høye, 2017). More accidents happen when a cyclist is coming in the opposite direction to the car traffic, and there is a greater uncertainty of who should yield when there is a two way cycle track (Høye, 2017).

The main conclusions of the safety of cyclists in roundabouts is summarised in the list below.

- It is safer to have a separate cycle path than a cycle lane or that cyclists share the road with cars.
- Most crashes occur at the entrance or exit of a roundabout, even with a cycle lane or a shared road with cars.
- Cyclists yielding to cars at crossings is safer for cyclists.
- Two-way cycle paths in a roundabout can be confusing and increases the risk of an accident between a cyclist and a car.

3.2.2 Safety of pedestrians in roundabouts

Pedestrian safety at roundabouts seems to have had limited research so far, but some research has been done in the last few years and pedestrian safety at roundabouts is starting to get more attention. Studies show that roundabouts are also safer for pedestrians than conventional intersections due to reduced speeds and fewer conflict points (Gruden et al., 2022). However, roundabouts are typically viewed as more dangerous than conventional types of intersections by pedestrians (Gruden et al., 2022). There are many factors that can affect the safety of active mode users. Few of these factors are the speed of cars, the roundabout design, and the crossing behaviour of pedestrians.

Speed in roundabouts

The speed of cars in the roundabout and when entering and exiting is a very important factor when it comes to pedestrian safety. Studies have shown that by decreasing the speed of cars from 48km/h to 32 km/h, the number of pedestrian casualties can be reduced by a factor of 3 or 9, or from 45% to 15% or 5 % (Fortuijn, 2003; Gruden et al., 2022). Hallgrímsdóttir et al. (2019) show that when cars are in free flow, there is a large difference between the speed of cars in one-lane roundabouts and two-lane roundabouts. The difference in speed of cars when entering the roundabouts and exiting is 5km/h for two lane roundabouts but less than 1km/h for single lane roundabouts (Hallgrímsdóttir et al., 2019). This shows that the speed of cars in one lane roundabouts is more constant than for two-lane roundabouts, where cars can increase their speed and have more room when in free flow.

Roundabout design

The design of the roundabouts also contributes to the pedestrian safety, as the design can have an effect on the speed of cars in the roundabout. Two-lane roundabouts have larger geometry and can lead to higher speeds (Hallgrímsdóttir et al., 2019; Kennedy, 2007). Fortuijn (2003) mentioned that deciding on the curvature on two-lane roundabouts might cause a dilemma, where increased curvature might increase the number of collisions between cars while a decreased curvature will increase the speed of cars which can lead to more severe accidents between cars and active mode users. The guidelines for the size and views of roundabouts can differ between countries. For instance, the Swedish, Danish, and Norwegian guidelines for roundabouts generally have larger designs than the guidelines in Germany, France, and the Netherlands (Kennedy, 2007). Two-lane roundabouts are generally not included in design guidelines or standards of many countries or only have a very limited section (Kennedy, 2007). Few guidelines even state that two-lane roundabouts are not recommended in urban areas (Kennedy, 2007).

Roundabout guidelines have also guidelines for pedestrian crossings at roundabouts. The type of crossing depends on the traffic flow, whereas where traffic flow is low, an informal crossing is acceptable but for higher flows and also where there are a lot of pedestrians, the crossing should be more formal and close to the roundabout (Kennedy, 2007). If there is a signal crossing for active mode users, that crossing should be located further away from the roundabout to avoid confusion and queuing into the roundabout (Kennedy, 2007). Additionally, it is generally not recommended to have an unsignalized pedestrian crossing where the pedestrians have to cross two or more lanes with traffic going in the same direction at a time (Hallgrímsdóttir et al., 2019; Hallgrímsdóttir et al., 2020).

Gap acceptance and crossing behaviour

When pedestrians (and cyclists) must cross an unsignalized crossing, such as a crossing at roundabouts, they must evaluate the gap between cars that they deem acceptable and safe. This gap acceptance can differ between countries due to multiple things, such as different behaviour, yielding behaviour, the visibility of the crossing, and different designs of both the roundabout and the crossing (Gruden et al., 2022). Gruden et al. (2022) performed a study where they investigated roundabouts in both Italy and Slovenia with regards to pedestrian safety and then compared the pedestrian crossing behaviour. They used the surrogate safety measures, Time-to-Conflict (TTC), Post Encroachment Time (PET), and the difference in speed between the cars and pedestrians to evaluate the severity of the conflicts. When they compared the crossing speed of the pedestrians, they noticed that in both countries the crossing speed is higher than at signalized intersections. This might indicate that pedestrians feel less comfortable when crossing unsignalized crossing and try to spend the shortest time crossing (Gruden et al., 2022). However, Gruden et al. (2022) also noticed a difference in the crossing speeds between countries, this could be because of different yielding behaviours in the countries whereas in Slovenia drivers are used to yield for pedestrians and stop the car with a large distance from the crossing, this might encourage the pedestrians to cross immediately and not stop completely before crossing, leading to faster crossing speeds. Unlike Slovenia, the yielding behaviour in Italy is different where the drivers stop closer to the crossing, which lead to that the pedestrians stop and wait until the car is completely stopped before crossing, leading to slower crossing speeds (Gruden et al., 2022).

There have been some conflicting arguments about the location at the roundabouts where pedestrian risk is the highest (Gruden et al., 2022). Some studies show that the most risk for pedestrians is at the exiting legs of the roundabout and at two-lane roundabouts, while other studies show that the highest risk is at the entering legs, and by controlling that area will decrease risk at the exiting legs as well (Gruden et al., 2022). Despite these conflicting arguments, pedestrians are exposed to a high risk of collision with a vehicle at crossings, at all legs of the roundabout, as well as that the risk is higher at two-lane roundabouts.

Pedestrian safety can be improved when crossing a BRT lane (or tramway), at all intersections as well as roundabouts, by installing warning bells that sound when a bus or a tram is approaching, in addition to flashing lights and possibly gates (Tzouras et al., 2020). Additionally, pedestrians are often unfamiliar or ignorant of the risks of interaction with priority public transport, such as trams and BRT (Tzouras et al., 2020). A design of an offset pedestrian crossing could increase the awareness of the people, however, a survey showed that, active mode users perceive a low crash risk with a tram and most respondents feel there is a low probability of being in a crash or an accident with a tram (Tzouras et al., 2020). Trams and BRT often have very similar features in how they are aligned and prioritized in cities and therefore, it can be assumed that this underestimation of the potential risks could also apply for a BRT.

The main conclusions for the safety of pedestrians in roundabouts are summarised in the following list.

- The speed of cars affects the safety of pedestrians.
- Two-lane roundabouts are less safe as the speed is higher than in one-lane roundabouts.
- The curvature and geometry of roundabouts can affect the speed of cars, which affects the safety of pedestrians.
- Larger roundabouts are less safe for pedestrians, if not signalized, as they have to cross more lanes unprotected.
- The crossing behaviour at roundabouts can differ between countries and should be calibrated depending on the behaviour of both pedestrians and car drivers.
- Highest risk for pedestrians at roundabouts is at crossings, at all legs of the roundabout, and the risk is higher at larger roundabouts.
- Pedestrians often underestimate the potential risk of an accident with a tram or BRT.

The safety of active mode users can be affected by multiple things, especially the design of the roundabouts. When considering new roundabout designs, it is important to keep these factors in mind to lower the risk for accidents of active mode users especially where the numbers of active mode users are high.

3.3 Research gaps

From the literature review chapters above, few research gaps can be identified. One research gap identified is that there are few and unclear guidelines for roundabouts with BRT and countries have come up with design solutions but disagree on the effectiveness and safety of roundabouts with BRT.

Another research gap identified is that the research on pedestrian safety at roundabouts has been very limited so far. Additionally, when roundabout designs have been evaluated, pedestrians have not been included and bicyclists have been included few times. As mentioned in the paper by Giæver and Tveit (2006), roundabouts with trams/BRT might be more popular in the city centre where there are many pedestrians. Furthermore, there should be good walking and cycling access along and to the BRT network. Therefore, it is important to include pedestrians and cyclists in the design and planning process.

This research will focus mostly on the first research gap identified, where the goal of the research is to develop a methodology that can evaluate different roundabout designs. This goal attempts to gain more knowledge on the effectiveness of roundabouts with BRT and find some criteria that can be used to evaluate the designs. The research also has a small focus on the second research gap identified as it includes active mode users and their safety in the evaluations.

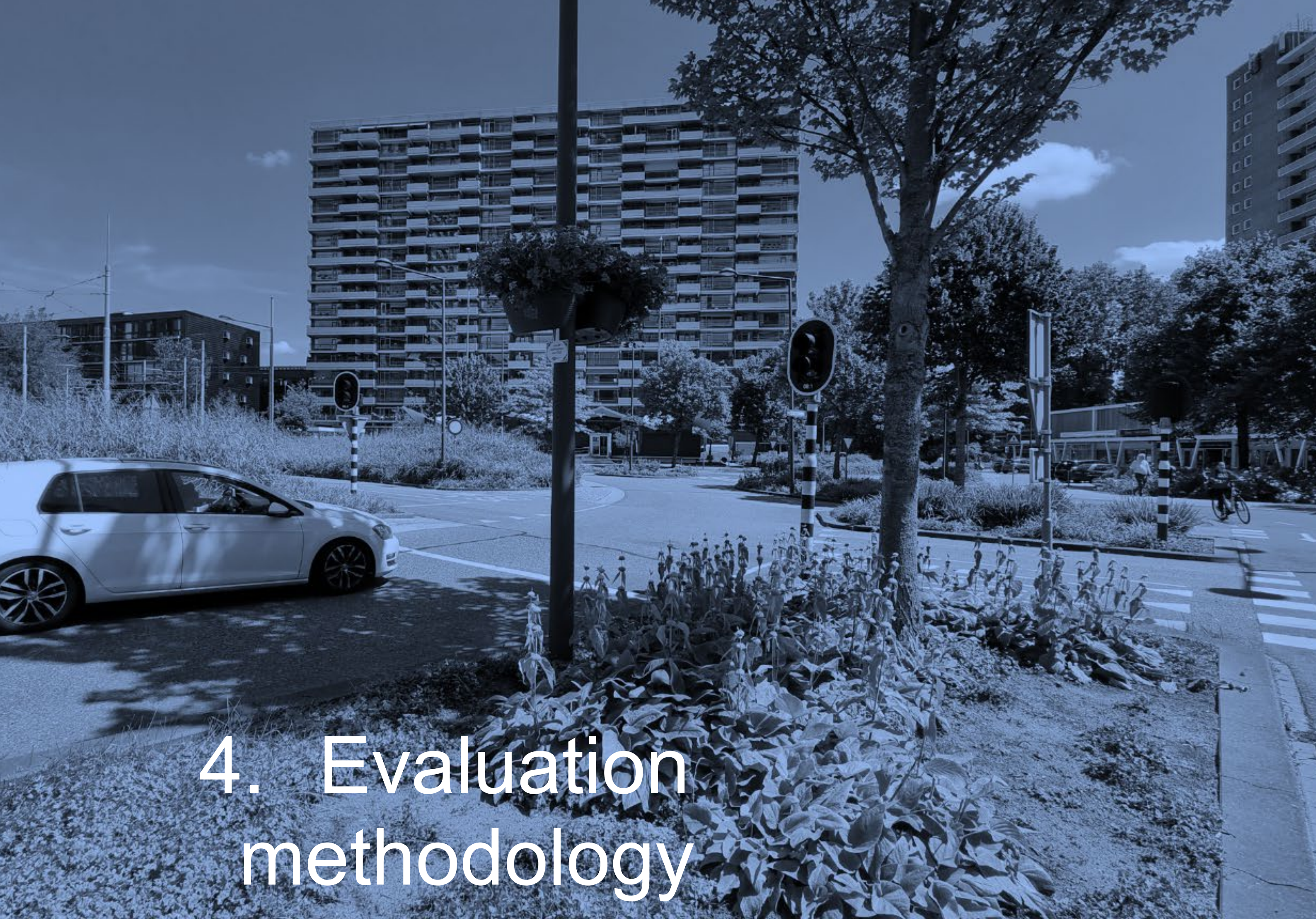
3.4 Conclusions

Table 6 summarises the key findings of the literature review, where it is divided up into the main topics of the above sections. The second column shows the papers that are relevant for each topic are mentioned, and the third column has a short summary of the key findings for each topic. Some papers are listed more than once in the table, as they covered more than one topic mentioned.

Table 6 Literature review summary table

Topic	Papers	Key findings
Cyclists' safety at roundabouts	(Dijkstra, 2005), (Høye, 2017), (Jensen, 2017), (Kennedy, 2007), (Poudel & Singleton, 2021)	It is safest to have a cycle path separate from the road and cyclists should yield to cars at crossings.
Pedestrian safety at roundabouts	(Fortuijn, 2003), (Gruden et al., 2022), (Hallgrímsdóttir et al., 2019), (Hallgrímsdóttir et al., 2020), (Kennedy, 2007)	Car speed in roundabouts is an important factor for pedestrian safety. Roundabout designs can have an effect on the speed and visibility of crossings. The highest risk for pedestrians is at crossings and at two lane roundabouts.
Exclusive Public transport lanes	(Duduta et al., 2012), (Tzouras et al., 2020), (VSÓ Ráðgjöf, 2019)	Having exclusive and separate lanes from car traffic increases safety and reliability of the service, and decreases driving stress of the public transport drivers. Left turns crossing the bus lanes at intersections are less safe than intersections only allowing right turns.
BRT in roundabouts	(Aakre & Aakre, 2017), (Bråtveit, 2016), (Frøyland et al., 2014), (Giæver & Tveit, 2006), (ITDP, 2017), (VSÓ Ráðgjöf, 2019), (Zakeri & Choupani, 2021)	There are many types of solutions for roundabout designs with BRT. Throughabouts have higher capacity than other types of design. Priority signal for BRT might be problematic where there is heavy traffic or where the bus route crosses a main road.
Effectiveness and safety impacts of roundabouts with BRT	(Aakre & Aakre, 2017), (Bråtveit, 2016), (Giæver & Tveit, 2006), (VSÓ Ráðgjöf, 2019)	There are different views on the effectiveness and safety impacts of roundabouts with BRT in different countries. Some have a positive experience and see reduced number of crashes, while others have seen more accidents in throughabouts than at signalized intersections.

The purpose of the literature review was to help to answer sub-question a, which is about what solutions or guidelines on the safety and roundabouts with BRT that have been developed in different countries.
The sub-questions of sub-question a further ask about what types of roundabout solutions have been found for roundabouts with BRT, in addition to what roundabout designs are safe for active mode users. The information gained in this chapter answers sub-question a.
There are many types of design solutions that have been found for roundabouts with BRT. These designs can range from where the bus merges into mixed traffic from its exclusive lane and crosses the intersection with mixed traffic, to designs where the exclusive bus lane goes through the centre island of the roundabout and the buses get full priority when crossing the intersection. There are some variations of how the buses can get priority with different locations of traffic signals, yielding rules, or warning lights.
Additionally, the safety of active mode users in roundabouts is considered. Factors such as the speed of vehicles, the size of the roundabout and separation of bicycle path from the vehicles have an effect on the safety of active mode users.
The literature review resulted in that there are few clear guidelines or criteria from countries that evaluate roundabout designs with BRT. Chapters 4.1 and 4.2 discuss in more detail about possible criteria that can be used to evaluate the effectiveness and safety of different designs and the safety of active mode users. That information is then used to continue making the evaluation methodology in Chapter 4.3 and 4.4. Then a case study is used to test the methodology in Chapters 5 and 6.



4. Evaluation methodology

Chapter 3 answered sub-question a and gave answers to what solutions have been developed and information about safety of active mode users in roundabouts. This chapter's purpose is to answer sub-question b which asks about what criteria can be used to evaluate roundabout solutions. Sub-question b is divided into four sub-sub-questions, which ask in more detail about the evaluation methods, approaches to evaluate the safety and performance of all modes, and the stakeholders.

Chapter 2.1 discussed about different evaluation methods that can be used for evaluations, and MCA is chosen to be the best. To perform MCA, the criteria and weights have to be decided, which are discussed in this chapter.

This chapter's aim is to investigate what measures can be used to evaluate safety and the performance all modes, investigate what criteria can be used for the MCA evaluation of the roundabout design solutions, and investigate what stakeholders are involved in the decision making and how they weigh the criteria. These steps are a part of the evaluation methodology that sets up the evaluation and comparison of the alternative designs. Chapter 4.1 discusses further about the approaches to evaluate the safety and traffic performance of all modes. Chapter 4.2 discusses about the possible criteria that is investigated and the criteria that is used for the MCA. Chapter 4.3 discusses about the different stakeholders that are involved in the project. Finally, chapter 4.4 discusses about the normalization of the scores and weight sets used.

These chapters will set up the evaluation methodology in order to evaluate the alternative design solutions that are considered for an intersection.

4.1 Evaluation measures

Criteria such as throughput or flow, average speed, travel time, delay, etc. are criteria commonly used to evaluate the traffic performance of an intersection. The performance of cars and active modes can be evaluated by using these criteria. Evaluation criteria to measure the performance of public transport and to measure safety from microsimulation are less common. The performance of public transport service can be based on a pyramid of customer needs, defined by van Hagen and Bron (2014), where the safety and reliability are the most important factors. Chapter 4.1.1 discusses these factors and evaluation measures further. The safety of an intersection can be calculated from a microsimulation output by using surrogate safety measures and calculate the number of conflicts for a certain period for that intersection in SSAM. Chapter 4.1.2 discusses the surrogate safety measures and evaluation measures further as well as the SSAM computation process.

4.1.1 Evaluation of public transport system and performance

A large part of the advantages and selling points of BRT is that it is faster, more frequent, and more reliable than regular bus service. To try to increase the usage of public transport and get customers to enjoy using it, it is important to design the public transport system so that it satisfies the customers' needs (Vuchic, 2005). Customers' needs can be ranked in a pyramid where the most basic needs are at the bottom, similar to Maslow's hierarchy of needs (van Hagen & Bron, 2014). Figure 16 shows the pyramid of customer needs. The most basic needs of customers are safety and reliability (van Hagen & Bron, 2014; Vuchic, 2005). Customers want to feel safe in travelling by the public transport service, and if they feel unsafe, they will avoid using it (van Hagen & Bron, 2014; Vuchic, 2005). Customers also want to have a reliable service, both in the sense that vehicles are on time and that the information the customers need is available and trustworthy (van Hagen & Bron, 2014). The next two needs, speed and ease, are so-called dissatisfiers, which means that if these do not meet the customer's expectation, it could have a negative effect of the view of the journey and mode (van Hagen & Bron, 2014). Speed can also be travel time, customers want to have their trip as short as possible from door to door (van Hagen & Bron, 2014; Vuchic, 2005). When the need of a fast trip has been fulfilled, then the customer wants the trip to be easy and convenient (van Hagen & Bron, 2014). To make the trip easy, travel information should be helpful, clear, and easy to understand (van Hagen & Bron, 2014).

The top two needs, comfort and experience, are so-called satisfiers, which means that if the customer values the trip positively, these factors are noticed (van Hagen & Bron, 2014). Customers expect some kind of physical comfort both on the public transport vehicle and at stops/ stations (van Hagen & Bron, 2014). This could be sheltered waiting areas, air conditioned environment, available seating, comfortable seats in the vehicle, and more factors that can be both physical and psychological (van Hagen & Bron, 2014; Vuchic, 2005). The customer's experience can be influenced by many things, such as design, cleanliness, lighting, smell, and music. At stations, having facilities such as shops and cafes can also enhance the experience (van Hagen & Bron, 2014).

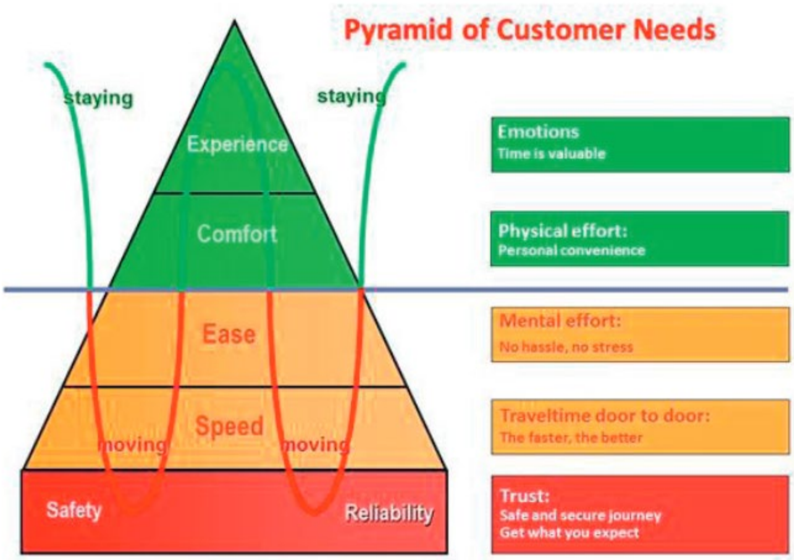


Figure 16 Pyramid of customer needs (van Hagen & Bron, 2014)

To measure the performance (or Level of Service) of a public transport service with microsimulation, the reliability and speed can be measured. The speed and reliability of the service can be shown by the average travel time and the standard deviation of the travel time and compare the travel time to a free flow travel time (Vuchic, 2005).
In this thesis, the trave time, and the variation in travel time of the BRT and bus services are considered. The variation in travel time can indicate the reliability of the service and the travel time is related to speed. The other parameters in the pyramid of customer needs are more related to the experience of the passengers, the stops, the bus service, etc. which is not being modelled in this research.

4.1.2 Safety evaluation of intersections with microsimulation

Chapter 2.2.2 mentions that SSAM can be used to calculate the number and types of conflicts based on surrogate safety measures and the vehicle trajectories from the simulation. Surrogate safety measures refers to "measures other than actual crash frequency" (Gettman et al., 2008). The surrogate safety measures mainly used in SSAM, and in this research are Time-To-Collision (TTC) and Post Encroachment Time (PET). TTC is the measure of the time until two vehicles would collide if they continue driving at their current speed and trajectory (Gettman et al., 2008). PET is the measure of the time difference between that the first vehicle leaves the conflict area of the two vehicles and the time when the second vehicle enters that area (Gettman et al., 2008). SSAM calculates all potential conflicts that could result in a crash. A conflict can be defined as a noticeable situation where two or more road users are approaching each other that could result in a crash if their speed and path does not change (Gettman et al., 2008).

Explanation of SSAM computation

SSAM works in a way that it takes a file with all the vehicle trajectories over the whole evaluation period from a simulation software (VISSIM) and looks at each interaction between vehicles and determines if it is classified as a conflict or not (Gettman et al., 2008). The trajectories from VISSIM do not identify different types of vehicles or road users and therefore, SSAM does not identify different road users as well. However, SSAM can filter conflicts based on links and therefore, can identify special active mode – vehicle conflicts because those modes always use separate links.
When SSAM is processing the trajectory files, it creates a grid of the network of rectangular zones, and the vehicles are placed on the grid as rectangles as well. SSAM looks for each vehicle and each time step the placement of the vehicle if it were to continue on its future path with its current speed (Gettman et al., 2008). The future placements are looked at from the current time step until the set threshold of the TTC (Gettman et al., 2008). This TTC threshold is usually 1.5 seconds (Gettman et al., 2008; Wu et al., 2016). For each vehicle pair, SSAM checks if at any time the two vehicles are in the same zone. If they are in the same zone, it is checked if the vehicles overlap and if they overlap, it is recorded as a conflict, that is, if it has not been recorded so far (Gettman et al., 2008). If vehicles did not overlap in any projection between 0 and the TTC threshold, SSAM checks for PET conflict (Gettman et al., 2008). If the time until the PET threshold has elapsed and no conflict has been recorded, the vehicle pair is no longer considered for a potential conflict (Gettman et al., 2008). Before the vehicle pair is no longer considered for a potential conflict, the remaining three surrogate safety measures, deceleration rate, maximum speed, and difference in speed, are computed, in addition to the conflict starting and end points, conflict angles, and the conflict type (Gettman et al., 2008). SSAM differentiates between three different conflict types, crossing, rear- end, or lane-change. The conflict type can be determined based on the angle of the hypothetical collision or the link and lane location of both vehicles at the starting and end point of the conflict (Gettman et al., 2008). The conflict angle is measured from the perspective of the first vehicle, where 0° means a collision from behind and 180° means a head on collision, Figure 17 shows an illustration of the conflict angles.

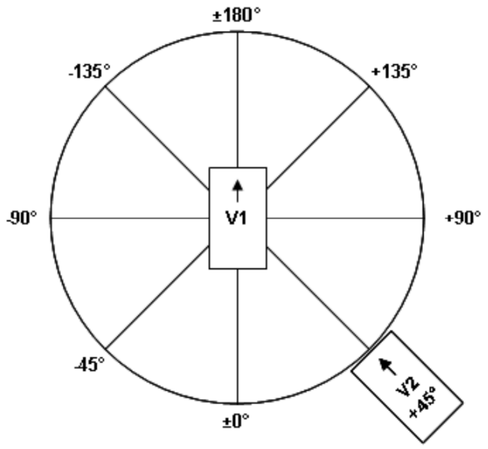


Figure 17 Illustration of conflict angles (Gettman et al., 2008)

The type of conflicts can be determined by the conflict angle, where angles between 85° and 180° are considered crossing conflicts, angles between 0° and 30° are considered rear-end conflicts, and angles between 30° and 85° are considered lane-changing conflicts (Gettman et al., 2008).
The type of conflicts can also be influenced by the link and lane location of the vehicles at the start and end of the conflict. If both vehicles are on the same link and lane both at the start and end of the conflict, then the conflict is considered rear-end conflict. If either vehicle ends on a different lane on the same link than it was on when the conflict started, the conflict is considered a lane change conflict. If either vehicle changes links during the conflict, or they are not on the same link, the conflict angle determines the type of conflict (Gettman et al., 2008).

By using SSAM for safety evaluations of intersection design, multiple alternatives can be compared and their safety effects as well. This can lead to that a safer option is chosen rather than an option would be built and then waited to see if there were any safety effects.

Limitations of SSAM
A limitation to SSAM is that it was made to be used to only identify conflicts between vehicles, and therefore does not differentiate between different road users. However, Muley et al. (2018) and Wu et al. (2016) performed studies where they showed that SSAM can also be used to determine conflicts between pedestrians and vehicles. SSAM is able to graphically show the location and severity of the conflicts but is not able to identify between what modes the conflicts are (Muley et al., 2018). Therefore, if it is wanted to use SSAM to identify conflicts between more than one combination of modes, for example identify all vehicle-vehicle, vehicle-pedestrian, or vehicle-bicycle conflicts, some extra steps will have to be taken to identify the type of conflict.
SSAM takes the VISSIM output trajectory files as an input and uses the vehicle trajectories to calculate the number of conflicts. In order to get trajectory files for pedestrians, they must be modelled as vehicles, with human characteristics and behaviour (Muley et al., 2018). However, by modelling the pedestrians as “vehicles” they have very limited interaction with each other, and are modelled by the car-following model, like the cars, and move in a mechanical way and in a single line[2]. VISSIM has an extension called VISWALK where pedestrians are modelled using the social force model where they can interact with each other and instead of walking on one-directional links there are pedestrian areas where they can walk and interact with

[2] PTV Group. *PTV VISSIM 2020: User Manual.* Traffic flow model and light signal control, pg. 27

pedestrians from all directions, which is more like real situations[3]. Both Wu et al. (2016) and Muley et al. (2018) tried to model the pedestrians using VISWALK at first, but found out that the trajectory files for the pedestrians were not created. Therefore, SSAM can be used to identify conflicts between vehicles and pedestrians, only if pedestrians are modelled as vehicles and not using the VISWALK extension.
As a result from their studies, Muley et al. (2018) and Wu et al. (2016) found that SSAM can properly identify the location of all conflicts and there is a strong statistical relationship between simulated conflicts and real conflicts, but SSAM tends to overestimate the number of vehicle conflicts and underestimate vehicle – active mode conflicts, compared to a video of that same location which was modelled. The underestimation of vehicle – active mode conflicts might be from the limitation of that modelling the active mode users and illegal behaviour (of all modes) cannot be modelled in VISSIM (Muley et al., 2018; Wu et al., 2016).
To make a model that represents real situations in VISSIM and SSAM, it is recommended that the model is well calibrated. When identifying the type and severity of a conflict in SSAM, the parameters TTC, PET, change of speed and acceleration, and conflict angles can be considered (Muley et al., 2018). The default parameters are 1.5 seconds as maximum TTC and 5 seconds as maximum PET values (Wu et al., 2016). However, these values are for vehicle – vehicle conflicts and active mode – vehicle conflicts are different from vehicle-vehicle conflicts and therefore, these threshold values need to be reconsidered for different types of conflicts (Wu et al., 2016). Wu et al. (2016) performed a study in Florida where the TTC and PET values were found from observed pedestrian-vehicle conflicts from videos. This resulted in that the calculated, mean average percent error was that the threshold value of TTC should be 2.7 seconds and the threshold for PET should be 8 seconds for vehicle-pedestrian conflicts (Wu et al., 2016). Muley et al. (2018) performed a similar study as Wu et al. (2016) but in Qatar, which resulted in that the best fit between simulated and observed conflicts between pedestrians and vehicles were 2.7 seconds as the maximum TTC value and 8 seconds as the PET value, which is the same result as Wu et al. (2016) found.

Conclusions
SSAM uses trajectory files from VISSIM or other microsimulation software and uses that to calculate the number of conflicts that occurred during the evaluation period of the simulation. SSAM has a limitation as it is only made to identify conflict between vehicles, however, conflicts between active modes and vehicles can be calculated by filtering the conflict data based on links and location for instance. The TTC and PET thresholds for conflicts between vehicles and conflicts between active mode users and vehicles are different. For this research, the TTC value for vehicle conflicts is 1.5 seconds and PET threshold of 5 seconds. For the active mode – vehicle conflicts a TTC threshold of 2.7 seconds and PET of 8 seconds is used, which are based on the research of Muley et al. (2018) and Wu et al. (2016).

4.2 Evaluation criteria
When thinking about what criteria could be used for MCA evaluation, multiple criteria come to mind. Due to limitation in data availability, output from VISSIM, time, the complexity of the MCA setup, and more, it's not reasonable to use all criteria that comes to mind. The criteria considered in this chapter can be divided into three criteria groups of traffic performance, safety, and other. Indicators such as costs, accessibility, and road alignment are considered in the 'other' criteria group. The following sub chapters will discuss possible criteria, and the criteria used for the remainder of the research.

[3] PTV Group. *PTV VISSIM 2020: User Manual.* Simulation of pedestrians with PTV Viswalk, pg. 25.

4.2.1 Traffic performance indicators

Traffic performance indicators are one of the main criteria used in this research. The traffic performance indicators can help evaluate the effectiveness of the intersection as they can indicate if there are changes in travel time, capacity, and flow for example.

There are a lot of traffic performance indicators that can be used for the evaluation. However, many of them are correlated with each other. The following list includes the performance indicators considered as a criterion.

- Total throughput or flow
- Capacity of intersection
- Travel time
- Delays
- Complexity of BRT route
- Number of stops (unplanned)
- Time stopped
- Speed
- Variation in travel time

Many of these indicators can be investigated after the simulations and be analysed and compared between the designs before the MCA is performed, but only the main indicators are included in the MCA. This is mainly due to correlation between many of the indicators.

The indicators that are not included in the MCA, but are investigated are the average speed, the number of stops and time stopped. By investigating these numbers and comparing between the design solutions, it can be concluded if the change in travel time might be from long stop and go queues or from slow traffic, for instance. Additionally, it is good to record these parameters, especially speed and travel time, for free flow conditions. This allows a comparison of the average speed and travel time between free flow conditions and the simulated design where the free flow case is used as a reference.

Indicators that are considered for both the comparison between design solutions and the MCA are travel time, total throughput of the intersection per hour, and variation in travel time. The indicators of delay, speed, time stopped, number of stops are not used in the evaluation methodology because of the correlation between them and travel time. Because the travel time becomes longer with more delays, the average speed becomes lower with more stops, and the delay becomes longer with more and longer stops as well. Because of this correlation, only **travel time** is considered in the MCA. Knowing of this correlation between the indicators and choosing only one of them mitigates the limitation of double counting of the MCA method. Additionally, the **throughput** per hour is used as a criterion. The throughput can indicate how much volume can go through the intersection in an hour. Furthermore, the **variation in travel time** is used as a criterion. This indicator is a good one to include, especially for the public transport, because it can indicate if there are many variations in the travel time, which affects the reliability of the public transport service.

4.2.2 Safety indicators

Safety is the other main criteria used in the analysis of the effectiveness of the different designs. The safety indicators can help with assessing the safety of the intersection design.

- Number of conflict points
- Conflicts between vehicles – crossing, rear end, and lane-changing conflicts
- Conflicts between active mode users and vehicles
- Number of lanes active mode users have to cross
- Signalized crossing for active mode users

The number of conflict points, conflicts between vehicles, and conflicts between active mode users and vehicles are considered when comparing the design solutions. The number of conflict points are not included in the evaluation methodology. This is because the three designs considered are similar to each other, and the number of conflict points are similar for all designs.

For this research, the **conflicts between vehicles** and **the conflicts between active mode users and vehicles** are considered as criteria in the evaluation methodology. The conflicts between vehicles can give an indication of how many conflicts are occurring at the different designs. The trajectories of all vehicles are taken from VISSIM and put into SSAM where these conflicts are calculated. Conflicts between vehicles can either be crossing, rear end, or lane change, where the crossing conflicts are the most severe and are especially wanted to minimise. The conflicts between active mode users and vehicles are collected the same way as the other conflicts. However, as the active mode users are only on the active mode crossings, only crossing conflicts are occurring. These conflicts can indicate how many potential crashes or accidents are reduced or increased between different design solutions.

4.2.3 Other indicators

There are a lot of other indicators that could be considered when evaluating intersection design. These are factors such as environmental factors, geometrical design factors, costs, land use, etc. Some of these factors are listed below.

- Emissions
- Noise pollution
- Costs
- Comfort
- Accessibility
- BRT alignment
- Size of roundabout
- Land use

For the purpose of this research, only **costs** are considered as other indicators in the MCA. Factors such as the size of roundabout and BRT alignment would be appropriate factors to include as well, but in this research the size is the same in each design solution and the BRT alignment changes very little between designs. The costs are included in the MCA in a qualitative way, where the exact value of costs is not known but rather valued if the cost is low, medium, or high.

4.2.4 Conclusions

There is a long list of criteria to choose from for a multicriteria analysis. For this research, it was chosen to split the first level of criteria into three criteria groups of traffic performance, safety, and other. Each of these criteria have sub criteria, which are split even further into other sub criteria levels. The sub criteria (level 2) of traffic performance includes the throughput, travel time, and variation in travel time. The travel time and variation in travel time will then have further sub criteria of direction and mode, which are in criteria levels 3 and 4. The sub criteria (level 2) of safety includes the number of conflicts between vehicles and the number of conflicts between active mode users and vehicles. The conflicts between vehicles are then further split up into types of conflict of crossing, rear end, and lane-changing conflicts, which are in criteria level 3. The conflicts between active mode users and vehicles only consist of crossing conflicts. For the other criteria, only costs are included. The setup of the list of criteria can be seen in Figure 18.

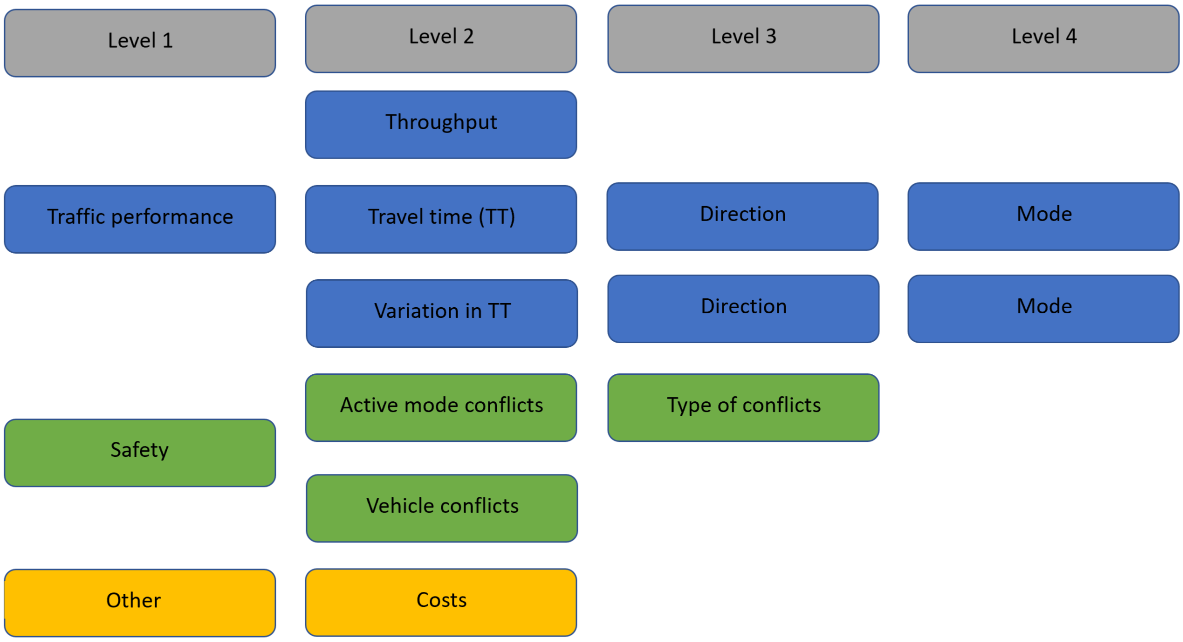


Figure 18 Setup of the MCA criteria and the criteria levels

4.3 Stakeholders

As mentioned in chapter 2.1.2, the subjective nature of the MCA is reduced by creating multiple weight sets, which are made from the view of different stakeholders. There are multiple stakeholders that could be used for stakeholder analysis for an intersection like this, such as the society, governmental authority, public transport operator, passengers, property owners, and road owners. For a stakeholder analysis, usually stakeholders that have decision power on the things that are being investigated are considered. This is because those that hold the decision power are more likely to use the results as guidelines in planning and designing processes, and the results of the analysis can help that process as well. For this research and case study, the stakeholders considered are the municipality of Reykjavík, as the intersection is in Reykjavík and the municipality owns the road going North and South, and they are involved in the Borgarlinan project. Another stakeholder considered is the Icelandic Road and Coastal Administration (IRCA), as they are also involved in the Borgarlinan project, and they own one of the roads of the intersection considered. Additionally, a third stakeholder is considered, which is the public transport authority in the capital area of Iceland, Strætó bs. Strætó is the operator of the public transport services in the capital area of Iceland and it also manages and takes care of the bus services and network, as well as providing on demand services for disabled and elderly people (Strætó bs., n.d.-a).
By performing stakeholder analysis, the results of the MCA might not be that a one alternative is the best, but rather the results will indicate if different views from different stakeholders have an effect on the results. The results could be that there is the same best case for all stakeholders, or always the same worst case, or any combination of ranking of alternatives. This can result in a better overview of the effectiveness on the different designs and can help with making the final decision of a design.
When choosing the weights for different stakeholders, one way is that the weights are chosen by the researcher, with reasoning from sources and expert judgement. This way will be used in this research. It is, however, recommended that for future research that the stakeholders give their views on the scores or weights of the MCA. This can be done by performing surveys and ask the different stakeholders questions, this could result in a more realistic weights that could be used for multiple studies.

To gain more information about the views and goals of the stakeholders, an email was sent to a representative of both the municipality of Reykjavík and IRCA to inquire about inputs from them about weights for the criteria considered in this thesis. An answer from the municipality of Reykjavík indicated that they did not have much data or experience with using MCA but were able to tell their views and goals related to the criteria considered and provided their municipal and safety plans for background information on those goals (G. L. Erlendsdóttir, personal communication, 7 June 2022). No reply came from IRCA, however, their website, vegagerdin.is, has their goals and safety plan accessible, which are used to assume and estimate weights from. The focuses and goals of Strætó bs. could be found on their webpage, streato.is. Furthermore, since there is little experience or data about using MCA in Iceland, it is recommended that future research will be performed where stakeholders can answer surveys and more data on weights can be collected for more accurate weights for future evaluations.

4.3.1 Municipality

One of the main decision powers for this intersection and multiple others in Reykjavík is the Municipality of Reykjavík. The municipality of Reykjavík is one of the parties that signed the agreement about the development of transportation infrastructure and public transportation in the capital area of Iceland for the next 15 years (Stjórnarráð Íslands). This agreement and the projects with it are discussed more in detail in chapter 5.1.1. Because of this, the Municipality of Reykjavík is a stakeholder in the case study for this research.

The municipality's goals and focuses include the new road user hierarchy, as introduced in chapter 1.2.1, and vision zero (Kröyer, Hallgrímsdóttir, & Stefánsdóttir, 2020; Reykjavíkurborg, 2021).The new road user hierarchy means that pedestrians, cyclists, and other active mode users are at the top of the hierarchy triangle and therefore are viewed the most important road users, as seen in Figure 19 (Reykjavíkurborg, 2021). Vision zero means that there should be no fatalities or serious injuries from traffic accidents (Kröyer et al., 2020).

For the municipality's point of view, this means that they value safety, especially the safety of active mode users, higher than traffic performance (G. L. Erlendsdóttir, personal communication, 7 June 2022). They also want to build cities for the people and focus on good accessibility for all modes, especially active modes and public transport (Kröyer et al., 2020).

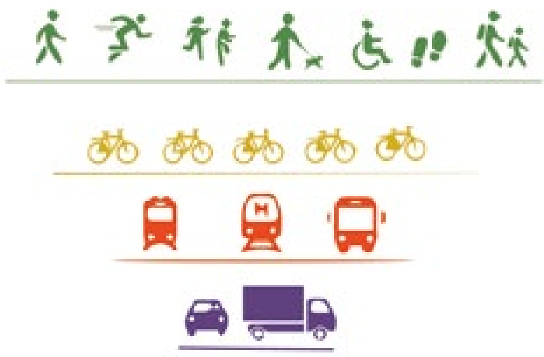


Figure 19 Road user hierarchy

4.3.2 Road authority

Another main decision power for this intersection, and multiple other intersections in the whole country, is the Icelandic Road and Coastal Administration (IRCA). The IRCA owns and oversees the main roads in Iceland (all roads outside of urban areas, and the main through roads in urban areas). In the case study considered in this research, the IRCA owns the road Hringbraut, which goes from South-East to North-West.

The IRCA's goals and focuses include that transport should be safe, accessible, and easy (Vegagerðin, n.d.). They also follow the vision zero views, where the safety plans state that the aim is to have no accidents leading to fatalities or serious injuries (Vegagerðin, 2022). Additionally, they are also involved in all the changes related to the transport agreement and favour eco-friendly and integrated transport networks (Vegagerðin, n.d.).
For the IRCA's point of view, this means that they also value safety above traffic performance, but they also want to make sure that access is good for all modes. Therefore, in comparison to the municipality, the IRCA might also give some focus on the traffic performance, which results in a smaller difference between the weight on the safety and traffic performance than for the municipality's point of view.

4.3.3 Public Transport authority

The third decision power for this intersection is Strætó bs. Strætó bs. is a regional association that is owned by the six municipalities of the capital area (Strætó bs., n.d.-a). It acts as the public transport authority because Strætó bs. focuses on the capital area as a whole and makes sure that there is access to public transport for the majority of people (Strætó bs., n.d.-b). Strætó bs. is also the operator of the public transport services in the capital area of Iceland, and manages and takes care of the bus services and network in the capital area, provides public transport service to the countryside, as well as providing on-demand services for disabled and elderly people (Strætó bs., n.d.-a).
The main goals of Strætó bs. are to provide good and high-quality service, by reducing travel time and increasing frequency. This can be done by providing more direct routes, adding exclusive lanes to the routes and having priority at signalized intersections (Strætó bs., 2020). Additionally, their goal is to make public transportation the first mode choice for commuting to work or school for the inhabitants in the capital area (Strætó bs., 2020). Strætó bs. also focuses on safe, quick and environmentally friendly travels to improve their services (Strætó bs., 2020, n.d.-c).
Therefore, for the public transport's authority point of view, the focus is mostly on the performance of the buses and their services and would therefore, weigh the traffic performance criteria higher than safety. The speed of the buses is an important factor for the performance of public transport, because with higher speed, both the operator and the passengers benefit from it, as the travel time becomes shorter, the trip becomes more comfortable for the passenger, and the bus line can have higher frequency but without having to add more buses of the system, which saves on costs for the operator. Additionally, the variation in travel time, or reliability of the buses, is also an important factor as it is wanted that there are as few delays as possible and that the buses are on time and reliable. Based on this, the public transport stakeholder perspective would give higher weights on public transport than other modes.

4.4 Normalization of scores and Weight sets

Based on the views of the stakeholders mentioned in chapter 4.3, the weights can be determined. There are multiple ways to decide weights for MCA. One way is called the point allocation method, where the decision maker allocates a number of points to each criterion according to its importance (Odu, 2019). If a criterion is more important, it is allocated more points (Dodgson et al., 2009; Odu, 2019). This method will be used in this research. The point allocation method is one of the simplest weighting methods, and therefore has some limitations, as it is not very precise and is subjective (Odu, 2019). However, by considering multiple weight sets, this limitation is reduced. The weight sets that are chosen and the reasoning behind the weights is discussed further in chapter 4.4.2.
Before the weights are applied, the scores for each criterion must me normalized, as they are not all in the same unit or magnitude. There are multiple ways that the scores can be normalized. These ways are discussed further in chapter 4.4.1.

4.4.1 Normalization of scores

The scores for different criteria for the MCA are some of different unit or magnitude. For instance, the throughput is in units of thousands of road users per hour while the variation in travel time is in tens of seconds. To make all these values comparable, they have to be normalized to values between 0 and 1. Additionally, some of the criteria are costs and some are benefits. A higher number for a cost criterion is more negative for the result while a higher number for a benefit criterion is more positive for the result. To adjust for this, and make all higher numbers be more positive for the result different calculation formulas for a cost criterion and a benefit criterion are used[4].
There are three linear calculation methods that can be used to normalize the scores[4]. There are also other methods that require more complex calculations, which will not be discussed in this thesis, since most the criteria is linear. Only the costs are categorical initially but are converted into numbers between 0 and 1 by using estimation, for simplification of the evaluation.
The first calculation method is the linear: max method, where all scores are related to 1[4]. For the benefits, each criterion value is divided by the max value of the alternatives for that criterion. The costs also use that ratio but subtract it from 1. This means that the alternative that has the max value for each criterion will get a score of 1 if it is a benefit criterion or a score of 0 if it is a cost criterion. The other alternatives will get a score related to the max score.
The second method is the linear: max-min method. This method calculates the normalized score based on the difference between the maximum and the minimum score of that criterion. The costs and benefits are calculated by using the formulas below[4].

$$benefits: n_{ij} = \frac{r_{ij} - r_{min}}{r_{max} - r_{min}}; costs: n_{ij} = \frac{r_{max} - r_{ij}}{r_{max} - r_{min}}$$

These formulas lead to that each criterion will have an alternative that scores a value of 0 and an alternative that scores a value of 1. If there are other alternatives considered, they will score a value between 0 and 1 based on the difference of that score and the max or the min score of the alternatives divided by the difference of the max and the min value.
The third calculation method is the linear: sum method, where the sum of the criteria for the alternatives equals one[4]. The benefits are calculated by dividing each criterion value, r_{ij}, by the sum of all the values for that criterion. The costs are calculated by taking the reverse of each criterion value, $1/r_{ij}$, and dividing it by the sum of all $1/r_{ij}$ for that criterion. This method results in that the sum of each normalized criterion is equal to 1, and there are no values of 1 or 0. Each value can be viewed as a percentage of the criterion where a value closer to 1 is the best option.
Since the first and second calculation methods depend on the maximum and/or the minimum score per criterion, they can get heavily influenced if the maximum or the minimum value is an outlier. For some of the criteria values, one alternative resulted in a value that is much larger than the other two, and the other two are close to each other. If using the first method in this case, the smaller two alternatives get a much lower score because it is compared to the value that is much larger than the values. This might cause that the other alternatives get smaller values assigned to them while in reality the values are not that bad.
For the second method, the alternative with the highest value always gets a normalized score of 1 and the alternative with the lowest value always gets a normalized score of 0. The alternative with a value between the highest and lowest gets a score relative to the highest and lowest score. A downside of this method is that for each criterion one alternatives always gets the value of 0 and another alternative always gets the value of 1. This occurs in all cases, even if the unnormalized values are similar to each other. This results in that the difference in points given to each alternative is very different, even if the difference should not be that large. However, by giving distinct higher or lower scores for each criterion, the visualisation becomes

[4] Lecture slides from lecture by A. van Binsbergen on the topic of Multi Criteria (Decision) Analysis in the course of CIE5817 Assessment of Transport Infrastructure and Systems

better and it's easier to look at the table and identify which alternative is the best or worst for each criterion. Additionally, this limitation could be reduced by giving lower weights to the criteria that scores similarly in all alternatives, even if the criterion is important (Dodgson et al., 2009).
The third method might assign more equal scores to each alternative per criterion as the sum of the scores for that criterion should equal 1. A downside of this method is that it distributes scores between 0 and 1 that add up to 1 for each criterion, therefore, it can give very similar scores for all the alternatives, even if there are some differences in the unnormalized scores between the alternatives. This also means that it becomes harder to visualise and read the table to see which alternative scores the best or the worst. However, for criterion that scores similarly for all alternatives, this method might give more logical and equal scores than the other methods.

For this thesis, the second method (linear: max-min) is chosen. Because even though it might exaggerate the differences between values that are similar to each other for the occasional criterion, the visualisation of that option is much better and easier to read the table with the normalized scores. Furthermore, it can be adjusted for this by giving criteria that scores similarly in all alternatives lower weight in the MCA. Additionally, it is much easier to see which alternative is the best or the worst per criterion while the third method shows less difference in the normalized scores which makes it more difficult to visualise which alternative is the best or worst per criterion because the numbers are often very close to each other. It is, however, important to note that due to the differences in the methods, they can result in different results.

4.4.2 Weight sets

When the scores have been normalized, they can be multiplied by the weight sets determined. The weights per criterion can help choose the best alternative because not all criteria might have the same weight. Since this research considers multiple stakeholders, each stakeholder might weigh the criteria differently, resulting in multiple weight sets.
To decide on the weight sets for the three stakeholders mentioned in the previous chapter (chapter 4.3), some assumptions must be made based on the goals and views of the stakeholders. The main assumptions are the following:

- Both the municipality and road authority focus on safety and therefore weigh it higher than the traffic performance.
- The municipality focuses a bit more on safety and therefore the difference between traffic performance and safety is larger for the municipality than the road authority.
- The municipality uses the road user hierarchy where active mode users are the most important. Therefore, they might weigh the safety and priority (traffic performance) of active modes, and public transport higher than cars.
- The road authority focuses on having access to transport for all modes and to have an integrated system, therefore they might weigh the traffic performance more equally between modes than the other stakeholders.
- The public transport authority focuses mainly on the speed and reliability of the buses. Therefore, they might weigh the traffic performance higher than safety and the performance of the buses higher than for other modes.
- The safety criterion is split up based on conflicts between vehicles and conflicts between vehicles and active modes. Since conflicts between vehicles and active modes are the most severe, they get the most weight. Within the conflicts between vehicles, the crossing conflicts are the most severe and therefore get the most weight as well.
- Because of limitations and simplifications in the model, which are explained further in chapter 7.3, it is likely that the lane-changing conflicts are overestimated in the model than in reality, therefore lane-changing conflicts get lower weight compared to the other types of conflict.

From these assumptions, each criteria level is given weights. The weights for each sub level are given weights that add up to 1. Then for each criterion level 4 element, all the previous weights are multiplied together to get the final weight for each criterion. Table 7 shows the weights assigned to each criterion from these calculations. More detailed calculations of the weights can be found in Appendix A - MCA weights. The abbreviations of the table represent the traffic performance indicators travel time (TT) and variation in travel time or standard deviation (SD), followed by the direction considered. More detailed explanations of the abbreviations are located in the footnote at the bottom of the page[5].

Table 7 Weights assigned to each criterion per stakeholder

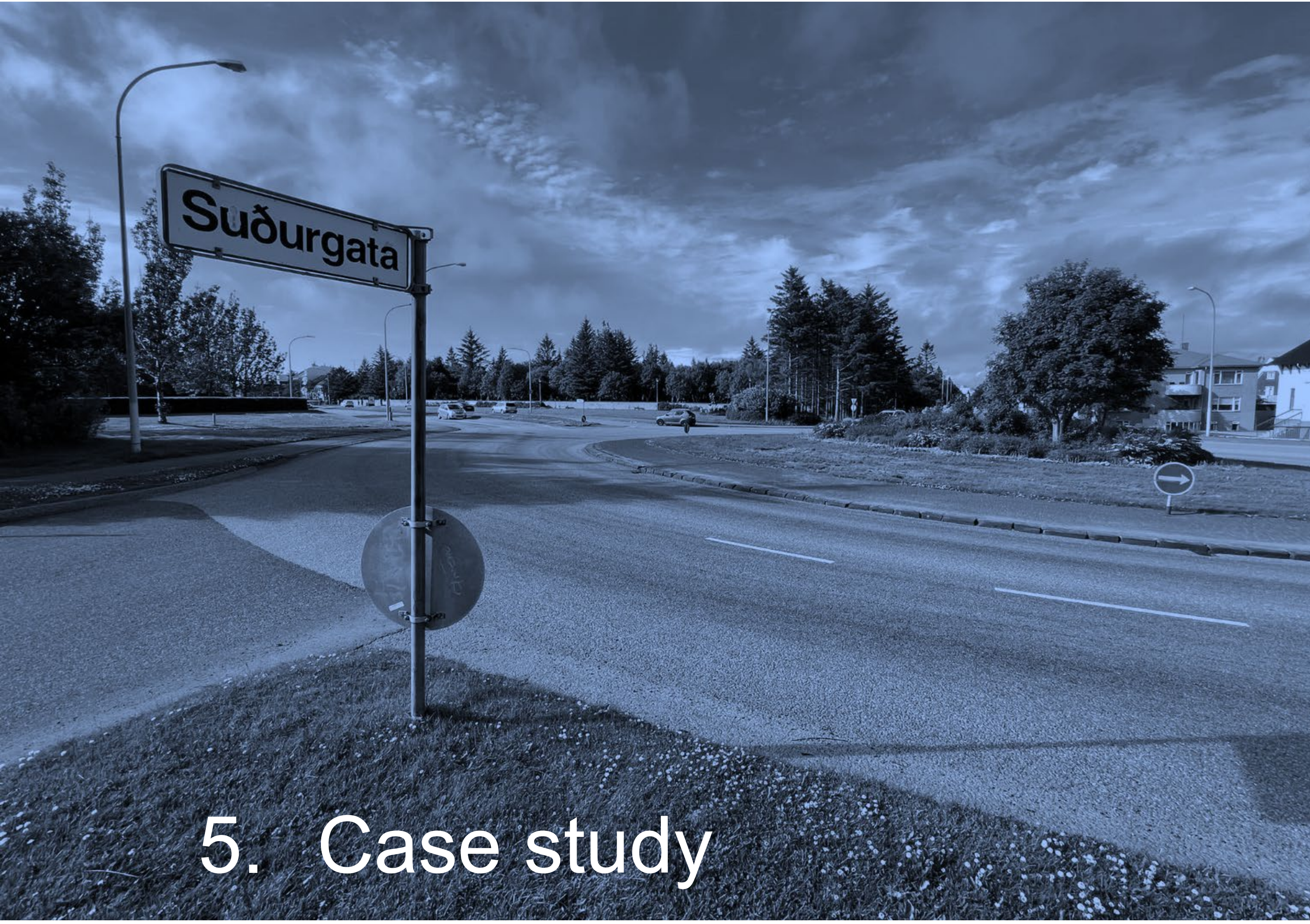
	Municipality	**Road authority**	**Public transport authority**
Throughput	0.099	0.1320	0.0700
TT NS vehicles	0.0074	0.0132	0.0095
TT NS PT	0.0173	0.0132	0.0851
TT SN vehicles	0.0074	0.0132	0.0095
TT SN PT	0.0173	0.0132	0.0851
TT EW vehicles	0.0050	0.0131	0.0063
TT EW PT	0.0099	0.0131	0.0441
TT EW active modes	0.0099	0.0131	0.0126
TT WE vehicles	0.0050	0.0131	0.0063
TT WE PT	0.0099	0.0131	0.0441
TT WE active modes	0.0099	0.0131	0.0126
SD NS vehicles	0.0074	0.0132	0.0095
SD NS PT	0.0173	0.0132	0.0851
SD SN vehicles	0.0074	0.0132	0.0095
SD SN PT	0.0173	0.0132	0.0851
SD EW vehicles	0.0050	0.0131	0.0063
SD EW PT	0.0099	0.0131	0.0441
SD EW active modes	0.0099	0.0131	0.0126
SD WE vehicles	0.0050	0.0131	0.0063
SD WE PT	0.0099	0.0131	0.0441
SD WE active modes	0.0099	0.0131	0.0126
crossing conflict	0.12	0.1	0.05
Lane change conflict	0.048	0.04	0.02
rear end conflict	0.072	0.06	0.03
active mode - vehicle conflict	0.36	0.3	0.1
Costs	0.1	0.1	0.1
Total	1	1	1

4.5 Conclusions

There are multiple decisions in the process of setting up the evaluation which could have an effect on the final results, for instance the normalizing methods and the weight sets. For this

[5] Abbreviations of table 4: TT – Travel time, SD – Standard deviation (variation in travel time), NS and SN – Directions along Sudurgata, EW and WE – Directions along Hringbraut, PT – public transport (buses and BRT).

research, stakeholder analysis is performed where three stakeholders' perspectives are considered. With different stakeholders, the weight set for the MCA is different for each stakeholder, which might lead to that there is not one alternative that is always the best or the worst.
To compare different criteria, the scores have to be normalized because they are not all of the same magnitude or unit. To normalize the scores a method of linear: max-min is used where each score of an alternative per criterion is given a score between 0 and 1, where 1 is the best alternative for that criterion. The weight sets are chosen by a point allocation method, where points or weights between 0 and 1 are allocated to each criterion based on sources from the stakeholders and expert judgement.



5. Case study

The aim of this chapter is to introduce the case study that is used to answer sub-question c on how the evaluation methodology that is developed in the previous chapters works for a case study.
The case study considered is at the intersection Melatorg in Reykjavík, Iceland. This is a roundabout intersection where multiple BRT lines are planned to drive through it in the coming years. Chapter 5.1 discusses further about the project of the new BRT network in the capital area of Iceland, in addition to the specific location for the case study, Melatorg. Chapter 5.2 discusses about the data collection and the data used for the VISSIM model input, followed by more discussions about the model setup, input, assumptions, and calibration and validation of the simulation model in Chapter 5.3.
Three design solution alternatives are chosen to be investigated and are set up in the VISSIM model, where each design solution differs in how much priority is given to the buses and the configuration of signals and regulation of the intersection. Chapter 5.4 discusses the three design solutions and how these three were chosen.
The case study can indicate how, and if, the methodology works, and how designs of roundabouts with BRT can be evaluated based on performance and safety. The case study can also give insights into the differences of the design solutions investigated and how they compare to each other, as well as which is the best solution.

5.1 Case study background

In the capital area of Iceland, many changes are happening regarding transport in the coming years. One of these changes are that a Bus Rapid Transit (BRT) network is being added to the whole region and the current bus network is redesigned to compliment the BRT network, where the BRT lines are the major lines, and the bus lines act as a feeder network to the BRT lines from the neighbourhood areas. This project is called Borgarlinan and is discussed further in chapter 5.1.1.

This case study focuses on one intersection in Reykjavík, which is one of the six municipalities that make up the capital area of Iceland (Figure 20). This intersection is called Melatorg and is a two-lane roundabout located on one of the main roads in Reykjavík and multiple bus and BRT lines are planned to go through this intersection. The location of the intersection and more details about it is discussed in chapter 5.1.2.

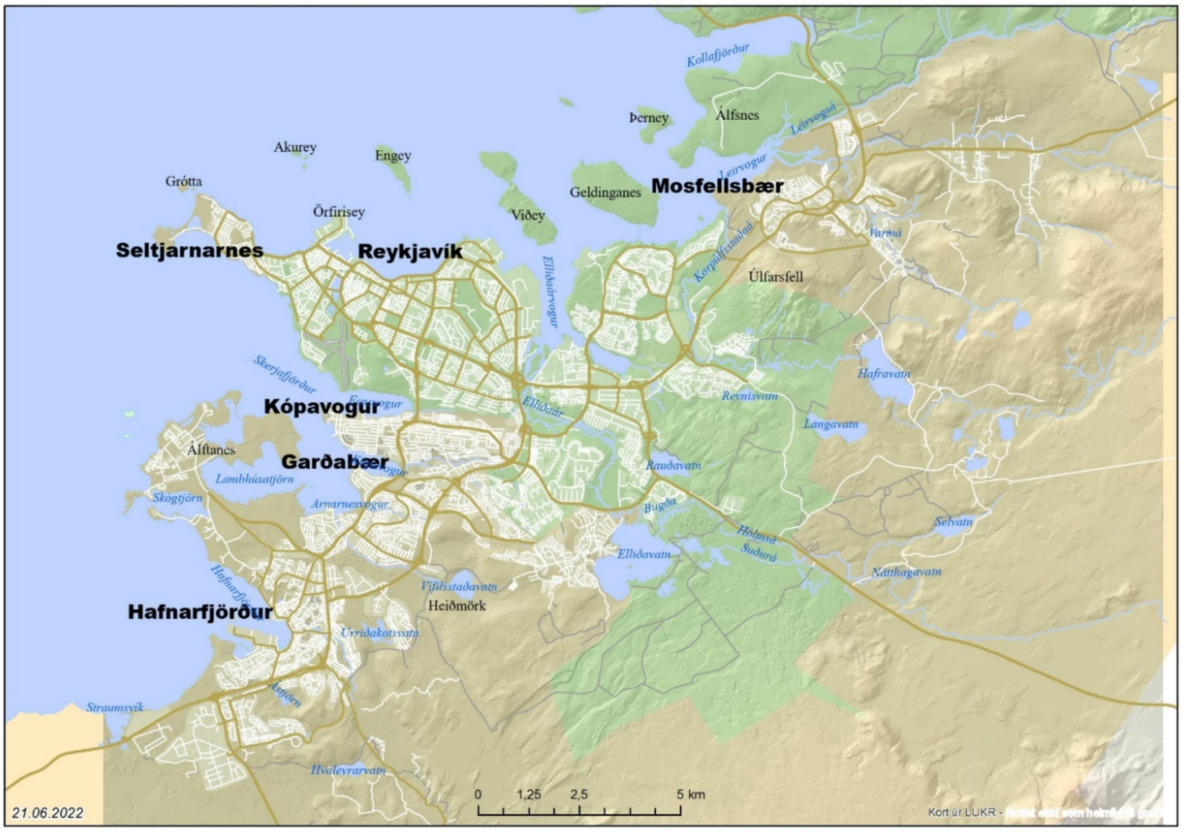


Figure 20 Map of the capital area of Iceland and the six municipalities (Reykjavíkurborg, n.d.).

5.1.1 The Borgarlinan project

In 2019, an agreement between the government of Iceland and all six municipalities of the capital area of Iceland was signed. This agreement is about the development of transportation infrastructure and public transportation in the capital area of Iceland for the next 15 years (Stjórnarráð Íslands, n.d.). The main goals of this agreement are to make transportation more accessible and have more variety of transportation modes available and competitive to the private car (Stjórnarráð Íslands, n.d.). Additionally, the goals are to have carbon-free society, to increase traffic safety, and enhance collaboration and efficient construction (Stjórnarráð Íslands, n.d.).

One of the largest projects in the agreement is a new Bus Rapid Transit (BRT) system. This system is called Borgarlinan and consists of seven lines, as shown in Figure 21. However, only six out of the seven Borgarlinan lines are classified as BRT lines because one of the lines (blue on Figure 21) has little to no exclusive lanes on its route (A. Skarphéðinsson, personal communication, 27.06.2022). The other six lines have exclusive lanes for most of their route. This can be seen in Figure 21 where the solid lines represent an exclusive lane and dotted lines are in mixed traffic (Borgarlinan.is, n.d.). These seven lines are made from the main routes of the current bus network in the region. The grey lines in Figure 21 show the bus lines that will not change to a Borgarlinan route and continue to be regular bus lines.

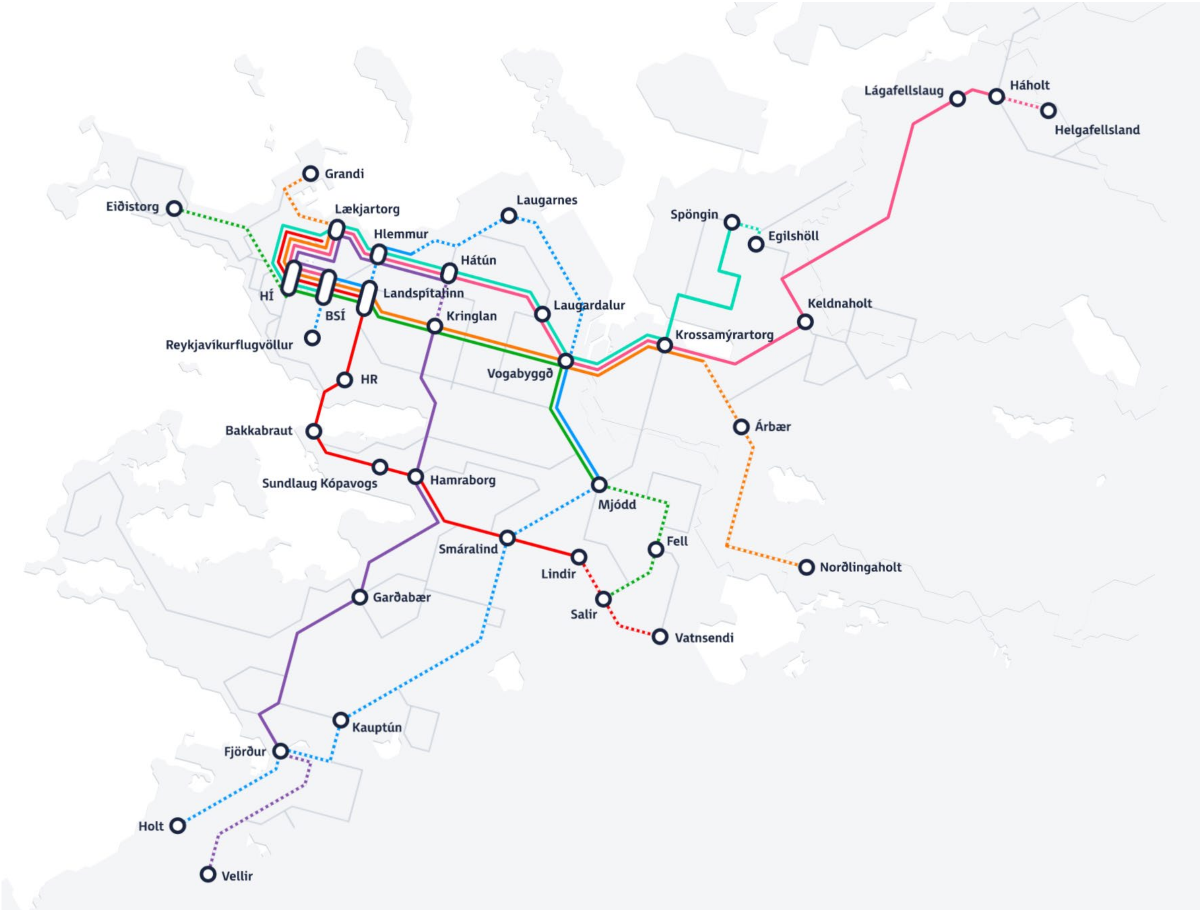


Figure 21 Map of the BRT network (Borgarlinan.is, n.d.)

Preliminary design of the first phase of the Borgarlinan system has been published and is used in this research as a basis for the bus alignment in the corridors close to the intersection. The exclusive bus lanes are proposed to be mostly in the centre of the road so that on intersections, only left turning traffic will have conflict with the buses (*1. lota forsendur og frumdrög*, 2021). Additionally, room for pedestrians and bicyclists is increased, by adding, for instance, bicycle paths or lanes by the side of the road. In this preliminary design document, there are no guidelines for the design of the intersections. There is, however, a suggestion that all crossings that the BRT goes though should be changed to signalized X-intersections or T-intersections, but that would be evaluated later in the process when needed (*1. lota forsendur og frumdrög*, 2021). In the capital area of Iceland, there are already a lot of roundabouts, and from the current network design, the six BRT lines would go through over 40 roundabouts in total (Borgarlinan.is, n.d.). It is, therefore, valuable to investigate if there is an effective solution where the BRT could drive through the roundabouts. This thesis adds to that knowledge by developing a methodology where design solutions of roundabouts with BRT can be evaluated and compared to other intersection design solutions.

5.1.2 Case study location

The intersection investigated in this research is located on the south side of central Reykjavík, and on the border of central and west side of Reykjavík, indicated with a red circle on Figure 22. The intersection is the intersection of one of the main roads in Reykjavík, Hringbraut (going NW and SE on Figure 22), and Sudurgata (going NE and SW on Figure 22), this intersection is also known as Melatorg.

Figure 22 Location of intersection (Reykjavíkurborg, n.d.)

Melatorg is a two-lane roundabout, and six out of the seven Borgarlinan lines are planned to go through this intersection, i.e., the six BRT lines. On the south side of the intersection, both on the east and west sides, is the University of Iceland campus, the University- and National Library, and the National Museum, as can be seen in Figure 23. On the north side, is the city centre, the lake in Reykjavík, parks and popular tourist destinations, along with neighbourhoods and workplaces. This means that there are quite some active mode users using this intersection daily, throughout the whole year.

Figure 23 Detailed map of Melatorg and its surroundings

The Borgarlinan project is in its first phase where the first two BRT lines are planned to be built in the next years. The preliminary design document recommends changing current roundabout intersections to signalized intersections, especially where the BRT lines are on

exclusive lanes (*1. lota forsendur og frumdrög*, 2021). However, literature indicates that roundabouts with BRT priority can have many benefits and therefore it is important to investigate the effectiveness and safety factors of these types of design. There are a lot of roundabouts in the capital area, and the BRT routes are planned to go through multiple of them, and thus, it is relevant to investigate the effectiveness of design solutions for roundabouts with BRT in the capital area of Iceland.
The location of Melatorg is one of the main intersections for the new Borgarlinan network, as six out of the seven Borgarlinan lines go through this intersection. This intersection is chosen as a case study because it is interesting to investigate if two-lane roundabouts are still effective and safe when BRT is going through it. Additionally, it is convenient to choose this roundabout because new data of the vehicle counts, and turning volumes is available. Even if this roundabout might not be representative of an average roundabout where BRT will go through, as it is a two-lane roundabout, and a lot of Borgarlinan and bus lines drive though it leading to high frequency of buses passing through, the results of this research can give an indication if there are some benefits of having priority for BRT through roundabouts. Since this roundabout is larger than the average case, positive results from this research would indicate that it is more likely that there are also positive results for smaller roundabouts. Additionally, negative results of this research could indicate that priority for BRT through roundabouts is not effective for larger roundabouts but might be for smaller ones and would need further research.
This case study can set up the base and knowledge for more intersections that are already roundabouts and eventually could help with deciding what can be done for other roundabout intersections.

5.2 Data

The data used for this case study was collected at Melatorg on Thursday 10-02-2022, for 24 hours, from 00:00 to 23:59. The total traffic through this intersection on this day was 35,000 vehicles (where 3.2% were heavy vehicles), 697 pedestrians, 54 cyclists, and 12 on standing e-scooters. Figure 24 shows the distribution of the traffic throughout the day. Figure 25 shows the total number of vehicles per approach for the whole day, shown in red. It also shows the turning volume and the number of active mode users which is split up between pedestrians/ cyclists/ e-scooter users.

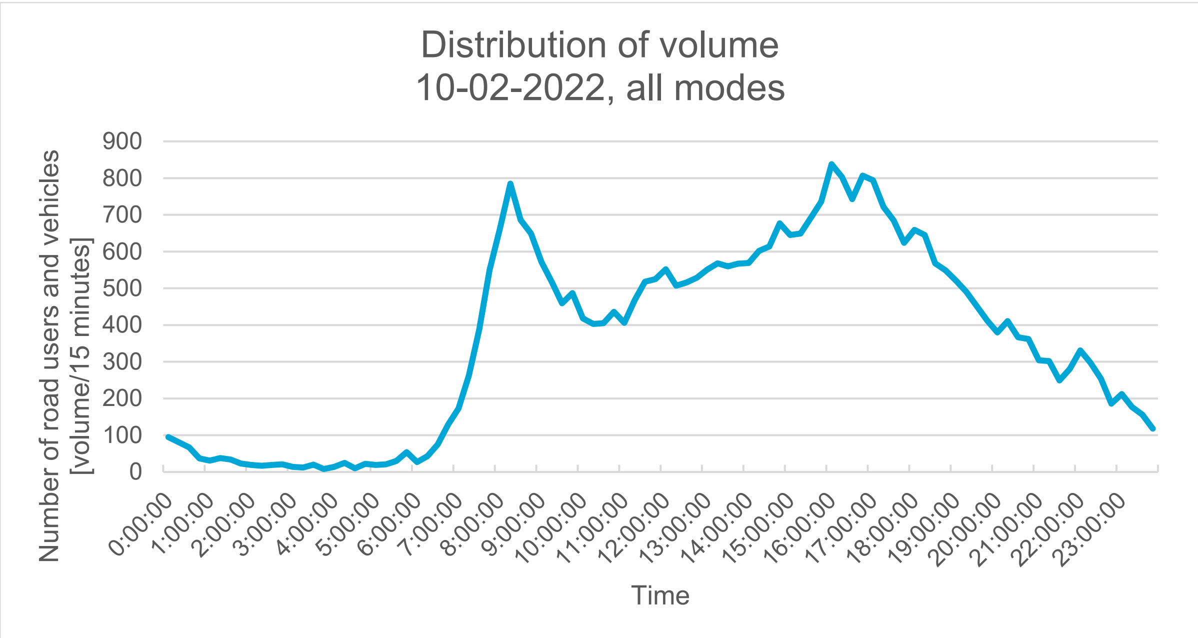


Figure 24 One day distribution of volume of road users, every 15 minutes

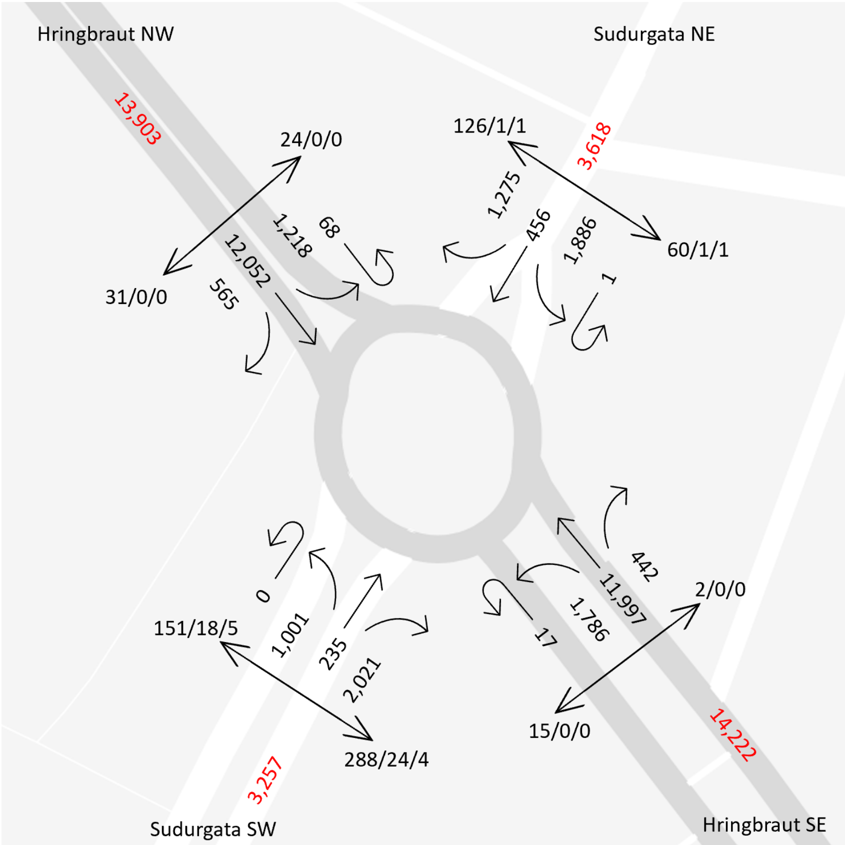


Figure 25 Total vehicle and turning volume per approach

The morning peak hour was between 08:00 and 09:00 where 2,782 vehicles and 109 active mode users crossed the intersection. The afternoon peak hour was between 16:00 and 17:00 where 3,191 vehicles and 81 active mode users crossed the intersection. The largest 15-minute period of the day was between 16:15 and 16:30, where 838 vehicles and 20 active mode users crossed the intersection.

Since the data collection was performed in February, the traffic volume for the active modes is lower than the average month. A common practice in Iceland is to use traffic volume from October, which is considered the most average month (A. Skarphéðinsson, personal communication, 22 Mar. 2022). Therefore, the numbers of active mode users are scaled up to an October traffic volume. To scale the volume of active mode users (pedestrians and cyclists), monthly data from a fixed counter located close to the intersection (Figure 26) is used. A scaling value to convert February traffic to October traffic can be computed by using the ratio of recordings from February 2022 and October 2021. Table 8 shows the total volume for February and October and the value that is used to scale the counted data with. The table shows that there are twice as many pedestrians in this area in October than in February and over four times as many cyclists.
The number of vehicles in this area is similar in October as it is in February, therefore the volume of counted vehicles in February 2022 is used in this research.

Figure 26 Location of pedestrian and cyclist counter

Table 8 Traffic scaling numbers

Total counts	**October 2021**	**February 2022**	**Scale value**
Pedestrians	7235	3537	2.05
Cyclists	6970	1657	4.21

Since the data collection took place in February 2022, there could be some impacts related to Covid-19 on the traffic volumes as well. Since April 2020, Covid-19 has had an impact on people's daily life and as an effect from that traffic volumes decreased. However, in 2022, Covid-19 has become less of a burden on life and society seems to be starting to go back to like it was before.
The data was collected in February 2022, and the question comes up if there are any effects from Covid-19 on this data collected due to restrictions in society resulting in reduced traffic.
In the end February 2022, more specifically the 25th of February, all restrictions in Iceland were lifted (Árnason, 2022a; Logadóttir, 2022). Before February 25th, restrictions had been reduced gradually from late mid-January, hence at the time of data collection, February 10th, the Icelandic society had started to become close to what is was before Covid-19 (Árnason, 2022b).
However, investigation of the general traffic numbers in the capital area of Iceland shows that traffic numbers are about 15% less than they were before Covid-19 (A. Skarphéðinsson, personal communication, 17.05.2022). This traffic that is missing can be related to rental cars and tourist traffic, which was still not to its previous numbers in February 2022 (A. Skarphéðinsson, personal communication, 17.05.2022).
Taking these numbers and knowledge into account, it can be assumed that local traffic is back to its normal state and is similar to how it was before Covid-19, but the tourist traffic is still less than before. It can be assumed that Covid-19 effects on traffic have little impacts on the results of this research.

5.3 Model setup

This chapter describes the data used as input in the VISSIM model and the three design solutions. Additionally, assumptions made in the set-up process and inputs of the model are discussed in this chapter. As mentioned in the previous chapter (5.2), the data for the active mode users is scaled up to better represent an average month for the whole year, while the data for other traffic is kept the same. Additionally, since the BRT network is not yet implemented, the recorded number of buses is not used in the model, rather, a higher frequency and more lines are modelled according to the planned frequency and lines of the BRT and new bus network. During the building of the model, it was realised that for the design solutions that give full priority to the buses (throughabouts), the location of the signal detectors could cause a gridlock of the network, this caused changes in the vehicle input from one approach (Sudurgata NE). This is further discussed in chapter 5.3.1 and Appendix B: Location of detectors.

The chapter starts with a discussion about the input volumes in chapter 5.3.1, which is then divided into smaller sections based on decisions made specifically for each mode. Chapter 5.3.2 discusses the assumptions made in the model, followed by chapter 5.3.3 which discusses the calibration and validation of the model.

5.3.1 Model inputs

The model will only simulate one hour from the day, therefore, an hour based on the largest 15-minute period of the day is used for the model input. The afternoon peak hour was larger than the morning peak hour, and the largest 15 minutes were from 16:00 to 16:15. To assess if the largest 15-minutes should be the second or third 15 minutes in the simulated hour, the total volumes are calculated. These calculations showed that the hour from 15:45 to 16:45 was larger than the hour from 15:30 to 16:30 and therefore the data for the hour of 15:45 – 16:45 is used. To load the network in the model, a warm-up period of 15 minutes is used, and another 15-minute period is used as a cool down period. This is done so that road users are already on the network when the evaluation period starts, and the network is still loaded when the evaluation period ends. The total number of input volume per mode per 15 minutes can be seen in Table 9.

All volumes in the model are stochastic. This means that the exact volume per 15 minutes might differ between simulation runs resulting in that the output of the simulation runs is not always the same. This might make the model more realistic as traffic volumes are not always the same and creates more variation between the simulation runs, and the average outputs such as travel time can be recorded. Table 9 shows the total number per mode, excluding buses, per 15 minutes, however, turning volumes per approach per 15 minutes is also an input into the model. The turning volumes used are from the data collection and the turning volumes counted there. Detailed tables with the input per direction and turning movement, per mode for each 15-minute period can be found in Appendix A: Model input.

However, the location of signal detectors to give priority to the buses in designs 2 and 3, which are both throughabouts, caused that some changes had to be made from the data counted and the current design. Currently, Sudurgata NE is a one-way street, with traffic travelling to the south towards the roundabout, with mixed traffic. The calculated distance for the detector resulted in that when a bus was detected, the lights turned red for the cars, however, sometimes the queue of cars was too long which resulted in that the bus could not continue, and a gridlock of the whole intersection was created. To fix this error, Sudurgata NE was changed to a bus only lane, with the exception of cars that have a purpose to go there, to the residential houses for instance, but those will not be included in the model as these cars do not go to the intersection. Additionally, the detector was moved closer to the intersection. These changes led to that other vehicles had to divert to other directions. This changed the input slightly. Table 9 and the tables in Appendix A include those changes. Further explanations of the gridlock problem, the calculations and decisions of the location of the detectors, and the multiple options explored can be found in Appendix B: Location of detectors.

Table 9 Total scaled and adjusted vehicle counts [users/15 min]

Time from	**Time to**	**Cars**	**Trucks**	**Pedestrians**	**Bicycles on road**	**Bicycles on crosswalk**	**e-scooters**
15:30	*15:45*	651	13	18	0	0	8
15:45	*16:00*	699	7	16	0	4	0
16:00	*16:15*	794	7	36	0	0	0
16:15	*16:30*	764	5	22	0	12	0
16:30	*16:45*	703	8	40	0	8	0
16:45	*17:00*	752	3	40	0	12	4

As seen in Table 9, bicycles can be both on the crosswalk or on the road. Since there are no bicycles on the road during any of the six 15-minute time periods investigated, and the total number of bicycles on the road for the whole day is very low, they are excluded from the model. The number of e-scooter users is also very low for this hour, and for the whole day and since the model uses stochastic input volumes, many of the simulation runs do not include e-scooter users. Therefore, e-scooter users are excluded from the analysis and evaluation of the designs. Additionally, no illegal behaviour such as active mode users crossing at a place that does not have a marked crossing, or red-light crossings are not included in the model, even if they are included in the collected data, such as illegal pedestrian crossings over Hringbraut. VISSIM is not able to model illegal pedestrian crossing because there needs to be a pedestrian link in the model to be able to model pedestrians, but by adding a pedestrian link to the model would change the behaviour of other users and would indicate that there is a pedestrian crossing there in reality when there is none. However, it is important to note that in the data and from local knowledge there are quite a lot of illegal pedestrian crossings, crossing Hringbraut on both sides of the intersection, as can be seen in Figure 25, but there are no crossings at that place, as Figure 30 shows. Therefore, when choosing an intersection design solution for this intersection it is important to account for these crossings. Illegal pedestrian crossing could also increase the risk of collision between cars and pedestrians on the intersection, as the drivers do not expect the pedestrians to cross at this location. Therefore, it is important to note this, as it might decrease the actual rating of the intersection design, because these are not included in the model.

Cars and trucks

In the collected data, only the vehicles that are entering the intersection are counted and it is noted from what direction they come and where they are going. On the NE side of the intersection is a smaller intersection of two roads, Sudurgata NE and Skothusavegur (Figure 27). The data collected on 10-02-2022 does not include the distribution or counts of these two roads. From yearly counts on Borgarvefsja, a web service from the municipality of Reykjavík that provides users with various geographical information, it was noted that the AADT on Skothusavegur is about twice as much as the AADT on Sudurgata (Reykjavíkurborg, n.d.). Therefore, when putting the counted volume into the model, one third comes from the NE on Sudurgata, and two thirds come from E on Skothusavegur. Since NE Sudurgata is a one-way street, all traffic that exits the roundabout on the NE side goes to Skothusavegur.

However, since it is model, Sudurgata NE is changed to a bus only street because of the problem with the location of the detectors (Appendix B: Location of detectors), that one third of the traffic coming down Sudurgata NE must be rerouted. It is assumed that 2/3 of the traffic changes their route and do not come to the intersection at all, while the other 1/3 either comes towards the intersection via Skothusavegur, or from either side of Hringbraut. More details about the distribution of traffic due to these changes can be found in Appendix B: Location of detectors.

Figure 27 Intersection of Sudurgata NE and Skothusavegur (Reykjavíkurborg, n.d.)

An additional input to the model for cars and trucks is their speed limit, or desired speed. The speed limit on the roads is 40 km/h, however, speed reduction zones must be placed at the entrances and inside the roundabout, because speed of cars is usually slower in roundabouts than at the corridors around it. Hallgrímsdóttir et al. (2019) performed a study about the speed of cars in five roundabouts located all over the capital area of Iceland. This study showed that cars usually enter roundabouts at a speed that is 10 km/h less than the posted speed limit on the road (Hallgrímsdóttir et al., 2019). Therefore, the reduced speed areas in the model, located at the entrances and inside the roundabout, have a desired speed of 30 km/h.
For analysis of the simulation output, the free flow conditions are also considered, to use as a reference. It is assumed that the free flow speed and travel time is the same for cars and trucks. However, it is expected that in reality, the free flow speed of trucks is slightly lower than for cars, but it might be very similar to cars in free flow conditions.

Buses

The public transport input in the model are the bus and BRT lines and their schedule or frequency. There are six bus and BRT lines going through this intersection. Four of the lines (A, B, D, and F) travel along Sudurgata, those travel on exclusive lanes. One line, (C) travels along Hringbraut, this line only travels in mixed traffic at this location as there are no plans for placing exclusive lanes on Hringbraut at this intersection. Furthermore, one line, (E) turns from NE on Sudurgata to SE on Hringbraut and vice versa. This line travels in mixed traffic while on Hringbraut and through the intersection, but can travel on the bus only road, Sudurgata NE.
In the model, three types of public transport are defined, BRT, bus, and mixed PT. The BRT and bus types are very similar to each other, but the regular buses are 12m long and the BRT vehicles are 18m long, both these types can travel on exclusive lanes and in mixed traffic.
Mixed PT is a category that was created for the buses that only drive in mixed traffic and not on the exclusive lanes, i.e., lines C and E. These lines are not included in the bus or BRT category because the research focuses on the effect that the exclusive lanes have on the BRT service and other modes. By separating the public transport that drive on the exclusive lanes from the public transport that does not allows to analyse this effect more effectively.

Table 10 shows the details of each line, where the length of the vehicles, the frequency of the line during the time investigated, the alignment, type in the model, and the colour of the line in the model is shown. Vehicles that are 18m are considered BRT vehicles, and those that are 12m regular buses (A. Skarphéðinsson, personal communication, 05.04.2022). During the peak hours, the bus and BRT lines all run at a frequency of 8 per hour (Borgarlinan.is, n.d.). Additionally, the alignment of the buses and the colour of each line in the model is based on the preliminary design document and the new network map (Figure 21) (*1. lota forsendur og frumdrög*, 2021; Borgarlinan.is, n.d.).

Table 10 Bus and BRT line details

Line	**Length of vehicle [m]**	**Frequency (15:45 – 17:00) [per h]**	**Alignment**	**Colour**	**Type of public transport in model**
A	18	8	Exclusive lanes	Red	BRT
B	18	8	Exclusive lanes	Turquoise	BRT
C	18	8	Mixed traffic	Green	Mixed PT
D	18	8	Exclusive lanes	Purple	BRT
E	12	8	Mixed traffic	Pink	Mixed PT
F	12	8	Exclusive lanes	Orange	Bus

Currently, there is no information available about the times that the bus lines cross the intersection as it is still in the planning process. Therefore, an estimation of the entry times of the first bus of each line is made for the model input. Figure 28 shows the time when the first buses enter the network of the model, where the arrow points to the driving direction. The headway of the buses is set to 7.5 minutes (450 seconds) which means that the pattern shown in Figure 28 is repeated every 7.5 minutes.

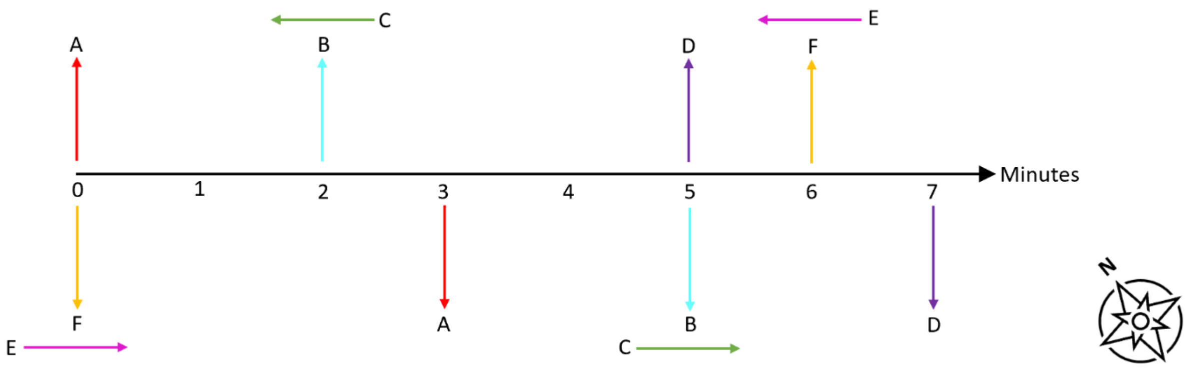


Figure 28 First entry times for each bus line in every direction

Buses are not always exactly on time in practice, but the model simulates a perfect punctuality by default. However, VISSIM offers an option of changing the entry time distribution of the buses. The entry time distribution defines an average delay, which is distributed in a normal distribution where the mean is the defined delay. For this model, a delay value of 20 seconds is chosen because even when all buses run on time, there is always some delay. For the model it is wanted to simulate an ideal system and therefore this delay value is chosen. Figure

29 shows the normal distribution of the delays of the buses, where the mean is 20 seconds and standard deviation is 2. This means that most buses will have a delay of 20 seconds, but the delay can vary between 14 and 26 seconds.

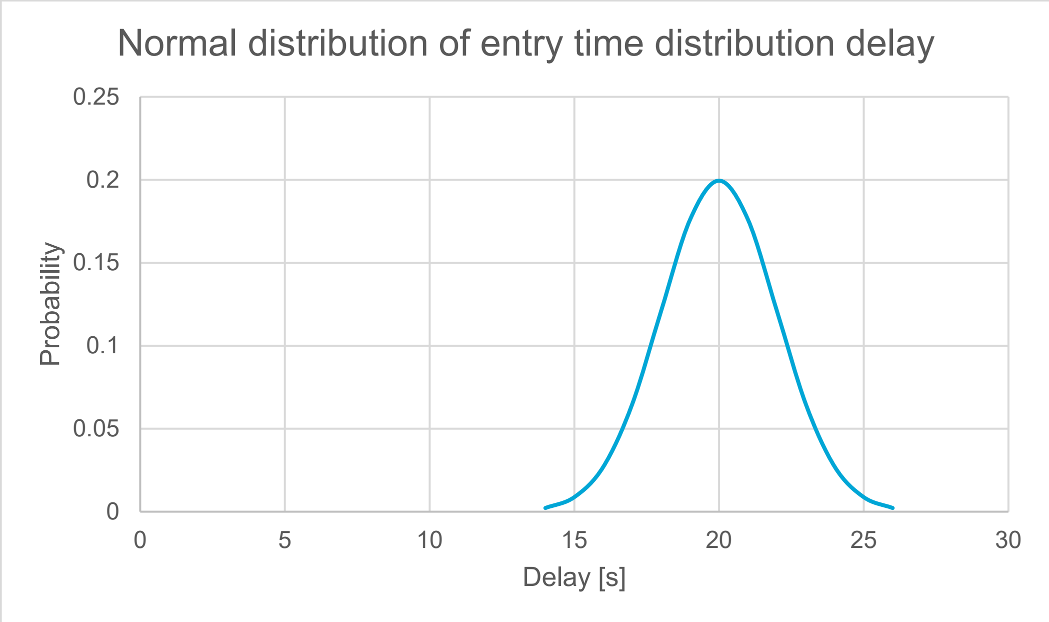


Figure 29 Normal distribution of entry time delay of 20 seconds

Bråtveit (2016) mentioned that the location of bus stops close to an intersection might have an effect on the performance of the intersection, especially when there is a priority signal for the approaching buses that does not take into account the potential stop. Therefore, the location of stops, in combination with the type of signal priority and location of detectors, must be considered when designing an intersection with BRT. However, the plans for Melatorg suggest that the bus stops will be that far away from the intersection so that they should not influence the signalling and the performance of the intersection (A. Skarphéðinsson, personal communication, 05.04.2022). Therefore, the model will exclude all nearby bus stops. However, it would be interesting to research if and/ or how the bus stops and the location of the bus stops can affect the performance of the intersection as future research.

Pedestrians and cyclists

At Melatorg, there are currently no separate cycling paths or cycle lanes, however, on Sudurgata, on the SW side of the intersection, cyclists can share the road with cars, but should stay to the right side of the road. The general rules in Iceland are that cyclists can take over a lane on a road that has a speed limit of 30 km/h or lower, otherwise they must cycle on the sidewalk, other paths designated for active mode users, or on the right side of a car lane, which is not recommended when speed or traffic volume is high (Samgöngustofa, n.d.). As Table 9 shows, all cyclists during the largest hour of the day cross the intersection on the crosswalk and very low number of cyclists cycled on the road throughout the day, indicating that most cyclists cycle on the sidewalk and paths with pedestrians. Therefore, in the model all cyclists share paths with pedestrians.

Currently there are only active mode crossings on the north and the south side of the intersection, crossing Sudurgata. The closest active mode crossings that cross Hringbraut are located 184m and 93m from the centre of the intersection, as shown in Figure 30. This large detour of crossing Hringbraut results in that there are many illegal crossings at the intersection, crossing Hringbraut. This can be seen both from local knowledge and the data collected. As shown in Figure 25, 72 active mode users crossed Hringbraut on both sides of the intersection during the 24-hour period of data collection. Crossing Hringbraut at the intersection is more

natural for the pedestrians than travelling to either of the crossings further away. This can also be confusing for people that are not familiar with the intersection, leading to more crossings where there is no marked crossing. It is therefore important to keep in mind what the natural route for active mode users could be and include marked crossings at those locations to increase safety and accessibility for active mode users.
These illegal crossings can also influence the results of the evaluation of the design solutions as they are not included in the model. The crossings over Hringbraut are not included in the model because currently there are no crossings there, which leads to that the actual number of pedestrians and other active mode users that would use that crossing, if it would be there, is unknown. Additionally, the model cannot model illegal behaviour, such as crossing a road where there is no marked crossing, as is assumes that everyone follows the rules. After a discussion with experts, it was concluded to not include those users in the model and not include any crossings over Hringbraut.

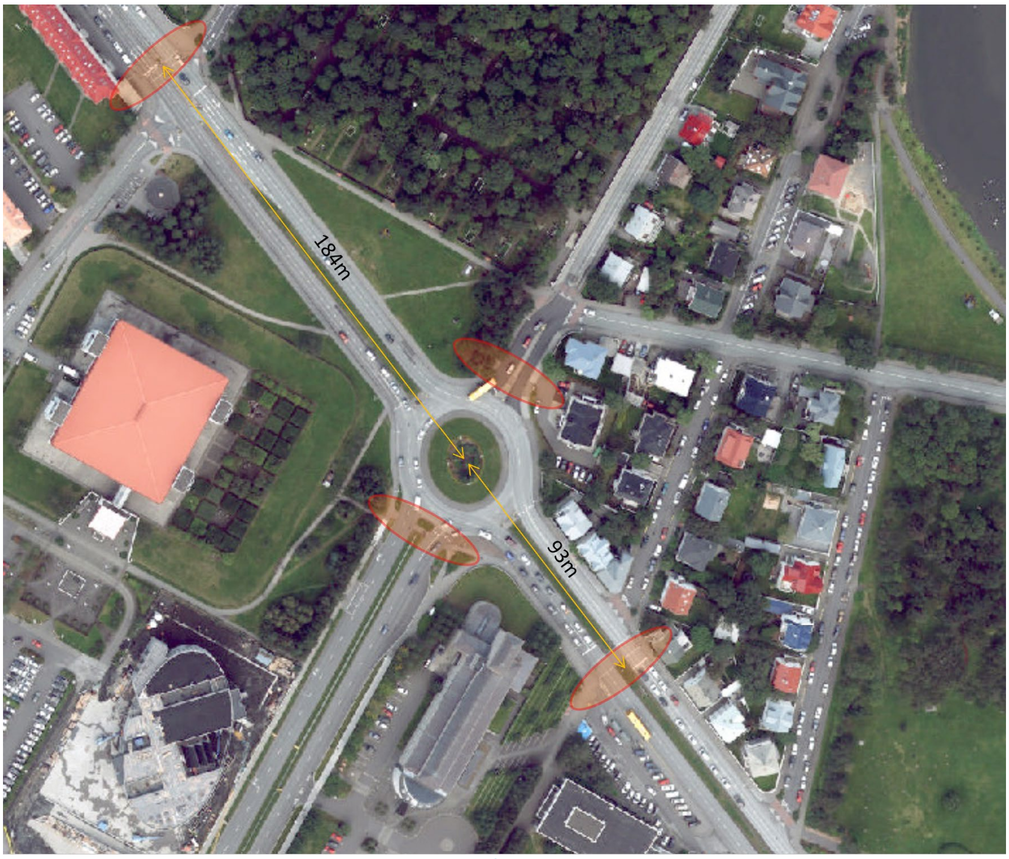


Figure 30 Location of active mode crossings

The speed, or desired speed, of the pedestrians and cyclists is also an input into the VISSIM model. The default value of 5km/h is chosen for the desired speed of a pedestrian. 5 km/h is also a very commonly used speed for walking. For the cyclists, a desired speed of 25km/h is chosen. Normally, an average cycle speed is more around 16 – 20 km/h. However, the number of e-bikes is increasing and becoming more popular, and the speed of those users is also increasing. The e-bikes usually can get to a speed of 25km/h. Therefore, the speed of 25km/h is chosen for the desired speed of cyclists. Furthermore, the desired speed defined in the model is not necessarily the speed that the users cycle at, except in free flow conditions. Therefore, a speed of 25 km/h is reasonable because it is not the actual speed in the simulations but rather the desired speed.

5.3.2 Assumptions and simplifications of the model

Many of the assumptions made in the VISSIM model and model development have already been discussed in the chapters above. This chapter further discusses some of these assumptions and other major assumptions made.

One major assumption of the model is the priority rules of cars when exiting the roundabout. It is assumed that the cars follow the Icelandic traffic rules, which state that the cars on the inner lane of a roundabout have priority exiting the roundabout ("Umferðarlög nr. 77/2019," 2019). This means that the cars on the outer lane that wish to continue further than the first exit have to yield to the exiting cars from the inner lane. To model this, conflict areas are defined in VISSIM where the cars that are exiting have priority. However, this resulted in that cars on the outer lane stopped and yielded to every car on the inner lane, regardless of if that car was planning to exit or not, creating unrealistic situations. To solve this, all vehicles in the roundabout at these conflict areas can anticipate the route of the other vehicles in the roundabout and therefore only yield if a car close by on the inner lane is about to exit.

Because the roundabout is a two-lane roundabout and that the inner lane has priority to exit the roundabout, the exiting and entering arms of the roundabout also have to be two lanes. This is due to a simplicity on the model. It is possible to connect two single lane connector links to the roundabout and a single lane arm, however, this creates unrealistic behaviour, where very small portion of the vehicles used the inner lane, as well as it was not possible to use the conflict areas in a way that the inner lane had priority when exiting the roundabout. Since Sudurgata, on both north and south side of the intersection, is planned to be a road with one lane in each direction, this challenge is faced. To solve this challenge, the part of Sudurgata that is closest to the circulatory part of the roundabout is modelled with two lanes that merge into one lane after a short distance. This, however, can create more conflicts, especially lane-changing conflicts, than would be seen in real life.

The road designs and bus alignments in the model are based on the suggestions proposed in the preliminary design document for the BRT and are kept constant for all design solutions while the design of the roundabout is changed for each design solution. It is assumed that the designs in the preliminary design document are already built, and are considered as part of the base case, or planned to be built, and not taken into consideration in the evaluation of the designs, for instance in the costs. The bus alignment along Sudurgata SW has exclusive bus lanes on the median, one in each direction, and one lane in each direction for mixed traffic. On the north side of the intersection, buses drive in mixed traffic, when driving away from the intersection on Skothusavegur. Additionally, the assumption that Sudurgata NE is a bus only street is also considered as a part of the base case.

The model does not include any illegal behaviour, and the active mode crossing behaviour that occurred in places that did not have any marked crossings are excluded from the model. As mentioned in Chapter 5.3.1, there are no pedestrian crossings that cross Hringbraut, however, the data showed that there are some people that cross Hringbraut at the roundabout, where there are no marked crossings. Excluding these active mode users from the research could lead to that the safety of the design is lower than the evaluation results indicate. Therefore, it is important to note about this exclusion so that these users can be considered in the final conclusions.

Active mode users are modelled as vehicle objects rather than pedestrians due to limitations of SSAM. SSAM is not able to calculate the surrogate safety measures between vehicles and active mode users if they are modelled as pedestrians because VISSIM only creates trajectories for vehicle objects, and SSAM uses those trajectories for the calculations. Because of this, the active mode crossings must be modelled as directional links, meaning that the active mode users from the opposite direction do not interact with each other, but behave more like vehicles and walk or cycle in one line, rather than more spread out over the whole crossing, as would be seen in real life. The pedestrians and cyclists can, however, interact with each other within one link, and can overtake to the left if needed. This creates more realistic output in travel times and speed as the cyclists are not stuck behind pedestrians for instance. However, the interaction between active mode users is not considered in this project, only the interaction between active mode users and vehicles. Therefore, only the crossings of the active modes are modelled as the considered area is only the intersection and the interaction of active modes and vehicles.

5.3.3 Calibration and validation

To calibrate a model, the model has to be adapted by an iterative process by changing factors such as behavioural parameters, speed, and TTC and PET thresholds so that the model output will be as representative of the location investigated as possible (Huang, Liu, Yu, & Wang, 2013). Starting with the default parameters, which are changed based on a collected data set, the model can be calibrated until the model is behaving accordingly and the output has a good fit to the collected data (Huang et al., 2013; Park & Schneeberger, 2003). After the calibration, a validation can be performed where different data sets are used in the model and the model output compared to the collected data (Huang et al., 2013; Park & Schneeberger, 2003). In order to calibrate and validate a model, data from other similar locations and studies of the behaviour of the people in the area is preferred. However, this information is not available at the time of the research which makes it difficult to calibrate and validate the model. The data at Melatorg was collected by video and the count or users and their origin and destination at the intersection noted. The video recording can be used to find other parameters, such as gap acceptance, speed, and minimum headway, but because of time constraints and a lot of extra work would be required to get those parameters, this information is not obtained. This could, however, have an impact on the accuracy of the model, and it is recommended to do this type of calibration in future research in order to get more accurate and more representative outputs since studies show that that a well calibrated model can represent reality better than a model that uses default values (Huang et al., 2013; Muley et al., 2018; Park & Schneeberger, 2003). Therefore, the values that are used for the gap acceptance for the vehicles when entering the roundabout are the values suggested in the VISSIM user manual[6]. The values for the gap acceptance of cars, trucks, and buses or BRT vehicles differ. Where the gap acceptance for cars is the shortest, about 2-3 seconds depending on lane location, then the trucks have a gap acceptance of one second longer than the cars, and buses 2 seconds longer than cars. For the surrogate safety measures, the TTC and PET values that are used are based on literature. Where the TTC and PET values for conflicts between vehicles are 1.5 seconds and 5 seconds respectively, and the TTC and PET values for conflicts between active modes and vehicles are 2.7 seconds and 8 seconds, respectively (Muley et al., 2018; Wu et al., 2016).

The simulations are also observed visually to check for reasonable behaviour in the model compared to the knowledge of the researcher and the video from the data collection. This is especially done for behaviour that is specific to Iceland, for example the rule that the inner lane has priority when exiting the roundabout, meaning that if a car on the outer lane wants to continue driving on the circulatory road and a car on the inner lane wants to exit, the car on the outer lane has to yield. This is calibrated by iterations of changing the gap acceptances and other parameters of the conflict areas of the exits and compared to the video and personal experience.

Due to lack of data from other locations or other data sets from this location, the model could not be validated in the way described above. This limits the model and makes the model more likely to be less accurate, since studies show that a well calibrated model can represent reality better than a model that uses default values (Huang et al., 2013; Muley et al., 2018; Park & Schneeberger, 2003). However, the calibration and validation process done for this model as described above is good enough for the purposes of this research as the three designs are

[6] PTV Group. *PTV VISSIM 2020: User Manual.* Priority rule Example 3: Dual-lane roundabout with dual-lane entry, pg. 591.

being compared, and not necessarily being compared to the real world. Also, the software that is being used, VISSIM and SSAM, are well calibrated models and the values used are based on research that has been done, it can be assumed that the model is well calibrated and representative to a general case.
For future research, it is recommended to collect more data, both for the location considered and other locations, and to research more about the local behaviour such as gap acceptance. That way the results from the model will be more representative of the real location.

5.4 Design solutions

The research compares three design solutions that change depending on the priority given to the BRT and the configuration of the regulation of the intersection.
When choosing what design solutions to use for the research multiple options are explored. The intersection could either be a roundabout, as it is currently, or it could be changed to a x-intersection, as Figure 31 shows. In this case the X-intersection could only be signalized because the traffic is too heavy for a non-signalized X-intersection. However, the main focus of this research is on roundabouts, and therefore a design solution of a X-intersection is not chosen.
The figure shows that there are three types of roundabouts that can be used. These are the types described in the literature chapter, chapter 3.1.2. The three types of roundabouts are where the buses drive in mixed traffic through the roundabout, where there is a bus lane in the inner lane of the roundabout, and a throughabout. Furthermore, a throughabout can be regulated in different ways.
The three design solutions that are in an oval shape in Figure 31 are the chosen designs. The design with the bus lane in the inner lane of the roundabout is not chosen as a design alternative because that design would require too much space, which is not available in many cases. It would also likely increase the speed of cars due to the extra bus lane in the roundabout, making this design less ideal for the safety of active mode users. Design 1 consists of a roundabout where the buses drive in mixed traffic through the roundabout and is further described in chapter 5.4.1. Designs 2 and 3 are throughabouts, where the configuration of the regulation is changed between the two designs. Design 2 has a fully regulated roundabout, where all entering traffic has traffic signals that turn on when a bus is passing through, and design 3 has a partially regulated roundabout, where there are only traffic signals for the traffic that is in conflict with the buses. Chapters 5.4.2 and 5.4.3 further describe these designs.
These designs are chosen because design 1: mixed traffic is the closest to the current situation and a conventional roundabout and has minimal changes to the base case, and therefore could be considered as a reference or close to a ‘do nothing’ case. Designs 2: traffic signals for entering traffic and 3: traffic signals for conflicting traffic are chosen because of the literature found about these types, which indicated that they are beneficial, as discussed in chapter 3, and these types of throughabouts can be seen in the real world in multiple countries.

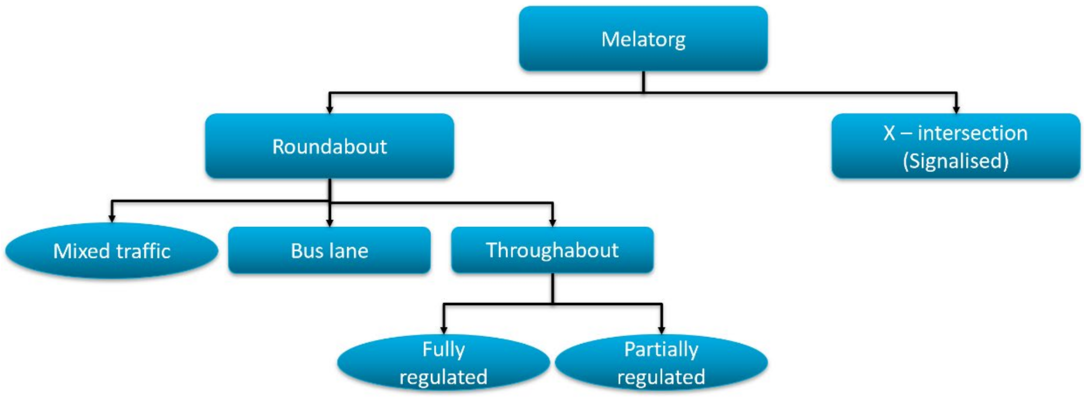


Figure 31 Design solutions decision tree

5.4.1 Design solution 1: Mixed traffic conditions

The first design solution that is tested is a design that requires the least change from the base case design. In the design solution, the buses drive in mixed traffic through the roundabout. Before the roundabout, the exclusive bus lane merges with the mixed traffic, and after the roundabout the buses can deviate from the mixed traffic again and enter the exclusive bus lane, as shown in Figure 32. For this case study, there are exclusive bus lanes on the south side of the roundabout. On the north side of the roundabout, the buses that are exiting the roundabout continue to drive in mixed traffic on Skothusavegur, while the buses that are entering the roundabout, driving south on Sudurgata, just continue to drive from the bus only road and automatically merge with mixed traffic when approaching the roundabout.

Since this design does not have exclusive lanes for the buses through the intersection, where most delay is expected to occur, it is expected that this design solution will result in being the worst for bus travel time and reliability, while it is likely that it will result in being the best for the car traffic, at least in terms of travel time and speed.

For the case of Melatorg, active mode crossings are located on the Sudurgata, the NE and SW arms of the intersection. In the model, active mode users have priority to cars. This design has a separate path for active mode users from the vehicles, which increases safety as mentioned in chapter 3.2.

Figure 33 shows the layout of design solution 1 in VISSIM. All dark grey links are for mixed traffic, and light grey links are for active modes. The bright orange links are exclusive bus lanes, and the darker red links is the road where there are no exclusive bus lanes, and the buses have to drive in mixed traffic. The road layout on the SW side of the roundabout on Sudurgata where there is one lane in each direction for mixed traffic and exclusive bus lanes in the median, and the mixed traffic solution on Skothusavegur, are based on the preliminary design of the BRT system, which was published in January 2021 (*1. lota forsendur og frumdrög*, 2021). These road designs and alignments are considered a part of the base case in this research. In these preliminary designs, Sudurgata NE was also designed to be with mixed traffic, but as explained in chapter 5.3.1 above, it was chosen to have this part exclusive for buses, with an exception for cars that have a reason for being there, for example to get to the residential houses there.

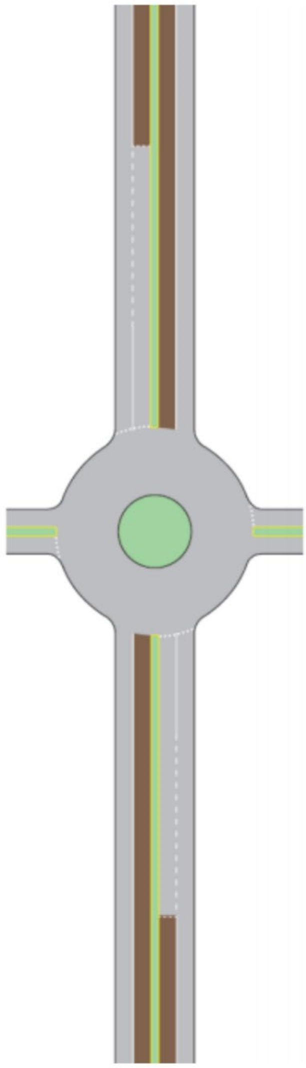


Figure 32 Design type for design solution 1

Figure 33 Design solution 1 setup in VISSIM

5.4.2 Design solution 2: Traffic signals for entering traffic

Design solution 1 has very minimal changes to the current roundabout design (base case) and gave no priority to buses and BRT that are travelling on the exclusive lanes through the intersection. Design solution 2 gives full priority to the buses by adding exclusive lanes though the centre island of the roundabout. These types of designs are called throughabouts, which were introduced in chapter 3.1.2. This design has traffic lights with yellow and red lights, as shown in Figure 34. These lights are turned off when there is no bus, and the normal yielding rules of roundabouts are used, but turn on when a bus is detected as it approaches the intersection.

Figure 34 Design type for design solution 2

Figure 35 shows the setup of design solution 2 in VISSIM. Since Skothusavegur does not have an exclusive bus lane but the buses drive in mixed traffic, the exclusive lane is merged with the road after the intersection. In this design solution, the exclusive bus lanes are extended through the intersection and the exclusive lanes on both sides of the intersection are connected to the lanes that go directly though the roundabout. In the base design, the median between the driving directions on the north side of the roundabout is not large enough for the extra exclusive lanes. In order to fit the exclusive lanes on the North side of the roundabout, the existing lanes of the southbound road are moved 3.5m NE.

The detectors for the traffic signals that detect if a bus is coming can be seen in Figure 35 and are indicated as the blue boxes on the exclusive lanes on Sudurgata. The detector on the south side is located at a calculated distance of around 112m which leads to that when a bus is detected and the lights for the cars are turned on, the bus can continue driving at its current speed and cross the intersection without stopping or slowing down. The detector on the north side of the intersection is located closer to the intersection because of the challenge of creating a gridlock, as explained in more details in Appendix B: Location of detectors. Appendix B also includes the calculation of the distance of the location for the detectors.

Figure 35 Design solution 2 setup in VISSIM

5.4.3 Design solution 3: Traffic signals for conflicting traffic

Design solution 3 looks very similar to design solution 2, the only difference is the location of the traffic lights. Design solution 3 has traffic lights only for the traffic that is in conflict with the exclusive bus lanes, as shown in Figure 36. The throughabout designs have little to no delay for the buses travelling on the exclusive lanes as they get priority through the intersection. It is expected that design solution 3 will result in a better performance for the cars than the second design solution because in that one, all entering cars have to stop when a bus is coming, but in design solution 3 only cars that are crossing the exclusive bus lanes have to stop, which likely leads to a better flow through the roundabout.

Figure 36 Design type for design solution 3

Figure 37 shows the setup of design solution 3 in VISSIM. Like design solution 2, Skothusavegur only has mixed traffic and therefore the exclusive lane merges with the mixed traffic lane on the North side of the roundabout. Like design solution 2, the entering lanes on the north side are moved 3.5m to the NE because the median between the driving directions on Sudurgata is not large enough to fit the extra exclusive bus lane.
To only change one variable, which is the location of the traffic signals, the locations of the detectors are the same as for design solution 2 and are shown as the blue boxed in Figure 37, however, for solutions such as a throughabout with traffic signals for conflicting traffic, it is likely that the detectors could be located further away from the intersection since the traffic is not blocked at the entrance and would likely still be able to enter the roundabout after a bus has been detected, but the location of the detectors is kept constant in this research and further investigation would have to be done to find the optimal location of the detectors for each case.

Figure 37 Design solution 3 setup in VISSIM

6. Results

This chapter aims to present and discuss the results from the simulations and calculations, as well as the results of the evaluation methodology for the case study. This chapter helps answering sub-question c which asks how the evaluation methodology works for a case study, as well as it provides the final information to answer the main research question as it indicates if and how the evaluation methodology works, which leads to knowing how the different designs can be evaluated. This chapter also indicates which design solution proves to be the most optimal.

The three design solutions introduced in chapter 5.4 are simulated in VISSIM. Each design of the case study is simulated for 10 runs each. From those 10 runs, the average, standard deviation, and the max value for each criterion investigated is recorded in tables, which can be found in Appendix C: Outputs (VISSIM output tables). Chapter 6.1 presents the results from individual design solutions for each criterion which is then compared in chapter 6.2.1. The criteria that are investigated are the throughput, average speed, travel time, variation in travel time, number of stops and time stopped, in addition to the number of conflicts per type of conflict, as introduced in chapter 4.2. Chapter 6.2.2 shows the results of the multicriteria analysis and therefore also the results of the evaluation of the designs. Since many steps of the evaluation methodology are made from assumptions, sensitivity analysis is performed to test the sensitivity and how the outcome is affected by changing the input of the model, the safety calculations by using different TTC and PET thresholds, and the MCA by using different weights. The sensitivity analysis is further discussed in chapter 6.3. The chapter is finalised by chapter 6.4 where the results of the evaluation are concluded and summarised, and the most optimal design is discussed and compared to the other designs and literature.

6.1 Results from individual design solution alternatives

The results for each design solution output from the simulation and calculations are presented in this chapter. Each design solution alternative is simulated for 10 runs each, where each run is 1.5 hours, with an hour evaluation period. From these 10 simulation runs, the average, standard deviation, and max scores are recorded for each criterion investigated. However, for design solution 2 one of the simulation runs resulted in that a gridlock occurred, due to the same problem as described in Appendix B: Location of detectors, where the bus activates the detector but cannot proceed through the intersection, causing a gridlock. Because of this, this simulation run was excluded from the analysis for design solution 2.

For each design solution alternative, the free flow speed and travel time for each mode and direction are also recorded, as discussed in chapters 4.2.1 and 5.3.1. This is done to be able to compare the average speed and travel time where the free flow conditions can be a point of reference. In chapter 5.3.1, it is assumed that the free flow speed and travel time of cars and trucks are the same. The simulations show that the average speed of trucks and cars is very similar, and therefore, this assumption is still valid. The actual free flow speed of buses in design solutions 2 and 3 can be affected because of the detector of the north side of the intersection is located closer than the detector on the south side, as discussed further in Appendix B: Location of detectors. For the free flow situation calculations, no detectors are placed in the system and the buses can drive freely. However, it is important to note that the location of the detector makes the average free flow travel time increase by 4 seconds for travel times from north to south.

In all the design solutions, there are three types of public transport, BRT, Bus, and Mixed PT. The BRT and buses are the buses that drive on the exclusive lanes and have routes along Sudurgata. Mixed PT are the two bus lines that drive in mixed traffic, along Hringbraut and turning from Hringbraut SE to Sudurgata NE or Skothusavegur. These types of public transport are differentiated in the model because the lengths of buses and BRT vehicles are different, and since the mixed PT vehicles are in mixed traffic, separating between mixed traffic buses and exclusive lane buses can give clearer picture of the effects of giving priority to the buses on the exclusive lane and not being influenced by the buses that are in mixed traffic.

6.1.1 Design solution 1: Mixed traffic conditions

The first design solution is where the buses merge from their exclusive lane into mixed traffic before the intersection and cross the intersection in mixed traffic. After the intersection they can go back to their exclusive lane.

Traffic performance

Traffic performance parameters that result from the VISSIM simulations is the total throughput, average speed, travel time, variation in travel time, number of stops and time stopped.

The throughput for this design solution for each mode is shown in Table 11. The total throughput of the intersection is 3,222 vehicles per hour, or users per hour for active modes.

Table 11 Total throughput and throughput per mode from design solution 1: Mixed traffic conditions

	Cars	Trucks	BRT	Bus	Mixed PT	Pedestrians	Cyclists	Total
Average throughput [veh/hr]	2,968	29	48	16	32	103	26	3,222

Figure 38 shows the average speed per mode. The figure shows that all modes travel at a less speed that free flow speed. The figure also shows that the buses travelling on the exclusive lanes show a larger deviation from their free flow speed than other vehicles. This could be because the traffic along Hringbraut is heavier than the traffic along Sudurgata, leading to fewer and smaller gaps to enter the roundabout from Sudurgata. This leads to that the buses, and other vehicles, which are entering the roundabout from Sudurgata NE and SW have to wait for some time before they are able to enter the roundabout. Since the buses also have a larger gap acceptance (chapter 5.3.3), they might have to wait even longer for an acceptable gap, causing this large difference in the free flow speed and average speed shown in the figure.

Additionally, the figure shows a large gap between the free flow speed and average speed of cyclists. This is due to the high desired speed set for cyclists (25km/h). The average speed of 12km/h for cyclists is close to a more normal cycling speed of 16 – 20 km/h leading to that the difference between more realistic free flow speed and the average speed is less than shown on the figure. The desired speed of 25km/h for cyclists is chosen because of the increasing numbers of e-bikes on the road, which can easily travel at 25km/h speed, as explained in chapter 5.3.1. In free flow conditions, the cyclists travel at the desired speed causing this difference shown in the figure.

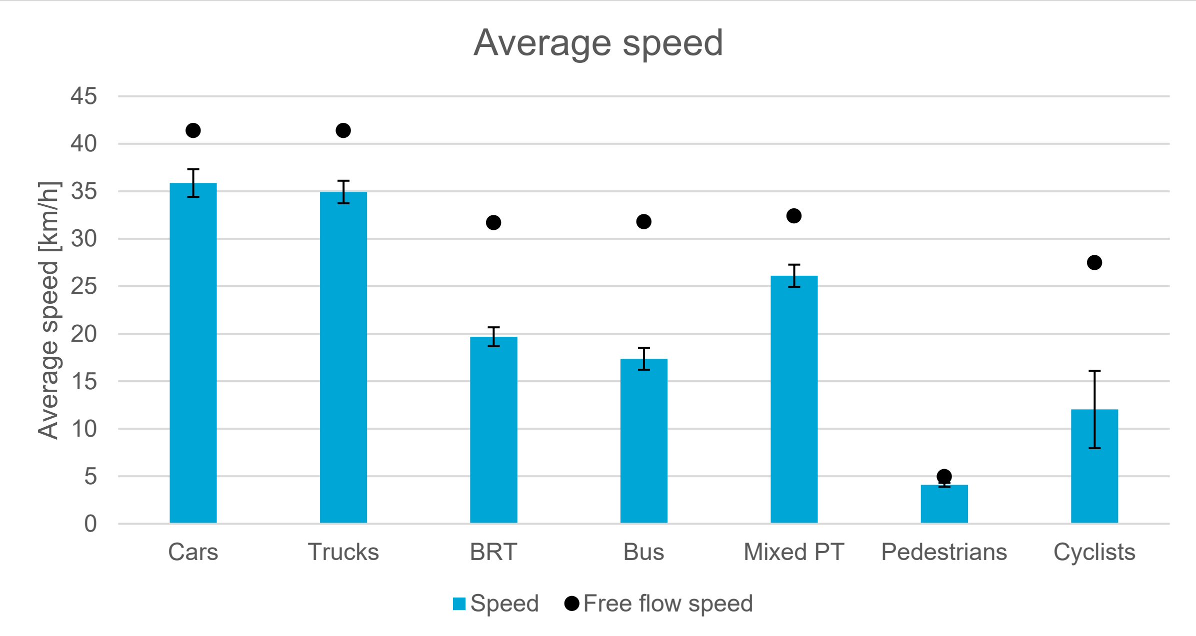


Figure 38 Average speed from design solution 1: Mixed traffic conditions

Figure 39 shows the travel times per mode per direction. It also shows the free flow travel times per mode per direction. The travel times were only collected for the vehicles that travel through the roundabout in each direction, and no turning movements were considered.

The figure shows that the vehicles travelling along Hringbraut (E-W and W-E) have a travel time similar to the free flow travel time. The travel times along Sudurgata are longer than free flow travel times, especially for the buses. This could be due to the same fact as for the speed, that Hringbraut is a main road and has much heavier flow than Sudurgata, causing the vehicles that are entering from Sudurgata to have to wait, which causes longer travel times. The travel time of the buses is even longer because they have larger gap acceptance and therefore might have to wait longer to get an acceptable gap to enter the roundabout.

The figure shows that pedestrians and cyclists have travel times similar to their free flow travel times, where cyclists have slightly higher travel time compared to the free flow travel times due to the high desired speed.

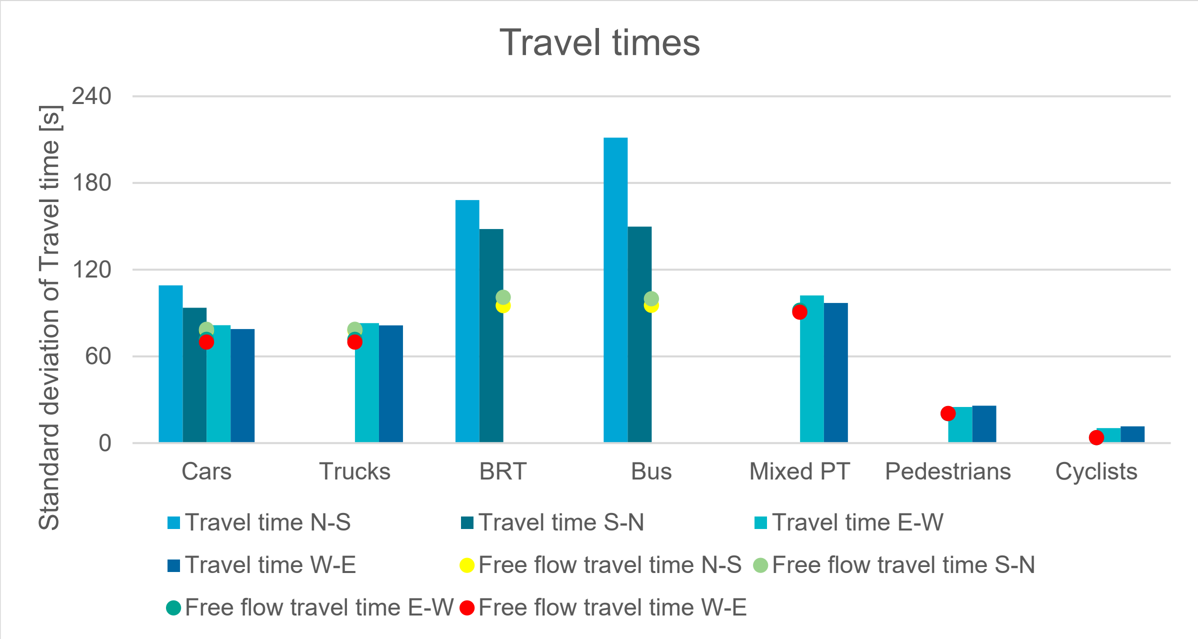


Figure 39 Travel times per direction and mode from design solution 1: Mixed traffic conditions

Figure 40 shows the variation in travel time per mode per direction. Low variation in travel times means that the average travel time is more reliable. Additionally, low variation in travel time for public transport is an important variable for a good service as a low variability in travel time means that the service is more reliable and on time.

The figure shows that there is high variation in the travel times along Sudurgata, for all modes, and especially for the southbound traffic. This variation is due to the few and small gaps that are created from the traffic that is already in the roundabout and that sometimes queues form on Sudurgata for entering the roundabout. The difference between northbound and southbound traffic is because of the extra intersection on the north side of the roundabout, the intersection of Sudurgata and Skothusavegur. This tends to create a queue, which increases the variation in travel time. The variation in travel time for buses travelling on the exclusive lanes is especially high for this design solution, or about 17s for southbound traffic and a bit lower for northbound traffic, or 3s for BRT and 11.6s for buses. The difference in variation between BRT and buses northbound is not expected, as they should behave the same, since the only difference is the vehicle length. But this difference might be from the number of vehicles driving through the intersection in the simulation, as there are only 16 buses but 48 BRT vehicles.

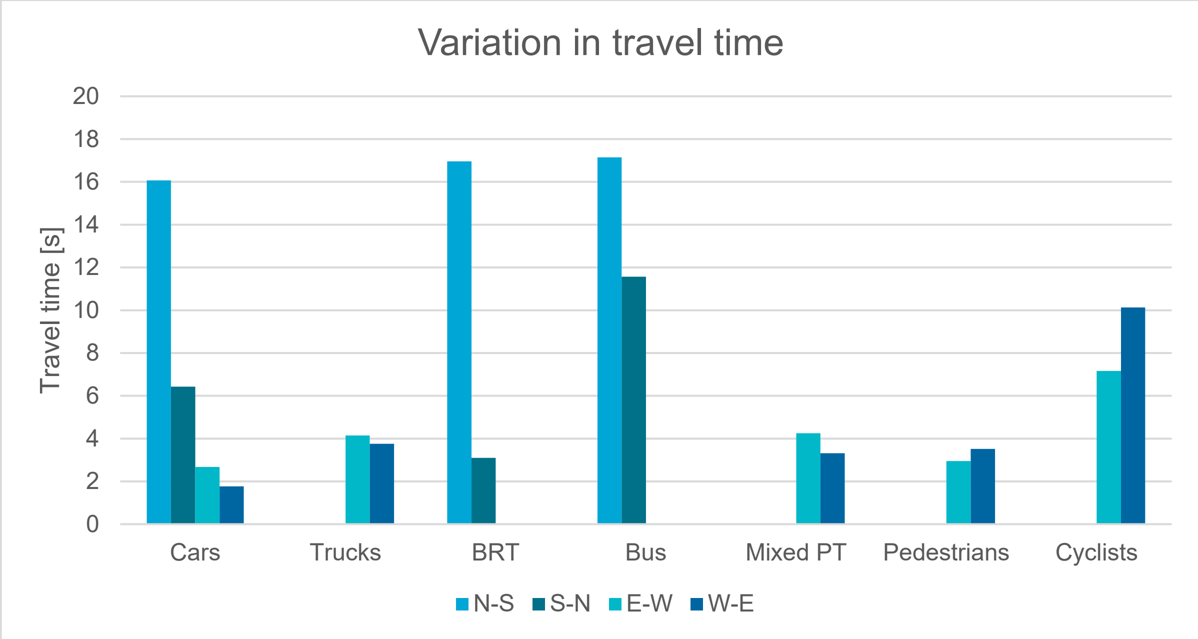


Figure 40 Variation in travel time per mode and direction from design solution 1: Mixed traffic conditions

Figure 41 shows the number of stops per mode and the time stopped during the trip. The figure shows that the buses, BRT vehicles, and active mode users are stopping often. Similar to the previous parameters, this is due to the heavy traffic on Hringbraut and having to wait to enter the roundabout from Sudurgata. The active mode users cross Sudurgata, which leads to more stops from the active mode users because of the queue.

However, the time stopped for the active mode users is very short but much longer for the buses. The time that buses are stopped is longer because they have longer gap acceptance and have to wait longer to get an acceptable gap. The figure shows that the active mode users are stopping very often despite the short distance. This could be due to a downside or a limitation in the model, as the active mode users should have priority crossing Sudurgata, but when there are queues of cars on the road, the active mode users might try to cross multiple times, but can't, but it is recorded over two timesteps, resulting in a recorded stop.

Cars and trucks stop less than once on average, but their speed is lower than free flow speed, which means that cars and trucks are mainly driving slower than in free flow conditions but the increase in travel time and lower speed is not from many stops.

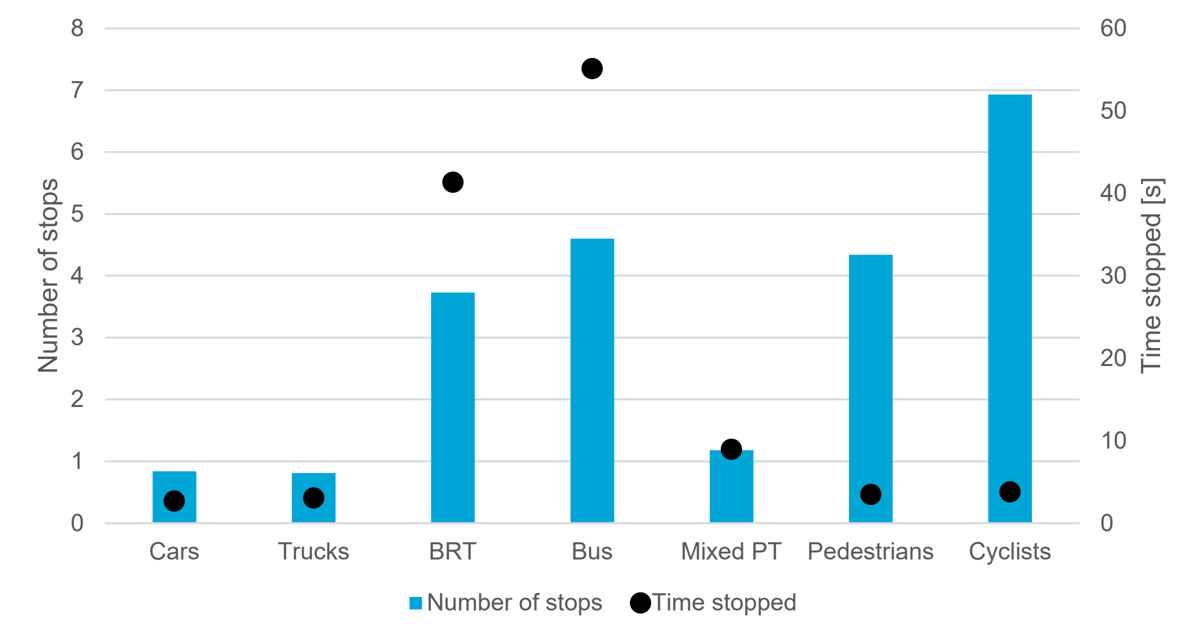


Figure 41 Number of stops and time stopped from design solution 1: Mixed traffic conditions

Safety

From observing the number of conflict points on the intersection, this design solution has 34 conflict points, where 32 are on the roundabout and 2 are from the merging and diverging of the exclusive bus lanes.

The trajectory files from each simulation run are put into SSAM. First, the TTC and PET thresholds are put to 2.7s and 8s, respectively. These thresholds are found from the studies of Wu et al. (2016) and Muley et al. (2018) for conflicts between pedestrians and vehicles. As mentioned in chapter 4.1.2, SSAM cannot distinguish between different vehicle types, however, conflicts can be filtered based on links. Since all active modes travel on specific links, and don’t share those links with vehicles, the conflicts between active modes and vehicles can be filtered out.

Because the active mode crossing crosses the road, all conflicts are crossing conflicts, conflicts between different active mode users are not considered due to limitations of the model and because it is out of the scope of this research. SSAM resulted in that the average number of conflicts between active mode users and vehicles are 27, with a standard deviation of 5.3 (Table 12).

When looking at conflicts between vehicles, the TTC and PET thresholds are changed to 1.5s and 5s, respectively. All conflicts related to the links with active modes are excluded from this analysis since these are counted in the active mode – vehicle conflicts. Table 12 shows that there are 350 rear end conflicts, 120 lane-changing conflicts, and 49 crossing conflicts.

Table 12 Number of conflicts from design solution 1: Mixed traffic conditions

	Average	**Standard deviation**
Crossing conflicts	49	6.2
Rear end conflicts	350.5	104
Lane-changing conflicts	120.4	20.4
Active mode crossing conflicts	27.1	5.3

Conclusions

The results from design solution 1 are as expected as the performance of the buses that are on the exclusive lane resulted in a high variability in travel time and longer travel times than other modes. This is due to that Hringbraut is a main road and the available gaps to enter the

roundabout might sometimes be infrequent and short. The buses have longer gap acceptance than other types of vehicles and therefore, must wait longer to enter the roundabout, leading to longer and more variable travel times.
This design solution results in a good performance for other vehicles, especially vehicles travelling along Hringbraut as their travel time was very similar to free flow travel times and they were stopping less than once on average.
According to literature, this design is not recommended design for the priority of BRT (VSÓ Ráðgjöf, 2019). However, it performs well for the other modes that are using the intersection. It has minimal changes of the current intersection design and therefore the costs of this design are low.

6.1.2 Design solution 2: Traffic signals for entering traffic

The second design solution is where the roundabout is changed to a throughabout, where the exclusive lanes are extended through the centre island of the roundabout. This design solution is fully regulated as it has traffic signals for all entering traffic.
As mentioned before in this chapter, one of the simulation runs for this design resulted in a gridlock and is therefore it is excluded from the analysis and evaluation of this design. Additionally, it was noticed during the simulations that design solution 2 created long queues on Hringbraut, especially on the NW side, as shown in Figure 42, and the queues continue to grow as the simulation continues. It is likely that these queues are created because the exclusive bus lanes are crossing a main road (Hringbraut), and with the high frequency of the buses, the traffic on Hringbraut gets congested. Because of the long queues, it is expected that this design solution will perform worse than the other designs.

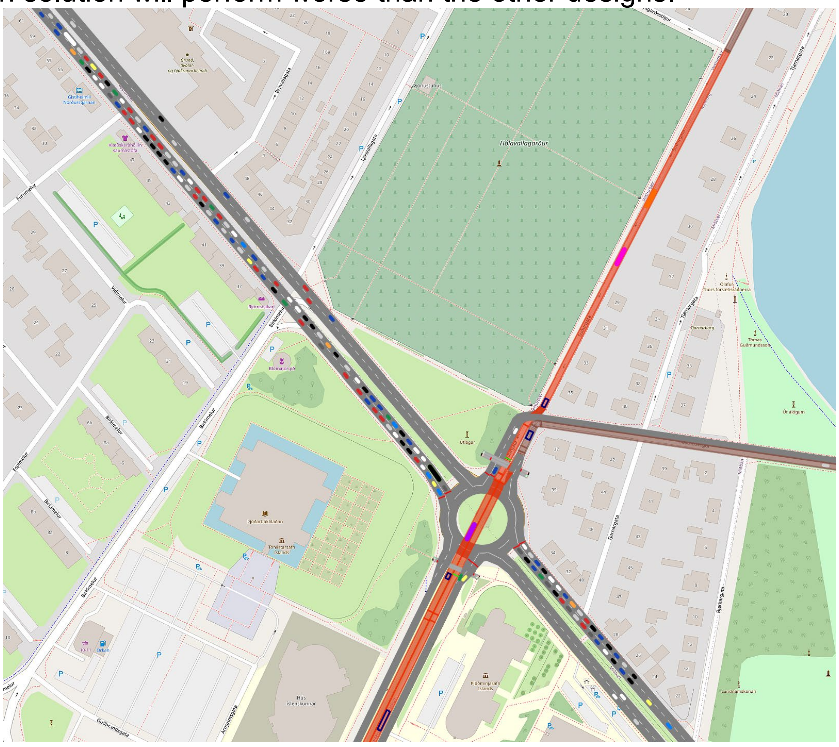


Figure 42 Queues created on Hringbraut in design solution 2: Traffic signals for entering traffic

Traffic performance

The throughput for this design solution for each mode is shown in Table 13. The total throughput of the intersection is 2,992 vehicles per hour, or users per hour for active modes.

Table 13 Total throughput and throughput per mode from design solution 2: Traffic signals for entering traffic

	Cars	Trucks	BRT	Bus	Mixed PT	Pedestrians	Cyclists	Total
Average throughput [veh/hr]	2,748	25	48	16	29	101	25	2,992

Figure 43 shows the average speed per mode. The figure shows that the buses driving on the exclusive lane almost drive at free flow speed. The small difference of the free flow speed and average speed might be from the location of the detector on the north side. That detector is located closer to the intersection (as explained further in Appendix B: Location of detectors) leading to that the buses might sometimes have to slow down slightly before getting a green light in order to clear the roundabout of other vehicles. The speed of buses and BRT is close to free flow speed, and much higher than for design solution 1 is because of the priority that is given to the buses, from the exclusive lanes and that they do not have to stop before passing through the intersection.

The speed of the cars, trucks, and mixed PT is much lower than free flow speed. This is due to the long queues and from having to stop at the traffic signals every time a bus is passing through the intersection. The speed of active mode users is similar to the previous design, where the difference between the free flow speed and average speed of cyclists is due to the high desired speed chosen.

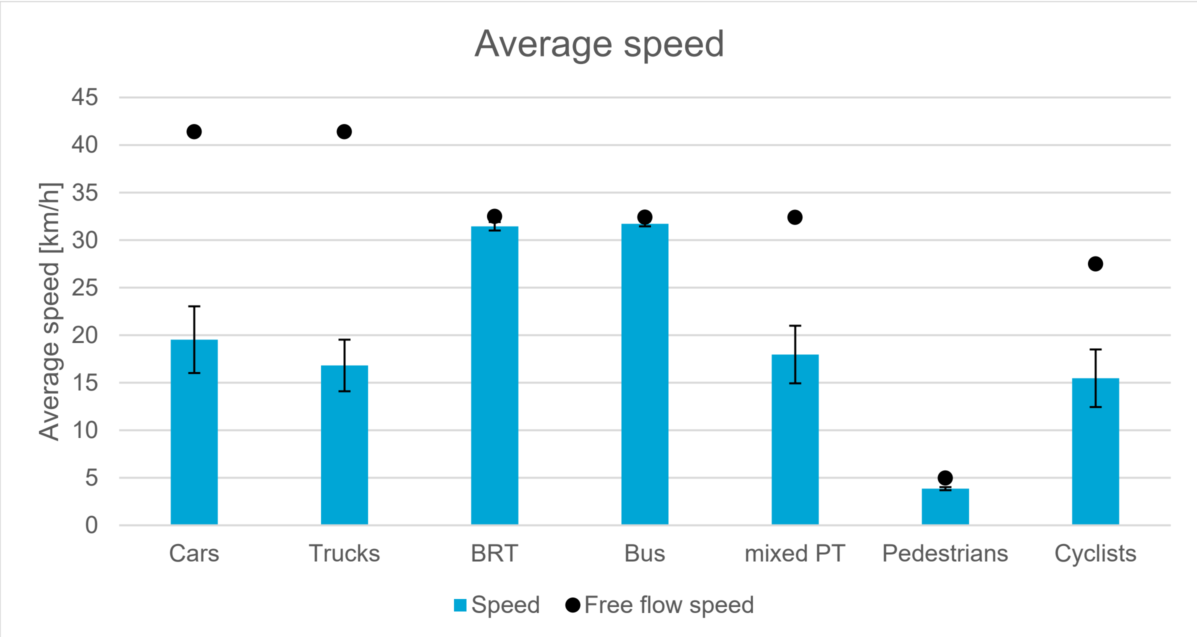


Figure 43 Average speed from design solution 2: Traffic signals for entering traffic

Figure 44 shows the average travel times per mode per direction. The directions considered are only through the intersection, and therefore not all modes are included in all directions, for example BRT only travels from S-N and N-S.

The figure shows that the travel time for buses on the exclusive lane (N-S and S-N) is similar to the free flow travel times. Compared to design solution 1, the travel times for the buses are at least 1.5 times shorter when they have full priority. This large reduction in travel time comes from the exclusive lanes through the roundabouts and that the buses get full priority in design solution 2 but are in mixed traffic and entering the roundabout from a minor road, causing long waiting times in design solution 1.

The travel times on Sudurgata (N-S and S-N) for cars are just slightly higher than free flow travel time. The vehicles travelling on Hringbraut see long travel times compared to free flow travel times, especially for the direction W-E, and can experience a delay of up to 5 minutes. The short travel times on Sudurgata might be from that whenever a bus has passed through the roundabout and the traffic signal turns off, the cars waiting to enter the roundabout have an empty roundabout for few seconds and can enter immediately. The longer travel times along Hringbraut is from the heavy traffic and queues that are formed due to the high frequency of buses and the red light signals every time a bus passes through the intersection. The reason why there is a large difference between the travel time W-E and E-W could be because of traffic volume, where more cars drive to the east in the afternoon peak and would likely be reversed during the morning peak.

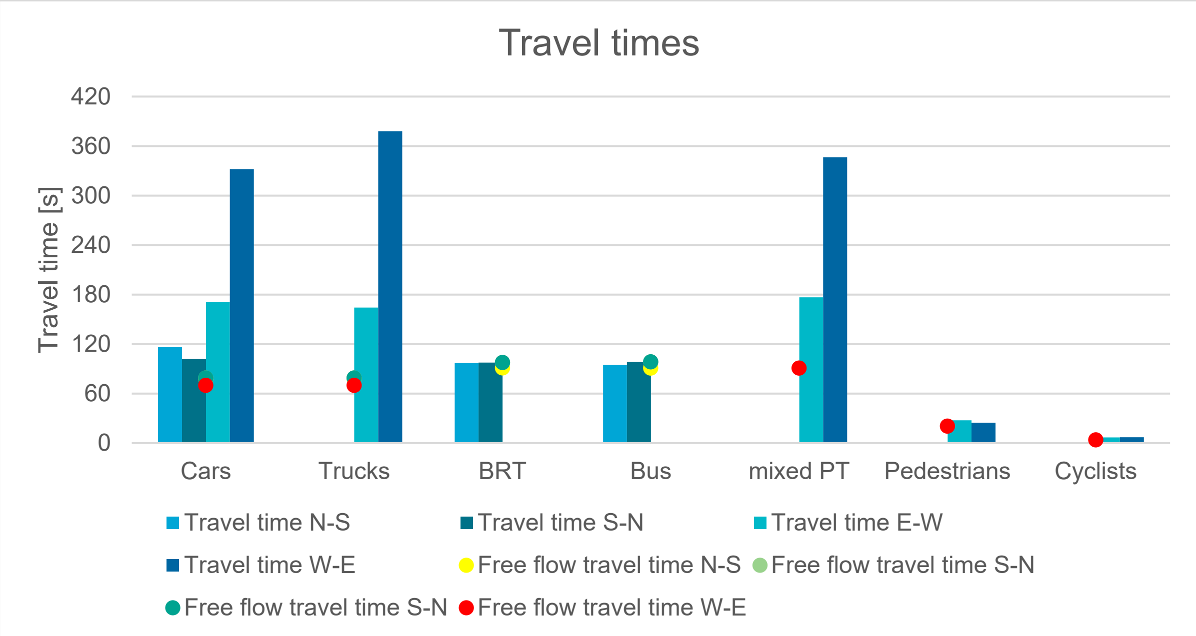


Figure 44 Travel time per mode and direction from design solution 2: Traffic signals for entering traffic

Figure 45 shows the variation in travel time per mode per direction. The variation in travel time for the buses on the exclusive lane is very low, making the service very reliable. This is because they get full priority through the intersection on the exclusive lanes and the traffic in the roundabout is stopped before the buses enter the roundabout.
The variation in travel time for cars on Sudurgata (N-S and S-N) is also low. However, the variation in travel time on Hringbraut (E-W and W-E) is very high, and the average travel time for cars, trucks, and buses (mixed PT) can vary up to one minute. This is due to the long queues that are formed because of the traffic signals and the priority of the buses. As the simulation runs longer, the queues get longer, varying the travel times more.

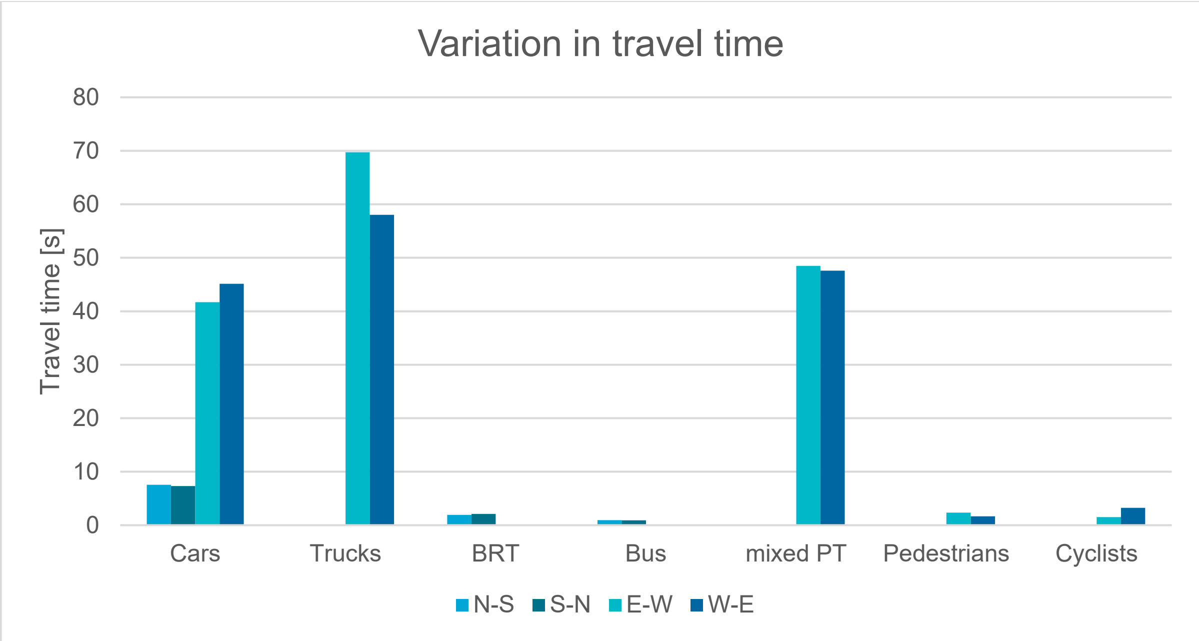


Figure 45 Variation in travel times per mode and direction from design solution 2: Traffic signals for entering traffic

Figure 46 shows the number of stops and time stopped per mode for this design solution. The figure shows that the buses on the exclusive lanes hardly make any stops because they get full priority through the intersection. The buses on the exclusive lanes may have to stop occasionally, especially on the north side, because the detector is located close to the intersection and the buses might have to stop and wait until the signal turns green for them.
The active mode users also stop very few times, compared to the previous design solution. The reason why this difference is so large is unclear but might be because now the active mode users have traffic signals as well and just stay stopped when they can't cross the road, when in design solution 1, they also had priority, but were blocked by cars, causing the program to always make the active mode users try to cross but having to stop because they were blocked by cars.
The figure also shows that cars, trucks, and mixed PT are stopping often and are stopped for a long time, from a little under a minute to about one and a half minute. These number of stops are from the long queues and staying in a stop and go traffic for some time, stopping many times when the lights turn red when a bus in passing through the roundabout.

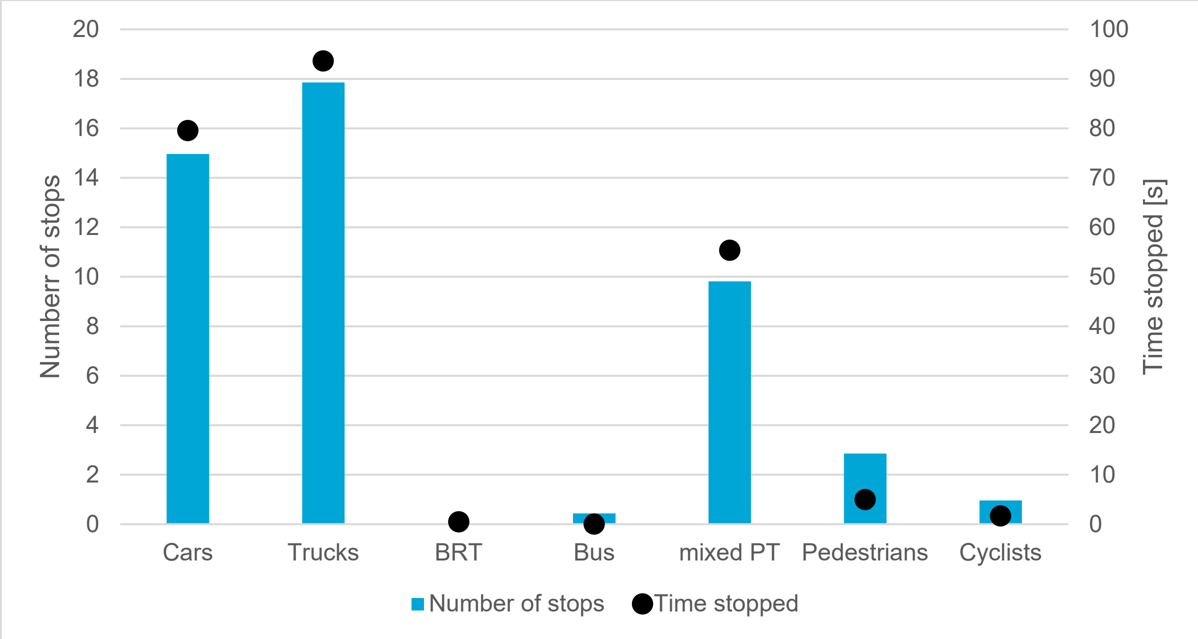


Figure 46 Number of stops and time stopped from design solution 2: Traffic signals for entering traffic

Safety

From observations of the design solution setup in VISSIM, the total number of conflict points of this design are 44. The number of conflicts between active mode users and vehicles are calculated using SSAM with a TTC value of 2.7s and a PET value of 8s. Table 14 shows that the number of conflicts between active mode users and vehicles are 12.4 with a standard deviation of 5.4. The number of conflicts between vehicles are calculated using SSAM with a TTC value of 1.5s and a PET value of 5s. Table 14 shows that the number of crossing conflicts are almost 20, which is much lower than for design solution 1 (which are 49). The reduction in crossing conflicts might be because of the traffic signals, because then there are less traffic jams in the roundabout where these conflicts tend to occur from the vehicles exiting or entering the roundabout from the inner lane. But as the traffic signals clear out the roundabout every time a bus is approaching the intersection, there are less conflicts in the roundabout. On the other hand, the number of rear end conflicts is high, or 2,338.3 with a standard deviation of 613. This is a large increase from design solution 1, where the rear end conflicts were only 350. This is due to the long queues that are formed on the roads, especially on Hringbraut. This difference can be seen in Figure 70 compared to Figure 69 in Appendix C: Outputs - SSAM maps, where all the conflicts for these designs are showed. The figures show that the rear end conflicts are indeed from the queues.

The number of lane-changing conflicts is 241.9. Which is about twice as much as design solution 1. This difference might be due to the queues as well and that cars are changing lanes, hoping that they might travel faster on the other lane. However, the number of lane-changing conflicts are likely to be overestimated due to simplifications in the model as discussed in chapter 5.3.2 in addition to that some unrealistic behaviour was seen in the models such as illegal lanes changing behaviour, this has also been seen in other research, for example in the research by Huang et al. (2013).

Table 14 Number of conflicts from design solution 2: Traffic signals for entering traffic

	Average	**Standard deviation**
Crossing conflicts	19.9	3.2
Rear end conflicts	2,338.3	613
Lane-changing conflicts	241.9	39.1
Active mode crossing conflicts	12.4	5.4

Conclusions
The results for the performance of the BRT and buses on the exclusive lanes are as expected. As this design gives these modes full priority through the intersection, it is expected that their performance would be good. The buses can drive on their desired speed and their travel time is very similar to free flow travel time. Additionally, as expected, the buses do not have to stop, except in very rare cases, when they are about to cross the intersection.
It was expected that the traffic on Hringbraut would perform worse compared to the previous design solution, as literature indicated that giving priority to BRT that crosses a main road has negative effects on the traffic on the main road (Frøyland et al., 2014; VSÓ Ráðgjöf, 2019). Also, the frequency of the buses is very high causing the traffic signals to turn red very often and the traffic on the road is heavy, causing long queues to build up and continuing to grow as the simulation continues.

6.1.3 Design solution 3: Traffic signals for conflicting traffic

Design solution 3 is similar to design solution 2, as it is a throughabout where the exclusive lanes are extended through the centre island of the roundabout. However, this design is partially regulated where there are traffic signals inside the circular road of the roundabout and stops the vehicles that are in conflict with the buses, as is explained in chapter 5.4.3.

Traffic performance
The throughput for this design solution for each mode is shown in Table 15. The total throughput of the intersection is 3,155 vehicles per hour, or users per hour for active modes, which is a similar total throughput as for design solution 1.

Table 15 Total throughput and throughput per mode from design solution 3: Traffic signals for conflicting traffic

	Cars	**Trucks**	**BRT**	**Bus**	**Mixed PT**	**Pedestrians**	**Cyclists**	**Total**
Average throughput [veh/hr]	2,903	28	48	16	31	103	26	3,155

Figure 47 shows the average speed per mode. The figure shows that the buses on the exclusive lanes have an average speed that is almost the same as the free flow speed. This is because the buses are given full priority through the intersection. The small differences in the average speed and the free flow speed in likely from the location of the detector on the north side of the intersection. The detector is located closer to the intersection, resulting in that the buses have to slow down or briefly stop to wait for a green light, reducing the average speed slightly.
The figure shows that the average speed of cars, trucks, and mixed PT is much lower than free flow speed and has a high variation in speed. However, compared to design solution 2, the speed of cars, trucks and mixed PT is higher in this design. This is because of the location of the signals is now only for the vehicles in conflict with the buses, making the flow through the intersection better, and shorter queues are formed. The high variation in speed is because of the traffic signals, where those that are driving northbound or southbound, can go faster through the roundabout, especially when a bus is passing through the roundabout it is clear for those vehicles to pass while those that are in conflict with the buses have to wait, lowering the average speed.
The speed of pedestrians and cyclists are similar to the previous design solutions. This indicates that the priority of buses and the configuration of the intersection does not affect the speed of active mode users a lot. However, due to limited number of active mode users at this location, the real effects of this are not known for cases where the number of active mode users is high.

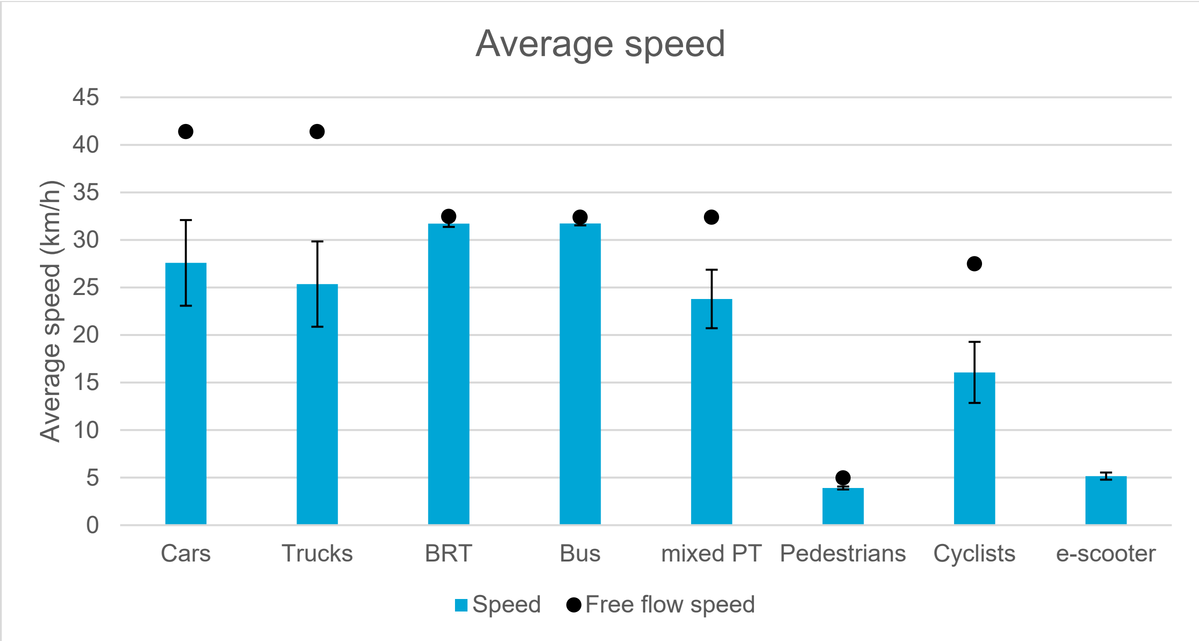


Figure 47 Average speed from design solution 3: Traffic signals for conflicting traffic

Figure 48 shows the travel times per mode per direction for this design solution. The figure shows that the travel times for the buses that drive on the exclusive lanes is the same as free flow travel times. This is because this design gives full priority to the buses on the exclusive lanes, which allows the buses to drive through the intersection without having to slow much down or stop.

The travel times for cars travelling along Sudurgata (N-S and S-N) are also close to free flow travel times. This is likely due to the fact that this design stops only traffic that is in conflict with the bus, meaning that the cars driving in the same or opposite direction to the buses, can enter the roundabout and continue their way. However, it was noticed that few times queues were created inside the roundabout obstructing the flow of the cars driving along Sudurgata, but these queues are shorter than in design solution 2: Traffic signals for entering traffic.

The figure shows that the traffic on Hringbraut has travel times that are much longer than free flow travel times and can have delays of up to 3 minutes. This is due to the priority given to the buses crossing Hringbraut, meaning that those that are travelling east or west have to stop and wait every time a bus passes through the intersection, causing the traffic performance on Hringbraut to decrease.

The travel times for active mode users are the same as free flow travel times. Which is in line with the conclusion that the different designs for the priority of buses does not affect the speed or travel time of active modes.

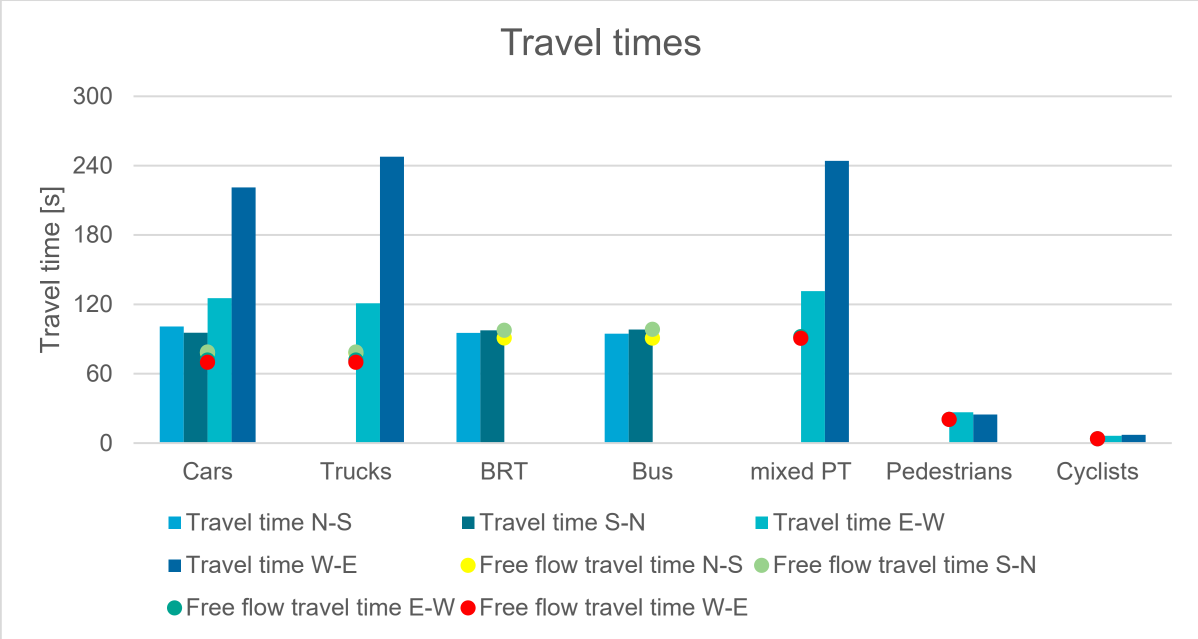


Figure 48 Travel times per mode and direction from design solution 3: Traffic signals for conflicting traffic

Figure 49 shows the variation in travel times per mode per direction for this design solution. The figure shows that the variation in travel times along Sudurgata (N-S and S-N) are very low for all modes. This means that the average travel times for those directions is often similar and very reliable. This also means that the BRT and bus service that use the exclusive lanes is very reliable. The variation in travel time for these directions is low because the buses get full priority and drive on the exclusive lanes, leading to more reliable travel times. Additionally, the variation in travel times for cars on Sudurgata is low. This is because of the location of the signals, whenever a bus passes through the roundabout, the circulating traffic is stopped leading to an 'empty' roundabout for the vehicles entering from Sudurgata, and since the buses have very high frequency, this occurs very often.

The variation in travel time for those driving along Hringbraut (E-W and W-E) is very high, especially for the direction from west to east and can vary up to over one minute. This is because of the priority given to the buses as the buses cross Hringbraut, causing these streams to have to stop every time a bus passes through the intersection.

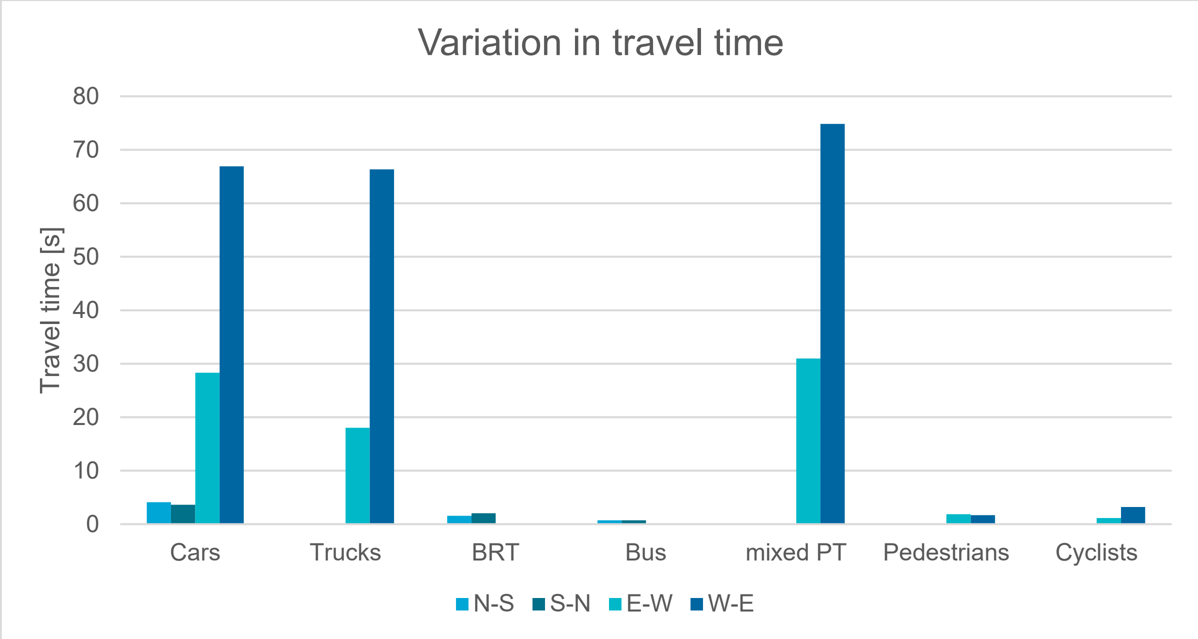


Figure 49 Variation in travel time from design solution 3: Traffic signals for conflicting traffic

Figure 50 shows the number of stops and time stopped per mode for this design solution. The figure shows that the buses on the exclusive lanes do not stop, as they get full priority through the intersection. However, other vehicles experience multiple stops and a time stopped of about 20 to 40 seconds. These many stops are due to the queues that are formed when the cars have to stop and wait for the buses to pass through the intersection, especially on Hringbraut, but also inside the roundabout. The number of stops and time stopped for active mode users is similar and slightly lower than for design solution 2: traffic signals for entering traffic. This is likely due to coincidence, but the number of stops and it is likely that the time stopped is lower than for the first design solution because of the traffic signals, making the active mode users only stop once and not trying to cross multiple times.

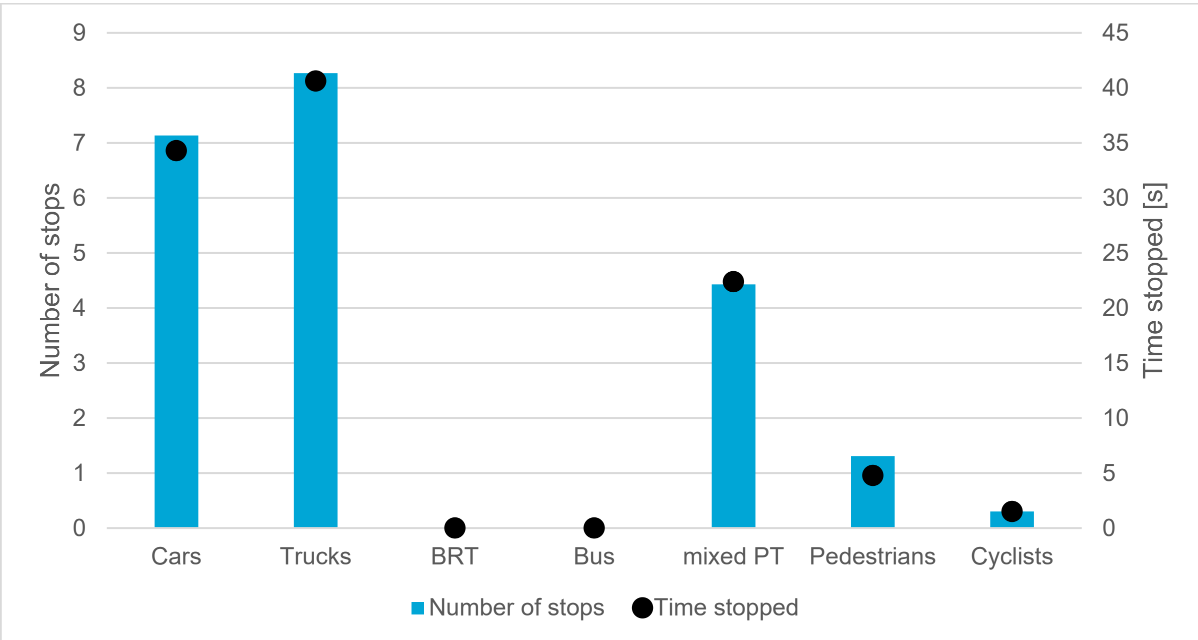


Figure 50 Number of stops and time stopped from design solution 3: Traffic signals for conflicting traffic

Safety
From observations of the intersection design in VISSIM, the design has 44 conflict points. The number of conflicts between active mode users and vehicles are calculated using SSAM with a TTC value of 2.7s and a PET value of 8s. Table 16 shows that the number of conflicts between active mode users and vehicles are 12.1 with a standard deviation of 4.3. The number of conflicts between vehicles are calculated using SSAM with a TTC value of 1.5s and a PET value of 5s. Table 16 shows that the number of crossing conflicts is almost 10, which is half the conflicts of the previous design solution (design solution 2: Traffic signals for entering traffic). However, the numbers of rear end conflicts (1,468.8) and lane-changing conflicts (246) are high, but much lower compared to design solution 2. The number of lane-changing conflicts are likely to be overestimated due to simplifications in the model and limitations of unrealistic lane-changing behaviour. The number of rear end conflicts are due to the queues that are formed, especially on Hringbraut, as Figure 71 in Appendix C: Outputs - SSAM maps indicates. Since the queues are also shorter than the queues in design solution 2, the lower number of rear end conflicts is expected.

Table 16 Number of conflicts from design solution 3: Traffic signals for conflicting traffic

	Average	**Standard deviation**
Crossing conflicts	9.7	3.5
Rear end conflicts	1,468.8	525.4
Lane-changing conflicts	246	37.4
Active mode crossing conflicts	12.1	4.7

Conclusions
The results of this design solution are similar to what was expected. The buses on the exclusive lanes can travel almost at free flow speed and travel time. The vehicles travelling along the same route as the buses can also travel with little delays. Additionally, the travel times for the road crossing the exclusive lanes (Hringbraut) see longer travel times and lower speed. This is because they have to wait at the red light every time a bus passes, and because of the high frequency of buses, longer queues build up.
Design solution 3: Traffic signals for conflicting traffic seems to perform better than design solution 2: Traffic signals for entering traffic, as only conflicting traffic must stop making the traffic flow smoother than if all entering traffic must stop. This was expected based on the research of Bråtveit (2016) and Aakre and Aakre (2017) which are further discussed in chapter 3.1.
Compared to design solution 2: Traffic signals for entering traffic, the number of conflicts between active modes and vehicles are similar in design solution 2 and 3 but other types of conflicts are lower in design solution 3 than in design solution 2.

6.2 Comparing design solutions

After investigating the results separately for each design solution, they need to be compared to determine which design is the best. Chapter 6.2.1 compares each design based on the criteria discussed in chapter 6.1 and investigates which design is best for each criterion. Since some criterion is more important than other this analysis is not enough, and MCA is performed. Chapter 6.2.2 discusses the results of the MCA and compares the design solutions based on the evaluation methodology discussed in chapter 4.

6.2.1 Results from simulation and calculations

Traffic performance
Figure 51 shows the throughput of vehicles per hour, including active mode users, for each design solution. The figure shows that design solution 1 has the highest throughput per hour of 3,222 vehicles per hour, followed by design solution 3 with throughput of 3,155 vehicles per hour. Design solution 2 shows a significantly lower throughput of 2,992. This large reduction

in throughput for design solution 2 is due to the traffic signals that stop all traffic, except the buses every time a bus needs to pass through the intersection. This, and the high frequency of the buses, causes much lower flow through the intersection and lot less vehicles can pass through the intersection in one hour.
Table 17 shows that the most difference in throughput is from cars. The table also shows that there is some difference between the throughput of trucks and mixed PT. These modes mostly travel on Hringbraut (E-W and W-E or turning). This is in line with the previous reason for the reduction in throughput for design 2, where the cars are blocked from passing through the intersection for multiple times during the simulation hour. This also causes long queues, as discussed in chapter 6.1, where designs 2 and 3 are more likely to create long queues on Hringbraut than design 1, causing delays and less throughput.

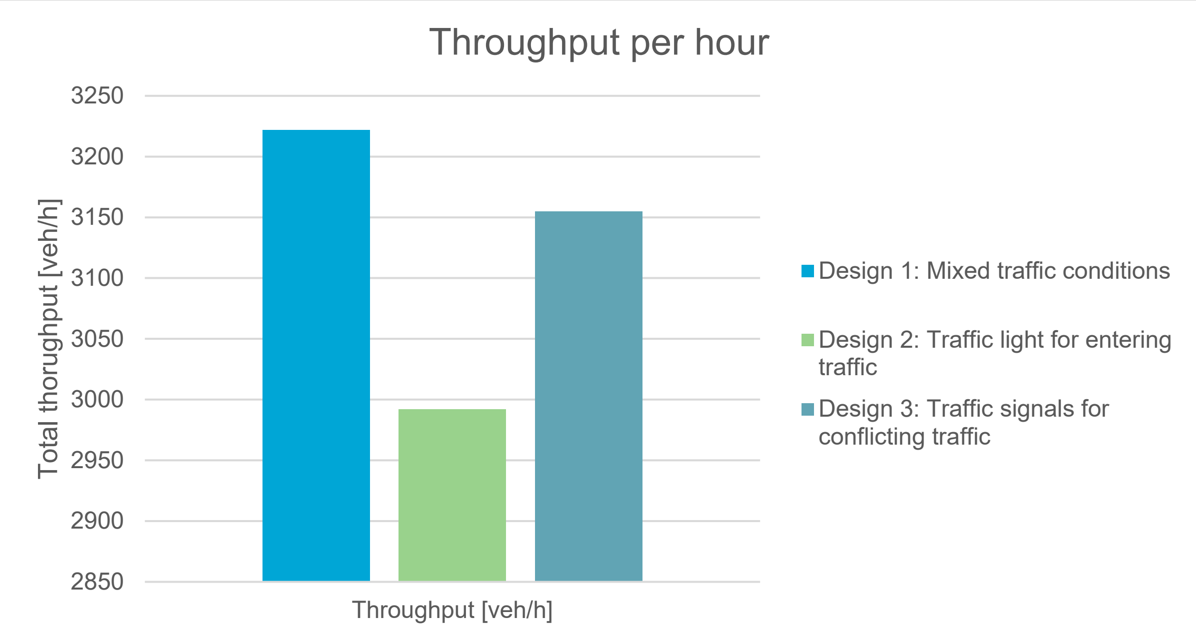


Figure 51 Throughput per hour per design solution

Table 17 Throughput per mode per design solution

Average throughput [veh/hr]	**Cars**	**Trucks**	**BRT**	**Bus**	**Mixed PT**	**Pedestrians**	**Cyclists**	**Total**
Design 1	2,968	29	48	16	32	103	26	3,222
Design 2	2,748	25	48	16	29	101	25	2,992
Design 3	2,903	28	48	16	31	103	26	3,155

Figure 52 shows the average speed of each mode for each design solution. Additionally, the figure shows the free flow speed of each mode per design solution. The free flow speed per mode is the same for each design solution, except that the buses and BRT (which are driving on the exclusive lane) have a lower free flow speed in design solution 1 than the other solutions due to having to drive in the roundabout in design solution 1 but can drive straight through the centre island of the roundabout in design solutions 2 and 3.
The figure shows that the speed of active mode users is almost the same for all design solutions. Which means that the configuration for the priority of buses does not affect the speed of active mode users. The figure shows that design 1 performs the best when focusing on cars, however, the speed of public transport is much lower in design 1 compared to the others. Design 3 shows that the speed of buses and BRT is at free flow speed, but the speed of the cars, trucks, and mixed PT is lower than in design solution 1. However, the difference between the speed of cars and buses on the exclusive lanes for design 3 is less than this

difference for design 1. This means that it is likely that design solution 3: Traffic signals for conflicting traffic performs the best in the speed category, but very close to design solution 1: Mixed traffic conditions.

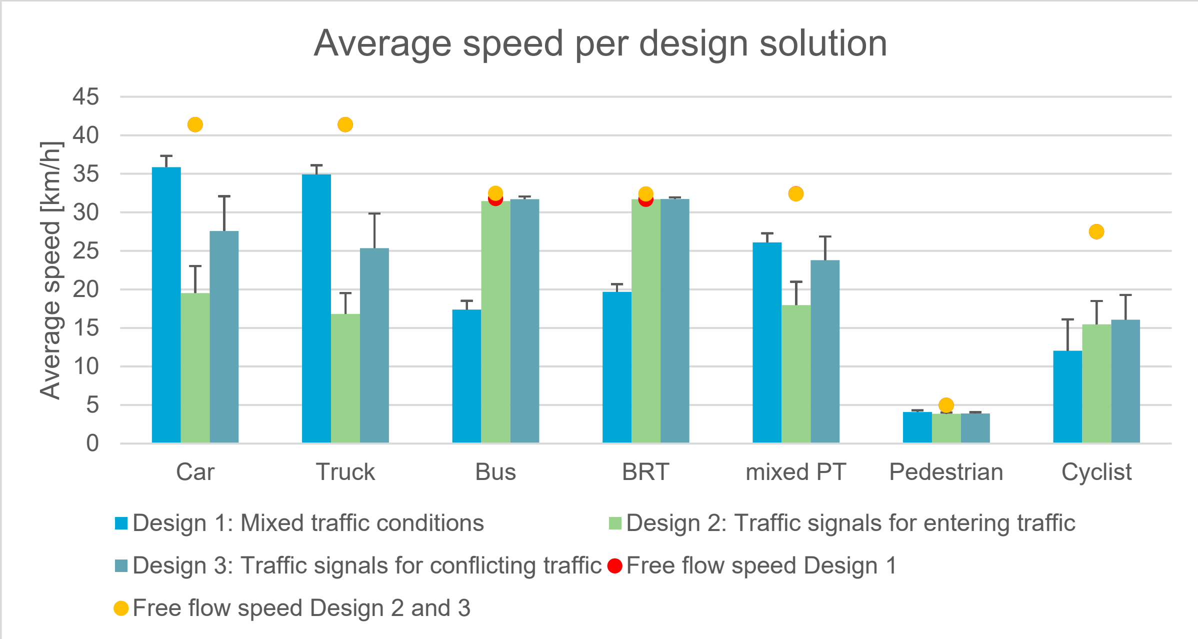


Figure 52 Average speed per mode per design solution

Figure 53 shows the comparison of travel time for the directions of north to south (upper) and south to north (lower) for each design solution. The figures show that the travel times of cars is similar for each design. The travel time of the buses and BRT in design solution 1 is much longer than it is in design solutions 2 and 3. This is because in the first design, the buses had to pass though the roundabout in mixed traffic, and sometimes had to wait for a long time for an acceptable gap to be able to enter the roundabout. The average travel times for buses and BRT for design solutions 2 and 3 are the same as the free flow travel times for those designs. This is due to the full priority given to the buses with the exclusive lanes in designs 2 and 3. The average travel time of cars are less than a minute longer than free flow travel time. The travel time of cars is the longest for design solution 2, which is due to the signals for the entering traffic causing many cars to have to stop and wait for the buses to pass through the intersection, and the high frequency of the buses causing this to occur often.
The total travel time for these directions is the longest for design 1, due to the long travel time of the buses and BRT, while design 3 has the shortest total travel time, and is therefore the best design in regard to travel time from north and south.

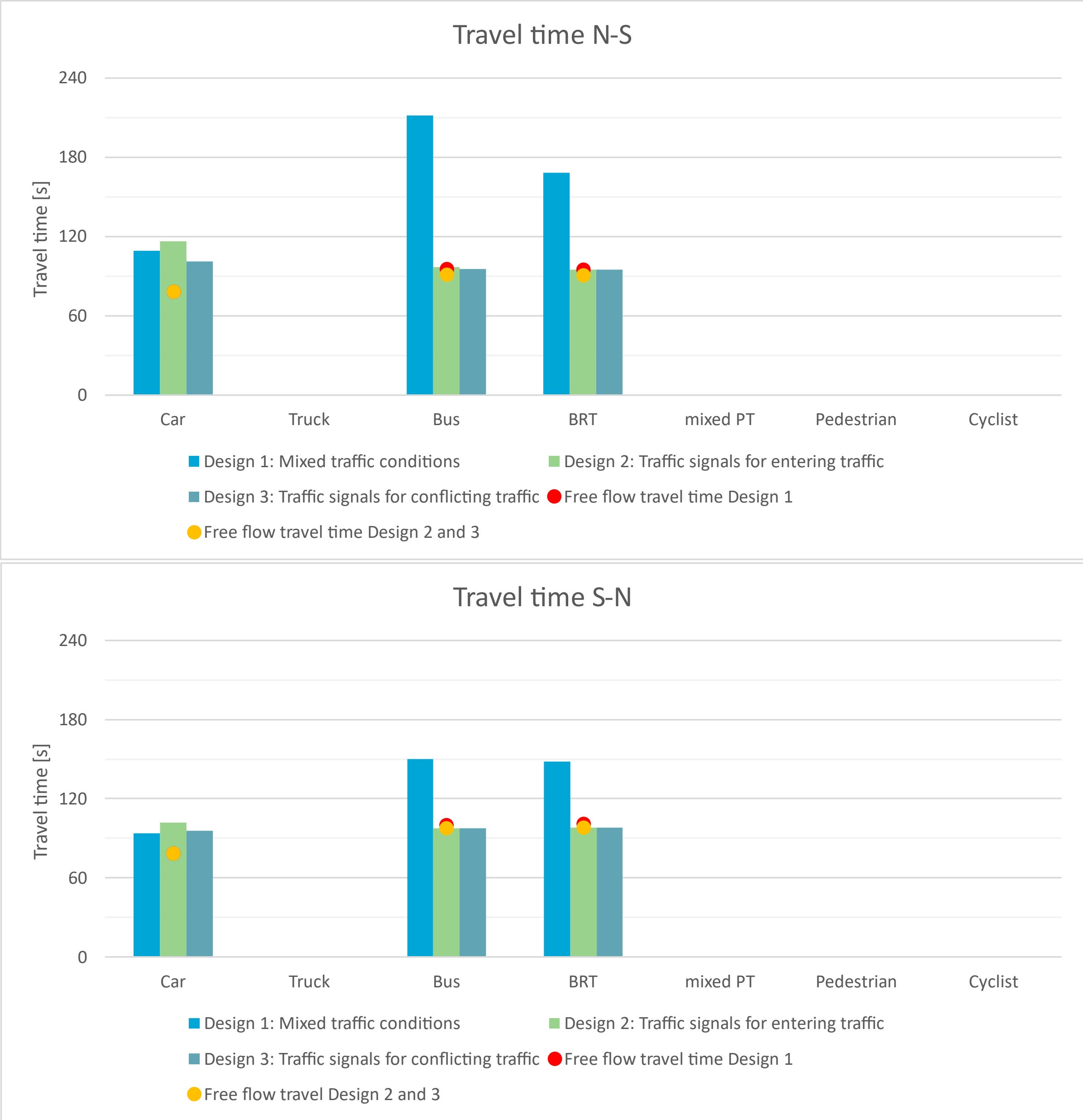


Figure 53 Travel time per mode per design solution in direction from north to south (upper) and south to north (lower)

Figure 54 shows the comparison of travel time for the directions from east to west (upper) and west to east (lower) between the alternative designs. The figure shows that there is much difference between the travel time travelling from east to west or west to east. The figure shows that design solution 1: Mixed traffic conditions performs the best with travel times close to free flow travel times. This is because there is no obstruction to this flow, like it is with the other designs, and since these directions are on the main road it flows much better than the north and south directions as it is easier to enter the roundabout. Design solution 2: Traffic signals for entering traffic has the worse travel times. This is due to the long queues created in this design solution and the traffic signals stopping all entering traffic when a bus is approaching the intersection. Design solution 3: Traffic signals for conflicting traffic has slightly better travel times compared to design solution 2. The difference in travel time between designs 2 and 3 is due to the location of the traffic signals, as design 3 allows for more flow even when a bus is approaching while design 2 stops everything.
Figure 54 shows that the travel time for active mode users is the same between each design solution. Resulting in that the performance of active mode users does not vary much between

the different designs, leading to the conclusions of that the priority of the BRT does not have much effect on the travel time of the active mode users for this intersection.

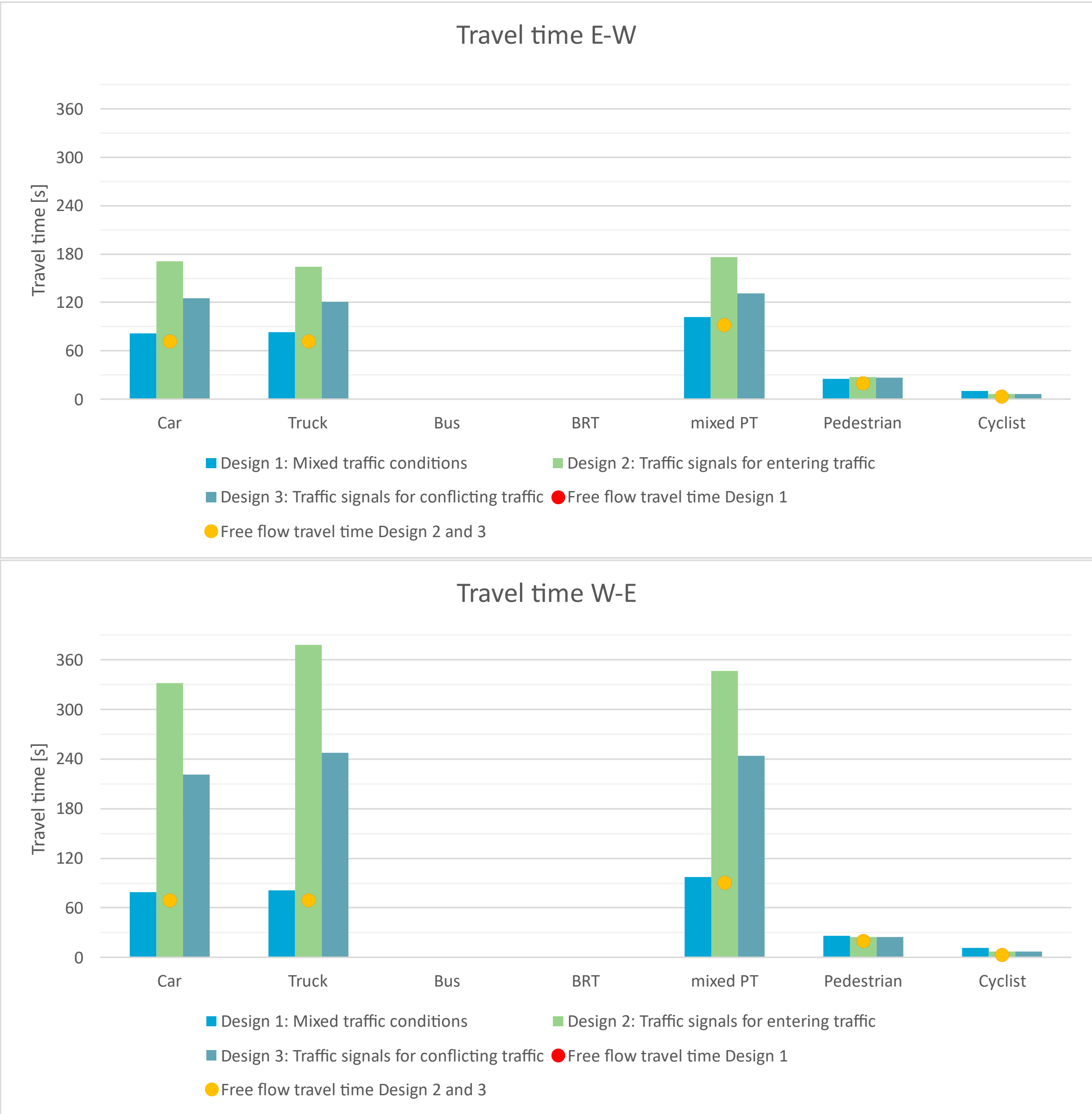


Figure 54 Travel time per mode per design solution in direction from east to west (upper) and west to east (lower)

Figure 55 shows the comparison of the variation in travel time for each alternative design solution for the directions from north to south (upper) and south to north (lower). The figure shows that design solution 1 has the highest variation in travel time where the travel time from north to south can vary by around 16 seconds and up to 11.5 seconds from south to north. Design solutions 2 and 3 show lower variation in travel time in both directions, especially for buses and BRT. The high variation in travel time for design 1 is because Sudurgata (northbound and southbound) is a minor road and the vehicles wanting to enter the roundabout have to wait for an acceptable gap. Since the buses are also travelling in mixed traffic in that design solution and they have larger gap acceptance, the variation in travel time becomes even larger. In the other designs (2 and 3), the buses travel on exclusive lanes and get full priority, leading to smaller variation in travel time.
Additionally, the figure shows that the variation in travel time is much higher for those travelling N-S, this might be because the traffic travelling from east to west comes in more waves,

causing there sometimes to sometime be large gaps and sometimes when the wait is long to enter the roundabout, leading to a larger variation in the travel times.

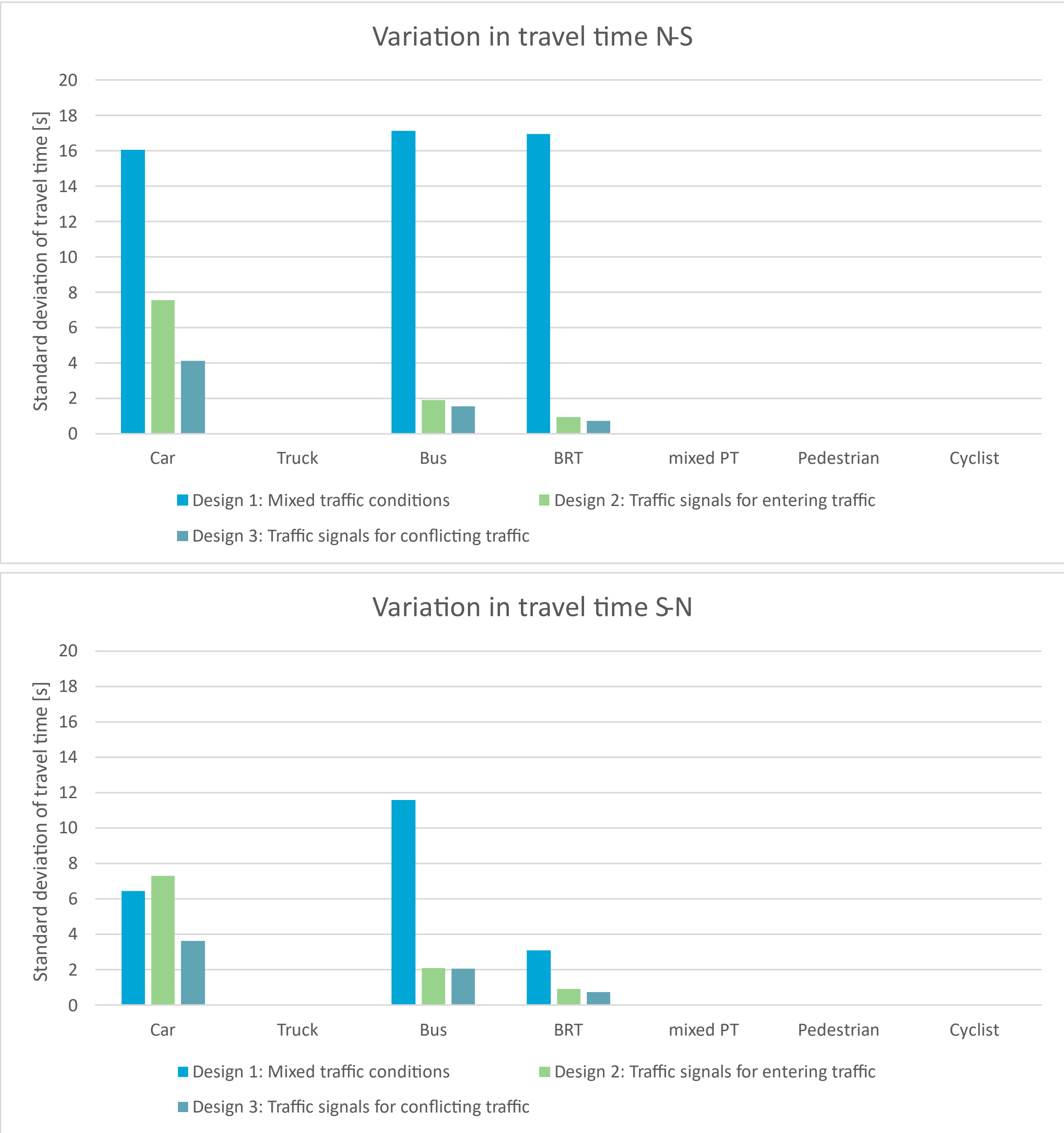


Figure 55 Variation in travel time per mode per design solution from north to south (upper) and south to north (lower)

Figure 56 shows the comparison between design solutions of variation in travel time from the directions of east to west (upper) and west to east (lower). The figures show that design solutions 2 and 3 show high variation in travel time, where the travel time can vary from about 40 seconds to 70 seconds. The queues formed in designs 2 and 3 are likely the cause of this high variability in travel time along Hringbraut, while design solution 1 has more constant flow resulting in much lower variation in travel time for these directions.
The variation in travel time for active mode users is low for all design solutions. However, design 1 shows more variation in travel time compared to the other designs. This could be due to that in designs 2 and 3 there are traffic signals that turn on (yellow and red) when a bus is approaching while design 1 has no signals for the active mode crossing.

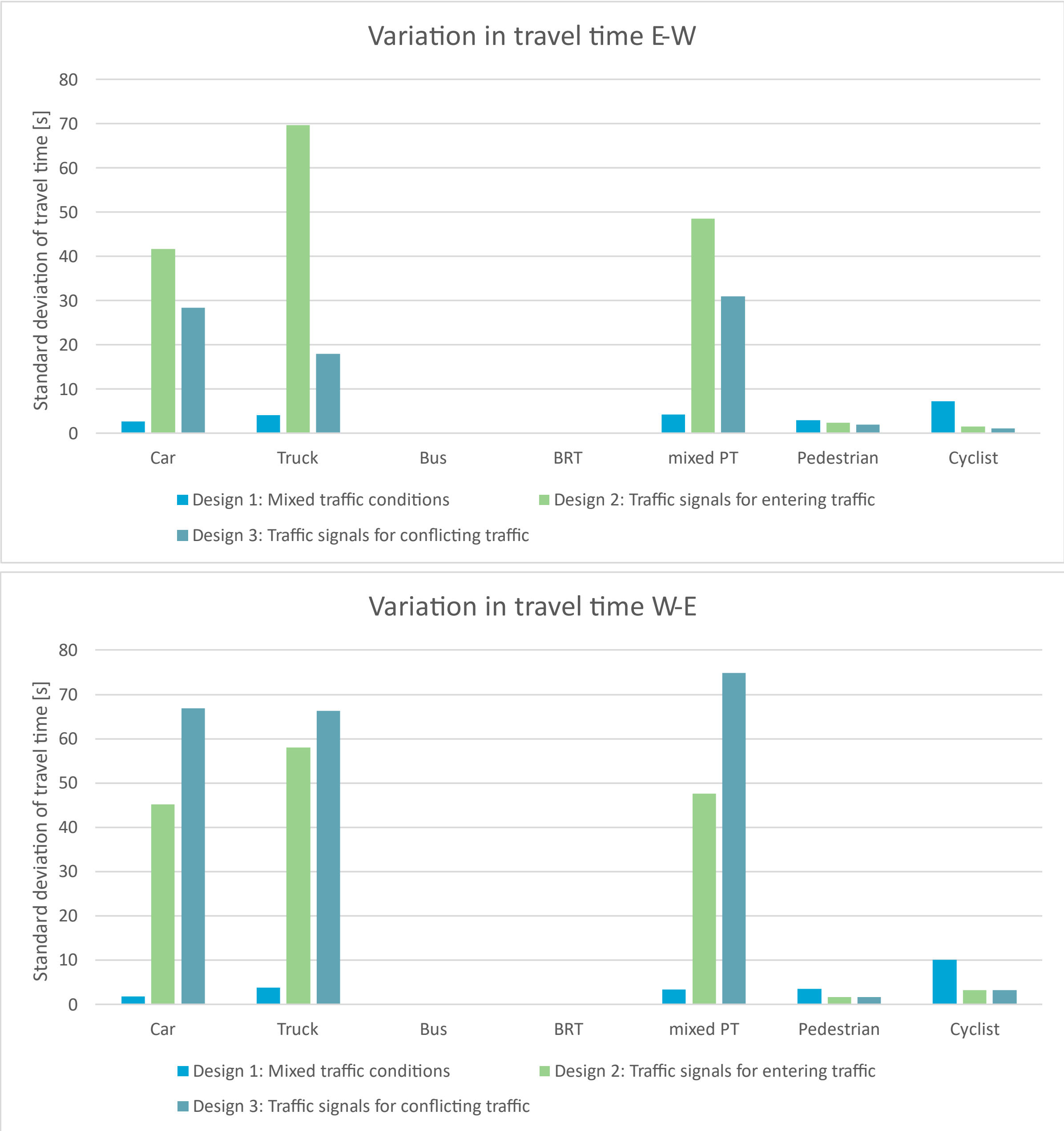


Figure 56 Variation in travel time per mode per design solution from east to west (upper) and west to east (lower)

Safety

Figure 57 shows the number of conflicts per design solution per type of conflict. The number of conflicts is calculated using SSAM. The TTC and PET values of 2.7s and 8s are used for the active mode conflicts, which are conflicts between vehicles and active mode users. Since active mode users are only using the active mode crossing links, the only types of conflicts occurring between active mode users and vehicles are crossing conflicts. The TTC and PET values of 1.5s and 5s are used for the conflicts between vehicles. These conflicts can be either crossing conflicts, rear end conflicts, or lane-changing conflicts. Chapter 4.1.2 explains further how these types of conflicts are defined.

The figure shows that overall, design solution 1 has the fewest number of conflicts. However, design 1 has more than double the conflicts between active modes and vehicles than designs 2 and 3, which have the same number of conflicts. Additionally, the figure shows that designs 2 and 3 have a very high number of rear end conflicts. These high numbers of rear end conflicts are due to the long queues formed in the design solutions. Appendix C: Outputs - SSAM maps shows maps from each design solution where the types and locations of the

conflicts can be seen, and those figures show that the increase in rear end conflicts are on Hringbraut. Therefore, it can be concluded that these increases in rear end conflicts are due to the queues on Hringbraut. Design solutions 2 and 3 also have more lane-changing conflicts than design solution 1. However, as mentioned in chapter 5.3.2, the model always includes two lanes shortly before and after the circulatory road of the roundabout, when there should only be one lane on the NE (exit) and SW (entrance and exit) arms of the roundabout. Additionally, during the simulations it was noticed that few cars were changing lanes inside the roundabout, despite not being allowed to change lanes, and some other unreasonable lane-changing behaviour was also noticed. Huang et al. (2013) also mentioned this unrealistic and illegal lane-changing behaviour in their research. Because of this it can be assumed that this behaviour is a limitation in VISSIM. Due to these limitations, the number of lane-changing conflicts are likely to be overestimated.
The number of crossing conflicts of design 1 is more than double the number of crossing conflicts for the other design solutions. This effect is expected even though the designs of the throughabout has more potential for crossing conflicts because of the lanes through the centre island, but because of the traffic signals and enough clear times, the number of crossing conflicts are reduced.

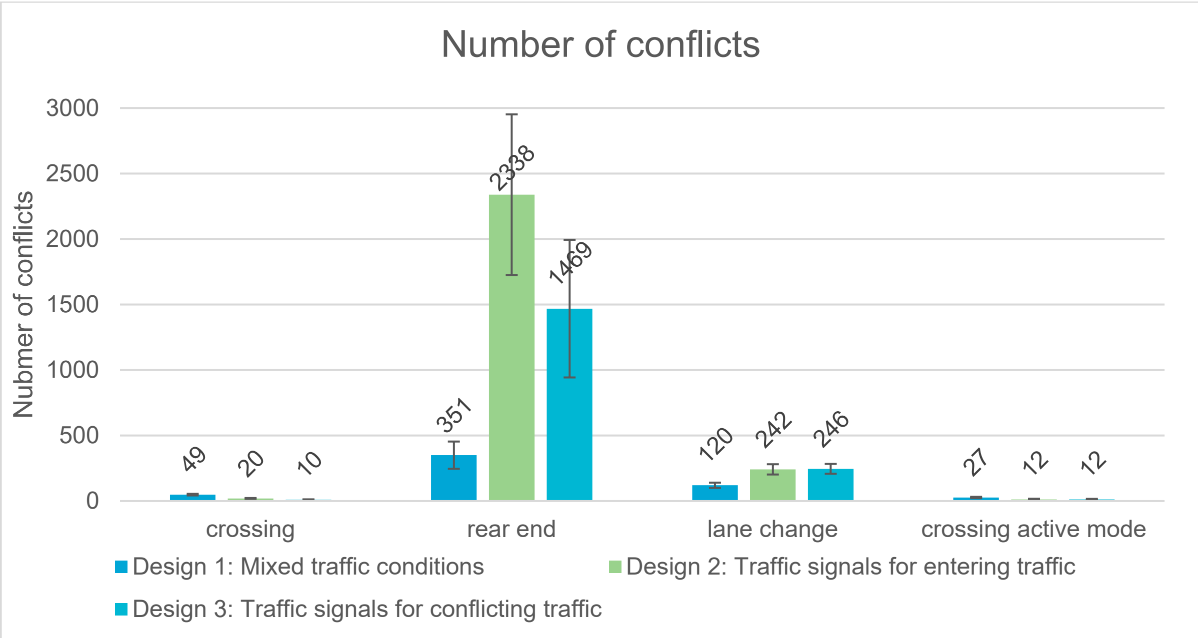


Figure 57 Number of conflicts for each design solution

Costs

One additional criterion that is not an output from the simulations or calculations is considered in the MCA. This criterion is costs. Because of limited information about the actual costs of these changes and project, the costs are evaluated for each criterion as a qualitative value from educated estimations. The qualitative ratings of the costs are rated from low to high and is based on construction or changes in design from the base design, in addition to maintenance costs, for instance from the presence of traffic signals.
The exclusive lanes that are not a part of the intersection, i.e., the median of SW Sudurgata, and the bus only road on NE Sudurgata, are not included in the construction costs because these parts are assumed to be a part of the base design.
Design solution 1: Mixed traffic conditions has the least changes from the base design as the intersection is the same as in the base. Additionally, there are no traffic signals in this design solution. Therefore, the costs for design solution 1 are rated as low.
Design solution 2: Traffic signals for entering traffic differs from the base design in a way that the exclusive lanes on Sudurgata are connected by adding exclusive lanes through the centre island of the roundabout. Additionally, traffic signals are added to each entering arm on the

roundabout and to every active mode crossing as well. Therefore, the costs for design solution 2 are rated as high.

Design solution 3: Traffic signals for conflicting traffic has a design similar to design solution 2 where the exclusive bus lanes go through the centre island of the roundabout. However, design 3 has fewer traffic signals compared to design 2, as this design solution only has signals where the vehicles in the roundabout are in conflict with the exclusive lanes. Design solution 3 also has traffic signals at the active mode crossings. Therefore, the costs for design 3 are rated as medium-high, as they are slightly lower than for design 2.

To be able to include the qualitative costs into the MCA, an estimation method is used to convert the costs to a normalized score. Using the same logic as the normalizing method, where the best option gets a score of 1 and the best 0, design solution 1 gets assigned a normalized score of 1, and design solution 2 gets a normalized score of 0. The score for design solution 3 must be between 0 and 1. Since the difference of costs between design solutions 2 and 3 are very little, the score is closer to 0. The score estimated for design solution 3 is 0.15, as shown in Table 18.

Table 18 Estimated normalized scores for costs

Design solution	**Estimated normalized score**
1	1
2	0
3	0.15

6.2.2 Multicriteria analysis

The results from the simulations and calculations indicate that design solution 2 might be the worst design of the three, as it is the often the worst design for each criterion, has much lower throughput, longer travel times, and more rear end conflicts from the long queues. Designs 1 and 3 might be closer to each other or might differ between stakeholders because design 1 has better flow (less queues), better performance for the cars, and less conflicts. But the performance of the public transport for that design is not good. Design 3 is better for public transport and at the same time the difference between the modes (cars and buses) is less than for design 1. Leading to that design 3 might score higher than the other two designs. However, due to that some criteria are more important to other criteria, this analysis is not enough to evaluate and compare the designs. As discussed in chapter 4, multicriteria analysis (MCA) is a good method to do this and is used to compare and evaluate the alternative design solutions.

As discussed in Chapter 4.3, stakeholder analysis is performed where the views of three stakeholders are considered. The stakeholder analysis is a way to test the sensitivity of the MCA as it uses multiple weight sets, one for each stakeholder. The stakeholders considered in this study are the municipality of Reykjavík, the Icelandic Road and Coastal Administration (IRCA), and a public transport authority Strætó bs. Both the municipality and IRCA value safety higher than traffic performance. However, the municipality puts more weight on the safety, and especially the safety of active mode users, than the IRCA. The public transport authority weights the traffic performance and especially the performance of the public transport service the highest. Chapter 4.3 discusses more in detail about the views of each stakeholder, followed by chapter 4.4.2 which discusses the weight sets per stakeholder.

The values for each criterion shown in chapter 6.1 are normalized using the linear: max-min method, as explained in chapter 4.4.1 and which are then multiplied by the weights defined in the weight sets in chapter 4.4.2. Table 19 shows the weighted score of each criterion per design solution for each stakeholder. Table 19 uses criteria level 4 where each criterion is divided into the specific direction and mode when appropriate. More details about the process to get the results of Table 19 from the simulation output can be found in Appendix C: Outputs (MCA scores). The table shows the abbreviations of the criteria, where TT is travel time, SD is the variation in travel time (standard deviation), NS, SN, WE, and EW are the directions, and PT is public transport.

Table 19 Multicriteria analysis result scores for criteria level 4

	Municipality			Road authority			Public transport authority		
Design solutions	1	2	3	1	2	3	1	2	3
Throughput	0.10	0.00	0.07	0.13	0.00	0.09	0.07	0.00	0.05
TT NS vehicle	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01
TT NS PT	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.08	0.09
TT SN vehicle	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01
TT SN PT	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.08	0.09
TT EW vehicle	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00
TT EW PT	0.01	0.00	0.01	0.01	0.00	0.01	0.04	0.00	0.03
TT EW active modes	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.01
TT WE vehicle	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
TT WE PT	0.01	0.00	0.00	0.01	0.00	0.01	0.04	0.00	0.02
TT WE active modes	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
SD NS vehicle	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
SD NS PT	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.08	0.09
SD SN vehicle	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
SD SN PT	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.08	0.09
SD EW vehicle	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00
SD EW PT	0.01	0.00	0.00	0.01	0.00	0.01	0.04	0.00	0.02
SD EW active modes	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
SD WE vehicle	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00
SD WE PT	0.01	0.00	0.00	0.01	0.00	0.00	0.04	0.02	0.00
SD WE active modes	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
Crossing conflict	0.00	0.09	0.12	0.00	0.07	0.10	0.00	0.04	0.05
Lane-changing conflict	0.05	0.00	0.02	0.04	0.00	0.02	0.02	0.00	0.01
Rear end conflict	0.07	0.00	0.00	0.06	0.00	0.00	0.03	0.00	0.00
Active mode-vehicle Conflict	0.00	0.36	0.36	0.00	0.30	0.30	0.00	0.10	0.10
Costs	0.10	0.00	0.02	0.10	0.00	0.02	0.10	0.00	0.02
Total	**0.39**	**0.56**	**0.74**	**0.46**	**0.49**	**0.72**	**0.44**	**0.54**	**0.72**

Table 19 displays a lot of values as the criteria of criteria level 4 is considered. When viewing the table, it is noticeable that the active mode – vehicle conflicts score high for design solutions 2 and 3. The higher weight on the public transport performance for the public transport authority can be seen in the table as the travel time for public transport criteria scores high for that stakeholder. However, as seen in the last row of the table, the ranking of the alternative designs is always the same for each stakeholder.

Since Table 19 shows a lot of detailed results, it can be difficult to see how the designs compare on a more aggregate level, such as the traffic performance, safety, and cost levels. Table 20 shows a more aggregate level of the MCA results where the scores are viewed at the criteria level 2. The table shows that design solution 3 never has the worst score of the three alternatives, and therefore it scores the highest in the end. This is seen for all stakeholders. This table can better show the differences in the traffic performance, safety, and cost criteria. It shows that design 3 scores the overall best in the traffic performance criteria, where it usually has the highest score out of the three designs, and never the lowest. Similarly with the safety criteria, but design 3 scores the highest in safety for all stakeholders as well.

Design 2 however, scores very close to design 3 in the safety criteria. This was expected as the number of conflicts, especially active mode conflicts, are very similar between designs 2 and 3, where 3 usually has lower conflicts.

Table 20 Multicriteria analysis resulting scores for criteria level 2

	Municipality			Road authority			Public transport authority		
Design solutions	1	2	3	1	2	3	1	2	3
Throughput	0.10	0.00	0.07	0.13	0.00	0.09	0.07	0.00	0.05
Travel time	0.04	0.05	0.08	0.07	0.04	0.10	0.11	0.19	0.26
Variation in travel time	0.03	0.06	0.08	0.06	0.07	0.09	0.10	0.22	0.24
Vehicle conflicts	0.12	0.09	0.14	0.10	0.08	0.12	0.05	0.04	0.06
Active mode conflicts	0.00	0.36	0.36	0.00	0.30	0.30	0.00	0.10	0.10
Costs	0.10	0.00	0.02	0.10	0.00	0.02	0.10	0.00	0.02
Total	0.39	0.56	0.74	0.46	0.49	0.72	0.44	0.54	0.72

It is noticeable from the tables that the weighted score of the conflicts between active modes and vehicles score higher than most other criterion. This means that the number of conflicts between active modes and vehicles might have a larger influence on the score and ranking of the design solutions. The sensitivity analysis in chapter 6.3 suggests that this criterion can have an effect on the final scores when it is more the four times the weight of the other criteria. However, it would only influence the final score slightly and since design 3 scores much higher than the other two designs, design 3 would still score the highest.

The tables show that the ranking of the design solution alternatives from best to worst is designs solution 3: Traffic signals for conflicting traffic, then design solution 2: Traffic signals for entering traffic, and last, design solution 1: Mixed traffic conditions. It is unexpected that design solution 2: Traffic signals for entering traffic scored higher than design 1: Mixed traffic conditions because the throughput is much worse, there are a lot of queuing, travel time on Hringbraut is much higher, and it has much more conflicts compared to design solution 1. However, the low crossing and active mode conflicts, and more equal travel time (less variation in travel time) for all directions seem to be the criteria that makes the difference in this case, especially the active mode crossings due to much higher weight on that criterion. The tables show that the scores of designs 1 and 2 are very close to each other, which could mean that the raking order of them could switch in some cases.
It was expected, from the simulation output, that design solution 3: Traffic signals for conflicting traffic would be one of the best alternatives because it gives priority to public transport, is safe for active modes and has fewer conflicts compared to design 2, while also keeping the difference in traffic performance between modes more equal than the other designs.

6.2.3 Conclusions

From the results presented in chapter 6.2.1, it was expected that design solution 3 would rank the highest for the municipality and the road authority because of the good performance of safety for active modes, in addition to the more equal traffic performance between modes, and better performance of the buses, which would also lead to a high score for the public transport authority. Table 19 and Table 20 show that this is indeed the case, where design 3: Traffic signals for conflicting traffic scores the highest score of the three alternative designs for each stakeholder. Design 3 also scores the best in terms of traffic performance and the safety. Design 3 is the best design because it gives full priority to the buses while still allowing the traffic to flow if they are not in conflict with the buses. Compared to design 2: Traffic signals for entering traffic, the flow of vehicles is better, since design 2 stops everything every time a bus is passing through the intersection, and when the frequency of the buses is high, more congestion is created. Design 1 is different from designs 2 and 3 in the way that is keeps a

better flow through the intersection but the performance of the public transport suffers, as seen in Table 19, and because one of the main goals of the city is to give more feasible travel options that can compete with the car, the score of design 1 decreases.
Another important aspect of the evaluation is the safety, especially the safety of active mode users because the collisions between active mode users and vehicles are more severe than the other types of collisions. Design 1 has twice as many active mode conflicts than the throughabout designs, resulting in a lower score. Design 3 had the same amount of active mode conflicts as design 2 but had lower number of all the other conflicts, resulting in being the best design in the safety criterion.
Design 1: Mixed traffic conditions scored the best in terms of costs, and design 2 the worst. The costs, however, do not affect the ranking of the best alternative because the difference between the scores of designs 3 and 1 is already large when only considering the traffic performance and safety criteria.
This results in that design 3: Traffic signals for conflicting traffic is the most optimal design for a roundabout with BRT when evaluating in terms of level of service and safety.

6.3 Sensitivity analysis

Before concluding that design 3: Traffic signals for conflicting traffic is the most optimal design and that design 1: Mixed traffic conditions is the worst, sensitivity analysis is performed to test how sensitive the model and methodology is to different inputs and assumptions. The sensitivity analysis can indicate how robust the model and methodology are and how the results are expected to change as inputs are changed.
Some of the different factors that can influence the methodology are the input into the model, the criteria, parameters, or thresholds used in the SSAM calculations, and the weights used in the MCA. To perform the sensitivity analysis, the most important factors that are thought to have the most impact on the results are investigated and the input and other factors are chosen based on these factors. The input parameters chosen to perform sensitivity analysis on, are the frequency and punctuality of buses. The frequency and punctuality of buses are chosen because when the frequency of the buses is higher, and they are given priority, the total red time for the other traffic increases, which can affect the performance significantly, especially in the case of Melatorg where the bus lane crosses a main road. The punctuality is also thought to have an effect on the time given for the priority of buses because when some buses are delayed, they are more likely to bunch. Which could lead to that many buses are close together when passing the intersection, causing the red light to be longer for the other traffic.
Additionally, sensitivity analysis is performed on the safety calculation, where the TTC and PET thresholds are the main factors that determine the number of conflicts. The thresholds of TTC and PET are chosen because when calculating the number of conflicts these thresholds define if a conflict is recorded or not. By varying these thresholds, it can be determined if there is a large change in the number of collisions for different thresholds. The number of collisions can affect the results of the evaluation and therefore it is important to know how the defined threshold changes the number of conflicts.
An additional sensitivity analysis is performed on the MCA, which is using different, theoretical weights for the criteria. The stakeholder analysis, performed in the case study and used in the methodology is already one type of sensitivity analysis, where different weight sets are used to test the sensitivity of the MCA. However, by testing more theoretical weights on the MCA can give an indication if there are criteria that have more influence on the results than others.
If the sensitivity analysis results in that the different inputs or assumptions do not change the final output or final results much, the model is considered to be robust which means that it is more likely to be valid for other cases and is not that sensitive to different inputs and assumptions.
The following chapters discuss the sensitivity analysis that are performed and the main results of the analysis. More detailed outputs, figures, and results of the analysis can be found in Appendix D: Sensitivity analysis.

6.3.1 Frequency of buses

The first input that is changed is the frequency of the buses. Since design solutions 2 and 3 give full priority to the buses driving along Sudurgata, it is likely that the flow of cars will be better if the frequency is lower. With changing the frequency of the buses on the exclusive lane, it can be investigated what effects it has on the output of the research.
This case study has four bus lines on the exclusive lanes that all have a high frequency going through the intersection which leads to the time of green light for the other users is limited. These four lines have a frequency of 8 buses per hour per line per direction, leading to a total of 64 buses per hour that pass through the intersection along Sudurgata.
For the sensitivity analysis, the frequency of all four lines is increased and decreased. While changing the frequency of the buses, the pattern of the arriving buses is tried to be kept as constant as possible. Chapter 5.3.1 introduces the arrival pattern of the buses in the base case. This pattern is used to make the arrival patterns of the higher and lower frequency cases.

Higher frequency
The base model already has quite high frequency of the buses. However, it could still be higher. To test for a higher frequency, the headway is changed form 7.5 minutes to 5 minutes, resulting in a frequency of 12 buses per hour for each bus line per direction. This leads to a total frequency of 96 buses per hour. Because of the reduction in headway, the arrival time pattern is slightly changed and is shown in Figure 58.

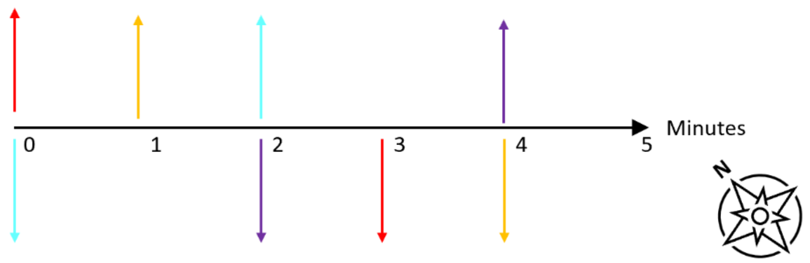


Figure 58 Bus arrival time pattern with higher frequency

All three design solutions are simulated in VISSIM, where each simulation has 10 simulation runs. However, 4 out of the 10 simulation runs in design solution 2: Traffic signals for entering traffic resulted in error message which indicate that the vehicle inputs of at least one link did not enter the network, indicating that a gridlock could have occurred during the simulation. Because of these error messages, only 6 simulation runs are included in the sensitivity analysis for design 2.

Lower frequency
A case where the frequency is lower is also tested. To test for lower frequency, the headway is changed from 7.5 minutes to 15 minutes, resulting in a frequency of 4 buses per hour per line per direction. This leads to a total frequency of 32 buses per hour that travel along Sudurgata. The arrival pattern from the base case is used for the lower frequency cases, where the time between arrivals is doubled, Figure 59 shows the arrival time pattern for the lower frequency case.

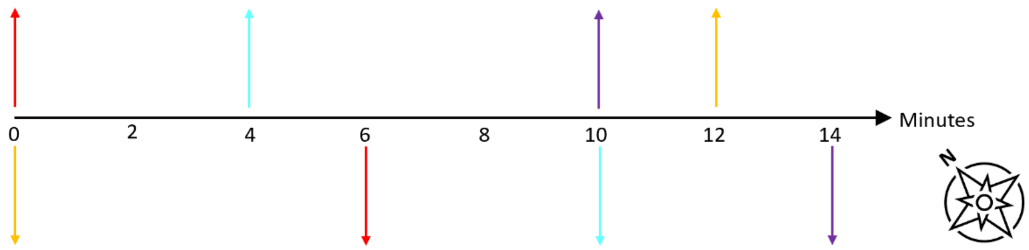


Figure 59 Bus arrival time pattern with lower frequency

Results
After running each design solution for both the higher and lower frequency cases is VISSIM, the results are obtained and compared to the results of the base case.
When the frequency of buses is increased, the throughput of design 1: Mixed traffic conditions is increased as well, but the throughput is decreased for designs 2 and 3 when the frequency of buses is increased. This is because design 1 allows for better flow than designs 2 and 3, which are throughabouts, and when the frequency of buses increases, the flow of other vehicles is decreased even more, as seen in Figure 60. This analysis also shows that when the frequency of buses is low, the throughput of the throughabouts is higher than for the mixed traffic case (design solution 1).

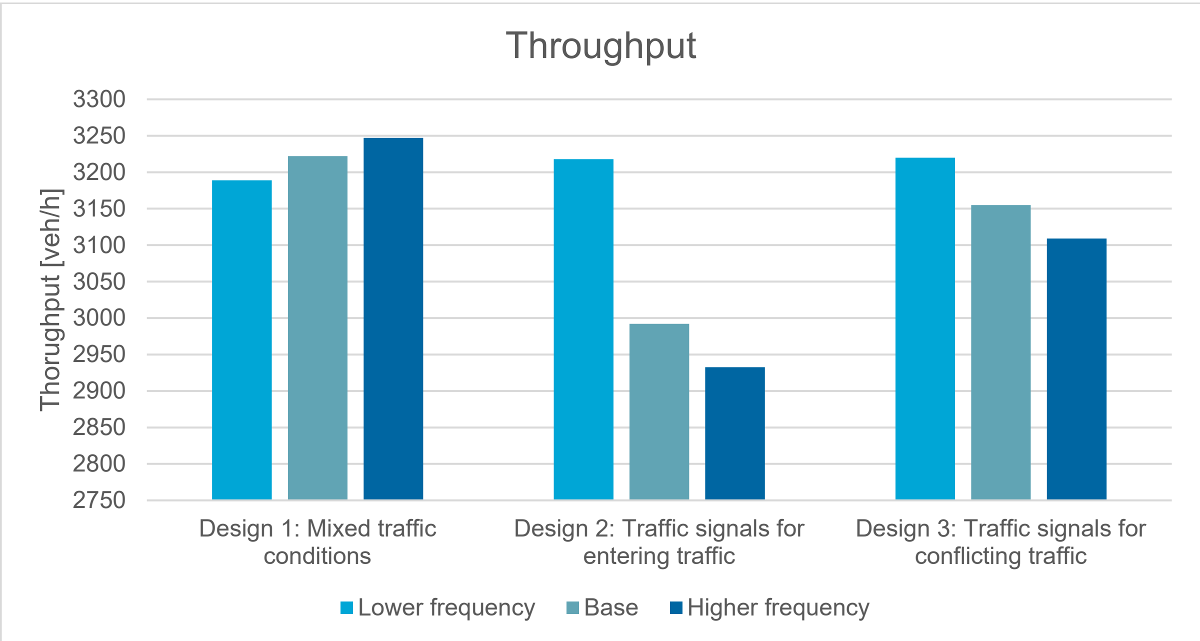


Figure 60 Throughput for different frequencies

The results show that the total travel time increases as the frequency of the buses in higher. This is expected because as the frequency is decreased, especially for the cases with exclusive lanes through the roundabout, the flow of the cars is better due to less red signals to let the buses pass through. The same pattern can be seen with the vehicle conflicts, where the number of conflicts increase as the frequency of buses is increased. This pattern is also seen with the active mode conflicts for design 1: mixed traffic conditions, but for the throughabout designs, the number of active mode conflicts stay constant. The variation in travel time did not show any general pattern when changing the frequency of buses.

However, even though the exact numbers for each criterion might increase or decrease as the frequency is changed, the order from best to worst of the alternative is constant for every level of frequency tested. Therefore, it is unlikely that the results of the evaluation will be affected by the change in frequency of buses.

6.3.2 Punctuality of buses

The second input that is changed to investigate the sensitivity of the model is the punctuality of the buses. One of the inputs into public transport lines in VISSIM is the distribution of entry times, which can add variation in delays to the buses when they enter the network.
In the base model, the distribution in entry times is 20 seconds. This means that on average, the buses enter the network 20 seconds after their scheduled entry time. The distribution of the entry times is a normal distribution with a mean of 20 seconds, and a standard deviation of 2 seconds.
Doing a sensitivity analysis on the punctuality of the buses can give an indication how sensitive the model is for delays of the buses and variability in entry time. It is expected that there could be better flow through the intersection when the buses are not delayed, as when they are delayed, the time between arrivals of buses could be less and time where the traffic signals are red for the cars increases, causing more congestion.
For the sensitivity analysis, the punctuality is changed to both no delay in entry times and delayed entry times. The change in punctuality is only varied for the bus lines on the exclusive lanes (that drive along Sudurgata). For the no delay case, the buses arrive exactly on the times written in the schedule. Figure 61 shows the entry time pattern for entry times.

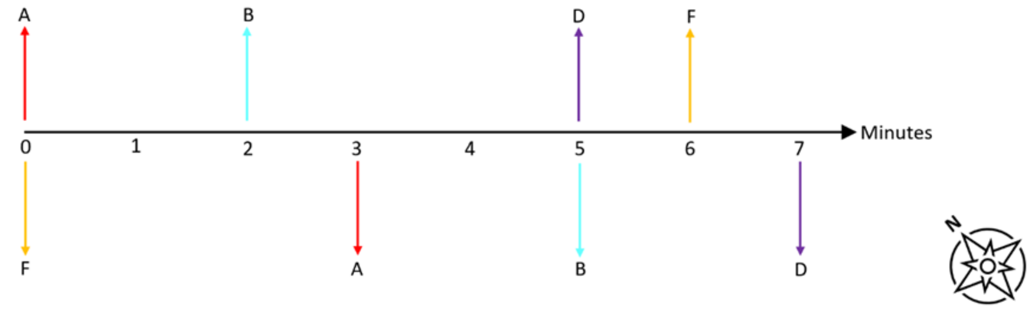


Figure 61 Entry time patten for no delayed case

For the delayed case, the average delay of the bus lines along Sudurgata is 3 minutes. The distribution of delayed entry times follows a normal distribution with a mean of 180 seconds (3 minutes), and a standard deviation of 60 seconds (one minute). Figure 62 shows the distribution of the probability of delay time. This means that on average, a bus is delayed by 3 minutes, however, the delays could go up to 6 minutes, but the probability is very low, and the majority of buses are delayed 2-4 minutes.

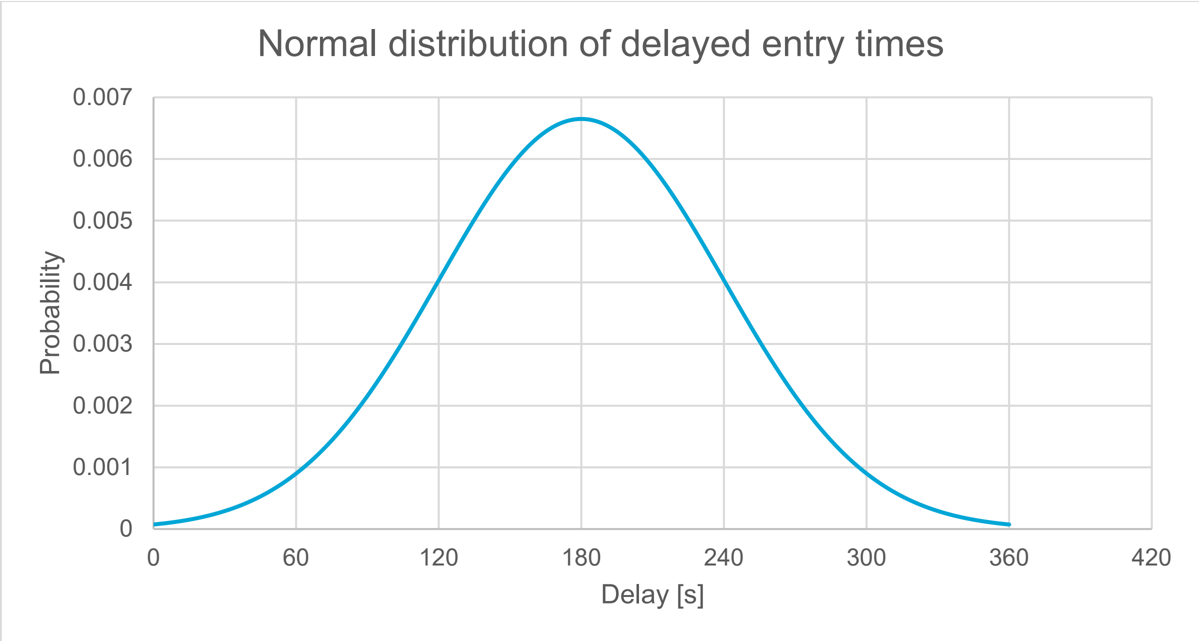


Figure 62 Normal distribution of delayed entry times

Figure 63 shows how the entry time pattern could change per 7.5 minutes. The figure shows how the pattern could change from the original entry time pattern.

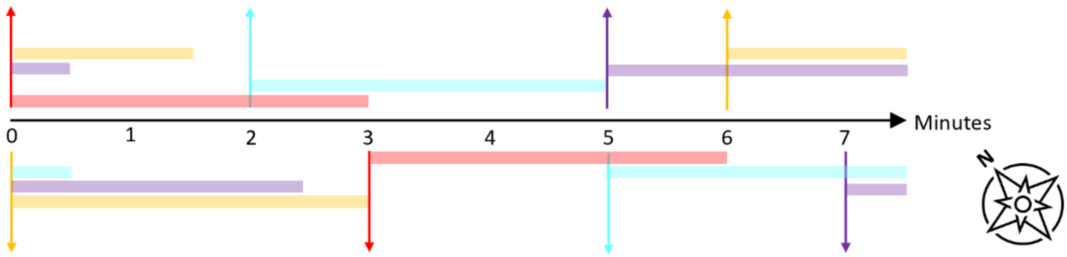


Figure 63 Entry time pattern for delayed case

Results

When changing the punctuality of buses, it was noticed that only the variation in travel time changed, all other criteria stayed constant or almost constant. The variation mostly changed for buses for design 1: Mixed traffic conditions. The variability in travel time for buses can be affected by the delays when the buses are in mixed traffic, but there are less effects when the buses travel on an exclusive lane through the intersection. The variation in travel time also changed the most for cars in designs 2 and 3. When buses are in mixed traffic, the delay of the buses do not affect the variation in travel times for vehicles crossing the bus route. However, when the punctuality of the buses varies, the variation in travel time for the vehicles crossing the bus route can vary as well.

These changes do not show any particular pattern and therefore the change in punctuality of the buses could have an effect on the output of the evaluation results, particularly if the variation in travel time is weighted high.

6.3.3 TTC and PET thresholds

The safety part of the evaluation is based on the TTC and PET thresholds chosen. The thresholds for the base case are the default values for conflicts between vehicles, which is a TTC value of 1.5s and PET value of 5s. Since the conflicts between active mode users and vehicles are different than conflicts between vehicles, different TTC and PET thresholds are

used. The thresholds used are chosen based on the research of Muley et al. (2018) and Wu et al. (2016). The TTC and PET values used for conflicts between active modes and vehicles are 2.7s for the TTC and 8s for the PET.
The sensitivity analysis can indicate whether the chosen threshold values have any effects on the results. As seen in chapter 4.4.2 and 6.2.2, the weight on safety is high, and often the number of conflicts between active modes and vehicles are high values when the values have been weighted (as seen in Table 19 and Table 20, in chapter 6.2.2).
Table 21 shows the different TTC and PET combinations tested, where the base case is in bold. As the table shows the base TTC values are changed by +/- 0.5. These values are tested for the base PET value and lower PET value that is 1.5s lower than the base.

Table 21 Combinations of TTC and PET tested for sensitivity analysis

TTC	PET	Conflict groups
1.5	**5**	**Vehicle – vehicle**
1.0	5	Vehicle – vehicle
2.0	5	Vehicle – vehicle
1.5	3.5	Vehicle – vehicle
1.0	3.5	Vehicle – vehicle
2.0	3.5	Vehicle – vehicle
2.7	**8**	**Active mode – vehicle**
2.2	8	Active mode – vehicle
3.2	8	Active mode – vehicle
2.7	6.5	Active mode – vehicle
2.2	6.5	Active mode – vehicle
3.2	6.5	Active mode – vehicle

The results of the sensitivity analysis show that all conflicts between vehicles (crossing, rear end, and lane-changing) show the same general pattern, where the number of conflicts increase as the TTC in increased and decrease when the PET is decreased. Figure 64 shows how this changed for the crossing conflicts.
The changes in conflicts between active modes and vehicles did not change much as the TTC and PET was changed and did not show any general pattern.
However, the patterns for all types of conflict show that even though the TTC and PET can influence the exact number of conflicts, the order of the best to worst design solution is generally constant. Therefore, it is unlikely that changing the TTC and PET thresholds by +/- 0.5s and -1.5s, respectively, will have an effect on the results on the ranking order of the design solutions in the evaluation.

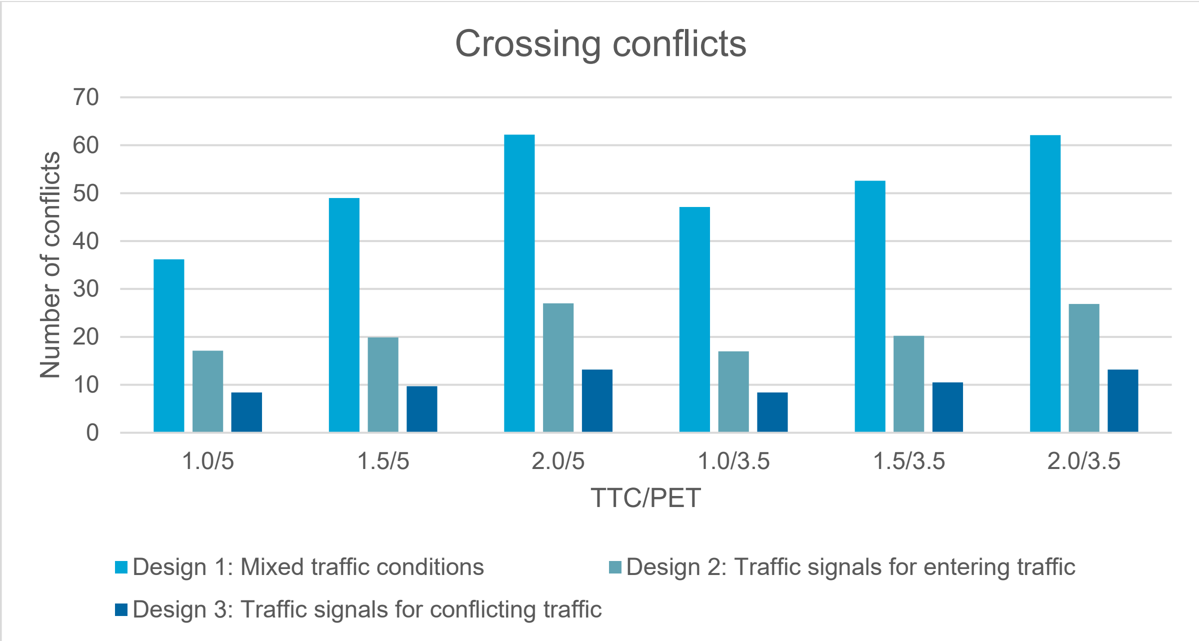


Figure 64 Crossing conflicts between vehicles for different TTC and PET thresholds

6.3.4 MCA weights

One of the major assumptions in the research are the weights selected for the MCA. Therefore, the sensitivity of the weights is tested. First, all weights are set to be equal. Second, each criterion is given a weight that is two times as high as the other criteria, when the other criteria all have the same weight. Changing the weights of the criteria can indicate if there are some criteria that influence the result more than other criteria.

Equal weights

There are 26 criteria considered in the MCA. The weights are split in a way that the sum of all the weights equals to 1. The weight used for each criterion is 0.038. Using the same normalization method as in the base case, the results of the MCA are shown in Table 22. Additionally, the table includes the results of the MCA from the base case for each stakeholder.

Table 22 Results from MCA with equal weights

	Design 1: Mixed traffic conditions	Design 2: Traffic signals for entering traffic	Design 3: Traffic signals for conflicting traffic
Equal weights	0.48	0.40	0.67
Base - Municipality	0.39	0.56	0.74
Base - Road authority	0.46	0.49	0.72
Base - Public transport authority	0.44	0.54	0.72

The table shows that when all weights are equal, design solution 3: Traffic signals for conflicting traffic still scores the best. The table also shows that when all weights are equal, the ranking of design solution 1 and 2 are switched compared to the base case. However, the total scores for design solution 1 and 2 are very close to each other.

One criterion is multiple of the weight of the rest of the criteria

Another test that is performed is that when one criterion has double the value of the other criteria when all the other criteria are equal to each other. This is tested for every criterion. The weights used are 0.074 for the double value and 0.037 for the rest of the criteria.

This resulted in that the ranking of the designs is always the same, where 3 is the best, then 1, then 2, like the results when all the weights are equal. However, because the base case results in a different order than the tested design solutions in the sensitivity analysis, another analysis is tested where one criterion has a triple value of the other criteria. This results in the same ranking order as before.
Finally, it is tested where each criterion has a weight that is four times higher than the other criteria, where the values used are 0.138 and 0.034. This results in that when some criterion is four times the weight of the rest of the criteria, the ranking order of the designs changes where designs 1 and 2 are switched, so that design 1 scores the lowest and design 2 the middle, like in the base case. The criteria that changed the order was the travel time of public transportation on Sudurgata (both directions) and the variation of those travel times. Also, the travel times and variation in travel times of active modes, and the active mode conflicts.

This indicates that the results from the base case could be influenced by the active mode conflicts, because the weight of that criteria is high compared to the other criteria. However, this only would influence the middle and worst design solutions as the sensitivity analysis always resulted in that design solution 3 was the best, and with a score much higher than the others.
The sensitivity analysis result in that the model and methodology are robust as it results in that design 3: Traffic signals for conflicting traffic always scores the highest.

6.4 Conclusions and discussions of the results

Chapter 6 discusses the main results from the simulations of each design solution and their safety calculations and compares them. MCA is used to compare and evaluate the designs and determine which design proves to be the most optimal. Sensitivity analysis is used to test the sensitivity of the VISSIM model, safety calculations, and MCA by changing the input of bus frequencies and punctuality, the thresholds of TTC and PET, and the weights of the MCA. The sensitivity analyses resulted in that it is unlikely that a change in these inputs and safety calculation thresholds will change the resulting order of the design solutions from the evaluation. However, when the weights of the travel time and variation in travel time for public transport on the exclusive lanes and the weight for the active mode conflicts become much higher than the rest of the weights, the order of the design solutions from the MCA results might change, and it could be that the case study results are influenced by the high weight of the active mode conflicts. However, design solution 3: Traffic signals for conflicting traffic always scores the best, and only the lower two designs are switched. This means that the evaluation methodology is robust, where different inputs will lead to the same results and very likely the same ranking order of the design solutions. This also means that the evaluation methodology is likely to also work for other case studies and locations.
The evaluation resulted in that design solution 3: Traffic signals for conflicting traffic is the most optimal design solution for roundabouts with BRT when evaluated and compared based on safety and performance of all modes. Followed by design solution 2: Traffic signals for entering traffic then design solution 1: Mixed traffic conditions which is ranked the least optimal solution.
The results of the MCA (Table 20) show that design 3 scores the best in terms of both traffic performance and safety.
Design 3: Traffic signals for conflicting traffic scored the best out of the three designs in terms of traffic performance. This is because the design allows for a steadier flow through the intersection than design 2: Traffic signals for entering traffic and gives more priority to public transport than design 1: Mixed traffic conditions. This resulted in higher total throughput and lower travel time and variation in travel time overall. These results of the performance criterion are in line with the literature discussed in chapter 3. Zakeri and Choupani (2021) mention that throughabouts can be very beneficial where the demand for BRT is high and priority is needed for the BRT, and that throughabouts could perform better than conventional roundabouts. However, as Frøyland et al. (2014) and VSÓ Ráðgjöf (2019) mention in their studies, that

cases where there is heavy traffic or where the bus route crosses a main road, the priority signalling for the buses can cause delays and reduce throughput of the intersection. Therefore, for cases where the bus route crosses a main road and the frequency is very high, a solution where full priority is given to the buses could cause delays for other users. Despite the high frequency of buses of the case study, design 3 scores much higher than the other design solutions, which contradicts the studies of Frøyland and VSÓ Ráðgjöf. However, the sensitivity analysis suggests that the frequency of buses does have an effect on the throughput of the throughabout, and when the frequency is very high, the throughput of throughabouts decreases, which supports the studies of Frøyland et al. (2014) and VSÓ Ráðgjöf (2019). On the other hand, when the frequency of buses is lower, at 32 buses per hour (4 buses per hour, per line per direction), the throughput for all three designs is almost the same where the throughput of the throughabouts are even slightly higher than for the mixed traffic conditions, which is in line with the study of Zakeri and Choupani (2021). This means that in cases where the bus route crosses a main road, a throughabout with traffic signals for conflicting traffic is the best solution, however if the frequency of buses using the exclusive bus lanes gets very high (higher than 64 per hour, 8 buses per hour per line per direction), then the throughput of this solution will reduce, and the queues and travel time for the vehicles on the main road will increase, and therefore the evaluation score of the design might decrease.

Design solution 3: Traffic signals for conflicting traffic also scored the highest out of the three designs in terms of safety. This is because this design has fewer active mode conflicts than design 1: Mixed traffic conditions but equal to design 2 which is also a throughabout. It also has fewer conflicts between vehicles than design 2: Traffic signals for entering traffic. This shows that throughabout designs are safer for active mode users than mixed traffic roundabouts. The number of crossing conflicts are also reduced when changing from a mixed traffic roundabout to a throughabout. This could be due to the presence of the traffic signals, which make sure that when the buses pass through there is no one in the roundabout. The traffic signals also clear out or reduce the number of vehicles in the roundabout every time a bus passes, causing less traffic jams. The results from the simulations show that both crossing conflicts and active mode conflicts are reduced by more than 50% when changing from a conventional roundabout to a throughabout. However, the number of rear end conflicts increased substantially when changing to a throughabout. These conflicts are mainly from the long queues that build up on Hringbraut which are mainly caused by having the BRT line cross a main road.

Design solution 3: Traffic signals for conflicting traffic is the most optimal solution for roundabouts with BRT. It is both the safest and performs the best out of the three designs investigated. The case study of Melatorg may not represent the average roundabout where BRT is planned to go through as it is a two-lane roundabout, the BRT route crosses a main road, and multiple BRT lines drive through it, which leads to high frequency of passing buses. However, these results indicate that this design is also the most optimal design solution for other cases. This is because even when the BRT line crosses the main road, this design is the best. This means that when the BRT line is along the main road, the performance of the intersection should score even higher as Melatorg because the buses, and the signals for the buses will not obstruct the main streams of traffic. Additionally, the results show that when the frequency of buses passing through the intersection is lower, i.e., lower frequency or fewer bus lines, the throughput of the intersection increases which would also lead to better performance of the roundabout.

7. Discussion

This chapter aims to reflect on the research, the methodology and methods used, and the impact of the assumptions made in the process. The chapter also discusses the limitations of the work.

Some of the major assumptions made in the research can have an impact on the results, both big and small, and it is important to discuss these impacts in order to be able to make improvements of the methodology in the future. Chapter 7.1 reflects and discusses these impacts and how they are mitigated and chapter 7.2 discusses and reflects on the research method used in the thesis.

This research has multiple limitations, which can also have impacts on the results of the research or lead to inspiration to de further research. Chapter 7.3 discusses the major limitations of the thesis.

7.1 Reflection and impact of assumptions

One of the assumptions in the model is the configuration of the base case. The bus alignment on Sudurgata SW is based on the preliminary design, with the bus lanes on the median of the current road and the mixed traffic lanes are one lane in each direction. Additionally, on the north side of the intersection, Skothusavegur does not have an exclusive bus lane and the buses drive in mixed traffic away from the intersection. When approaching the intersection on Sudurgata NE, the road is assumed to be a bus only street, whereas in reality it is for mixed traffic. This was changed because of the challenge with the location of the detectors and is explained in more detail in Appendix B: Location of detectors. Another assumption or more of a limitation to the model was the addition of lanes for mixed traffic on Sudurgata SW and the exit of Sudurgata NE. This was changed because of the model could not connect a two-lane roundabout to a one lane road while keeping the priority rules needed and to get realistic driving behaviour. Furthermore, the focus of this research is mostly the bus routes that are going straight through the roundabout along Sudurgata, but there are two other bus lines that

go through the roundabout, one along Hringbraut in mixed traffic and one that turns from/to Hringbraut SE and to/from Sudurgata NE. These bus lines are however, not planned to be on exclusive lanes and therefore, it is expected that the results are not affected by this simplification, but it is important to keep in mind that these lines are also in the intersection even though the focus is not on them.
These assumptions mentioned above can all influence the output of the model. The extra lanes on the entrances and exits of the roundabout can affect the number of conflicts, both between vehicles, from changing lanes, and between active mode users and vehicles. Because the lane drop from two to one lane is located close to the active mode crossing, there might be some impact on the number of conflicts between active mode users and vehicles at these locations. These assumptions, however, are not expected to have large impact on the outcome of the research as all design solution alternatives are based on this same base case.

Other assumptions were made in the methods used for the research. The weights used in the MCA for the stakeholders are assumed based on the goals and plans of each stakeholder. These assumptions could lead to that the weights chosen are not quite accurate or representative of the stakeholders, which leads to less accurate results. In future research, this limitation can be reduced by involving each stakeholder in the process of selecting weights. Multiple stakeholders can be asked to assign scores to the criteria which can then be normalized and used as the weights for that stakeholder. This would also lead to different assumptions, but it would, however, likely better represent a truer view of the stakeholder.
The sensitivity analysis performed was also limited. The inputs and factors chosen to investigate were based on the major factors that were thought to have most impact on the results. The frequency and punctuality of buses were chosen because when the frequency of the buses is higher, and they are given priority, the total red time for the other traffic increases, which can affect the performance significantly, especially in the case of Melatorg where the bus lane crosses a main road. The punctuality was also thought to have an effect on the time given for the priority of buses because when some buses are delayed, they are more likely to bunch. Which could lead to that many buses are close together when passing the intersection, causing the red light to be longer for the other traffic. However, it is likely that other factors, such as the number of active mode users, or the location of active mode crossings could also influence the results of the research. Because the number of active mode users at the intersection is limited, it would have been interesting to see how increased number of active mode users, or different configurations of active mode crossings would impact the results of the evaluation of the designs. But due to limitations of VISSIM in modelling pedestrians and limited scope of only changing one variable of the designs, i.e., the priority of BRT, this was not included in the sensitivity analysis and the frequency and punctuality of buses were chosen as the most important factors, as they are the most likely to be able to change quickly as well as being more representative for other cases.

7.2 Reflection on the research methods

The research is performed using three main research methods, as described in chapter 2. These methods are literature review, evaluation method, and simulations and calculations. These methods are used to develop an evaluation methodology for evaluating and comparing different design solutions of roundabouts with BRT based on traffic safety and level of service of all modes.

MCA is a good method to give indication to the decision makers how the designs differ considering the criteria selected and in which order the design alternatives rank when doing this evaluation. Because of the subjectivity of MCA, this method should often be used as a suggestion, but it can be made more reliable by performing sensitivity analysis, involving multiple stakeholders, and testing different normalization methods. This research considered multiple normalization methods and chose the most fitting one. Additionally, stakeholders were considered to get multiple weight sets, which also tested for the sensitivity of the method.

However, the weight sets likely could have been made more representative of the views of the stakeholders by involving the stakeholders and ask them to give weights rather than deriving them from their goals and views. This would have made the results more accurate to the views of each stakeholder. However, the sensitivity analysis of the MCA showed that the model is very robust, always leading to the same result. This means that even though the stakeholders would have been more involved in the weights, the result of the evaluation is unlikely to have changed.

The VISSIM software has some limitations that impacted the model, such as limited availability in modelling active mode users and lane-changing behaviour. Additionally, the model had to be simplified by adding extra lanes when entering and exiting the roundabout to keep desired behaviour, when those roads should only have one lane in each direction. The calibration and validation of the VISSIM model is also limited, which limits the representability of the model of the real intersection. If there would have been more information about behavioural parameters such as speed and gap acceptance of the local traffic at this specific intersection, the model could have been improved and be more representative of the real location. This leads to many assumptions and simplifications.
While these limitations are mitigated and minimally impact the results of the thesis, these factors would improve the model and would make it more realistic and representative of the real world.

The evaluation methodology developed in this thesis includes an evaluation method, evaluation criteria, microsimulation software, calculation methods, stakeholders, and more. With all these steps and methods come assumptions and choices that lead to the final result. During the development of the methodology, multiple options of methods and choices were considered, and the most fitting option chosen for each decision. There are, however, probably other options that could be considered for future research, that were not thought of during this research. The methodology developed can however successfully compare and evaluate different roundabout designs with BRT which are compared based on multiple criteria related to performance (level of service), safety, and costs.

7.3 Limitations

This study only focuses on the difference in priority and configurations for BRT while the rest of the intersection and nearest environment is kept as it is today or how it will be based on the preliminary design document[7]. However, when looking at a new design for BRT it is important to also consider more access to active mode users, by adding bike lanes, crossings, and walking paths/ sidewalk when needed. In this research, this was not considered, however, the data shows that for this intersection, active mode crossings over Hringbraut are needed. This might affect the results in a way that safety might be decreased (underestimated in the evaluation methodology), and may also affect the performance of the intersection, both for vehicle users and active mode users.

In the VISSIM model, a lot of lane-changing behaviour that is not realistic was noticed. For instance, changing of lanes inside the roundabout (which is illegal in Iceland), cars making last minute lane changes, changing lanes halfway and then turning back onto the first lane, or changing to the left lane when entering the roundabout and using the inner lane to turn right. Huang et al. (2013) also noticed this unrealistic behaviour in their research, where vehicles were changing lanes unrealistically and illegally. Additionally, the simplification of the VISSIM model of adding two lanes on the entrances and exits of Sudurgata increased the number of lane changes as well. This limitation makes the model less accurate, and the number of lane-changing conflicts calculated in SSAM is more likely to be overestimated. This limitation is, however, reduced by weighing the lane-changing conflicts with a low weight, leading to less

[7] *1. lota forsendur og frumdrög*. (2021). Retrieved from: https://borgarlinan.is/utgefid-efni/skyrslur/frumdragaskyrsla

influence from the high number of lane-changing conflicts on the final score from the evaluation.
Another limitation of the model is the modelling of active mode users in VISSIM. The active mode users are modelled as vehicle objects and therefore behave in a more mechanical way, similar to cars rather than pedestrians. Because of this, the active mode users in the model tend to walk in one line on the right side of the link but can overtake each other when needed. Additionally, the links for the active mode users are only one directional, meaning that the active mode users that are coming from opposite directions cannot interact with each other. The active mode users were modelled this way in order to be able to record the trajectories from the active mode users and use SSAM to calculate the number of conflicts. This limits the model in a way that the focus and what can be investigated about active mode users is reduced. However, since the scope of this project was to mainly investigate the conflicts between vehicles and active mode users, and not between different active mode users, this limitation minimally affects the results of this research. Due to this limitation, the active mode users, pedestrians, cyclists, and e-scooter users, were all modelled on the same links. Currently, at Melatorg, all active mode users use the same path, namely the sidewalk, but in the preliminary design, more and separate space is designed for active mode users. It is however, recommended to look further into how increased accessibility and more space for active mode users can affect the evaluation of the intersection. This is important to investigate further because of the new road user hierarchy, which leads to more accessibility for active mode users, which leads to higher number of active mode users.

The results of the VISSIM model and evaluation indicate that the change in priority of BRT does not affect the travel time or speed of active mode users. However, the number of active mode users used in the case study is limited. This means that when there are more active mode users at the intersection, their travel time could be affected when BRT has more (or less) priority and needs to be investigated further. Additionally, the case study used in this thesis only had active mode crossings on the roads where the BRT route is, and therefore it is not known how the performance and safety of active mode users is affected when there are crossings on the other roads as well.

8. Conclusions and recommendations

The objective of this thesis is to develop a methodology that evaluates design solutions of roundabouts with a priority public transport service (BRT). The methodology is able to evaluate and compare the design solutions based on safety and the performance of all modes that are using the intersection. Which leads to finding which design solution proves to be the most optimal. The previous chapters have both set up and tested this methodology, comparing three different roundabout design solutions where the priority or BRT is varied along with how this priority is given.
This chapter answers the research questions that are proposed in chapter 1.2.2, followed by a chapter about recommendations for both scientific research and practice.

8.1 Answers to the research questions

Considering the objective and the goal of the thesis, the following research question is proposed:

> *How can roundabouts with different priority configurations for Bus Rapid Transit be evaluated and compared based on safety and performance of all modes and which alternative proves to be the most optimal?*

To answer the main research question, three sub questions are proposed. This chapter will present these sub-questions and their answer, which leads to answering the main research question.

Sub-question a. *What design solutions or guidelines on the safety and roundabouts with BRT have been developed in different countries?*

This sub-question is further divided into two questions which focus on what types of design solutions have been developed and what factors affect the safety of active mode users in roundabouts.

The literature review (Chapter 3) shows that many countries have developed and built multiple different design solutions for roundabouts with BRT. The BRT Planning Guide by ITDP (2017) listed several suggestions of design solutions where BRT can get priority through roundabouts. Other literature, such as, Bråtveit (2016), Frøyland et al. (2014), Giæver and Tveit (2006), VSÓ Ráðgjöf (2019), and Zakeri and Choupani (2021) also suggest some of these types of design solutions in their research. The main types of design solutions found in the literature review are:

1. Mixed traffic conditions, where the BRT merges with traffic shortly before the intersection and crosses the intersection in mixed traffic.
2. Exclusive bus lane inside the roundabout, where the innermost lane of the circulatory road of the roundabout is an exclusive bus lane.
3. Throughabout with traffic signals for entering traffic, where the exclusive bus lanes go through the centre island of the roundabout and priority is given to the buses by stopping entering traffic with traffic lights when a bus is about to cross the intersection.
4. Throughabout with traffic signals for conflicting traffic, where the circulating traffic that is in conflict with the buses are stopped before the conflicting area when a bus is about to cross the intersection.
5. Other types of throughabouts are also used, with different configurations of signals or yielding. For instance, placing yield signs or warning lights for the conflicting traffic.

The literature suggests that a throughabout with traffic signals for the conflicting traffic is the best design and the mixed traffic conditions would be the worst design for the performance of the public transport. Which is in line with the results of this research.

The BRT Planning Guide gives a lot of information on possible design solutions, and some countries have included suggestions or recommendations of how to give priority for public transport, such as buses or trams, at roundabouts. The Norwegian guidelines suggest that a throughabout with signals for entering traffic is the best option and suggest a throughabout with signals for conflicting traffic as a second option, due to complexity. The Dutch guidelines mention that public transport can be given priority at roundabouts by adding traffic signals and/ or an exclusive bus lane (CROW, 2015). Their guidelines do not suggest a specific design, but throughabouts with traffic signals for conflicting traffic can be found in multiple places in the Netherlands.

Based on the literature found from Norway, the Netherlands, and Iran, the research and guidelines from those countries indicate that the experience about throughabouts is generally positive, even though the configuration of the traffic signals differs (CROW, 2015; Duduta et al., 2012; Giæver & Tveit, 2006; VSÓ Ráðgjöf, 2019; Zakeri & Choupani, 2021). However, other countries such as France and Denmark seem to have more negative views and experiences with throughabouts and their effectiveness (VSÓ Ráðgjöf, 2019).

The results of this thesis indicate that throughabouts, and especially throughabouts with traffic signals for conflicting traffic are effective and safe, as they score the highest in both traffic performance and safety criteria in the evaluation.

The second part of sub-question a focuses on the safety of active mode users in roundabouts and what factors make the design solutions safer for those users. The research resulted in that the safest design is to have the paths for active mode users separate from the vehicle traffic. Additionally, to increase the safety for active mode users, the speed of the vehicles in the roundabout should be low, and the crossing lengths for the active mode users should be short, or maximum 2 lanes in one direction at a time. Furthermore, a two-lane cycle path can increase the risk of collision between cyclists and vehicles as it can be confusing and complex. This means that design solutions such as a roundabout with a bus lane inside the circulatory road of the roundabout is less safe for active mode users, as it requires larger geometry. Other design solutions of roundabouts with BRT should be able to accommodate active modes safely, by keeping these factors in mind during the design process.

The BRT Planning Guide and other research show that there are multiple design solutions where BRT can be designed thorough roundabouts, where the priority of the BRT is varied. From roundabouts where the BRT drives in mixed traffic and gives the least priority to the BRT, to a throughabout where the BRT can get full priority and can be varied by different configurations of the signalling on the roundabout. These solutions can be seen in multiple countries such as France, Indonesia, the Netherlands, Norway, and Sweden (ITDP, 2017; Mannvit, 2019; VSÓ Ráðgjöf, 2019). However, fewer countries have developed guidelines on what solutions are available or best in different situations.

Sub-question b. *What criteria can be used to evaluate the roundabout design solutions and how can they be evaluated?*

To answer this sub-question, it is divided into four sub-sub-questions. The following paragraphs present these questions and their answers.

i. What evaluation methods are available for possible criteria used?

The two main methods to evaluate different designs based on multiple criteria are multicriteria analysis (MCA) and cost-benefit analysis (CBA). When the criteria used is not all in monetary terms or easy to monetize, MCA is the more appropriate method to use, as CBA requires all values to be in monetary terms. Therefore, MCA is chosen to be the best method to compare and evaluate the different roundabout design solutions in this research.

MCA has many advantages as it is flexible and open, and it can show the scores of the alternatives in a simple, comprehensive way. It can also include both qualitative and quantitative criteria, while CBA can only include quantitative criteria, which means that MCA can compare multiple types of factors and aggregate it into a single score (Annema et al., 2015; Dodgson et al., 2009; Wee et al., 2012). However, MCA also has some disadvantages, where the main one it the subjective nature of choosing the weights. This disadvantage can be mitigated by investigating multiple weight sets by performing sensitivity analysis and considering multiple stakeholders.

ii. How is the safety of all modes evaluated at roundabouts?

The safety of all modes can be evaluated by calculating the number and types of conflicts that occur during a time period, for instance during a simulation. The number and types of conflicts can be calculated by using SSAM, which uses the surrogate safety measures of Time-to-Collision (TTC) and Post Encroachment time (PET) along with the trajectories of the vehicles, which are obtained from the output of the simulation of the VISSIM model.

Due to limitations of SSAM, the number and types of conflicts for every mode cannot be calculated. Therefore, the groups used for the conflicts are conflicts between vehicles, where all types of vehicles are considered, and conflicts between active mode users and vehicles, where all conflicts involving a user using the active mode crossing links are used.

The difference between the calculations for each groups is in the TTC and PET thresholds used, where the TTC is 1.5s and PET is 5s for conflicts between vehicles and the TTC is 2.7s and PET is 8s for conflicts between active modes and vehicles (Muley et al., 2018; Wu et al., 2016).

By using SSAM to calculate the number of conflicts and types of conflicts, the safety of the roundabout design can be compared to other designs, where the number of conflicts per type of conflict can be compared. The types of conflict can indicate how severe the conflict is, where crossing conflicts are the most severe conflict types between vehicles.

iii. How can the traffic performance and the performance of public transport be evaluated at roundabouts?

The traffic performance can be evaluated by examining criteria such as throughput, travel time, variation in travel time, and speed. These values can be obtained by using microsimulation using software such as VISSIM. Other simulation software that works with SSAM can also be used, such as AIMSUN.

Multiple traffic performance indicators can be measured and recorded in the VISSIM simulations. The traffic performance for cars can be measured by the travel time since the travel time can indicate about the speed and delays of the performance of cars when compared to free flow conditions. The main factors to evaluate the performance of public transportation is speed and reliability (Vuchic, 2005). Since speed is correlated with travel time, the travel time can be used to evaluate that part, and the variation in travel time can indicate about the reliability of the buses, as when the variability in travel time is low, the travel time is often very constant, increasing the reliability of the service. The performance of other modes such as cars and trucks can be measured by travel time and variation in travel time. The total throughput of the intersection can also give an indication of the performance of the design as it indicates how many vehicles pass through the intersection in one hour. Therefore, the traffic performance indicators chosen to evaluate the traffic performance of all modes in this methodology are total throughput, travel time per mode per direction, and variation in travel time per mode per direction.

iv. What stakeholders can be considered in the evaluation and what weight sets should be used for each stakeholder?

Like mentioned in sub-question b-i, stakeholder analysis is used to investigate multiple weight sets for the MCA, which also tests the sensitivity of the MCA as it shows how sensitive the analysis is to different weight sets. The stakeholders considered are the stakeholders that have the decision power for the intersection in question. By considering the stakeholders that have decision power, the results of the analysis can help with the decision making and planning. The stakeholders that might be appropriate to consider, are the municipality, the road authority, the owner of the road(s), and the public transport authority or operator.

The weight sets for each stakeholder can be made from asking the stakeholders about their views and goals and rate the importance of the considered criteria. The weight sets can also be derived from different sources and published goals and plans from each stakeholder to estimate how each stakeholder would weight different criteria.

These sub-sub-questions can be combined to answer sub-question b. The criteria that can be used to evaluate designs are traffic performance indicators, such as throughput, travel time, and variation in travel time. Additionally, safety indicators such as number of conflicts per conflict type, and other indicators such as costs can be included in the evaluation. These criteria can be combined into an evaluation method that fits the criteria, such as MCA, where the scores of the criteria can be summarized into one score per alternative. Which makes it easy to compare and evaluate the different design alternatives.

Sub-question b leads to that an evaluation methodology is developed, which can evaluate and compare different design solutions for roundabouts with BRT.

However, this methodology has to be tested to investigate if it works, which leads to sub-question c.

Sub-question c. *How does this methodology work in a case study at the roundabout Melatorg in Reykjavík, Iceland?*

Using the methodology developed in this research, first the evaluation method and simulation software are chosen to be MCA and VISSIM. These are chosen because the MCA does not depend on making every criterion value into a monetary based value and can easily show the differences between different alternatives by using normalized scores, colour scales and one single value for each alternative. VISSIM is chosen as the simulation software used because it matches all the requirements needed for this study.

After the evaluation methods have been chosen, the criteria used to evaluate the designs are determined. Since the comparison and evaluation of the designs is based on performance and safety, the throughput, travel time, variation in travel time, number of conflicts per type of conflict, and costs are used as evaluation criteria.

The Municipality of Reykjavík, the Icelandic Road and Coastal Administration (IRCA), and Strætó bs. are the considered stakeholders at Melatorg.

The alternative design solutions tested for this case study are a roundabout with mixed traffic conditions (design solution 1), and two throughabouts, one with traffic signals for all entering traffic (design solution 2) and one with traffic signals for conflicting traffic (design solution 3).

These designs are chosen because the focus of the research is on roundabouts, excluding conventional X-intersections, which leads to design 1 being the closest to the base case of the current roundabout at Melatorg. The literature discusses throughabouts as good solutions for giving priority to BRT, as well as they can be seen already used in multiple countries and are therefore chosen as the other two design solutions.
When all these decisions are made, the simulations are run and the results of the output of VISSIM and calculations of SSAM are placed in the MCA criteria. Sensitivity analysis of the model, safety calculations and the MCA shows that the VISSIM model is robust and not affected by the main assumptions or weights chosen. The evaluation and comparison of the three designs results in that design solution 1: Mixed traffic conditions performs the worst, then design solution 2: Traffic signals for entering traffic, and design solution 3: Traffic signals for conflicting traffic scores the highest and proves to be the most optimal design.
Therefore, it can be concluded that the developed methodology works well and is able to both compare and evaluate different designs for roundabouts with BRT based on traffic performance and safety.

With answers to all the sub-questions, the main research question can be presented again and answered.

> *How can roundabouts with different priority configurations for Bus Rapid Transit be evaluated and compared based on safety and performance of all modes and which alternative proves to be the most optimal?*

The results of the thesis show that a method to evaluate and compare different configurations of roundabout with BRT based on safety and performance of all modes is multicriteria analysis (MCA). The values for the analysis are collected from simulation and calculations, where VISSIM and SSAM can be used to get the traffic performance and safety indicators. Additionally, other indicators such as costs are good to include in the analysis as well.
Using the methodology developed in the thesis and the beforementioned methods and software, different design solutions where the priority configuration of BRT is differed between designs can be evaluated and compared successfully based on safety and performance of all modes.
The thesis resulted in that the most optimal alternative design solution for a roundabout intersection where BRT is being added is a throughabout with traffic signals for conflicting traffic. The results imply that this solution is the most optimal design solution for most roundabouts. It is however, suggested that this design solution is also compared with a signalized intersection to investigate its effectiveness compared to that type of design.
A throughabout design with traffic signals for conflicting traffic proved to be both the safest and best performing design solution. The research also resulted in finding that there are multiple advantages to throughabouts when it comes to the performance and safety. They are more comfortable for public transport users as throughabouts increase the speed of the buses and increases the comfort of the passengers, as the buses do not have to slow down as often and have to make less turns (ITDP, 2017; Nikitas & Karlsson, 2015). This means that throughabouts are a good solution for cities that have goals to shift their focus from the private car to active modes and public transport, or to give more access to public transport and active modes. Throughabouts help with the change of the road user hierarchy, where pedestrians should be at the top and have the most focus and priority, followed by cyclists, then public transport, and the cars at the bottom, as introduced in chapter 1.2.1 (Department of Transport, 2022; Gemeente Rotterdam, 2020). Changing this road user hierarchy makes the city safer and more accessible for active mode users. Furthermore, modes that are environmentally friendly, such as active modes and public transport become more attractive and more competitive to the car. The research shows that throughabouts can help with this change in making environmentally friendly modes more attractive and possibly reduce car uses by providing more priority to the buses and safer and more comfortable environment for these modes.

One of the research gaps identified in the beginning of the thesis is about the disagreement of the effectiveness of roundabouts with BRT priority. This thesis shows that it is very effective, both in terms of the performance and safety of all users, to have BRT priority compared to other roundabout designs. However, this thesis did not compare throughabouts with traffic signals for conflicting traffic to conventional signalized intersections. Therefore, this research gap is only partially solved, and it is recommended to compare throughabouts to other types of intersection design to determine its full effectiveness.
Another research gap is that there are few and not clear guidelines available for roundabouts with BRT. The methodology developed in this thesis can help with deciding between different roundabout or intersection designs, which can be used in guidelines or as a methodology to make a decision on the most optimal design. Additionally, this thesis shows that a throughabout with traffic signals for conflicting traffic is the most optimal solution for roundabouts with BRT, which could be used as a base or a guide for guidelines.

8.2 Limitations and Recommendations

The research resulted in new knowledge about the evaluation of roundabouts with BRT and the effectiveness of few roundabout solutions. This knowledge can be used to build on for future research but can also be used for practical recommendations.
During the research, many assumptions were made, and limitations encountered. These lead to other interesting questions, topics, and aspects that should be investigated further in scientific research which are discussed in chapter 8.2.1. Recommendations for further investigations and use for practice are suggested and discussed in chapter 8.2.2.

8.2.1 Recommendations for scientific research

This research only focused on roundabout solutions for BRT and showed the most optimal design out of the design solutions considered. The results also indicate that a throughabout with traffic signals for conflicting traffic is also likely to be the best solution in other cases. However, the research does not compare the roundabout solutions to changing the intersection to a signalized X-intersection, two T-intersections, or other intersection solutions. By including a comparison to these types of intersections, the results could show if there are benefits of keeping a roundabout as a roundabout. The model and evaluation methodology developed in this research can also be used for this comparison of the different types of intersections. This would also give more knowledge into if, and in what circumstances, an intersection could be kept as a roundabout while providing priority to BRT and other public transport.

It would also be interesting to investigate the effects of the location of bus stops close to the intersection. Bråtveit (2016) mentioned in his research that the bus stop that was close by the roundabout was causing a lot of extra delays, and VSÓ Ráðgjöf (2019) suggest that the location of bus stops should not be close to the intersection. It is possible that with different roundabout solutions, the location of stops has less (or more) effects on the performance of the intersection, and therefore interesting to investigate further.

The limited number of active mode users at the intersection also limited the results that could be found in this thesis. The results indicated that active mode users are not affected by the different priority of BRT, however, the research did not include a design solution where the number of active mode users is very high, nor when there are active mode crossings on all sides of the intersection. This could affect the results of the performance and safety of the active mode users and is therefore recommended to investigate further.

Additionally, the research method used, and the microsimulation can be further researched and investigated how it can be made more accurate. There are multiple limitations in the microsimulation model that is used. One major limitation is the simulation of active mode users and the safety calculations for those modes. VISSIM can model active mode users as pedestrians, where their behaviour is more realistic, using the module VISWALK. However,

when using VISWALK, the trajectories of the active mode users are not registered. This means that they cannot be used in SSAM for calculations of the number of conflicts. Therefore, it is recommended to look further into methods or ways how active mode users can be modelled more realistically, while being able to calculate the number of conflicts that occur between active mode users and other modes. This further research could also address the research gap identified of limited research of pedestrian safety at roundabouts. This thesis did not address this research gap as much as was wanted because of these limitations, and because the focus was more on the roundabouts and the different configurations for priority of BRT.
The calibration and validation of the microsimulation model is also limited, and it would be recommended to improve this aspect of the methodology and model in order to get more representative results. It is recommended to collect more data, both for the location considered and other locations, and to research more about the local behaviour such as gap acceptance. This would make the results of the model more representative of the real location that is being investigated and the effects that the evaluation shows are likely to be more accurate.

8.2.2 Recommendations for practice

Since one of the major assumptions of the model was to exclude all active mode users that crossed at the intersection illegally, i.e., at a location that is not a marked crossing, it is important to note that these must also be included when considering a design solution in practice. By excluding the illegal active mode crossings, the number of conflicts between active mode users and vehicles are underestimated. Additionally, the risk of an accident between an active mode user and a vehicle is increased because the driver does not expect an active mode user to be crossing at this location. Therefore, for a more accurate evaluation of the design, or for a safer design, these illegal crossings must be considered, and solutions need to be found to ensure their safety as well.

The results of this thesis can add to the knowledge of the effectiveness of throughabouts and how different types of solutions for roundabouts with BRT can be evaluated and compared to each other. A recommendation for an authority or a consultant wanting to add a BRT route to a road where there are two-lane roundabouts, is to use throughabouts with traffic signals for conflicting traffic. Furthermore, if a roundabout is smaller, has low traffic volume, or the total frequency of buses passing through the intersection is relatively low, the option of adding a throughabout with yielding signs, warning signs, or warning lights and bells might be a good solution as well. By removing the traffic lights, the waiting time can get shorter, and the flow can get smoother. However, this solution should be investigated further as this solution could result in more crossing conflicts because the circulating cars are not required to stop, or it's less clear to the drivers when a bus is approaching.
Additionally, it is recommended to look further into the views and goals of the stakeholders. This can be done by asking multiple people from each stakeholder to rank the criteria by allocating points to each criterion, which can then be normalized. This would lead to more accurate results of the MCA where a more accurate view of the stakeholder is considered.

Bibliography

1. lota forsendur og frumdrög. (2021). Retrieved from Reykjavík: https://borgarlinan.is/utgefid-efni/skyrslur/frumdragaskyrsla

Aakre, E., & Aakre, A. (2017). Simulating transit priority: Continuous median lane roundabouts. *Procedia Computer Science, 109*, 849-854. doi:https://doi.org/10.1016/j.procs.2017.05.400

Ahmed, B. (2014). Exploring New Bus Priority Methods at Isolated Vehicle Actuated Junctions. *Transportation Research Procedia, 4*, 391-406. doi:https://doi.org/10.1016/j.trpro.2014.11.030

AIMSUN. (n.d.). aimsun. Retrieved from https://www.aimsun.com/

Annema, J. A., Mouter, N., & Razaei, J. (2015). Cost-benefit Analysis (CBA), or Multi-criteria Decision-making (MCDM) or Both: Politicians' Perspective in Transport Policy Appraisal. *Transportation Research Procedia, 10*, 788-797. doi:https://doi.org/10.1016/j.trpro.2015.09.032

Árnason, E. Þ. (2022a). Aflétta öllum takmörkunum á föstudag. *vísir.is*. Retrieved from https://www.visir.is/g/20222226613d

Árnason, E. Þ. (2022b). Fimmtíu mega koma saman á miðnætti og stefna á að aflétta öllu í mars. *vísir.is*. Retrieved from https://www.visir.is/g/20222214792d/fimmtiu-mega-koma-saman-a-midnaetti-og-stefna-a-ad-afletta-ollu-i-mars

Azlan, N. N. N., & Rohani, M. M. (2018). *Overview of application of traffic simulation model.* Paper presented at the MATEC Web of Conferences.

Borgarlinan.is. (n.d.). Retrieved from https://borgarlinan.is/

Brand, J., Hoogendoorn, S., Oort, N. v., & Schalkwijk, B. (2017, 26-28 June 2017). *Modelling multimodal transit networks integration of bus networks with walking and cycling.* Paper presented at the 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS).

Bråtveit, L. A. (2016). *Prioritering av kollektivtrafikk i signalregulerte rundkjøringer med midstilt kollektivfelt.* NTNU,

BRT Data. (2021). Global BRT Data. Retrieved from https://brtdata.org/

CROW. (2015). Basiskenmerken kruispunten en rotondes. In *Rotondes met ov-banen binnen de bebouwde kom*.

Department of Transport. (2022). The Highway Code. Retrieved from https://www.gov.uk/guidance/the-highway-code

Dijkstra, I. A. (2005). *Rotondes met vrijliggende fietspaden ook veilig voor fietsers?; Welke voorrangsregeling voor fietsers is veilig op rotondes in de bebouwde kom?* Retrieved from Leidschendam:

Dodgson, J., Spackman, M., Pearman, A., & Phillips, L. (2009). Multi-Criteria Analysis: A Manual.

Duduta, N., Adriazola, C., Hidalgo, D., Lindau, L. A., & Jaffe, R. (2012). Understanding Road Safety Impact of High-Performance Bus Rapid Transit and Busway Design Features. *Transportation Research Record, 2317*(1), 8-14. doi:10.3141/2317-02

FHWA. (2021). Surrogate Safety Assessment Model Overview. Retrieved from https://highways.dot.gov/research/safety/ssam/surrogate-safety-assessment-model-overview

Finn, B., Heddebaut, O., Kerkhof, A., Rambaud, F., Lozano, O., & Soulas, C. (2011). *Buses with High Level of Service Fundamental characteristics and recommendations for decision-making and research Results from 35 European cities*.

Finn, B., Heddebaut, O., & Rabuel, S. (2010). *Bus with a high level of service (BHLS): the European BRT concept.* Paper presented at the Transportation Research Board 89th Annual Meeting, Washington, DC.

Fortuijn, L. (2003). *Pedestrian and bicycle-friendly roundabouts. Dilemma of comfort and safety.* Paper presented at the Annual Meeting of the Institute of Transportation Engineers (ITE), Seattle, Washington (USA).
Frøyland, P., Ristesund, Ø., & Simonsen, S. (2014). Superbusskonsept og midtstilt kollektivfelt.
Gemeente Rotterdam. (2020). *Rotterdamse Mobiliteits Aanpak*. Retrieved from https://www.rotterdam.nl/wonen-leven/mobiliteitsaanpak/
Gettman, D., & Head, L. (2003). *Surrogate Safety Measures From Traffic Simulation Models, Final Report*. Retrieved from https://www.fhwa.dot.gov/publications/research/safety/03050/03050.pdf
Gettman, D., Pu, L., Sayed, T., Shelby, S. G., & Energy, S. (2008). *Surrogate safety assessment model and validation*. Retrieved from https://www.fhwa.dot.gov/publications/research/safety/08051/08051.pdf
Ghanim, M. S., & Shaaban, K. (2019). A Case Study for Surrogate Safety Assessment Model in Predicting Real-Life Conflicts. *Arabian Journal for Science and Engineering, 44*(5), 4225-4231. doi:10.1007/s13369-018-3326-8
Giæver, T., & Tveit, Ø. M. (2006). Rundkjøringer og kollektivtrafikkens fremkommelighet. *Sintef rapport STF50 A, 6048*.
Gruden, C., Otković, I. I., & Šraml, M. (2022). Pedestrian safety at roundabouts: a comparison of the behavior in Italy and Slovenia. *Transportation Research Procedia, 60*, 528-535. doi:https://doi.org/10.1016/j.trpro.2021.12.068
Hallgrímsdóttir, B., Ottósson, D. B., & Hafsteinsdóttir, G. B. (2019). *Umferðarhraði í hringtorgum*. Retrieved from https://www.vegagerdin.is/vefur2.nsf/Files/umferdarhardi_hringtorg_skyrsla/$file/Umfer%C3%B0arhra%C3%B0i%20%C3%AD%20hringtorgum.pdf
Hallgrímsdóttir, B., Skarphéðinsson, H., Hreinsdóttir, E. B., Halldórsdóttir, K., Friðriksdóttir, B., & Grétarsson, B. (2020). *Hönnun hringtorga: Rannsóknarverkefni um hönnun hringtorga*. Retrieved from https://www.vegagerdin.is/vefur2.nsf/Files/Honnun_hringtorga_juni_2021/$file/VEG-Hringtorgaleidbeiningar-2103-13.pdf
Hidalgo, D., & Gutiérrez, L. (2013). BRT and BHLS around the world: Explosive growth, large positive impacts and many issues outstanding. *Research in Transportation Economics, 39*(1), 8-13. doi:https://doi.org/10.1016/j.retrec.2012.05.018
Høye, A. (2017). *Trafikksikkerhet for syklister*. Retrieved from https://www.toi.no/getfile.php?mmfileid=46551
Huang, F., Liu, P., Yu, H., & Wang, W. (2013). Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. *Accident Analysis & Prevention, 50*, 1014-1024. doi:https://doi.org/10.1016/j.aap.2012.08.018
ITDP. (2017). The BRT Planning Guide. Retrieved from https://brtguide.itdp.org/
ITDP. (2022). The Bus Rapid Transit Standard. Retrieved from https://www.itdp.org/library/standards-and-guides/the-bus-rapid-transit-standard/
Jensen, S. U. (2017). Safe roundabouts for cyclists. *Accident Analysis & Prevention, 105*, 30-37. doi:https://doi.org/10.1016/j.aap.2016.09.005
Kennedy, J. (2007). *International comparison of roundabout design guidelines*: TRL.
Knoop, V. L., Hegyi, A., Salomons, M., van Lint, H., Yuan, Y., & Landman, R. (2020). *Traffic Flow Modelling & Control: CIE4825 and CIE5821 Lecture notes*. Lecture notes. TU Delft.
Kröyer, H., Hallgrímsdóttir, B., & Stefánsdóttir, A. G. (2020). *Umferðaröryggisáætlun Reykjavíkur 2019-2023*. Retrieved from https://Reykjavík.is/sites/default/files/umferdaroryggisaaetlun_Reykjavíkur_2019-2023.pdf
Liu, H., Skabardonis, A., Zhang, W.-b., & Li, M. (2004). Optimal Detector Location for Bus Signal Priority. *Transportation Research Record, 1867*(1), 144-150. doi:10.3141/1867-17

Logadóttir, F. B. (2022). Engar takmarkandir lengur í gildi vegna Covid. *vísir.is*. Retrieved from https://www.visir.is/g/20222227407d/engar-takmarkanir-lengur-i-gildi-vegna-covid
Mannvit. (2019). Samantekt á erlendum hönnunarleiðbeiningum fyrir hágæða almenningssamgöngur. *Vegagerðin og Reykjavíkurborg*. Retrieved from https://www.vegagerdin.is/vefur2.nsf/Files/samatekt_erl_honnunarleidb_almenningssamgongur/$file/Samantekt%20%C3%A1%20erlendum%20h%C3%B6nnunarlei%C3%B0beiningum%20fyrir%20h%C3%A1g%C3%A6%C3%B0a%20almenningssamg%C3%B6ngur%20n%C3%BDtt.pdf
Ministerie van Infrastructuur en Waterstaat. (2016, June 16). *The choice of the passenger*. Video Retrieved from https://www.youtube.com/watch?v=XGwbGAM5YII
Muley, D., Ghanim, M., & Kharbeche, M. (2018). Prediction of Traffic Conflicts at Signalized Intersections using SSAM. *Procedia Computer Science, 130*, 255-262. doi:https://doi.org/10.1016/j.procs.2018.04.037
National BRT Institute. (n.d.). BRT Basics. Retrieved from https://nbrti.org/
Nikitas, A., & Karlsson, M. (2015). A worldwide state-of-the-art analysis for bus rapid transit: Looking for the success formula. *Journal of Public Transportation, 18*(1), 3.
Odu, G. (2019). Weighting methods for multi-criteria decision making technique. *Journal of Applied Sciences and Environmental Management, 23*(8), 1449-1457.
Ogden, B. D., & Cooper, C. (2019). *Highway-rail crossing handbook*. Retrieved from
Paramics Microsimulation. (n.d.). Paramics Microsimulation. Retrieved from https://www.paramics.co.uk/en/
Park, B., & Schneeberger, J. D. (2003). Microscopic Simulation Model Calibration and Validation: Case Study of VISSIM Simulation Model for a Coordinated Actuated Signal System. *Transportation Research Record, 1856*(1), 185-192. doi:10.3141/1856-20
Poudel, N., & Singleton, P. A. (2021). Bicycle safety at roundabouts: a systematic literature review. *Transport Reviews, 41*(5), 617-642. doi:10.1080/01441647.2021.1877207
PTV Group. (n.d.). Fields of applicaiton for PTV VISSIM. Retrieved from https://www.ptvgroup.com/nl/oplossingen/producten/ptv-vissim/toepassingsgebieden/
Reykjavíkurborg. (2021). Aðalskipulag Reykjavíkur 2040. Retrieved from https://Reykjavík.is/sites/default/files/2022-01/AR2040_greinargerd_2021_des-vefutgafa.pdf
Reykjavíkurborg. (n.d.). Borgarvefsja.is. Retrieved from https://borgarvefsja.Reykjavík.is/borgarvefsja/
Rijsman, L., Oort, N. v., Ton, D., Hoogendoorn, S., Molin, E., & Teijl, T. (2019, 5-7 June 2019). *Walking and bicycle catchment areas of tram stops: factors and insights.* Paper presented at the 2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS).
Samgöngustofa. (n.d.). Hjólreiðar. Retrieved from https://www.samgongustofa.is/umferd/fraedsla-og-oryggi/fraedsla/reidhjol/
Stjórnarráð Íslands. (n.d.). Sáttmáli um samgöngur á höfuðborgarsvæðinu. Retrieved from https://www.stjornarradid.is/verkefni/samgongur-og-fjarskipti/samgonguaaetlun/sattmali-um-samgongur-a-hofudborgarsvaedinu/#Tab0
Strætó bs. (2020). *Stefnumótun 2020*. Retrieved from https://straeto.is/media/2021/10/stefnumotun-2020.pdf
Strætó bs. (n.d.-a). Eigendur, stjórn og skipurit. Retrieved from https://straeto.is/um-straeto/eigendur-stjorn-skipurit
Strætó bs. (n.d.-b). Leiðakerfi: Nýtt leiðanet. Retrieved from https://straeto.is/um-straeto/leidakerfi/nytt-leidanet
Strætó bs. (n.d.-c). Þjónustustefna. Retrieved from https://straeto.is/um-straeto/fundargerdir-fjarhagur-utgefidefni/stefnur/thjonustustefna
SWOV. (2022). *Roundabouts and other intersections*. Retrieved from The Huage: https://swov.nl/en/fact-sheet/roundabouts-and-other-intersections

Terentyev, V., Andreev, K., Anikin, N., Morozova, N., & Shemyakin, A. (2020). *The use of simulation when designing road junctions.* Paper presented at the E3S Web of Conferences.

Tzouras, P. G., Farah, H., Papadimitriou, E., van Oort, N., & Hagenzieker, M. (2020). Tram drivers' perceived safety and driving stress evaluation. A stated preference experiment. *Transportation Research Interdisciplinary Perspectives, 7*, 100205. doi:https://doi.org/10.1016/j.trip.2020.100205

Umferðarlög nr. 77/2019, (2019).

Van der Meijs, P. R. (2015). *Bus Rapid Transit: Establishment of a BRT Design Model to Design and Evaluate BRT Configurations.* (Master's thesis). Delft University of Technology, Retrieved from http://resolver.tudelft.nl/uuid:30d70a3f-773d-430f-a7b5-f484eb13e5ae

van Hagen, M., & Bron, P. (2014). Enhancing the Experience of the Train Journey: Changing the Focus from Satisfaction to Emotional Experience of Customers. *Transportation Research Procedia, 1*(1), 253-263. doi:https://doi.org/10.1016/j.trpro.2014.07.025

Vegagerðin. (2022). Umferðaröryggisstefna. Retrieved from https://www.vegagerdin.is/um-vegagerdina/markmid-og-stefnur/umferdaroryggismal/

Vegagerðin. (n.d.). Meginmarkmið, hlutverk, gildi og stefnur ásamt nýju skipuriti. Retrieved from https://www.vegagerdin.is/um-vegagerdina/markmid-og-stefnur/

VSÓ Ráðgjöf. (2019). Borgarlína og umferðaröryggi. *Vegagerðin*. Retrieved from http://www.vegagerdin.is/vefur2.nsf/Files/borgarlina_umferdaroryggi/$file/Borgarl%C3%ADnu%20og%20umfer%C3%B0ar%C3%B6ryggi.pdf

Vuchic, V. R. (2005). *Urban Transit: Operations, planning and economics*. Hoboken, New Jersey: John Wiley & Sons, Inc.

Wee, B. v., Annema, J. A., & Banister, D. (2012). *The Transport System and Transport Policy : An Introduction*. Cheltenham, Gloucestershire, UNITED KINGDOM: Edward Elgar Publishing Limited.

Wu, J., Radwan, E., & Abou-Senna, H. (2016). *Pedestrian-vehicle conflict analysis at signalized intersections using micro-simulation.* Paper presented at the 17th International Conference Road Safety On Five Continents (RS5C 2016), Rio de Janeiro, Brazil, 17-19 May 2016.

Zakeri, S., & Choupani, A.-A. (2021). Operational Evaluation of a Throughabout to Give Priority to Public Transport at Standard Roundabouts. *Journal of Advanced Transportation, 2021*, 1840040. doi:10.1155/2021/1840040

Appendix A: Model input

Appendix A includes more detailed information about the model inputs and is divided into two sub-sections of the MCA weights and Volume inputs.

MCA weights

The criteria considered in the MCA can be divided into four levels of sub-criteria, as shown in Figure 65.

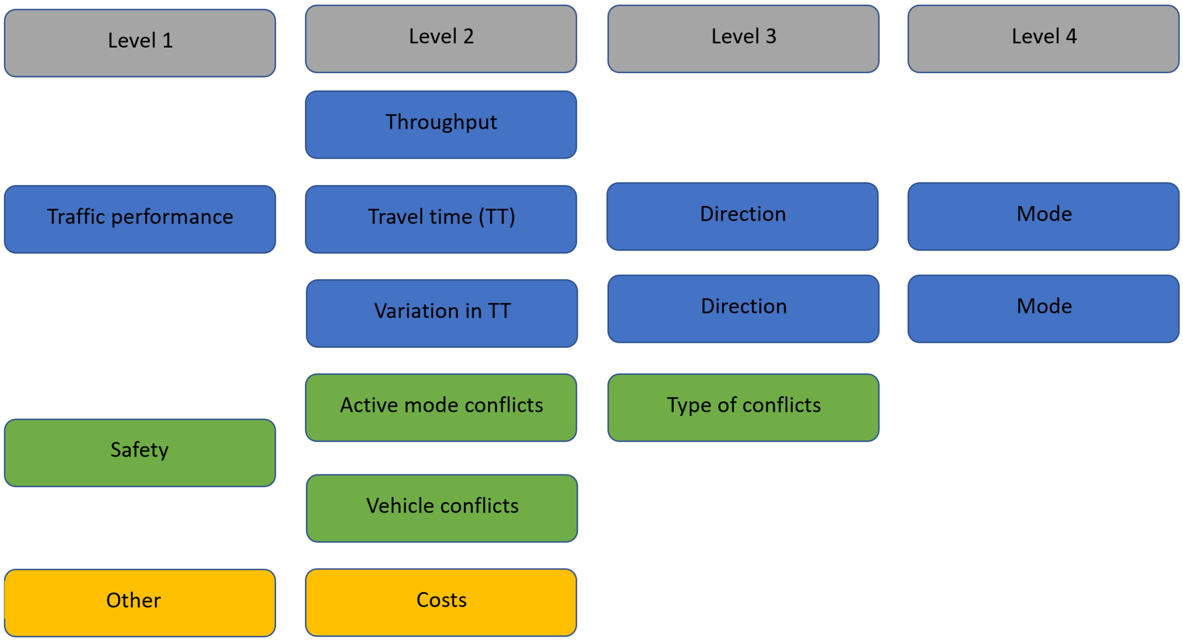


Figure 65 Setup of MCA criteria and the criteria levels

Based on the stakeholders' views and goals (as discussed in Chapter 4.3), weights can be assigned to each criterion in Figure 65. The weights are based on the following assumptions:

- Both the municipality and road authority focus on safety and therefore weigh it higher than the traffic performance.
- The municipality focuses a bit more on safety and therefore the difference between traffic performance and safety is larger for the municipality than the road authority.
- The municipality uses the road user hierarchy where active mode users are on top. Therefore, they might weigh the safety and priority (traffic performance) of active modes, and public transport higher than cars.
- The road authority focuses on having access to transport for all modes and to have integrated system, therefore they might weigh the traffic performance more equally between modes than the other stakeholders.
- The public transport stakeholder perspective focuses mainly on the speed and reliability of the buses. Therefore, they might weigh the traffic performance higher than safety and the performance of the buses higher than for other modes.
- The safety criterion is split up based on conflicts between vehicles and conflicts between vehicles and active modes. Since conflicts between vehicles and active modes are the most severe, they get the most weight. Within the conflicts between vehicles, the crossing conflicts are the most severe and therefore get the most weight as well.
- Because of limitations and simplifications in the model, which are explained further in chapter 5.3, it is likely that the lane-changing conflicts are overestimated in the model than in reality, therefore lane-changing conflicts get lower weight compared to the other types of conflict.

The weights assigned to each criterion, in each criterion level can be seen in Table 23.

Table 23 Weights assigned to each criterion per criteria level

Criteria				Municipality				Road Authority				Public Transport authority			
L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4
Traffic performance	Throughput			0.3	0.33	-	-	0.7	0.33			0.7	0.1		
	Travel time	N-S	Cars + Trucks		0.33	0.25	0.3		0.33	0.2	0.5		0.45	0.3	0.1
			PT				0.7				0.5				0.9
		S-N	Cars + Trucks			0.25	0.3			0.2	0.5			0.3	0.1
			PT				0.7				0.5				0.9
		E-W	Cars + Trucks			0.25	0.2			0.3	0.33			0.2	0.1
			PT				0.4				0.33				0.7
			Active modes				0.4				0.33				0.2
		W-E	Cars + Trucks			0.25	0.2			0.3	0.33			0.2	0.1
			PT				0.4				0.33				0.7
			Active modes				0.4				0.33				0.2
	Variability in travel time	N-S	Cars + Trucks		0.33	0.25	0.3		0.33	0.2	0.5		0.45	0.3	0.1
			PT				0.7				0.5				0.9
		S-N	Cars + Trucks			0.25	0.3			0.2	0.5			0.3	0.1
			PT				0.7				0.5				0.9
		E-W	Cars + Trucks			0.25	0.2			0.3	0.33			0.2	0.1
			PT				0.4				0.33				0.7
			Active modes				0.4				0.33				0.2
		W-E	Cars + Trucks			0.25	0.2			0.3	0.33			0.2	0.1
			PT				0.4				0.33				0.7
			Active modes				0.4				0.33				0.2
Safety	Veh - Veh conflicts	Crossing		0.6	0.4	0.5	-	0.5	0.4	0.5	-	0.2	0.5	0.5	-
		Lane change				0.2	-			0.2	-			0.2	-
		Rear end				0.3	-			0.3	-			0.3	-
	Veh-active mode conflicts	Crossing			0.6	1	-		0.6	1	-		0.5	1	-
Other	Costs			0.1	1	-	-	0.1	1	-	-	0.1	1	-	-

To combine all these criteria levels into one criteria level, (which is the most detailed level, level 4), the product of all the levels is recorded for each criterion.

$$Combined\ weight\ for\ each\ criterion = Weight_{L1} * Weight_{L2} * Weight_{L3} * Weight_{L4}$$

For example, the travel time for vehicles travelling from N-S for the municipality will have a weight of 0.0074

$$0.3 * 0.33 * 0.25 * 0.3 = 0.0074$$

When a criterion does not have an element in level 4, then the weight for the lower level is equal to 1. For example, the weight for active mode conflicts is calculated $0.6 * 0.6 * 1 * 1 = 0.36$, and the weight for costs is calculated $0.1 * 1 * 1 * 1 = 0.1$.

Doing these calculations for all criteria and stakeholder, results in the weight sets showed in Table 24. Where the sum of all the weights for each stakeholder is equal to 1.

Table 24 Weights assigned to each criterion per stakeholder

	Municipality	**Road authority**	**Public transport authority**
Throughput	0.099	0.1320	0.0700
TT NS vehicles	0.0074	0.0132	0.0095
TT NS PT	0.0173	0.0132	0.0851
TT SN vehicles	0.0074	0.0132	0.0095
TT SN PT	0.0173	0.0132	0.0851
TT EW vehicles	0.0050	0.0131	0.0063
TT EW PT	0.0099	0.0131	0.0441
TT EW active modes	0.0099	0.0131	0.0126
TT WE vehicles	0.0050	0.0131	0.0063
TT WE PT	0.0099	0.0131	0.0441
TT WE active modes	0.0099	0.0131	0.0126
SD NS vehicles	0.0074	0.0132	0.0095
SD NS PT	0.0173	0.0132	0.0851
SD SN vehicles	0.0074	0.0132	0.0095
SD SN PT	0.0173	0.0132	0.0851
SD EW vehicles	0.0050	0.0131	0.0063
SD EW PT	0.0099	0.0131	0.0441
SD EW active modes	0.0099	0.0131	0.0126
SD WE vehicles	0.0050	0.0131	0.0063
SD WE PT	0.0099	0.0131	0.0441
SD WE active modes	0.0099	0.0131	0.0126
crossing conflict	0.1200	0.1	0.05
Lane change conflict	0.0480	0.04	0.02
rear end conflict	0.0720	0.06	0.03
active mode - vehicle conflict	0.3600	0.3	0.1
Costs	0.1000	0.1	0.1
Total	1	1	1

To calculate the scores for criteria levels 2, as shown in Table 20, each value for the level 4 criteria is multiplied by its respective weight, as shown in Table 23. The sum of the sub criteria in level 4 are then multiplied by the weight of the criteria level above, and so on until criteria level 2 is reached. Each value obtained for criteria level 2 is multiplied by the weight of criteria level 1. This results in the scores shown in Table 20.

Volume

The tables displayed in this appendix show the volume inputs per 15 minutes per mode per turning movement. For example, during the first 15 minutes (15:30 – 15:45), 22 cars approach the intersection from Sudurgata NE and turn right. The values in the table are the numbers from the data collection explained in chapter 5.2 and are the scaled and adjusted values. The volumes that are used as input into the VISSIM model are 4 times higher than the values shown in these tables because VISSIM volumes are in the units of vehicles per hour and the values in the tables are shown as vehicles per 15 minutes.

15:30 – 15:45		**Right**	**Through**	**Left**	**U-turn**	**Crosswalk CW**	**Crosswalk CCW**
Sudurgata NE	Cars	22	3	22	0	-	-
	Trucks	1	0	0	0	-	-
	Pedestrians	-	-	-	-	0	6
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	4
Hringbraut SE	Cars	5	238	25	0	-	-
	Trucks	0	4	1	0	-	-
Sudurgata SW	Cars	44	2	13	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	4	8
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	4
Hringbraut NW	Cars	10	252	15	0	-	-
	Trucks	0	7	0	0	-	-

15:45 – 16:00		**Right**	**Through**	**Left**	**U-turn**	**Crosswalk CW**	**Crosswalk CCW**
Sudurgata NE	Cars	22	4	19	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	4	2
	Bikes	-	-	-	-	4	0
	e-scooter	-	-	-	-	0	0
Hringbraut SE	Cars	1	267	42	0	-	-
	Trucks	0	3	1	0	-	-
Sudurgata SW	Cars	42	2	19	0	-	-
	Trucks	1	0	1	0	-	-
	Pedestrians	-	-	-	-	2	8
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut NW	Cars	13	248	20	0	-	-
	Trucks	0	1	0	0	-	-

16:00 – 16:15		Right	Through	Left	U-turn	Crosswalk CW	Crosswalk CCW
Sudurgata NE	Cars	29	10	30	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	4	2
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut SE	Cars	0	315	31	0	-	-
	Trucks	0	3	0	0	-	-
Sudurgata SW	Cars	49	3	33	0	-	-
	Trucks	1	0	0	0	-	-
	Pedestrians	-	-	-	-	14	16
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut NW	Cars	13	253	28	0	-	-
	Trucks	0	3	0	0	-	-

16:15 – 16:30		Right	Through	Left	U-turn	Crosswalk CW	Crosswalk CCW
Sudurgata NE	Cars	25	8	22	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	0	0
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut SE	Cars	4	312	30	0	-	-
	Trucks	0	0	0	0	-	-
Sudurgata SW	Cars	49	6	21	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	6	16
	Bikes	-	-	-	-	8	4
	e-scooter	-	-	-	-	0	0
Hringbraut NW	Cars	9	260	18	0	-	-
	Trucks	0	4	1	0	-	-

16:30 – 16:45		Right	Through	Left	U-turn	Crosswalk CW	Crosswalk CCW
Sudurgata NE	Cars	23	7	22	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	2	16
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut SE	Cars	4	291	31	0	-	-
	Trucks	0	2	1	0	-	-
Sudurgata SW	Cars	45	2	33	0	-	-
	Trucks	1	0	0	0	-	-
	Pedestrians	-	-	-	-	12	10
	Bikes	-	-	-	-	8	0
	e-scooter	-	-	-	-	0	0
Hringbraut NW	Cars	10	214	21	0	-	-
	Trucks	0	4	0	0	-	-

16:45 – 17:00		Right	Through	Left	U-turn	Crosswalk CW	Crosswalk CCW
Sudurgata NE	Cars	19	3	26	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	0	10
	Bikes	-	-	-	-	0	0
	e-scooter	-	-	-	-	0	0
Hringbraut SE	Cars	2	313	37	0	-	-
	Trucks	0	0	0	0	-	-
Sudurgata SW	Cars	63	0	26	0	-	-
	Trucks	0	0	0	0	-	-
	Pedestrians	-	-	-	-	14	16
	Bikes	-	-	-	-	4	8
	e-scooter	-	-	-	-	4	0
Hringbraut NW	Cars	12	242	9	0	-	-
	Trucks	0	3	0	0	-	-

Appendix B: Location of detectors

With priority signals for the buses driving on the bus lane through the intersection, the buses should be able to drive through the intersection without having to stop or slow down. In order for this to be possible, the timing of the signals have to be in a way that the buses have a clear way when they approach the intersection and can clear the intersection while the lights are green for them.

VISSIM has a signal controller type that is called *Railway crossing* where two types of groups are identified: the main road, where the signals are green by default, and the bus lane, where the signals are controlled by calling signals from detectors. To identify when the bus is approaching the intersection, a detector is placed before the intersection which triggers the signals to change when the detector is activated by the bus. After the intersection, another detector is located which changes the signals back to the default state when the bus passes that detector.

In order to allow the buses to drive through the intersection without having to stop or slow down, the distance of the detectors from the intersection has to be determined. The distance can be found based on the speed of the buses and the signal times. Literature shows that yellow times are around 3 seconds and minimum green times are around 5-6 seconds[8]. When looking at literature about level crossing signal times, both for trains and trams, results in that the time should be minimised for warning time to reduce the chance of illegal crossings (crossings on red) (Ogden & Cooper, 2019). Minimising the warning time also minimises the waiting time. Ogden and Cooper (2019) also mention that the warning time before the train passes should be minimum 20 seconds, but usually longer. There is a difference between trains and buses since trains have a much longer stopping time, however, literature suggests that the detectors for buses to get priority at signalized intersections should be from 112m to 300m upstream of the intersection (Ahmed, 2014; Liu, Skabardonis, Zhang, & Li, 2004). This distance depends on the signal timings, the speed of the bus, and the queue length of the queue that the bus is in (Ahmed, 2014; Liu et al., 2004). Since the case study considered in this research has an exclusive bus lane, the queue aspect is not considered and thus, a distance on the shorter side of the range is appropriate to minimize waiting time.

In addition to the literature, empirical measurements from three roundabouts on N196 in Aalsmeer, the Netherlands were performed. For each roundabout, the times from the start of the warning that a bus was approaching (yellow light turns on), until the bus passed the circulatory road on the roundabout, and until the red light for the cars turned off were recorded. For each roundabout, the recordings were for about one hour, resulting in around 8 measurements at each roundabout. Table 25 shows the summary of the empirical measurements from the location.

Table 25 Empirical measurements from three roundabouts on N196 in Aalsmeer in the Netherlands

	Average	**Standard deviation**
Total time (s)	18.27	5.0
Yellow time (s)	2.76	0.69
Time from detection to passing (s)	13.00	3.05
Time from passing to end (s)	6.62	1.13

[8] Lecture slides from lecture by A. M. Salomons, 7 Jan. 2021 on the topic of Local intersection control in the course of CIE4825 Traffic Flow Modelling and Control part 1

From this data, the detector locations can be calculated with the time from when the bus is detected until it passes the intersection. The time measured from the start of the yellow light until the bus passed the circulatory road, can be used to calculate the distance for the upstream detector, and the downstream detector can be calculated from the time between when the bus passed the circulatory road until the light turns off. These distances are all measured from the middle of the circulatory road, as that was the reference point for time measurements. The speed of the buses in the model is 30km/h (8.33m/s), which is used to calculate the distance required. The calculations below show the detector locations both upstream and downstream of an average throughabout.

$$detector\ location\ (m) = required\ time\ (s) * speedof\ bus\ (^m/_s)$$

$$detector\ upstream\ = 13 * 8.33 = 108.3m$$

$$detector\ downstream\ = 6.62 * 8.33 = 55.2m$$

Using the empirical data to calculate the detector locations the detector upstream should be located 108 m from the intersection, and the detector downstream 55m from the intersection.

As the empirical data has not been tested further, was only collected for limited time at few places, and prone to more errors, the numbers from the literature have more weight when choosing a distance for the detectors. However, when the numbers from literature and the collected data are compared, the difference is not very large.
As a conclusion, a starting distance for detectors upstream should be around 112 m and 55 m downstream. However, when building the model this distance could be adjusted to make the buses not have to slow down, for the upstream location, or to shorten waiting time, for downstream location if the bus has cleared the intersection before the suggested detector location.

First location: Locate detector at the calculated distance.
The suggested locations for the detectors are placed in design solution 2: Traffic signals for entering traffic and a simulation is run. However, the simulation run resulted in a gridlock due to a long queue on Sudurgata NE, and the bus cannot move forward, but has passed the detector which caused the light for the cars to turn red, causing a gridlock, as the light does not change again until the bus passes the downstream detector. This gridlock is shown in Figure 66.

Figure 66 Gridlock starting after a bus passed the detector but is stuck in a queue

This problem leads to having to explore few options in order to avoid this gridlock. Few options are tested where the detector is moved closer to the intersection, so that the bus will have a clear way when it passes the detector. Additionally, the different locations of detectors are tested when Sudurgata NE is a bus only street.

Option 1: Locate the detector closer to the intersection.
Since the problem is that cars will be in front of the bus when the detector is activated, one solution could be to move the detector closer to the intersection, to a place where the exclusive bus lane starts, resulting in that the bus always has a clear way when the detector is activated.

Testing this solution in one VISSIM simulation run results in that the throughput of the intersection is 3,076 veh/hr and the speed and travel times of the buses are shown in Table 26 below.

Table 26 Speed and travel time of affected traffic when the bus detector is closer to the intersection

	Bus	**BRT**	**Car**
Speed (km/h)	30.13	31.08	16.43
Travel time (S-N) (s)	94.16	98.16	
Travel time (N-S) (s)	108.05	98.29	

With this solution, the bus has to slow down before entering the roundabout, as it is waiting for the signals to change. Additionally, because the bus is already close to the intersection, it crosses the intersection immediately when the light turns green, instead of few seconds after, like when the detector is further away, causing that sometimes there are cars still on the roundabout when the bus crosses. However, this could be changed by adding few seconds to the signal times, yellow times, or all-red times to avoid this, and it will not affect the speed of the other direction of the buses.
As a result of this simulation run, the queue of vehicles is very long and 60 vehicles did not enter the network, this error can be fixed by making the links longer, but the queues will still be long.

Option 2: Extend the bus only lane further north.
As the issue lies in that the bus gets blocked by cars that are in a queue to enter the roundabout, one solution could be to extend the exclusive bus lane further north to keep the detector at the calculated distance.

In the case of Melatorg, there is not space to have two lanes on Sudurgata NE, where one would be for mixed traffic and one a bus lane. Therefore, to test this option Sudurgata would become a bus only lane and other traffic would be redistributed on other roads. A potential redistribution routes can be seen in Figure 67 below.

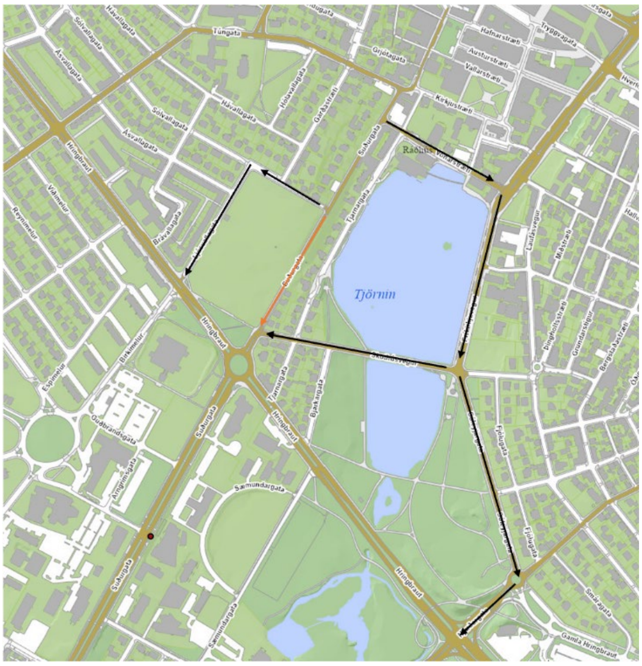


Figure 67 Potential redistribution of traffic by changing Sudurgata NE into a bus only street

The mixed traffic could turn left before the lake or to the right before Sudurgata would become bus only lane. A downside of this option is that Sudurgata is a residential street and there are houses where the bus only street would be, and therefore the street would allow limited access for those that are going to the houses while still being mostly bus only street.

This option is run in a VISSIM simulation, where the detector is located at the calculated distance upstream of the intersection. However, this simulation also results in a gridlock, as there is a bus line (pink line) that turns at the intersection and does not go on the bus lane through the intersection, and when the queue gets long enough that the pink bus cannot proceed, and a bus arrives and triggers the signals to change, everything gets stuck, as shown in Figure 68.

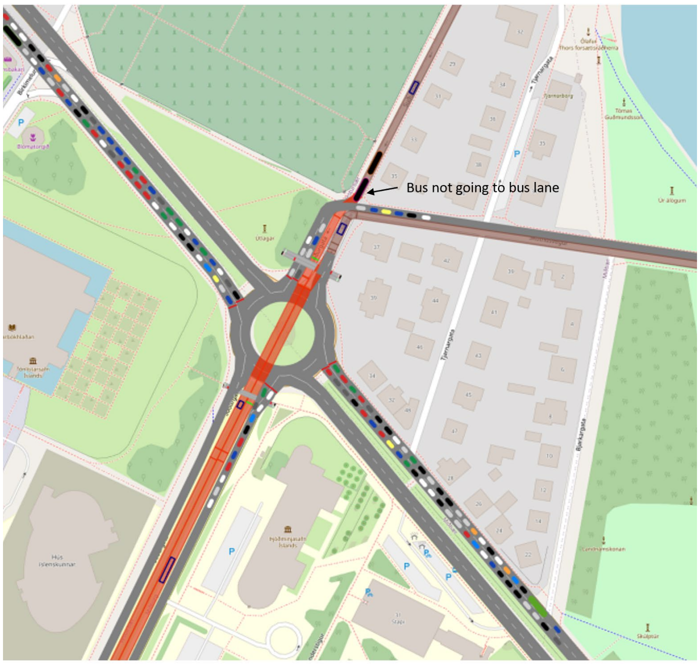


Figure 68 Gridlock occurring when Sudurgata is a bus only street and detector location is at the calculated distance

To investigate if the turning bus was the only factor causing this problem a solution was tested when the turning buses were excluded from the model. This resulted in a throughput of 2,913 veh/hr (2,669cars/hr) and the following table, Table 27.

Table 27 VISSIM output for the option 2 case where only bus lines on the exclusive lane are included

	Bus	BRT	Car
Speed (km/h)	32.92	32.19	14.27
Travel time (S-N) (s)	94.16	98.15	
Travel time (N-S) (s)	90.96	91.38	

This results in that the gridlock did not occur when all the buses were using the exclusive lane. This means that for cases where all the bus lines at the intersection are using the exclusive lane, extending the exclusive lane further, at least until the location of the detector is ideal.

Option 3: detector closer to the intersection and bus lane longer to the north.
Since this case study has all the bus lines, the turning bus line should be considered in the model as well. Therefore, as a last option, a solution where the detector is moved closer to the intersection, on the exclusive bus lane, and Sudurgata is restricted for only buses is tested. This simulation run results in a throughput of 3,035 veh/hr (2,792 cars/hr) and Table 28.

Table 28 VISSIM output for the option 3 case where the detector is located closer to the intersection

	Bus	BRT	Car
Speed (km/h)	32.13	31.38	22.52
Travel time (S-N) (s)	94.16	98.12	
Travel time (N-S) (s)	95.29	96.41	

This option results in that the queues on Hringbraut are long, but shorter than before, as all cars are able to enter the network, but this might change depending on simulation runs as volumes are stochastic.

Summary

For this case study, locating the detector at the calculated distance results in a gridlock of the network. Option 3, where the detector is located closer to the intersection and Sudurgata is a bus lane, results in the best performance. The speed of the buses and cars are higher and travel time shorter. However, the difference is not that large as Table 29 below shows.

Table 29 Comparison of option 1 and option 3 for the detector location

	Option 1 (O1)	Option 3 (O3)	Difference (O3 – O1)	Comment
Throughput (users/hr)	3,076	3,035	-41	Less throughput in O3
Speed – Cars	16.43	22.52	6.09	Drive faster in O3
Speed – Bus	30.13	32.13	2	Drive faster in O3
Speed – BRT	31.08	31.38	0.3	Drive very similar speed in both
Travel time (S-N) - Bus	94.16	94.16	0	Same travel time
Travel time (S-N) - BRT	98.16	98.12	-0.04	Same travel time
Travel time (N-S) - Bus	108.05	95.29	-12.76	Save 12.76s in O3
Travel time (N-S) - BRT	98.29	96.41	-1.88	Save 1.88s in O3

From these results, it can be concluded that there is not that much of a difference between the performance of option 1 and option 3. However, since the speed of cars is much better and the travel times for buses is better in option 3, this option is chosen to be used for the remainder of the research.
Additionally, it is important to note that the free flow speed of the buses can be affected by the location of the detectors. When a free flow case is run where there are no detectors and only buses in the system, allowing them to drive freely, the travel time from north to south is 4 seconds less than when the chosen location of the detectors is placed in the model. However, since these extra 4 seconds are not substantially increasing the travel time, the results of the model are compared to a free flow situation where there are no detectors in the system.

Appendix C: Outputs

Appendix C includes more detailed information about the outputs from the VISSIM simulations, SSAM calculations, and more details about the MCA scores.

VISSIM output tables

The tables displayed in this appendix show the outputs from the VISSIM simulations and the output from the SSAM calculations.

Table 30 shows the average, standard deviation and max values for each traffic performance criterion for each mode from the 10 simulation runs for design solution 1: Mixed traffic conditions

Table 30 VISSIM output for design solution 1: Mixed traffic conditions

Traffic efficiency table		**Cars**	**Trucks**	**BRT**	**Bus**	**Mixed PT**	**Pedestrians**	**Cyclists**
Throughput [veh/hr]	Average	2968	29	48	16	32	103	26
	Standard deviation	68	4	1	0	0	7	5
	Max	3053	36	49	16	32	116	34
Travel time N-S [s]	Average	109.2	-	168.2	211.4	-	-	-
	Standard deviation	16.1	-	17	17.2	-	-	-
	Max	150.5	-	203.4	238.2	-	-	-
Travel time S-N [s]	Average	93.7	-	148.2	149.9	-	-	-
	Standard deviation	6.4	-	3.1	11.6	-	-	-
	Max	106.3	-	151.8	174.7	-	-	-
Travel time E-W [s]	Average	81.6	83	-	-	102.2	25	10.3
	Standard deviation	2.7	4.2	-	-	4.3	3	7.2
	Max	85.2	87.9	-	-	111.4	30.6	29.2
Travel time W-E [s]	Average	79	81.49	-	-	97	26	11.5
	Standard deviation	1.8	3.8	-	-	3.3	3.5	10.1
	Max	82.3	88.4	-	-	102.4	33.4	36.2
Speed [km/h]	Average	35.9	34.9	19.7	17.4	26.1	4.1	12
	Standard deviation	1.5	1.2	1	1.2	1.2	0.2	4.1
	Max	37.5	36.7	21.1	20	27.4	4.5	18.5
Number of stops	Average	0.8	0.8	3.7	4.6	1.2	4.3	7
	Standard deviation	0.3	0.3	0.2	0.7	0.2	2.2	8.7
	Max	1.4	1.3	4	5.4	1.5	8.2	29.7
Time stopped [s]	Average	2.7	3.	41.3	55.1	9	3.5	3.8
	Standard deviation	1.4	1	6.6	8.3	3.5	1.1	4.7
	Max	6.2	4.6	54.8	65.1	16.1	5.4	16

Table 31 shows the safety criterion from SSAM and manual counting of the conflict points of the roundabout design.

Table 31 SSAM output and other safety parameters for design solution 1: Mixed traffic conditions

Safety table		Average	Standard deviation
Number of conflict points		32 (excluding BRT lane merge)	-
Vehicle – Vehicle conflict	Crossing	49	6.2
	Rear end	350.5	104
	Lane change	120.4	20.4
Vehicle – active mode conflict	Crossing	27.1	5.3
Number of lanes to cross at a time (active modes)		2	-
Signalized crossing		no	-

Table 32 shows the output from the 10 VISSIM simulations for design solution 2: Traffic signals for entering traffic. Table 33 shows the safety criterion from SSAM and manual counting of the conflict points of the roundabout design for design solution 2.

Table 32 VISSIM output for design solution 2: Traffic signals for entering traffic

Traffic efficiency table		**Cars**	**Trucks**	**BRT**	**Bus**	**Mixed PT**	**Pedestrians**	**Cyclists**
Throughput [veh/hr]	Average	2748	25	16	48	29	101	25
	Standard deviation	19	3	0	0	1	6	4
	Max	2775	29	16	48	31	109	32
Travel time N-S [s]	Average	116.1	-	96.9	94.7	-	-	-
	Standard deviation	7.5	-	1.9	0.9	-	-	-
	Max	126.9	-	100.7	96.3	-	-	-
Travel time S-N [s]	Average	101.8	-	97.6	98.3	-	-	-
	Standard deviation	7.3	-	2.1	0.9	-	-	-
	Max	113.9		100.4	99.8	-	-	-
Travel time E-W [s]	Average	171.2	164.3	-	-	176.7	27.5	6.9
	Standard deviation	41.7	69.7	-	-	48.5	2.3	1.5
	Max	219.7	312.5	-	-	227.1	31.5	9.4
Travel time W-E [s]	Average	332.2	377.9	-	-	346.5	24.6	7.0
	Standard deviation	45.1	58.0	-	-	47.6	1.7	3.2
	Max	392.9	496.5	-	-	409.8	27.4	13.5
Speed [km/h]	Average	19.5	16.8	31.4	31.7	18.0	3.9	15.5
	Standard deviation	3.5	2.7	0.4	0.3	3.0	0.2	3.0
	Max	25.6	22.4	32.2	32.1	22.6	4.1	21.4
Number of stops	Average	15.0	17.9	0.0	0.4	9.8	2.9	1.0
	Standard deviation	4.8	5.7	0.0	1.3	3.7	1.8	1.3
	Max	21.1	25.8	0.1	3.9	15.2	5.4	4.1
Time stopped [s]	Average	79.5	93.6	0.5	0.0	55.4	5.0	1.7
	Standard deviation	25.5	24.9	0.9	0.0	20.2	0.9	0.8
	Max	117.9	129.2	2.3	0.1	77.8	6.7	2.7

Table 33 SSAM output and other safety parameters for design solution 2: Traffic signals for entering traffic

Safety table		**Average**	**Standard deviation**
Number of conflict points		44	-
Vehicle – Vehicle conflict	Crossing	19.9	3.2
	Rear end	2338.3	613
	Lane change	241.9	39.1
Vehicle – active mode conflict	Crossing	12.4	5.4
Number of lanes to cross at a time (active modes)		2	-
Signalized crossing		Partially	-

Table 34 shows the output from the 10 VISSIM simulations for design solution 3: Traffic signals for conflicting traffic. Table 35 shows the safety criterion from SSAM and manual counting of the conflict points of the roundabout design for design solution 3.

Table 34 VISSIM output for design solution 3: Traffic signals for conflicting traffic

Traffic efficiency table		**Cars**	**Trucks**	**BRT**	**Bus**	**Mixed PT**	**Pedestrians**	**Cyclists**
Throughput [veh/hr]	Average	2903	28	16	48	31	103	26
	Standard deviation	33	3	0	0	1	7	5
	Max	2959	34	16	48	32	115	34
Travel time N-S [s]	Average	100.9	-	95.4	94.7	-	-	-
	Standard deviation	4.1	-	1.6	0.7	-	-	-
	Max	106.1	-	98.5	95.8	-	-	-
Travel time S-N [s]	Average	95.5	-	97.5	98.2	-	-	-
	Standard deviation	3.6	-	2.0	0.7	-	-	-
	Max	100.7	-	100.4	99.4	-	-	-
Travel time E-W [s]	Average	125.4	121.0	-	-	131.5	26.7	6.3
	Standard deviation	28.3	18.0	-	-	31.0	1.9	1.1
	Max	172.8	146.0	-	-	186.1	31.2	8.2
Travel time W-E [s]	Average	221.1	247.7	-	-	244.2	24.8	7.2
	Standard deviation	66.9	66.4	-	-	74.8	1.7	3.2
	Max	324.5	363.6	-	-	358.1	28.3	15.5
Speed [km/h]	Average	27.6	25.4	31.7	31.7	23.8	3.9	16.1
	Standard deviation	4.5	4.5	0.3	0.2	3.1	0.2	3.2
	Max	33.6	32.8	32.3	32.1	27.8	4.1	23.6
Number of stops	Average	7.1	8.3	0.0	0.0	4.4	1.3	0.3
	Standard deviation	3.7	3.8	0.0	0.0	2.4	0.9	0.4
	Max	14.0	15.0	0.0	0.0	8.6	3.9	1.4
Time stopped [s]	Average	34.3	40.6	0.0	0.0	22.4	4.8	1.5
	Standard deviation	16.5	19.2	0.0	0.0	12.3	0.9	0.7
	Max	65.1	72.0	0.0	0.0	44.7	6.8	2.3

Table 35 SSAM output and other safety parameters for design solution 3: Traffic signals for conflicting traffic

Safety table		**Average**	**Standard deviation**
Number of conflict points		44	-
Vehicle – Vehicle conflict	Crossing	9.7	3.5
	Rear end	1468.8	525.4
	Lane change	246	37.4
Vehicle – active mode conflict	Crossing	12.1	4.7
Number of lanes to cross at a time (active modes)		2	-
Signalized crossing		Partially	-

SSAM maps

The figures in this appendix show the location and type of the conflicts in the simulation run for each design solution that is closest to the average. The types of conflicts are distinguished by different colours, where crossing conflicts are red, lane-changing conflicts are blue, and rear end conflicts are yellow. The figures include all conflicts, both conflicts between vehicles, and vehicles and active modes.
The figures show that most crossing conflicts occur at the active mode crossings, or when exiting the roundabout.

Figure 70 and Figure 71 show that majority of the rear end conflicts come from Hringbraut, and from the queues that are formed in the design solution. The figures show that the increase in rear end conflicts in design solutions 2 and 3 come from the long queues.

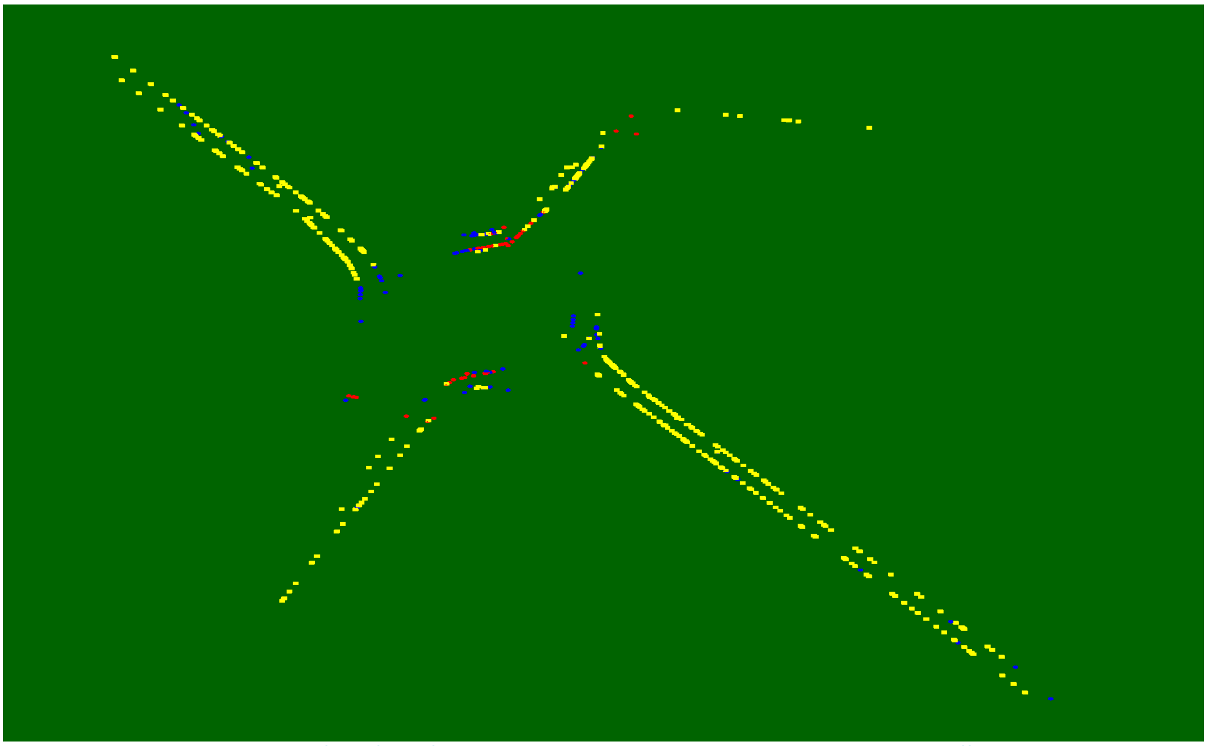


Figure 69 Number of conflicts from simulation run 4, design solution 1: Mixed traffic conditions

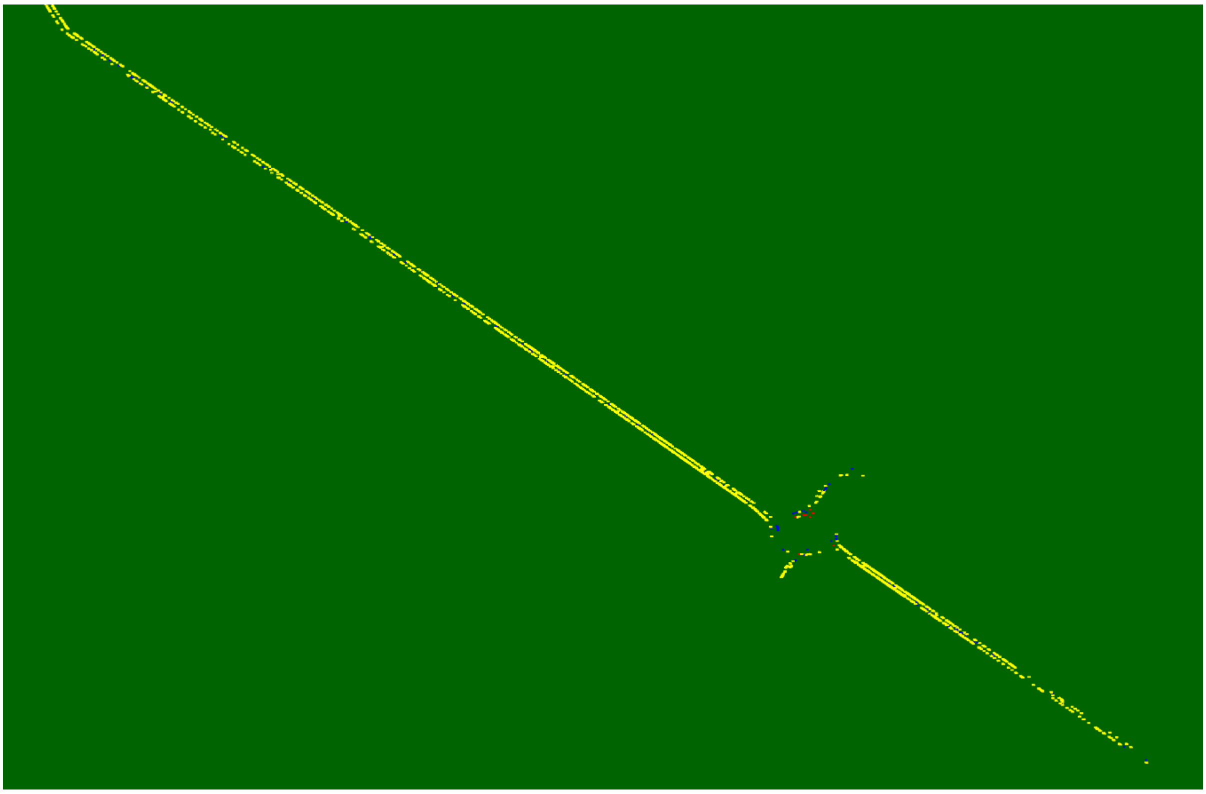


Figure 70 Number of conflicts from simulation run 3, design solution 2: Traffic signals for entering traffic

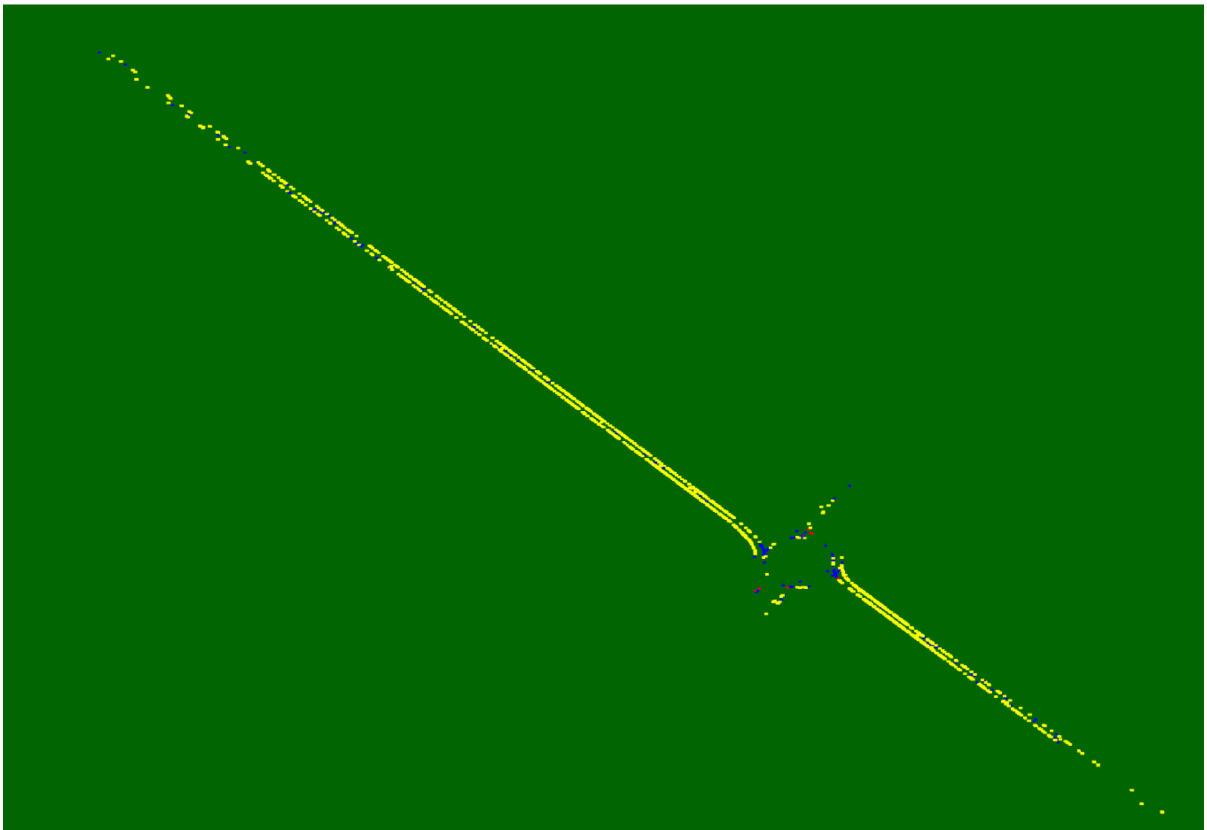


Figure 71 Number of conflicts from simulation run 9, design solution 3: Traffic signals for conflicting traffic

MCA scores

This appendix shows the MCA scores in more detail and the results of each step of the calculations to get the scores in Table 19.
Table 36 shows the scores from the output of the VISSIM simulations and number of conflicts per type of conflict from the SSAM calculations.

Table 36 Simulation and calculation outputs per design solution for each criterion

	Design 1	Design 2	Design 3
Throughput	3222	2992	3155
TT NS vehicles	109.2	116.1	100.9
TT NS PT	194.8	95.8	95.0
TT SN vehicles	93.7	101.8	95.5
TT SN PT	149.0	98.0	97.8
TT EW vehicles	82.3	167.7	123.2
TT EW PT	102.2	176.7	131.5
TT EW active modes	17.7	17.2	16.5
TT WE vehicles	80.2	255.1	234.4
TT WE PT	97.0	346.5	244.2
TT WE active modes	194.0	15.8	16.0
SD NS vehicles	16.1	7.6	4.1
SD NS PT	16.9	1.4	1.2
SD SN vehicles	6.4	7.3	3.6
SD SN PT	7.3	1.5	1.4
SD EW vehicles	3.4	60.9	23.2
SD EW PT	4.3	48.5	31.0
SD EW active modes	5.1	1.9	1.5
SD WE vehicles	26.9	51.6	66.6
SD WE PT	3.3	47.6	74.8
SD WE active modes	6.8	2.5	2.4
crossing conflict	49	20	10
Lane change conflict	351	2338	1469
rear end conflict	120	242	246
active mode - vehicle conflict	27	12	12
costs	Low	high	Med/High

The values in Table 36 are normalized to a value between 0 and 1. Table 37 shows the normalized scores.

Table 37 Normalized scores

	Design 1	Design 2	Design 3
throughput	1.00	0.00	0.71
TT NS vehicles	0.46	0.00	1.00
TT NS PT	0.00	0.99	1.00
TT SN vehicles	1.00	0.00	0.78
TT SN PT	0.00	1.00	1.00
TT EW vehicles	1.00	0.00	0.52
TT EW PT	1.00	0.00	0.61
TT EW active modes	0.00	0.40	1.00
TT WE vehicles	1.00	0.00	0.12
TT WE PT	1.00	0.00	0.41
TT WE active modes	0.00	1.00	1.00
SD NS vehicles	0.00	0.71	1.00
SD NS PT	0.00	0.98	1.00
SD SN vehicles	0.24	0.00	1.00
SD SN PT	0.00	0.98	1.00
SD EW vehicles	1.00	0.00	0.66
SD EW PT	1.00	0.00	0.40
SD EW active modes	0.00	0.88	1.00
SD WE vehicles	1.00	0.38	0.00
SD WE PT	1.00	0.38	0.00
SD WE active modes	0.00	1.00	1.00
crossing conflict	0.00	0.74	1.00
Lane change conflict	1.00	0.00	0.44
rear end conflict	1.00	0.03	0.00
active mode - vehicle conflict	0.00	1.00	1.00
Costs	1	0	0.15

Using the normalized scores and the weights shown in Table 24 in Appendix A: Model input (MCA weights), the weighted score of each criterion is found as shown in chapter 6.4.2 in Table 19.

Appendix D: Sensitivity analysis

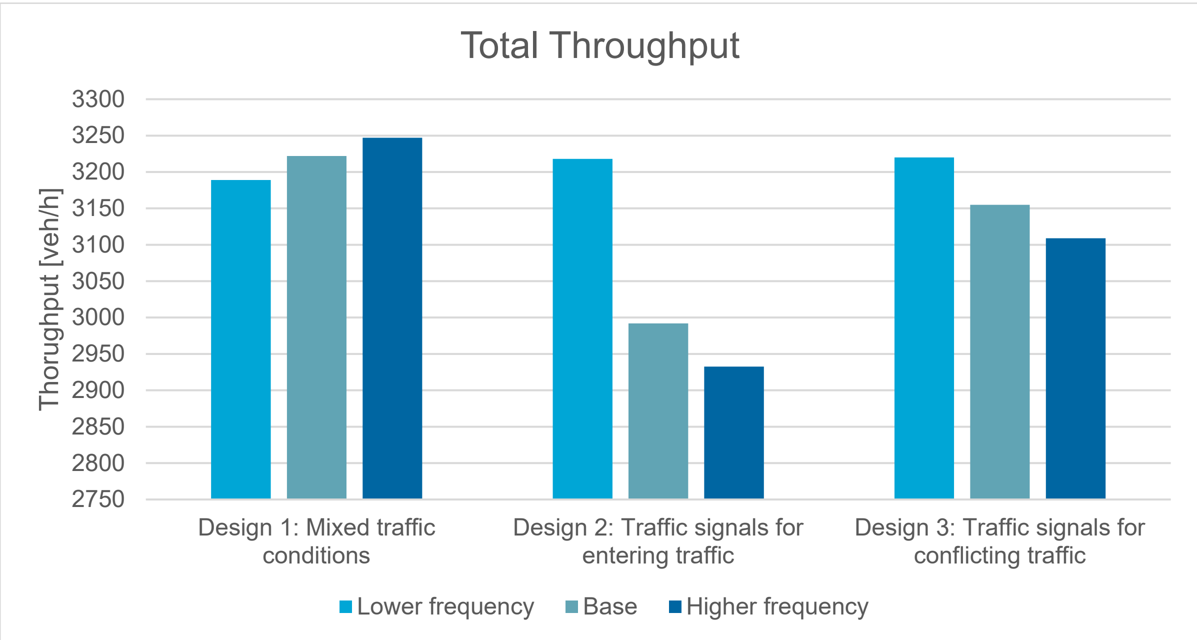
Chapter 6.3 discusses about the sensitivity analysis performed on the input parameters frequency and punctuality of buses, also on the safety calculation thresholds for TTC and PET, and the MCA weights. Chapter 6.3 discusses the main reasons for choosing these parameters to test, how they are varied for the analysis, and the main findings and results of the sensitivity analysis.

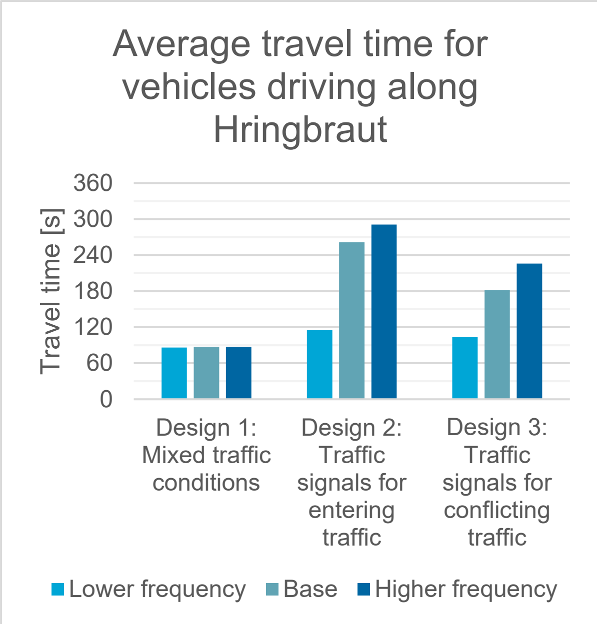
This appendix includes further information and figures of the results from this analysis. The figures mainly show how the different criteria is changed as the parameters are varied.

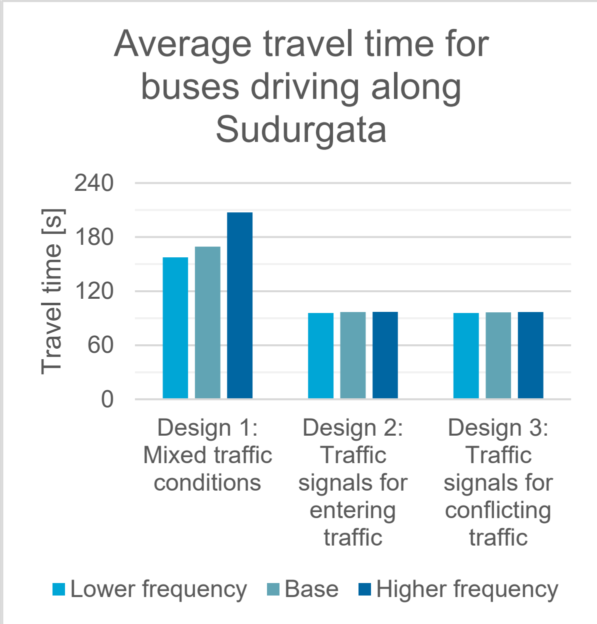
Frequency of buses

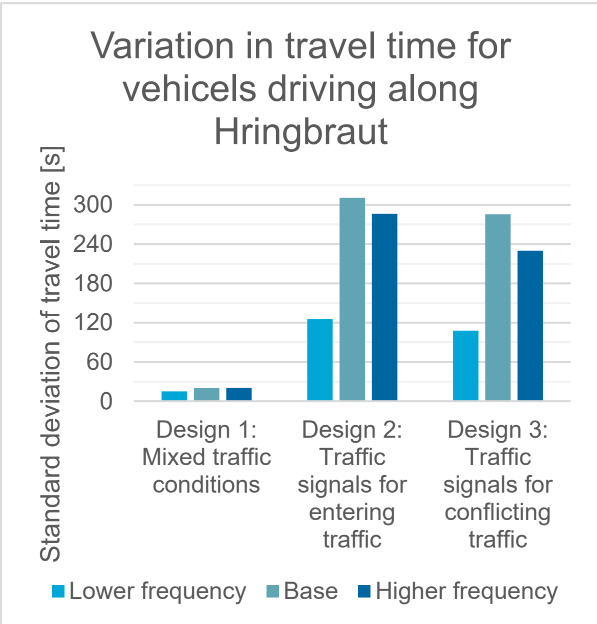
Chapter 6.3.1 shows how the frequency of buses affects the output of the VISSIM model as the frequency of buses is either increased or decreased based on the base case. The chapter discusses how the total throughput of the throughabout designs is decreased as the frequency of buses is increased, but the throughput is increased for the mixed traffic conditions case. The ranking order of the design solution alternatives is however the same for all frequencies. Similar patterns are seen with the travel times, variation in travel times, and number of conflicts for all types of conflicts, that the ranking order from best to worst alternative design is always the same, even though the exact number for the criteria is changed.

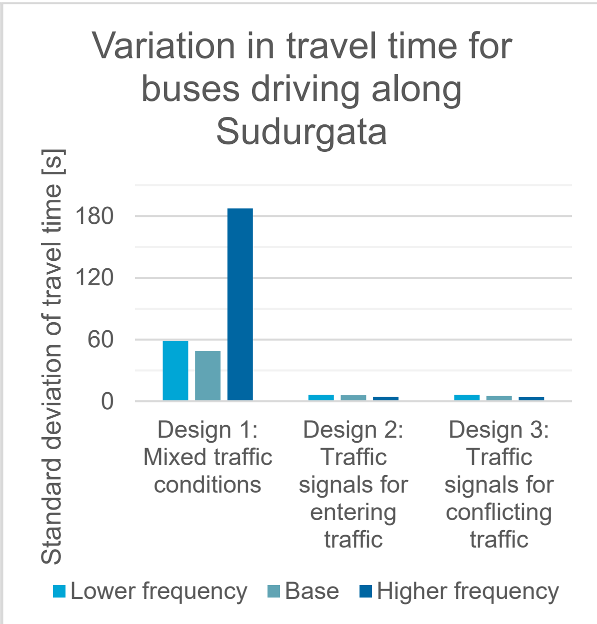
The following 9 figures show how these criteria change as the frequency of buses is increased and decreased compared to the base case.

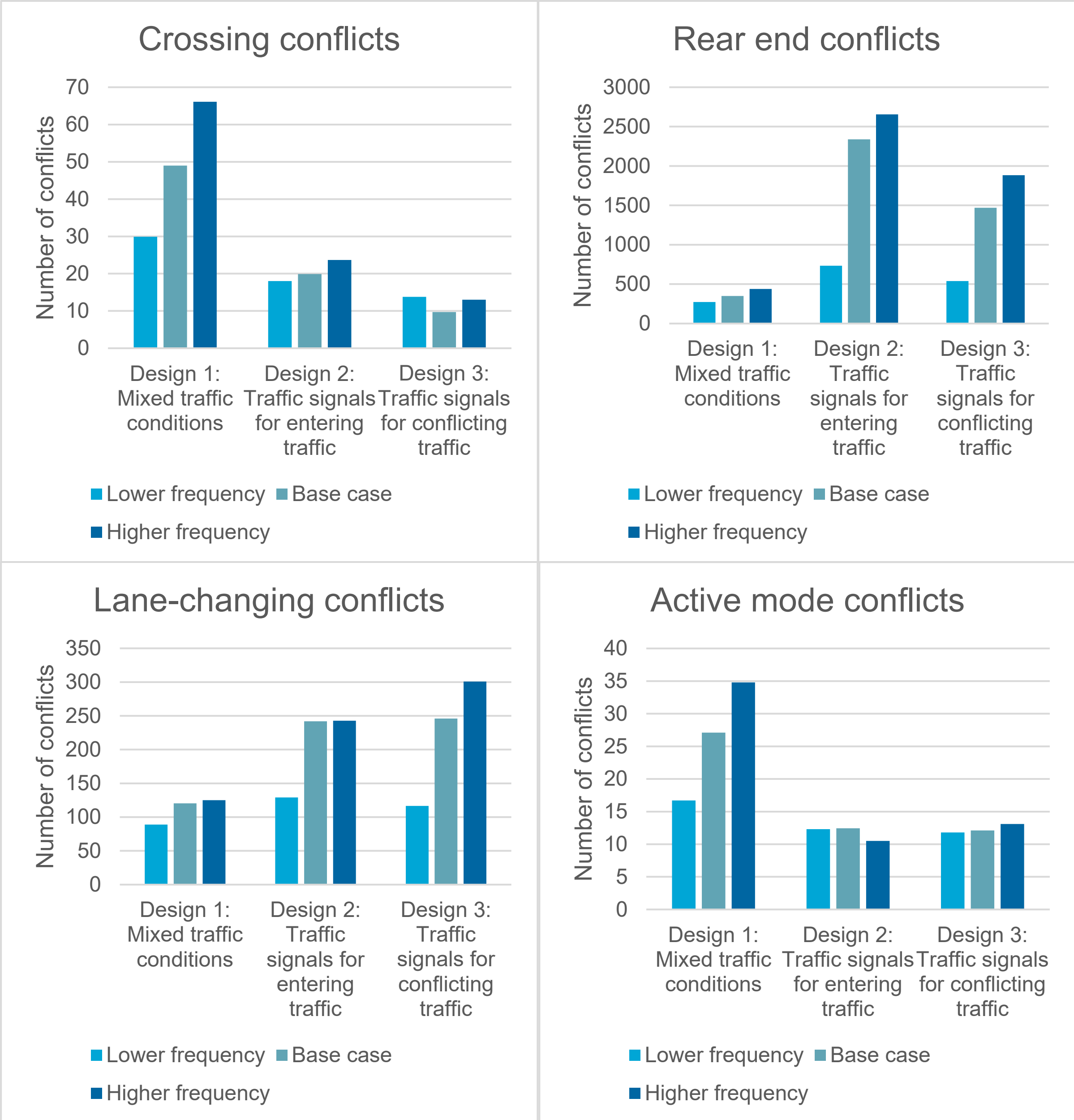



Average travel time for vehicles driving along Hringbraut
Travel time [s]
360
300
240
180
120
60
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Lower frequency
Base
Higher frequency


Average travel time for buses driving along Sudurgata
Travel time [s]
240
180
120
60
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Lower frequency
Base
Higher frequency


Variation in travel time for vehicels driving along Hringbraut
Standard deviation of travel time [s]
300
240
180
120
60
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Lower frequency
Base
Higher frequency


Variation in travel time for buses driving along Sudurgata
Standard deviation of travel time [s]
180
120
60
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Lower frequency
Base
Higher frequency

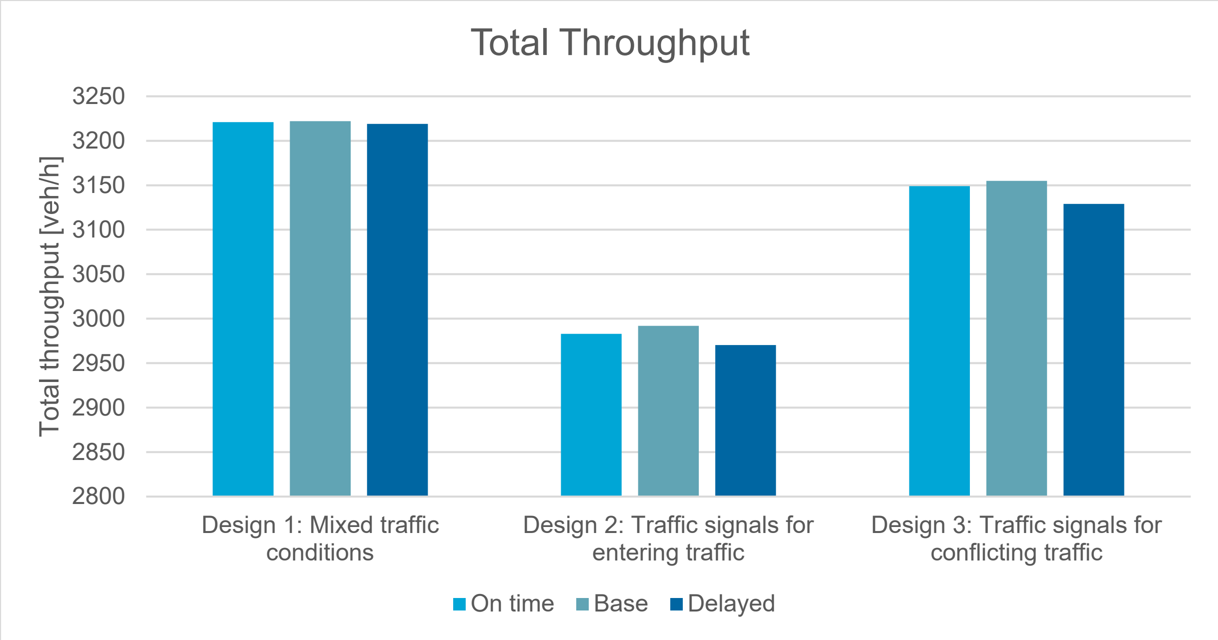


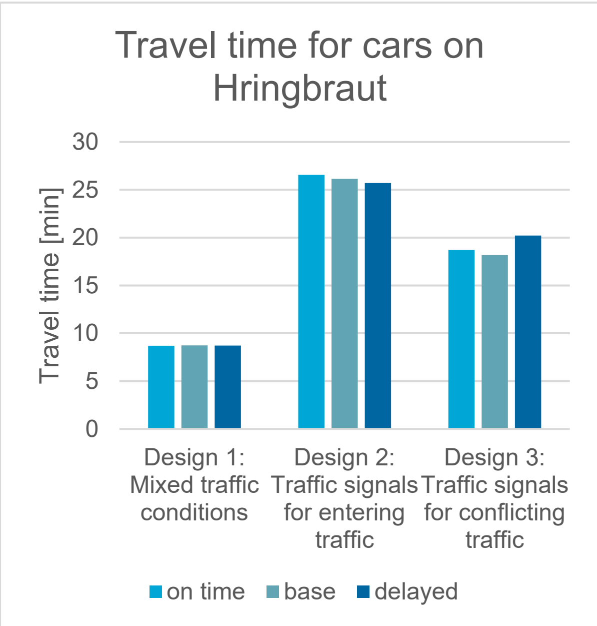
Punctuality of buses

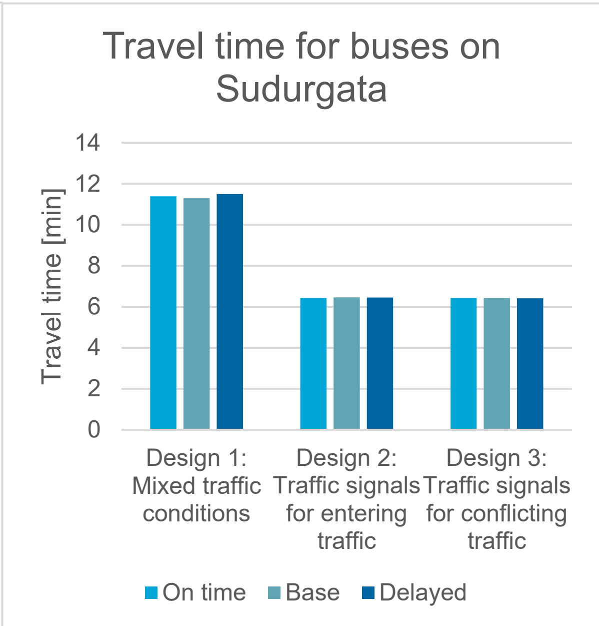
Chapter 6.3.2 shows how the output of the VISSIM model is affected by changing the punctuality of buses. The punctuality of buses is changed so that they are perfectly on time, and more delayed compared to the base case.

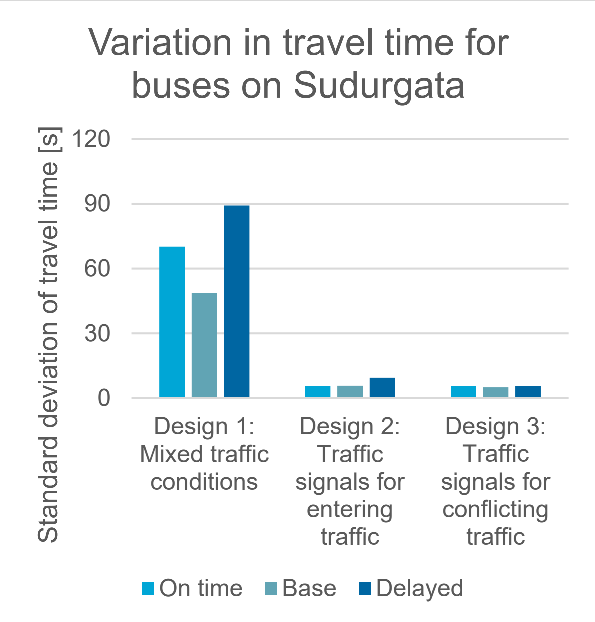
The sensitivity analysis resulted in that most criteria showed the same or very similar results to the base case, with no specific patters, i.e., the criteria considered is not affected greatly by the difference in punctuality of buses. This also leads to that the ranking order of the alternatives from best to worst is the same for all punctualities.

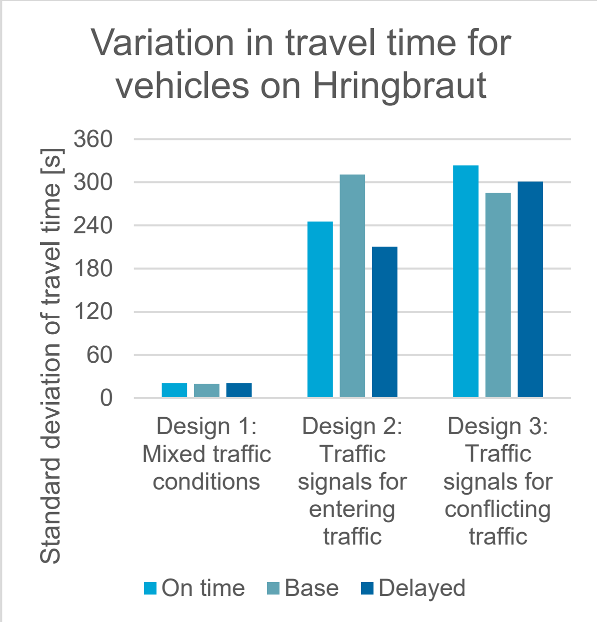
The following 6 figures show some of the criteria and how they are affected when the punctuality of buses is varied.

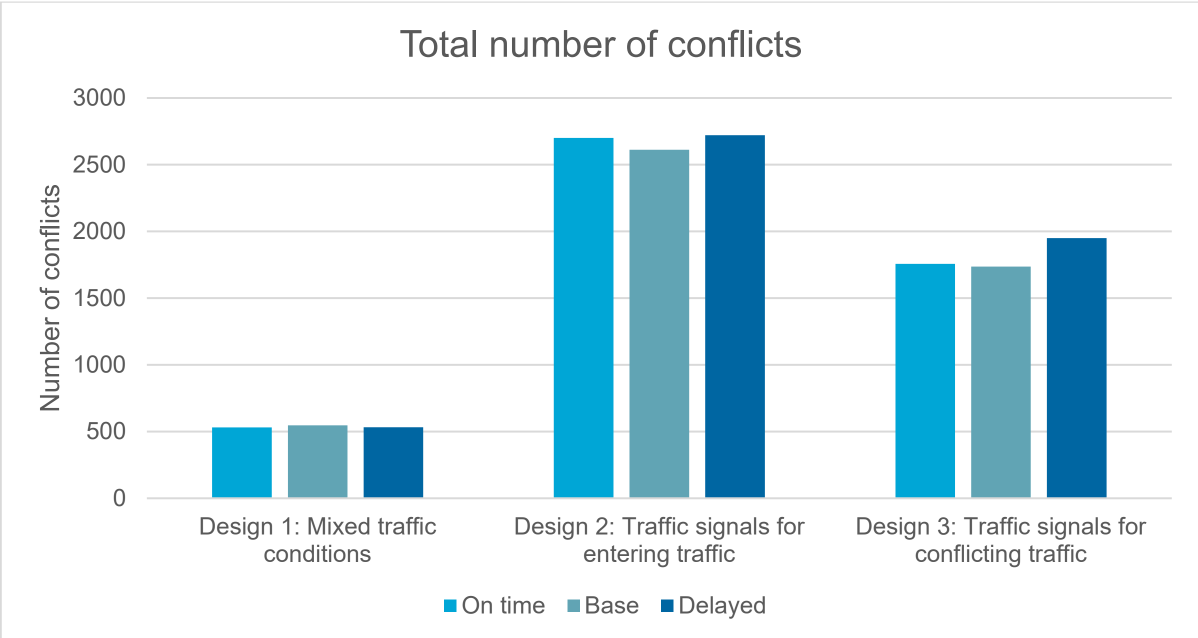

Total Throughput
Total throughput [veh/h]
3250
3200
3150
3100
3050
3000
2950
2900
2850
2800
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
On time
Base
Delayed


Travel time for cars on Hringbraut
Travel time [min]
30
25
20
15
10
5
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
on time
base
delayed


Travel time for buses on Sudurgata
Travel time [min]
14
12
10
8
6
4
2
0
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
On time
Base
Delayed





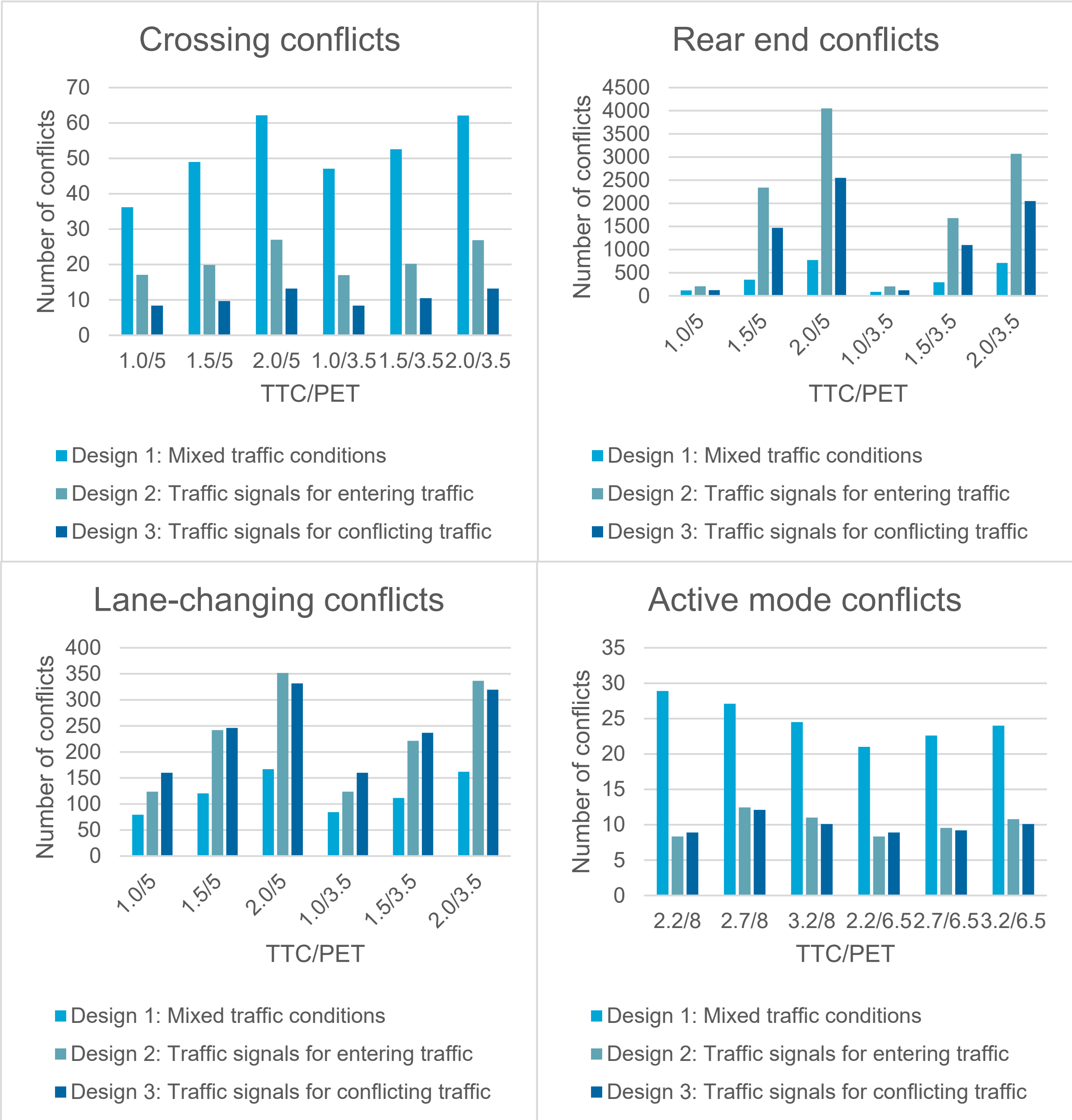


TTC and PET thresholds

Chapter 6.3.3 shows how varying the TTC and PET thresholds changes the number of conflicts calculated in SSAM. The TTC values, for vehicle – vehicle conflicts and active mode – vehicle conflicts, are both increased and decreased by 0.5s and then each TTC value is tested with the PET values for the base case and PET values that are 1.5s lower.

The sensitivity analysis results in that as the TTC in increased, the number on conflicts increase, and with lower PET value, the number of conflicts is also lower. This pattern is seen with all types of conflict. This also leads to that the ranking order of the alternatives is the same for all combinations of TTC and PET.

The following 4 figures show how the different TTC and PET values affected the number of conflicts.


Crossing conflicts
Number of conflicts
70
60
50
40
30
20
10
0
1.0/5
1.5/5
2.0/5
1.0/3.5
1.5/3.5
2.0/3.5
TTC/PET
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Rear end conflicts
Number of conflicts
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1.0/5
1.5/5
2.0/5
1.0/3.5
1.5/3.5
2.0/3.5
TTC/PET
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Lane-changing conflicts
Number of conflicts
400
350
300
250
200
150
100
50
0
1.0/5
1.5/5
2.0/5
1.0/3.5
1.5/3.5
2.0/3.5
TTC/PET
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic
Active mode conflicts
Number of conflicts
35
30
25
20
15
10
5
0
2.2/8
2.7/8
3.2/8
2.2/6.5
2.7/6.5
3.2/6.5
TTC/PET
Design 1: Mixed traffic conditions
Design 2: Traffic signals for entering traffic
Design 3: Traffic signals for conflicting traffic