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Prioritizing bicycles and public transport at intersections

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Abstract:

Traffic growth is an occurring challenge today due to exceeded road capacities and increased pollution; both locally and globally. Increasing attractiveness of public transport, biking, and walking is desired, as acknowledged environmentally friendly and passenger efficient transport modes.

Attractiveness is improved by increased efficiency through a new intersection design. The experimental design is presented and elaborated, serving absolute priority of public transport and high priority of cyclists and pedestrians. Major movements are not signal controlled to reduce delays for present traffic.

Assessment is based on models and analyses performed in traffic software; SIDRA INTERSECTION and AIMSUN. Public transport is guided through the intersection without necessary speed reduction due to traffic signals, geometric design, or other traffic. For tested scenarios of the full model in AIMSUN, results show that different volumes of buses with absolute priority is not significantly impacting other traffic at the experimental design. Cyclists and pedestrians are provided with high priority, and small delays. General purpose traffic sees most delay with the lowest priority in the network, though delays in most tested scenarios are not unreasonable severe.

Traffic safety is considered, intendedly preserved. This Master's thesis constitutes a basis for further investigation and development of the design.

Keywords:

1. Priority
2. Public transport
3. Bicycle
4. Intersection
5. Roundabout
6. Throughabout
7. Delay

Øyvind Høsser

PREFACE

This Master's thesis is written by Øyvind Høsser as a final delivery of the Master's degree programme for *Civil and Environmental Engineering* at the Norwegian University of Science and Technology (NTNU). The thesis constitutes 30 study points, performed over the spring semester of 2017; January-June.

The thesis is divided into a process report, and a scientific article. It comprehends the design process of a hybrid roundabout/intersection solution, referred to as a *throughabout*, and associated traffic analyses by two modelling programs; SIDRA INTERSECTION and AIMSUN. Right-hand driving rules are considered, making the described intersection design suitable for future implementation in Norway, EU, and US, among others.

I would like to thank my supervisor Arvid Aakre for excellent guidance, support, and professional input during the process. This have been very valuable for the final delivery.

Task description has been formed in cooperation with supervisor Arvid Aakre and the Norwegian Public Roads Administration (NPRA). NPRA has financially supported this thesis. I would like to thank my external contact Malin Bismo Lerudsmoen in NPRA for support and professional input early in the process. I would also like to thank Silje Hjelle Strand (NPRA), Helge Ytreland (NPRA), and Steinar Simonsen (NPRA), for meetings during different stages of the thesis. Discussions and professional input gained valuable knowledge, resulting in an enhanced thesis.

Trondheim, 11.06.2017

Øyvind Høsser

SUMMARY

Traffic growth leads to challenges regarding road capacities and pollution levels; locally and globally. Increasing attractiveness of public transport, biking, and walking is desired, as acknowledged environmentally friendly and passenger efficient transport modes. In urban areas in Norway, public transport and cyclists are often provided with dedicated lanes. At intersections, these dedicated lanes are traditionally terminated for allowing other movements of general purpose traffic. This reduces priority of public transport and bicycles, and associated attractiveness. Pedestrians are traditionally provided with high priority in the current road network. This is intendedly preserved. Objective of the thesis is investigating a way to improve priority of bicycles and public transport at intersections.

Buses are investigated as public transport mode as the most used public transport service in Norway. Other limitations to the thesis are at-graded junctions with buses entering and exiting along one axis due to one major and one minor road connecting; four-way intersection. Right-hand driving rules are considered.

Priority of bicycles and public transport is improved through a new intersection design. The experimental design is acknowledged as a "throughabout" as lanes penetrate the central island of a traditional roundabout. Buses are provided with absolute priority through the central island in segregated meridian bus lanes, resulting in no delay for buses. Cyclists are provided with a continuous, one-way regulated circulatory bike lane segregated from other motorised traffic. At conflict points, cyclists have higher priority, except for the busway where buses have absolute priority. Pedestrians are also obliged to give way for buses, but have highest priority at all other crossings.

The experimental design consists mostly of elements from other existing designs. Though elements are known separately, a similar throughabout with these elements combined are not found. Assessment and analyses are performed by modelling and simulations in traffic software: SIDRA INTERSECTION 7.0.5 and AIMSUN 8.2.0. SIDRA INTERSECTION is used for investigation of conflict points in the circulatory lane between buses and general purpose traffic. AIMSUN is used for investigation of the full design with all transport modes interacting. Traffic management and traffic safety are main focus for assessment of the design.

Based on tested scenarios with defined volumes and movements; cyclists and pedestrians are rarely affected by other transport modes, and buses not affected at all. General purpose traffic sees most delay in the network with lowest priority. By *back of queue* results at conflict points in the circulatory lane from SIDRA INTERSECTION, buses do not have a severe impact on general purpose traffic with volumes of 350 veh/h or lower. Larger flows result in problematic queues; blockage of other traffic. Results from AIMSUN show that different tested bus frequencies do not impact general purpose traffic, though lower frequencies are tested compared to SIDRA INTERSECTION. The biggest impact on delay for general purpose traffic is respective volume. Frequencies of cyclists and pedestrians also contribute. Cyclists and pedestrians are not notably impacted by general purpose traffic; mainly impacted by respective volumes. By tested flows in AIMSUN, different bus frequencies are not affecting other transport groups.

Crossings between general purpose traffic and buses are exposed conflict points. These movements are not frequent for general purpose traffic as most traffic is assumed to continue

the main road. In tested scenarios in AIMSUN, these movements are performed by 25 % of all general purpose traffic. Give way regulated crossings are not assumed to be a problem for these transport modes as similar solutions exist today with passing trams. General purpose drivers are considered by separating conflict points from each other, thus; focusing on one conflict point at a time. This preserves traffic safety for all transport modes at the throughabout. Unsignalised crossings over the busway for pedestrians and cyclists can lead to severe impacts with buses. Traffic safety is preserved by low bus speeds of 40 km/h, designated crossings with an additional signalised crossing, implemented waiting spaces, and universal design.

Assessment of the design is based on traffic software; a simplification of reality. Investigated scenarios in this Master's thesis give an indication of occurring queues and delays for selected traffic volumes and associated movements at presented design. More analyses should be performed by test of more scenarios with greater variations in volumes and movements, and larger scaled models with close monitoring. This thesis constitutes a basis for further investigation and development of the design.

SAMMENDRAG

Trafikkvekst fører til overfylte veger og økte utslipp lokalt og globalt. Det er ønskelig å øke attraktiviteten til kollektivtransport, syklende, og gående, som anerkjente mer miljøvennlige transportmidler og mer plasseffektive. I Norge eksisterer kollektivfelt og sykkelfelt i de fleste urbane områder. Disse dedikerte feltene avsluttes tradisjonelt før kryss for å tillate høyresving til øvrig trafikk. Dette reduserer prioriteten av kollektivtransporten og syklende, noe som også reduserer attraktiviteten. Fotgjengere er tradisjonelt høyt prioritert i dagens vegnett. Dette er ønskelig å bevare. Formålet med denne oppgaven er å foreslå og undersøke en måte for forbedret prioritet av syklende og kollektivtrafikk gjennom kryss.

Buss er fokus i oppgaven da dette er det mest brukte kollektivtransportmiddelet i Norge. Oppgaven er begrenset til kryssløsninger i ett plan, med én hovedveg som møter en mindre veg. Dette resulterer i et kryss med fire armer hvor busser kun går langs hovedvegen. Oppgaven tar for seg høyrekjøring; norske forhold.

En ny kryssløsning sørger for økt prioritet av syklende og busser. Dette designet er omtalt som en ”throughabout” i oppgaven da kjørebaner går gjennom sentraløya til en tradisjonell rundkjøring. Ordet *throughabout* er basert på det engelske ordet ”roundabout” som betyr rundkjøring. Busser har full prioritet gjennom kryssløsningen ved midtstilte kollektivfelt rett gjennom sentraløya. Dette resulterer i null forsinkelse for bussene. Syklister har et eget sykkelnett; en-veis regulert, sirkulerende sykkelfelt hovedsakelig separert fra motorisert trafikk. Ved konfliktpunkt må bilister vike for syklistene. Over de midtstilte kollektivfeltene må syklister vike for busser da bussene har høyeste prioritet gjennom kryssløsningen. Gående må også vike for bussene, men har ellers høyest prioritet i systemet.

Kryssløsningen presentert i denne oppgaven består hovedsakelig av kjente elementer fra andre kryssløsninger. Til tross for at disse elementene er kjente enkeltvis er ikke kombinasjonen funnet andre steder. Analyser og vurderinger av kryssløsningen er basert på to modelleringsprogrammer; SIDRA INTERSECTION 7.0.5 og AIMSUN 8.2.0. SIDRA INTERSECTION er benyttet for å undersøke konfliktpunkter mellom busser og annen motorisert trafikk i det sirkulerende feltet. I AIMSUN er kryssløsningen i sin helhet modellert med all tilstedeværende trafikk inkludert. Vurdering av designet er hovedsakelig basert på oppstående køer og forsinkelser ved forskjellige trafikkstrømmer. I tillegg er trafikksikkerhet vurdert.

Basert på testede scenarioer i dataprogrammene med gitte trafikkmengder og bevegelser er syklende og gående ubetydelig affisert av andre trafikkstrømmer. Busser er ikke affisert i det hele tatt med full prioritet. Øvrig trafikk er mest forsinket i systemet med lavest prioritet. *Back of queue*-resultater fra SIDRA INTERSECTION viser til liten betydning av bussmengder opptil biltrafikk på 350 kjøretøy per time. Større kjøretøymengder blir påvirket av busstrafikken, noe som resulterer i mer problematiske køer; blokkering av utganger fra det sirkulerende feltet. Testede trafikkmengder i AIMSUN og SIDRA INTERSECTION er forskjellige. Resultater fra AIMSUN viser at forskjellige testede bussmengder ikke påvirker øvrig motorisert trafikk. Største påvirkning for forsinkelse til personbiler er egne trafikkmengder. Andel syklende og gående har også en betydelig innvirkning på forsinkelser av persontrafikken. Store mengder av personbiler har ikke like stor effekt på syklister og gående. Forsinkelser for syklister og gående er mest avhengig av respektive mengder. Resultater fra AIMSUN viser at forskjellig bussfrekvenser ikke har betydelig påvirkning på øvrig trafikk for testede mengder.

Krysninger mellom busser og øvrig motorisert trafikk i det sirkulerende feltet er spesielt utsatte krysningspunkter. Disse krysningene er heller sjeldne bevegelser da mesteparten av trafikken er antatt å fortsette på hovedvegen. Ved modelleringer i AIMSUN er det benyttet en krysningsandel på 25 % av all motorisert persontrafikk. Vikepliktregulerte krysninger er ikke antatt å være et spesielt problem da lignende løsninger finnes for passerende trikker i dag. Persontrafikk er tatt i betraktning ved å separere konfliktpunktene. Dette gjør at kjørende ikke må fokusere på flere trafikanter samtidig, men ett og ett konfliktområde. Dette øker trafikksikkerhet for alle trafikanter ved krysset. Gående og syklende er i hovedsak ikke signalregulerte over kollektivfeltene. Konflikt mellom myke trafikanter og busser er uønsket da konsekvensene kan være fatale. Trafikksikkerhet er her bevart ved lav busshastighet; 40 km/t, godt merkede krysningspunkter, en ekstra signalregulert krysning spesielt tiltenkt for synshemmede, ventefelt for bilister før fotgjengerovergang, og universell utforming.

Vurdering av designet er basert på modeller i dataprogrammer. Dette fremstiller en forenklet versjon av virkeligheten ved teoretisk tilnærming med matematiske formler. Utførte modelleringer i denne oppgaven gir en indikasjon på oppstående køer og forsinkelser i kryssløsningen for testede trafikkmengder og bevegelser. Løsningen burde undersøkes videre med større variasjon i mengder og bevegelser, og en fysisk modell i større skala med tett oppfølging for observasjon av effekter. Denne masteroppgaven utgjør et grunnlag for videre undersøkelser og utvikling av presentert kryssløsning.

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DEFINITIONS AND ACRONYMS

Back of queue – *Back of queue* measures length from stop line to the last vehicle affected by the queue. Measured in metres or in number of potential queueing vehicles.

Bike lane – Dedicated area for cyclists inside the road kerbs, along other traffic lanes.

Bike path – Dedicated area for cyclists separated from other traffic. Though cyclists are separated from driving lanes in the circulating area, *circulatory bike lane* is used in this report.

BRT – *Bus Rapid Transit* describes the state of an urban mobility system. BRT relies on several factors; most reminiscent factors are efficiency for travellers, comfortability, and cost-effectiveness (Wright and Hook, 2007).

Control delay – Delay due to road regulations by traffic signs or traffic signal control.

Critical time gap – The smallest gap an "average driver" accept for entering or cross a conflict point where the driver does not have priority (Aakre et al., 2012, p. 42).

Follow-up time – Critical time gap for vehicles behind the first vehicle entering or crossing the conflict point. Measured from front to front on the vehicles. Typically, follow-up time is 60 % of critical time gap (Aakre, 2016c, p. 12).

Gap – Difference between two vehicles measured in time or distance; from back of the first car to the front of the second car.

Geometric delay – Delay caused by reduced speed of an uninterrupted vehicle due to narrowed road widths or turning movements.

Handbook – Public road manuals compiled and published by the *Norwegian Public Roads Administration* (NPRA). The handbooks provide obligations and guidelines on two levels; respectively by the N-series and V-series. Exemptions from the N-series must be processed.

Headway – Difference between two vehicles measured in time or distance; from front to front.

Intersection – At-graded junction. The connection of two or more roads in one level.

Kerb lane – The outer lane of the road; the lane closest to the kerbstone.

NPRA – *Norwegian Public Roads Administration* is the national road administration in Norway, consisting of five regional units and the Directorate of Public Roads.

NTP – *National Transport Plan* is a provident plan for transport in Norway, issued by the department of Transport and Communications every fourth year. Used edition in this report is 2014-2023.
Note: On April 5'th 2017, a new NTP was published; National Transport Plan 2018-2029. As it was published in the middle of the thesis, the newest NTP is not considered here.

Roundabout – A roundabout consist of a circulatory lane with three or more roads connecting; constituting associated intersections. Traditionally, the lane inside the roundabout circulates around a central island without other interruptions than connecting entries and exits.

Segregated meridian busway – Dedicated bus lanes in the middle of the road.

Superbuss – "Superbuss" is a planned BRT-system with implementation in 2019 in the city of Trondheim; Norway. As this thesis mainly focus on Norwegian conditions, the "Superbuss"-BRT-system is often used as basis for design values and comparisons.

Throughabout – Meridian opened roundabout with traffic lanes through the central island.

Traffic delay – Delay caused by other traffic.

Waiting space – Area for stopping and waiting without obstructing other traffic. Typically used at intersections and roundabouts. In Norway, waiting space for motorised vehicles is usually designed for one personal car to queue up; 5 metres (Statens vegvesen (N100), 2014a, p. 128), and 2 metres for cyclists and pedestrians (Statens vegvesen (V127), 2014f, p. 30).

LIST OF ATTACHMENTS

Enclosed attachments

Digital attachments

- ExperimentalDesign.pdf
- AIMSUN_OutputData.xlsx
- AIMSUN.ang
- SIDRAINTERSECTION_OutputData.xlsx
- SIDRAINTERSECTION.sip7

PART I – PROCESS REPORT

1. INTRODUCTION

Introduction considers background on the subject based on the National Transport Plan of Norway and an introduction to current priority of public transport and cyclists in Norway. Further, limitations to the thesis is described, followed by a task description and research questions. A subchapter explaining structure of the report is included as the thesis consist of two reports and three parts.

1.1 Background

The National Transport Plan (NTP) of Norway is a quadrennial plan stating future goals and guidelines in the national transport sector. During this Master's thesis, NTP between year 2014 and 2023 is used as it was current for the first part of the process. On April 5'th 2017, a new NTP was published; 2018-2029, not considered in the thesis.

The main objective in NTP 2014-2023 is providing an efficient, user-friendly, safe, and environmentally friendly transport system that meets today's societal needs and promotes regional development (Meld. St. 26 (2012-2013), p. 17). One contributing strategy is taking all future growth in personal transportation by public transport, biking, and going by foot. Achieving a zero-growth in use of personal cars requires a modal change in today's choice of transportation mode. Both current and upcoming users can contribute towards this objective. Increasing the attractiveness of public transport, going by bike and foot can be approached by several actions, and is an important measure for future users' choice of transportation. These transport modes have hence gained an increased attention in Norway in recent years.

In Norway, pedestrians are provided with the highest priority in the road network, together with trams, see *Attachment 2* for current tram rules. Other traffic must give way to pedestrians; buses and cyclists included. With today's high priority of pedestrians, buses and cyclists are hence of great importance for improvements. Reducing travel time for these transport modes is an important measure for increased attractiveness, and can be achieved by improving priority.

Dedicated bike lanes and public transport lanes are present at all larger Norwegian cities today, though to different extents. Separating these transport modes from other traffic provides rapid transportation, and reduces time lost to disturbance from alternating vehicles in and out of lanes. Eventually, the road network must necessarily facilitate different turning movements with entries and exits between different roads, resulting in junctions. Providing dedicated transport lanes along stretches without conflict points makes a difference for high traffic volumes, but is especially important at junctions where several transport modes meet.

Expediting different turning movements are solved in various ways. Where space is not an issue, grade-separated junctions can be constructed. By separating movements, several conflict points are eliminated and congestion related delays can be reduced. In area-restricted places; e.g. cities and urban areas, at-grade intersections might be the only possible solution. Depending on circumstances, different types of intersections can be implemented; e.g. T or Y junction, crossroad, or roundabout. Roundabouts can be discerned as several individual intersections at entry points to the circulatory lane.

At intersections in Norway, it is common practise to terminate the dedicated public transport lane about 100 metres in front of the intersection. This allows right-turns for all vehicles, but constitutes two major problems:

Firstly; allowing cars to queue up in the same lane as public vehicles leads to public transport waiting for the congested lane to dissolve before passing the intersection. This generates unnecessary delays for buses.

Secondly; not dedicating lanes for public transport results in buses waiting behind other vehicles using the same lane before entering the intersection. Priority of buses is hence more challenging as the bus is not first in line. Future solutions for priority have greater potential when buses are present all the way up in front of the intersection, making it easier for buses to directly enter the intersection.

For cyclists, dedicated lanes are usually terminated just before the intersection. In addition to abolished priority, cyclists must pass the intersection as any other motorised transport mode due to the absence of a dedicated lane. This is a concern regarding traffic safety, and efficiency of the cyclists. Both these two aspects are important for the attractiveness of the transport mode.

Described issues and delays have negative effects on public transport and bicycles as attractive transport modes. The main competitive transport mode is car driver; a generally attractive transport alternative due to travel time, comfort, privacy, flexibility, etc. A common rule for making public transport attractive compared to car is ensuring a door-to-door transportation time less than twice the time of a personal car (Strand et al., 2010, p. 4). Hence, improving efficiency is important. With knowledge of today's situation in Norway and road solutions around the world, improvements can be achieved.

1.2 Scope limitations

This report focus on at-grade junctions. By area use, it makes the design appropriate for implementation in urban areas. Hence, traffic volumes are not assumed to be of extreme values where level separated junctions are more suitable and effective. Though the design aims for minimised area use while fulfilling objective functions, costs and emissions are not in-depth considered in this report. Focus lies mainly on traffic management and assessment of traffic safety.

The intersection area is assumed to have one major road going through. Hence, buses enter and exit the intersection along one axis. Two other roads connect with the major road, resulting in a four-way intersection. These connecting roads are assumed to contain less traffic volumes, and not provide any bus service.

Right-hand driving rules are considered throughout the thesis, not left-handed traffic. Right-hand driving makes the design suited for Norwegian, EU, and US conditions, among others.

1.3 Task description

The objective of this report is to improve priority of buses and cyclists by constructing a new intersection design. Primarily, the design aims for future implementation in Norway. Constructing and analysing the design are based on four research questions:

1. Which design improvements at intersections facilitate increased priority of public transport and cyclists in Norway, preserving high priority of pedestrians?
2. Which traffic volumes constitute a tolerable delay with the new design?
3. How does the design affect different transport groups?
4. How is traffic safety preserved with this design?

1.4 Structure of the report

This Master's thesis considers firstly the construction of the design, then quantitative and visual analyses by modelling programs. The Master's thesis is divided into three main parts:

PART I: Process report
PART II: Scientific article
PART III: Attachments

The process report in *PART I* describes background and literature on priority and priority at intersections, about the experimental design, methods and approach, about simulation programs, and supplementing results, discussion, and conclusion to the scientific article. The construction and properties of the experimental design is thoroughly elaborated in *Chapter 3*. Several aspects related to the discussion part is considered in this chapter. *PART I* is written in accordance to the Department's guidelines for writing such a report (Institutt for bygg, anlegg og transport, 2013).

The scientific article in *PART II* compromises the essence of the Master's thesis to a minimum, written to meet standards of an internationally published scientific paper. Main elements in the article are introduction to the investigated topic, methodology, data, results, discussion, and conclusion. The construction of the experimental design is not included in *PART II*. Traffic management by occurring delays are investigated by defined volumes and movements. Additionally, traffic safety is discussed. Hence, only the three last research questions apply for the scientific article.

PART III are attachments. Additional to three enclosed attachments, five digital attachments are listed.

Combined, *PART I*, *II*, and *III* constitute a traditional Master's thesis.

2. STATE OF THE ART

State of the art discusses today's road network, efficiency of different transport modes, and supporting literature for creating a new design with increased priority of public transport and cyclists. Literature considers today's situation regarding priority of different transport modes in Norway, BRT-systems, and selected examples of interest.

Various vehicle types exist in today's road network, serving both person and freight transport. Globally and nationally, personal cars show significant appearance. In Norway, design values for occurring heavy vehicles vary between 5-15 % on different roads (Statens vegvesen (N200), 2014b, p. 209). Regarding person transport, capacity is limited in these personal vehicles compared to larger personal transport vehicles, and utility is rarely filled. (Transportøkonomisk institutt, 2015, p. 9) states an average number of 1,55 travellers per car per travel in 2014 for a research group of about 60 000 Norwegians. Additionally, the trend has been negative from the first registered data in 1995, with 1,66 travellers per car per travel. These values show the potential in a modal change to larger vehicles regarding area, congestion, and capacity issues.

(Frøyland et al., 2016, p. 10) have made a figure from results by the *Deutsche Gesellschaft für Internationale Zusammenarbeit* displaying the efficiency in personal transport by different transport modes. Though numbers in the figure are debatable, the figure gives an indication of potential for increased transport capacity compared to today's mixed traffic.

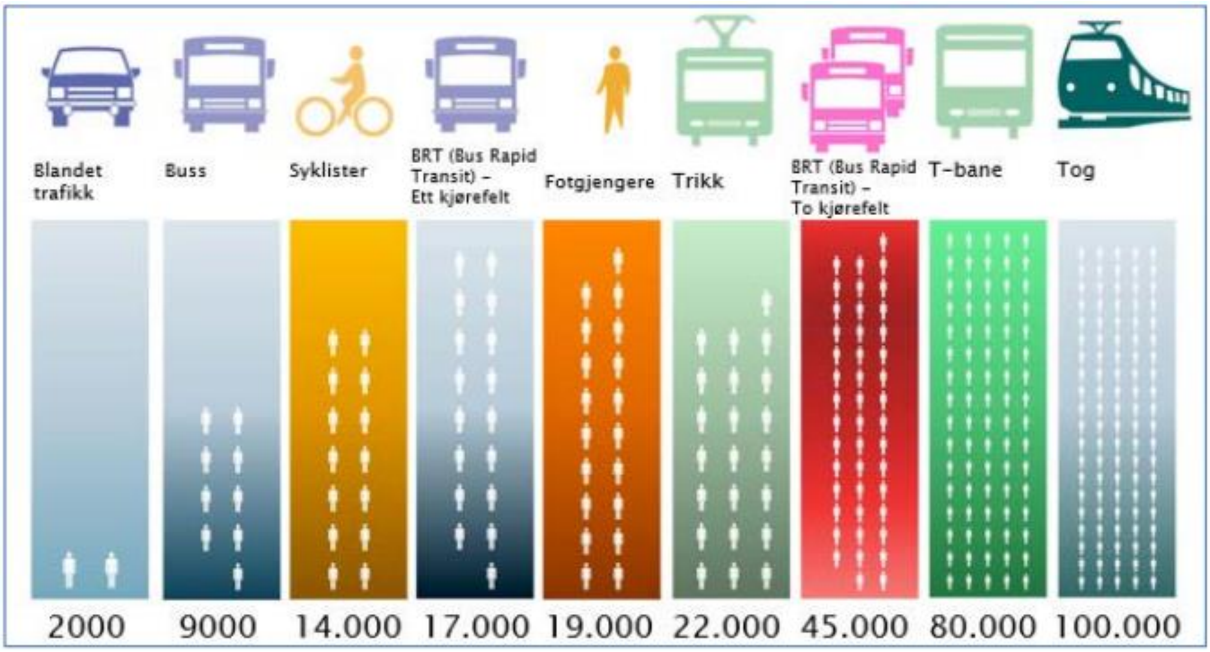

Figure 1: Hourly capacity of person transport by different transport modes.
[Source: (Frøyland et al., 2016, p. 10)]

Based on 3,5-metre-wide lanes, *Figure 1* shows the potential in prioritizing other transport modes than personal cars; constituting most of today's traditional mixed traffic. The size of cars and the limited number of persons it usually carries constitutes a small capacity in comparison to other transport modes. Utilizing less space or carrying more people per area will increase capacity with significant potential. Pedestrians require less space, and increases capacity with 9,5 times compared to regular mixed traffic according to the figure. Though capacity is notably higher, most trips are incomparable due to travel speeds and distances. A transport mode more competitive is bike. Cyclists increase capacity by 7 times compared to mixed traffic, and can cover longer distances than pedestrians with higher speeds. This transport mode is particularly interesting due to the recent increase in popularity of electrical bikes. Comparing mixed traffic with motorised traffic is relevant for comparative numbers with longer trips. For buses, capacity is increased by 4,5 times. For a dedicated bus lane in a BRT system, capacity is increased by a factor of 8,5. Hence, cars need much more space than buses to transport a certain number of people. Compared to bus systems, underground transportation has relatively expensive investment costs associated. Underground systems prove to serve even more people; hence suited for highly congested areas.

Figure 1 gives an indication of change in capacity for modal change to today's mixed traffic, but numbers are questionable. An hourly train capacity of 100 000 passengers is unlikely as it constitutes an average passage of 28 passengers per second. In Norway, typical capacity on single-track railway is five trains per hour, meaning each train serving 20 000 passengers. As the figure consider 3,5-metre-wide lanes, capacity is also questioned for other transport modes. A realistic bike speed in congested surroundings is 10 km/h, and maximum three cyclists can utilize the width of the lane simultaneously. Hence, each "row" of cyclists have two metres between each passage; resulting in 20 cm space between the rows in this organised pattern for the design bicycle (Statens vegvesen (N100), 2014a, p. 151). Also, capacity is not the best measure for comparison. Traditional personal vehicles have a capacity of five people, but each personal car trip transport 1,55 persons on average (Transportøkonomisk institutt, 2015, p. 9). Though public transport is not always fully utilized, capacity might be a misleading measure compared to a realistic situation.

Creating a new intersection design with universal functionality requires knowledge of users. In addition to public transport vehicles, cyclists, and pedestrians, other travellers utilize the road network as well. The design must be suitable and accessible for all relevant transport modes. Main transport groups found in today's road network are consecutively listed in *Table 1*:

Table 1: Transport groups at intersections

Transport groups
• Trucks
• Public transport (bus, tram, etc.)
• Commercial vehicles
• Personal cars
• Taxis
• Motorcyclist and moped riders
• Cyclists
• Pedestrians

Table 1 lists appearing transport groups in a ranked order by typical sizes. Associated sub-groups should be carefully considered as people have different abilities. This is particularly noticeable with pedestrians as this is the most accessible transport form. There are several

disabilities to be considered for making road designs universally functional; e.g. using a wheelchair, not seeing true colours, reduced vision, blind, partly or fully deaf, etc. Guide dogs are also present, assisting visually impaired persons.

Countries have different situations regarding traffic issues, climatic conditions, demography, and economic strength. Hence, priority of the different transport modes vary. In the following, the current traffic situation regarding public transport, cyclists, and pedestrians in Norway is discussed. Subsequent, selected examples are described for creating a design suited for implementation in Norway.

2.1 Priority of public transport

Public transport is relevant in larger cities where travel distances require motorised transport. Demand for a public transportation service increases with high numbers of vehicles in the road network. Though bus is the most used public transport form (Finn et al., 2011, p. 3), there are various other public transportat services as well; tram, metro, trolley bus, taxi, gondola, ferry, monorail, train, etc. In Norway, bus is also the most frequently used public transportation service (Statistisk sentralbyrå, 2016). Additional to the national bus networks, Bergen and Trondheim have a few tram lines, while the largest city; Oslo, has a larger tram network and a subway system. As bus is an extensively used transport service in Norway and globally, it is hence area of focus in this report.

Bus Rapid Transit (BRT) has become a widely-used conception on a global level where major traffic issues occur. BRT systems have different quality levels, but comprehends an efficient and attractive bus system; inducing a comfortable, fast, and cost-effective urban mobility. Important factors for fulfilling a BRT-status with high quality are consecutively listed in *Table 2* (Wright and Hook, 2007, p. 11).

Table 2: Factors in a BRT system

BRT system	
1. Physical infrastructure	Dedicated lanes
	A well-serving and extensive network of the public transportation service
	Comfortable, easy accessible, safe, and weather-protected stations
	Universal design
2. Operations	Rapid and frequent transportation between major destinations
	Fare system where tickets are prepaid before boarding, and can be used for further travel on different routes
	Voluminous capacity for passengers
3. Business and institutional structure	Contract processes should be kept transparent and competitively-bid
	Minimizing public-sector subsidies
	A fare system independently operated and managed
4. Technology	Technologies providing low emissions from the vehicles
	Technologies providing low noise-levels from the vehicles
	Fare system and verification that runs automatic
	ITS-solutions and signal priority can often improve priority
5. Marketing and customer service	Good and comfortable customer service
	Easy access between different transport modes; as walking to the tram, or taking both bus and bike to reach a destination
	User-friendly overview of the network and use of the service
	Clean and comfortable vehicles
	Real-time information
	Universal design to provide equal service to all users

Dedicated lanes for public transport is an important measure for high priority as other traffic is excluded. Additional to mentioned aspects of a BRT system, there are other measures to acknowledge regarding public transport efficiency. (Statens vegvesen (V123), 2014e, p. 41) lists important factors for efficiency of public transport; presented in *Table 3*.

Table 3: Factors for efficiency of public transport

Factors for efficiency of public transport
• Placement of lane
• Priority on stretches and at intersections
• Placement of public transport stop
• Stop design
• Entry and exit of stop
• Number of doors on public transport vehicles
• Ticketing system
• Lane design

Table 3 lists important factors to consider for prioritizing public transport. These factors are sequentially elaborated in the following.

Placement of lane regarding dedicated lanes for public transport is divided into level separated, kerbside, and segregated meridian lanes. Level separated public transport lanes are expensive to construct, but provides segregated lanes from other traffic. It can be placed under and over ordinary traffic, and is popularly used for metro systems and railways. As this report focuses on at-graded junctions, kerbside and centred public transport lanes are more thoroughly elaborated.

(Gran, 2013, p. 23) states both negative and positive aspects of kerbside and centred public transport lanes. For centred lanes, on- and off boarding stations must be placed in between the different lanes. Passengers must cross the road accessing the stations, constituting a conflict point between these pedestrians and driving vehicles. This is avoided with kerbside lanes and stops.

Kerbside lanes conflict with on- and off-ramps in the road network. This is avoided with centred public transport lanes, resulting in increased efficiency due to less disturbance.

At intersections, straight-forward and right-turn movements for general purpose traffic result in conflict points with kerbside public transport lanes. To avoid this, public transport lanes must necessarily be terminated in front of the intersection. These conflicts do not exist for centred public transport lanes. With centred public transport lanes, left-turn movements result in conflict points at the intersection for general purpose traffic. Crossing of dedicated public transport lanes is executed when absence of public transport vehicles or by signal control.

Priority on stretches and at intersections is achieved in various ways. On stretches, priority is usually provided by segregating lanes for public transport. In Norway among other countries, trams are given close to full priority by traffic laws, see *Attachment 2* for current tram rules in Norway. As for now, buses do not have the same regulated priority as trams. This is an interesting subject as a modern way of thinking public transport planning in Norway today is: *plan tram - use bus* (Frøyland et al., 2014, p. 7).

On stretches, dedicated lanes contribute to improved headway for public transport when traffic volumes are high. When traffic flows in the speed of the speed limit, public transport will neither be delayed or go faster than general purpose traffic. Thus, dedicated lanes might be excessive. If only peak periods result in reduced speed, there might still be a need of segregated lanes for public transport.

At intersections, delays occur as public transport blend with other traffic. Traditionally, public transport vehicles have often been prioritized with signal control systems. Searching the web for “bus priority” gives the impression of it being completely reminiscent with signal control. Priority can also be done by unsignalised solutions, and through geometric design.

Signalised and unsignalised regulation mean respectively traffic lights and give-way signs. (Aakre, 2016a) lists advantages and disadvantages with traffic signals, here presented in *Table 4*.

Table 4: Advantages and disadvantages with traffic signals

Traffic signals	
Advantages	**Disadvantages**
• Reduces accidents between crossing movements • Might increase safety for pedestrians and cyclists • Controls priority (e.g. increasing priority to the main road) • Allocates priority to different transport groups (e.g. buses) • Limits traffic volume entering a road section or area for avoiding downstream congestion or other problems (traffic metering) • Constitutes efficient traffic flow at high volumes	• Increases number of rear-end collisions • Probability of more severe accidents for vehicles not obeying red signal • Difficulties with controlling signals to adapt traffic flow • Relatively high maintenance costs • Unnecessary delays at low traffic flows

Table 4 shows advantages and disadvantages with traffic signals. These factors will vary with traffic signal systems as signals are operated differently. Signal systems are divided into two main systems: active and passive signal priority (Statens vegvesen (V123), 2014e, p. 47). Active signal priority is dynamic signal control by detecting certain traffic groups. For a bus approaching an intersection, detection can provide green signal to the bus throughout the intersection. *PTPS*, *UTOPIA/SPOT*, *SCOOT*, *SCATS*, *MOTION*, and *ImFlow* are examples of such adaptive signal systems (Wahlstedt, 2013, p. 1543).

Passive signal priority is static signal control, prioritizing certain traffic groups through pre-set cycle times. Periodic presence of many prioritized or non-prioritized traffic groups do not change the signals as active signal systems can do. (Statens vegvesen (V123), 2014e, p. 47) lists examples of applicable functions with active and passive signal priority of buses, here presented in *Table 5*.

Table 5: Functions of active and passive signal priority

Signal priority	
Active systems	**Passive systems**
• Extend green time for buses approaching the intersection • Reduce others signal phases serving green signal to buses • Change phase orders to increase the portion of green phases to public transport • Dedicated signal phase for buses • Different priority of public transport vehicles (e.g. by number of passengers or delays)	• Increase green time for public transport • Reduced cycle time for reducing waiting time for buses • Green wave; green time for public transport at several intersections in a row • Lead buses past other traffic in the same direction

Priority can also be provided without signalised solutions. Regulating traffic by give way signs is an unsignalised solution, requiring drivers to act in accordance to each other. At intersections and roundabouts, give way rules are often present. This constitutes a more dynamic traffic flow where drivers must interact and adapt to the traffic situation. For low volume roads with signal systems, vehicles might end up waiting for red signal but not any vehicles. This constitutes an unnecessary delay for waiting vehicles. With give way rules, this is never an issue. (Bernetti et al., 2003, p. 16) presents study results from selected signalised vs. unsignalised roundabouts in Italy. The article states that queueing delays at low traffic volumes are essentially negligible for unsignalised roundabouts, resulting in better performance than a signalised roundabout. At high traffic volumes, vehicle delays from all approaching legs are more balanced and limited with a signalised solution. This could improve the overall capacity.

Geometric design can also provide priority in the road network. Separating lanes is an efficient measure for giving high priority, both on stretches and at intersections. At intersections or roundabouts, a separate lane can be created outside the conflict area; serving uninterrupted right turn movements for an at-graded solution. This is an efficient solution, additionally resulting in less vehicles through the conflict area. Hence, other traffic also benefit from this separated lane. Another geometric design for prioritizing public transport is opening roundabouts in the centre. This is used for trams in Norway and other countries; reducing travel distance and avoiding turning movements due to independence from the circulatory lane. Additionally, delay from other traffic in the circulatory lane is avoided. This solution is widespread for trams, but rare for buses.

Placement of public transport stop impacts efficiency by number of bus stops, intermediary distances, and bus stop pattern. Short distances between bus stops serve many position needs for the travellers, but affect travel time and efficiency in a negative way. Deceleration and acceleration to and from full stop result in increased travel time with low average speed. Additionally, deceleration and acceleration is slow for heavy vehicles as buses. Hence, many bus stops are negatively affecting efficiency as well. Long distances between bus stops increase average speed on routes and increases efficiency. Too long distances may seem excluding for disabled travellers, and affects the attractiveness of the public transport service. (Statens vegvesen (V123), 2014e, p. 11) recommends a spacing of 500-800 metres between bus stops in urban areas. In less populated areas, intermediate distances can advantageously be longer.

The placement of bus stops along routes also impacts efficiency. Straight lining bus routes result in optimised travel patterns avoiding delayed detours. Combining a straight bus route with long distances between bus stops result in an efficient public transport service, on the behalf of users' access to the bus stop.

Stop design is here divided into bus stops along kerbside lanes and centred public transport lanes. For kerbside lanes, the bus stop can either be separated from other traffic or placed in the driving lane. Separating the bus stop from traffic requires more road area, but serves passengers without interrupting other traffic. This applies for buses both in dedicated public transport lanes and ordinary general purpose lanes. With such separated bus stop, buses are delayed due to the detour; negative impact on efficiency. Additionally, buses must merge in and out from the bus stop to the driving lane.

Kerbside bus stop in the driving lane avoid delays caused by detours. For dedicated public transport lanes, bus frequency is often small, resulting in stops not interrupting other buses. For bus stops in general purpose lanes, traffic volumes are usually higher, resulting in full stop and delays for other traffic. High bus volumes in dedicated bus lanes will result equally, though this rarely is the situation. This translates specially to bus stops on centred public transport lanes where area is not commonly designated for separated bus stops.

Entry and exit of stop affect efficiency by delays from detours and merging between lanes. Bus stops along the kerbstone or next to the driving lane result in less delays than entering a bus station with larger detours. Larger bus stops with long distances from the main road affect efficiency measured in time negatively. Larger bus stops; bus stations, might lead to more people in one stop, making the passenger transportation more effective. One larger stop could therefore make up for two or more complying bus stops. This balance impacts time efficiency as well.

Number of doors on public transport vehicles impact the on- and off boarding of passengers. This affect the efficiency at bus stops where more people can enter the public vehicle in less time with more and bigger doors.

Ticketing system also affect efficiency at bus stops. Purchasing tickets on the bus result in delays due to longer time at the stop. Systems where tickets are purchased and validated before entering the bus eliminate this delay with no on-board operations.

Lane design impacts traffic flow and capacity by type of road segments in the network. Highest bus capacity is retrieved by straight lining dedicated public transport lanes due to no interruptions. (Gran, 2013, p. 28) has analysed capacity at different road segments for buses in exclusively dedicated bus lanes. Results from the handbook are shown in *Table 6*.

Table 6: Hourly bus capacity at different road segments

	Bus capacity in exclusive bus lanes *[bus/h]*
Straight line (no interruption)	450-500
Right turn (no interruption)	250-330
Roundabout/give way intersection	130-250
Signalised intersection	40-320

Table 6 displays hourly bus capacity for exclusively dedicated bus lanes at different road segments. Capacity is reduced at conflict points, and straight lines increases capacity compared to right-turn movements. Investigating capacity at signalised to non-signalised intersections, signalising provides potentially both lower and higher capacity; varying between 40 and 320 buses per hour according to the figure. Different green- and red time portions in the system explains the span as longer red time portion results in reduced capacity for the affected traffic stream.

Values in *Table 6* are debatable. Especially at unsignalised intersections, capacity will vary largely by present situation and surrounding traffic. Bus stops are included in the results of the table, constituting greater capacity span than mentioned at undisturbed public transport lanes. Still, the table gives an indication of bus capacity at different road sections.

As number of conflict points affect headway and traffic safety, it is of interest to investigate occurring conflict points at crossroads. (Ruud and Siedler, 2012, p. 35) have made a figure displaying conflict points for vehicles and vehicles/pedestrians at different types of crossroads, shown in *Figure 2*.

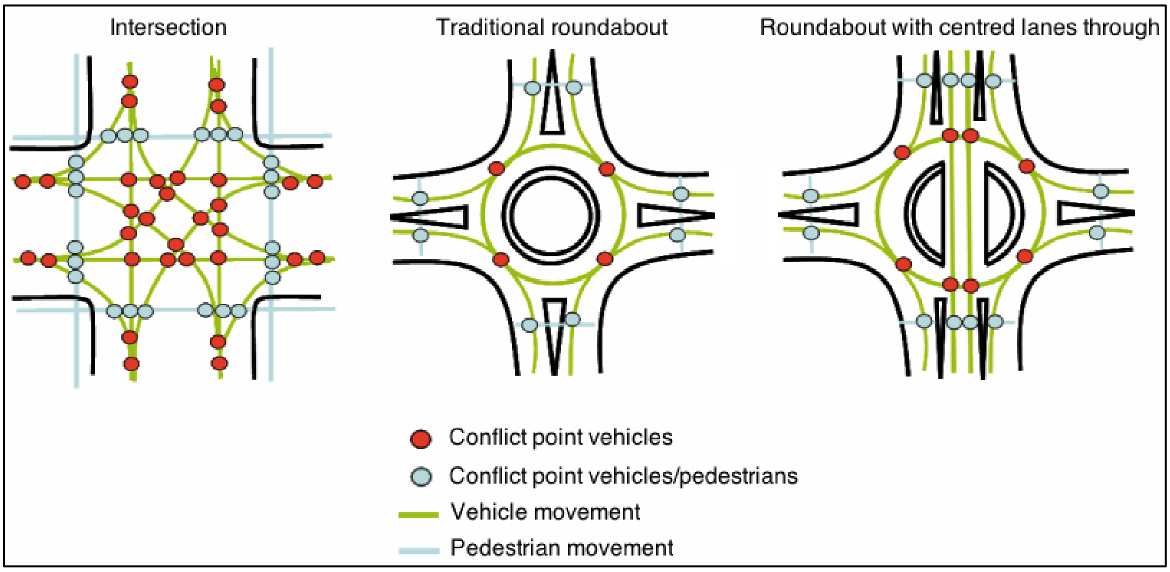

Figure 2: Conflict points at different intersection designs.
[Source: (Ruud and Siedler, 2012, p. 35)]

The intersection and traditional roundabout in *Figure 2* have four entries and four exits. The figure shows that number of conflict points are higher for intersections than for roundabouts. With the meridian opened roundabout, eight additional conflict points to the traditional roundabout appear; four conflict points between buses and general purpose vehicles, and four between vehicles and pedestrians. The difference is caused by two extra lanes along north-south bound roads inserted for the meridian opened roundabout. Thus, capacity is increased by the additional conflict points.

2.1.1 Current situation in Norway

In Norway, priority of public transport has gained focus the last decades due to traffic issues in larger cities, and by objectives in National Transport Plans. Buses are often provided with dedicated bus lanes for uninterrupted driving to improve efficiency. The most common bus lane design is use of the outer right lane, with only a few exceptions of segregated meridian bus lanes. These centred busways are mainly established as test stretches in Norway; one along *Hillevågsveien* in *Stavanger*, and one along *Drammensveien* close to *Skøyen* in *Oslo*. Dedication of traditional kerbside public transport lanes are usually terminated when approaching intersections.

Figure 3: Termination of dedicated public transport lane at intersections in Norway. [Source: Google Maps – street view]

Figure 3 shows an example of traditional termination of dedicated public transport lanes at intersections in Norway. The termination allows right turning movements for other traffic, on the behalf of the efficiency of public transport. When congested, buses are inconveniently delayed, making this transport mode less attractive.

In Norway, kerbside public transport lanes are not exclusive for public buses. These lanes also serve taxis, electrical and hydrogen vehicles, private buses, motorbikes, mopeds, and bikes. Selected public transport lanes also permit carpooling with personal cars, meaning that vehicles with a certain number of passengers can use the same lane; *high-occupancy vehicle lanes* (HOV-lanes). This is not generally granted; thus, such lanes must be marked with road signs. At busy periods, traditional dedicated public transport lanes are hence exposed to congestions due to the many users. Especially when approaching intersections.

2.1.2 Selected examples

Prioritizing public transport is of importance on a global level where traffic volumes are high. Health and efficiency issues related to high traffic volumes have been considered variously; hence, several solutions for priority exist today. Acknowledging existing solutions constitutes an important basis for constructing new designs and further improvements.

Figure 4: Segregated meridian busway in Curitiba, Brazil.
[Source: Google Maps – street view]

Figure 4 shows an example of the current public transport system in Curitiba, Brazil, with segregated meridian bus lanes. Curitiba was one of the earlier places to introduce centred public transport lanes, a road system still existing today. Originally planned in 1965, it was delayed and physically implemented first in 1974 (Goodman et al., 2006). Curitiba have successfully managed to establish a well-working, heavily used bus transport system at low costs for operation and the passengers. About 70 percent of the city's commuters utilize this bus system for travelling to work. A travel survey conducted in 1991 gave the results of a 28 percent modal change from car driver to this public transport system (Curitiba, Brazil, BRT Case Study, 1999). Such results have large impacts on the inhabitants and society, especially in larger cities like Curitiba with its almost 2 million inhabitants. Impacts include local and global pollution level affecting health, reduced traffic time, and reduced area use due to an otherwise increased demand in traffic capacity. Results from Curitiba show no negative change in traffic safety. It is more likely that traffic accidents are reduced due to the increased number of inhabitants using transportation operated by experienced drivers. The success story of Curitiba shows the potential and importance of smart city- and road planning.

Investigating existing solutions of segregated meridian busways raises an alternative to the traditional kerbside dedication in Norway. Dedicating public transport lanes in the middle of the road have been practised since the 1950s, with a notably strong trend in Latin American countries (Frøyland et al., 2014, p. 5). In recent years, this solution has gained popularity in Europe as well; especially in France and Sweden. It has also been tested in Norway in the public road network. In 2011, a test stretch of approximately 2 km was implemented in Stavanger.

Figure 5: Dedicated, centred bus lanes through a roundabout in Hillevågsveien, Stavanger. [Source: Google Maps – street view]

Figure 5 shows a test stretch with segregated meridian busways implemented at Hillevågsveien in Stavanger. The busway goes along the major road, with two minor roads connecting with the circulatory lane. The centred lanes serve public buses exclusively; not taxis, electrical vehicles, bikes, etc. They are constructed to be convertible into tram lines in the future, which reflects the modern way of thinking public transport priority in Norway: *plan tram - use bus* (Frøyland et al., 2014, p. 7). Further information is mainly based on a meeting with Helge Ytreland (NPRA), see *Attachment 3*. He works as an engineer at the Norwegian Public Roads Administration, and have been largely involved in the construction and development of this design in Stavanger, Norway.

Buses are given absolute priority throughout all conflict points due to red signals at all other entries when a bus is near. Hence, no other vehicles are present in the circulatory lane, making speed reduction excessive for the buses. As current laws for buses and trams in the national road network are different to some extent today, give way markings have been implemented in the central island. Buses do not have to relate to these markings whenever signals operate correctly.

Though delay for buses are reduced, other drivers are inconveniently affected as the signalised design constitutes longer waiting times (Bråtveit, 2016, p. 75). Additionally, red traffic signal is given to all vehicles at entries, resulting in vehicles not in conflict with buses to also wait. This affects vehicles performing right- and straight movements from the major road, and right turns from minor roads. Helge Ytreland states that this problem is caused by existing property boundaries; hence, shortage of area. As available space restricts entries and exits to single lanes, all vehicles must stop for red signal when a bus is approaching.

In countries where segregated meridian busways are implemented, associated intersections seem to frequently be regulated by signals, with exception of trams. Priority of buses and trams have to some extent been practised differently, possibly due to different traffic rules. In Norway, trams are statutory given more priority than buses, an advantage for trams in transport planning.

Figure 6: Dedicated, centred tram lanes through a roundabout in Nantes, France. [Source: Google Maps – street view]

Figure 6 shows an intersection in the circulatory lane in Nantes, France, where trams are passing with absolute priority. By presence of trams, vehicles with intention of crossing the tram lines must wait in front of a give way line until the crossing is free. Not signalising road entries facilitates other movements not in conflict with the tram constantly, depending on the circulating flow. Queueing in front of the tram line can cause obstruction of exits. This solution result in less delay for general purpose vehicles while preserving absolute priority of trams.

2.2 Priority of cyclists

Cyclists have gained an increased attention in recent years due to high global CO_2-contents and other emissions from motorised vehicles. This transport mode got even more attention when the local issues of NO_x-emissions from diesel engines became present. Combining less motor related emissions and the users' health benefits of biking, cyclists have positive impacts on the local and global environment, also individual benefits for the users. Additional to health benefits of the associated exercise, biking is also a cheap alternative to usage of motorised vehicles, and space for parking is rarely an issue.

2.2.1 Current situation in Norway

As with public transport, cyclists have gained increased attention the last decade due to previous National Transport Plans. Associated health benefits for cyclists and others in the same environment are regarded as beneficial socioeconomically. Number of motorised vehicles is reduced, resulting in less congestion and reduction in emissions. This saves time for other travellers in the road network, and health benefits from the exercise of biking reduce absence from work (Helsedirektoratet, 2017). Therefore, cyclists are often provided with dedicated bike lanes and paths in urban areas in Norway.

Figure 7: Termination of bike lane at a roundabout in Trondheim, Norway. [Source: Google Maps – street view]

Figure 7 shows a design commonly practised in Norway where dedicated kerbside bike lanes are terminated in front of the intersection. This solution is primarily used at roundabouts, as road geometry is here already changing for entries and exits. Dedicated bike lanes provide designated and undisturbed space for cyclists towards the roundabout, but no further. When these bike lanes are terminated, cyclists are on their own. They must pass the intersection as any other motorised vehicle, or stepping off the bike and use pedestrian crossings. Cyclists are obviously not prioritized with this solution, and safety issues are also raised.

Figure 8: Termination of bike lane before an intersection in Trondheim, Norway. [Source: Google Maps – street view]

Figure 8 shows another design for cyclists at intersections. This solution has been more present over the last years in Norway, and can be observed in several cities. The dedicated bike lane is extended with a designated waiting area in front of all other vehicles; *bike box*. This accommodates high priority of cyclists on the behalf of the motorised vehicles. Cyclists can legally “sneak up” in front of queueing vehicles, making cyclists the firsts to leave the road arm on green signal. Safety issues have been addressed between cyclists and heavy vehicles for trucks being the first queueing vehicle. Cyclists sneak up on the side and stop in front of the truck, out of sight for the truck driver. This could lead to fatal consequences for cyclists accelerating slower than the truck on green signal. The design reduces queue time for cyclists, but they are still to wait for the red signal to turn green. Additionally, the design does not provide continuous biking throughout the intersection, resulting in mixed traffic.

2.2.2 Selected examples

Priority of cyclists exists in various forms. As with priority of public transport, traffic issues, climatic conditions, demography, and economic strength differs with countries. A universal similarity is that traffic safety is a more significant issue with cyclists due to their exposure to severe impacts. Safety equipment is rarely compulsory; usually limited to a bike helmet if any requirements. Additionally, bike helmets scantly reduce damage for impacts with heavier vehicles.

Despite unstable weather, many countries in the northern part of Europe have emphasized biking. Especially Denmark and Netherlands are acknowledged as pioneers for bike priority. A distinct advantage for both countries are the geographical conditions of being generally flat with few hills. This makes biking more attractive as users are not to struggle with exhausting climbs. Additionally, traffic safety is an important measure for attractiveness. In Copenhagen, Denmark, the risk of being involved in a severe accident have been reduced by 72 % compared to 1996 (Københavns Kommune, 2011, p. 26). These countries have succeeded in making biking even more attractive due to smart designs and high priority.

Figure 9: Priority of cyclists through an intersection in Fredrikshavn, Denmark. [Source: Google Maps – street view]

The design in *Figure 9* shows a signalised intersection in Fredrikshavn, Denmark with throughout dedicated bike lanes. Bike lanes are clearly marked with colour and road symbols of bikes. This visualises cyclists for all traffic at the intersection. In Denmark, the clearly marked bike lanes are common practise due to the national policy of easily visible, blue-coloured dedicated bike lanes (Andersen et al., 2012, p. 67). Going by bike through the intersection in *Figure 9*, especially for straight-forward movements, is uncomplicated with strict guide lines throughout all conflict zones. The clear visibility and easy understanding for all traffic ensures preservation of traffic safety. One weakness is the left-turn movement for cyclists. This movement is performed by first crossing one arm, then turning ninety degrees, and cross the next arm. This inconvenient geometry constitutes an unfortunate route and detour for the cyclists. Additionally, cyclists are signalised at this intersection, resulting in delays due to red signal time.

Figure 10: Priority of cyclists through a roundabout in the Netherlands. [Source: (State of the Art Bikeway Design – A further look, 2011)]

Figure 10 shows a roundabout in the Netherlands with continuous bike lanes. Bike lanes are easily visible and easy in use; beneficial to both cyclists and others at the roundabout. By road markings and the continuous bicycle network, this design provides high priority of cyclists. The traditional high priority of pedestrians is preserved as well. One issue regarding traffic safety is raised with this design: the lack of space between the bike- and pedestrian crossing, and the circulatory vehicle lane. Presence of cyclists or pedestrians at the intersections results in vehicles inside the roundabout to stop in front of the exit. Detecting crossing cyclists and pedestrians is a challenge while driving in the circulatory lane as other vehicles at the roundabout is to be considered simultaneously. Additionally, a stop in the circulatory lane might necessarily cause other vehicles inside the roundabout to stop, causing queues and increased risk of rear-end collisions.

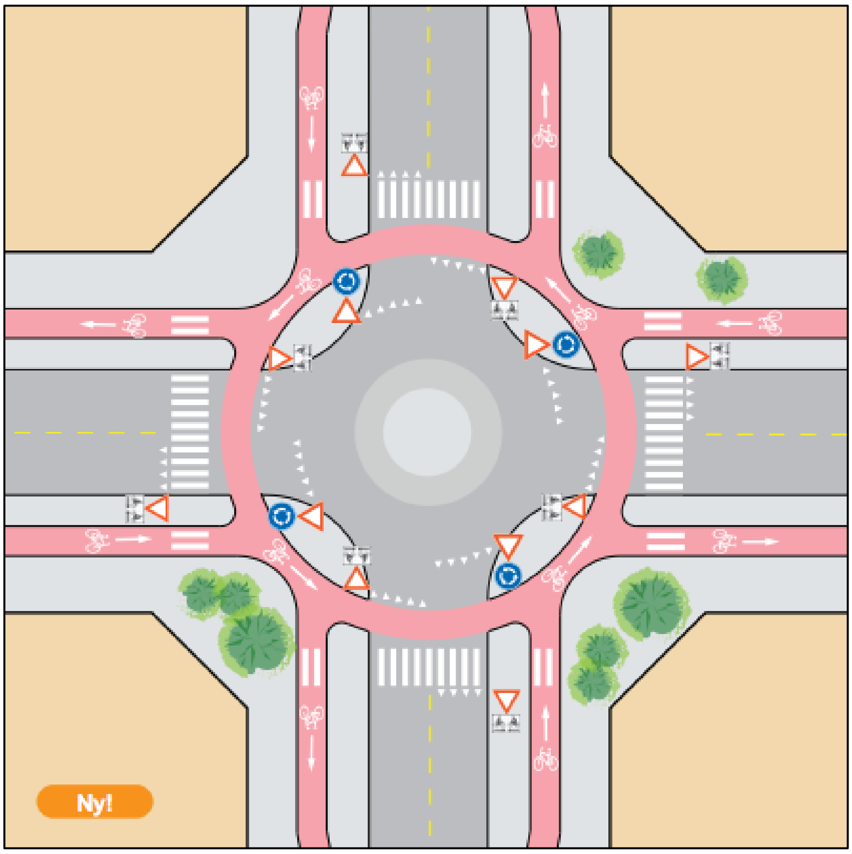

Figure 11: Priority of cyclists at a roundabout from the draft to "Oslostandarden". [Source: (Urheim and Winsvold, 2016, p.57)]

Figure 11 shows a design from the preliminary edition of "*Oslostandarden for sykkeltilrettelegging*" (Urheim and Winsvold, 2016, p. 57), presenting a similar bicycle network as in *Figure 10*, but different placement. Waiting area is here established for vehicles when exiting the circulatory lane, in front of the cyclist- and pedestrian crossings. This results in cyclists being more isolated from the motorised vehicles by having designated paths separate from the vehicle lanes. Entering the intersection require focus on cyclists and pedestrians for general purpose drivers, and solely other vehicles when driving in the circulatory lane. In *Figure 10*, vehicles passing the roundabout must simultaneously focus on cyclists, pedestrians, and vehicles at all times. Hence, traffic safety seems to be better preserved with the design in *Figure 11*; an important measure in Norwegian road designing.

2.3 Priority of pedestrians

Pedestrians are given high priority in Norway. (Trafikkregler, 2004) states current rules for pedestrians in the road network. At unsignalised crossings, all other traffic must give way for pedestrians using or approaching the crossing. Pedestrian crossing of minor roads without designated crossing area is also legal. Before entering the road, pedestrians must ascertain that other vehicles are not affected or disturbed, and that the crossing does not lead to dangerous situations. Preferably, crossing roads without zebra crossings or grade-separated crossings should take place close to intersections.

The current high priority of pedestrians makes walking an attractive transport mode. As pedestrians are given way for, other travellers must accelerate and decelerate. Changing speeds requires more energy, time, and breaking distance for heavier objects. Additionally, vehicle speeds are usually higher than the walking speed of pedestrians, making this energy-, time- and distance gap even bigger.

3. EXPERIMENTAL DESIGN

Described solutions in *Chapter 2* gain knowledge for improving priority of public transport and cyclists in Norway. With this basis, one specific design is constructed in cooperation with supervisor of this report: Arvid Aakre. This solution combine elements from centred bus systems through meridian opened roundabouts; e.g. Hillevågsveien, and a bicycle network used in the Netherlands, also described in the preliminary edition to the new *Oslostandarden for sykkeltilrettelegging*. The experimental design is shown in *Figure 12*.

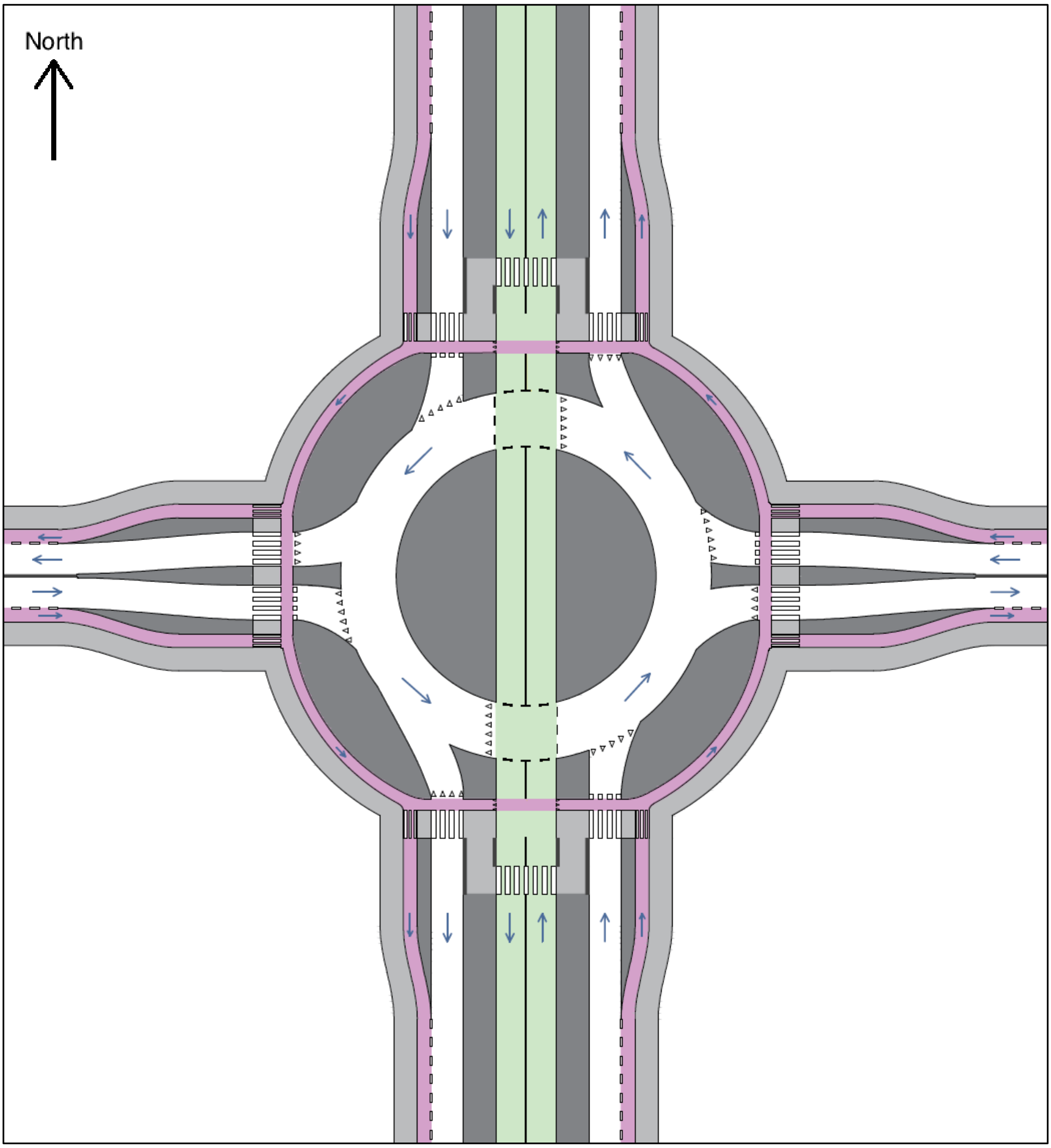

Figure 12: Experimental design; "throughabout".
[Figure made in AutoCAD]

Figure 12 shows principles of the experimental design with designated traffic movements. The roundabout design with two intersections in the circulatory lane will provide absolute priority of buses. In separate lanes, high priority of cyclists and pedestrians are preserved. Not being a traditional roundabout as bus lanes go through the central island, it is a hybrid solution. Similar designs have also been called *through-abouts* or *hamburger roundabouts* (U.S. Department of Transportation, 2014). The experimental design is described as a *throughabout* in the following.

Centred bus lanes are displayed with green colour in the figure. Colouring or highlighting these lanes are not necessarily defined, but displays the public transport lanes in the figure. Lanes for general purpose traffic are displayed with white colour and direction arrows. The bicycle network is marked with red colour, compliant to today's standard of colouring bike lanes in Norway. Designated walking area for pedestrians are displayed with bright grey colour. Dark grey colour is used for area unintentional for traffic.

3.1 Geometry

Geometry is to the feasible extent based on handbooks by the Norwegian Public Roads Administration. Chapter E.1.2 in handbook N100 (Statens vegvesen (N100), 2014a) provides dimensions for constructing traditional roundabouts in Norway. This gives the basic geometry of the design together with handbook V121 (Statens vegvesen (V121), 2014d). Making the throughabout accessible for all vehicle types, "truck" is set as design vehicle. This constitutes a wide circulatory lane of 6 metres. As this design is not yet existing, all dimensions are not found in the handbooks. Hence, some measures are created and adjusted to meet functional requirements. Main geometry dimensions of the experimental design are listed in *Table 7*.

Table 7: Geometry of the experimental design

Geometry parameters and values	
Diameter of central island	28 m
Inscribed circle diameter	40 m
Width of circulatory lane	6,0 m
Width of public transport lane	3,25 m
Width of general purpose lane	3,5 m
Width of bike lane	1,25 m
Width of pedestrian sidewalk	2,5 m
Width of pedestrian crossing	3,0 m
Length of splitter island	10 m
Waiting space between circulatory lane and bike/pedestrian crossing	5 m
Waiting space in circulatory lane in front of public transport lane	5 m
Distance between public transport lane and general purpose lane (bus stop)	3,5 m

Table 7 shows geometry dimensions of the experimental design. With defined geometry, specific area use of different transport groups and total area use of the design can be measured. For future implementation, the experimental design should be adjusted to local conditions; causing changes in area use. The experimental design measured within main conflict points constitute following area use.

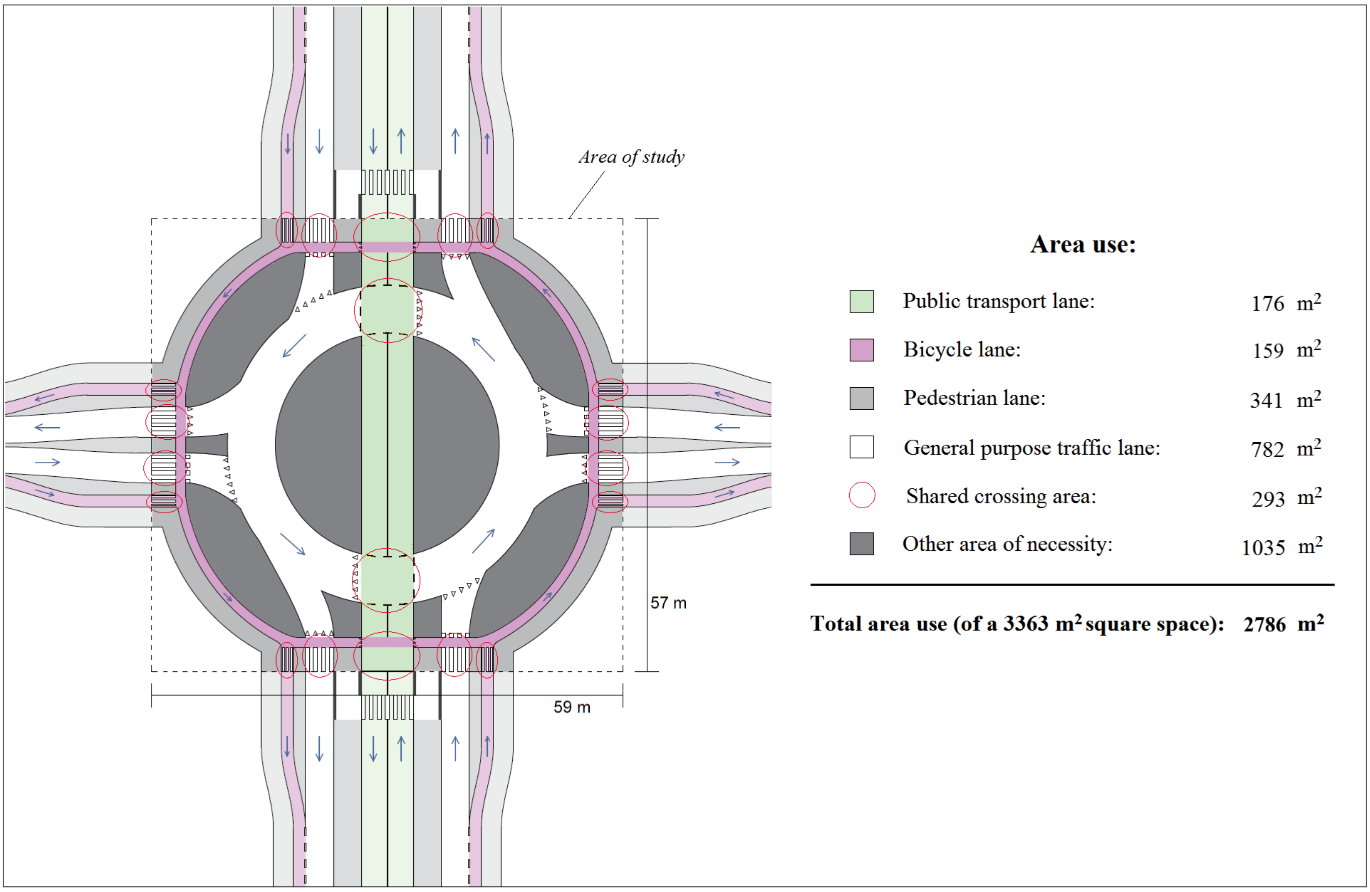

Figure 13: Area use in experimental design.
[Figure made in AutoCAD]

Figure 13 shows the experimental design area with respective area use for different transport groups and total area of the design. Boundaries are drawn to include all main crossings, constituting a 57 x 59 metre rectangle of 3363 m^2. This gives an indication of area requirements for the design, given comparable connecting entries. In addition, a transition length of 19 metres for the major road, and 21 metres for the minor road are recommended for changes in cross sections towards main pedestrian crossings.

The cross sections of the major and minor roads are shown in *Figure 14* and *Figure 15*. Variants of the experimental design are conceivable, and might be suitable depending on the area of implementation. Hence, widths of cross sections may vary; e.g. with two-way bike paths instead of one-way lanes. Following cross sections applies for the sketched experimental design.

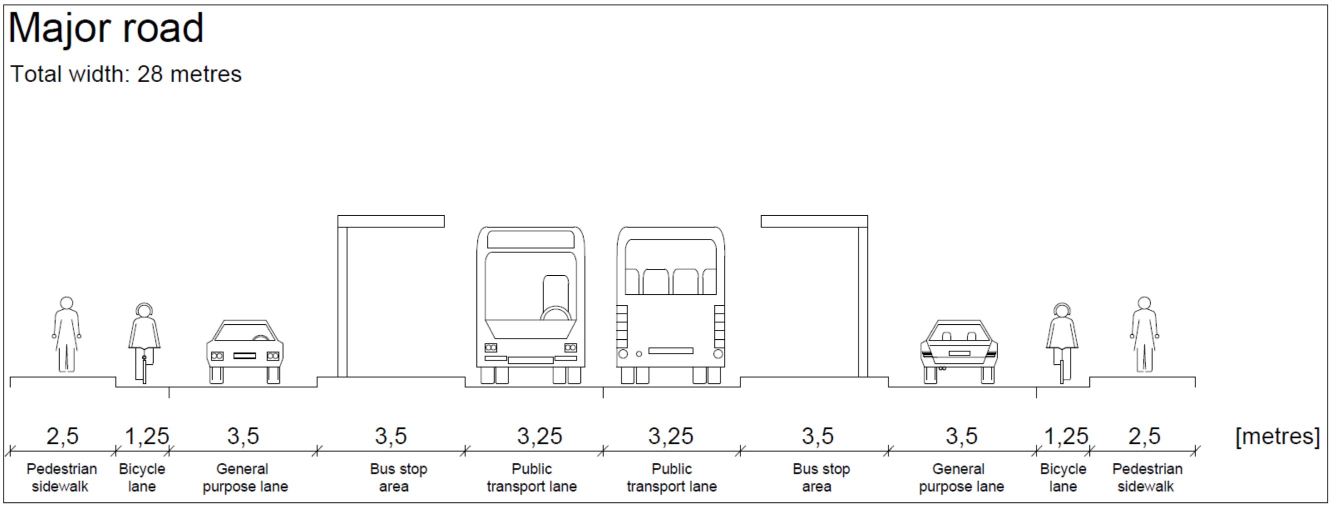

Figure 14: Cross section of the major road.
[Figure made in AutoCAD]

Figure 14 shows cross section of major roads approaching the throughabout. This cross section shows the different transport modes with allocated lane widths. Bus stop area is included, making this the largest existing cross section for the major road. Widths of 3,5 metres for separating bus lanes and general purpose lanes are not necessary for distant bus stops. Hence, this cross section can be reduced for an adjusted separating area between the motorised lanes. Reducing separating areas between these lanes to 0,5 metres result in a total width of 22 metres.

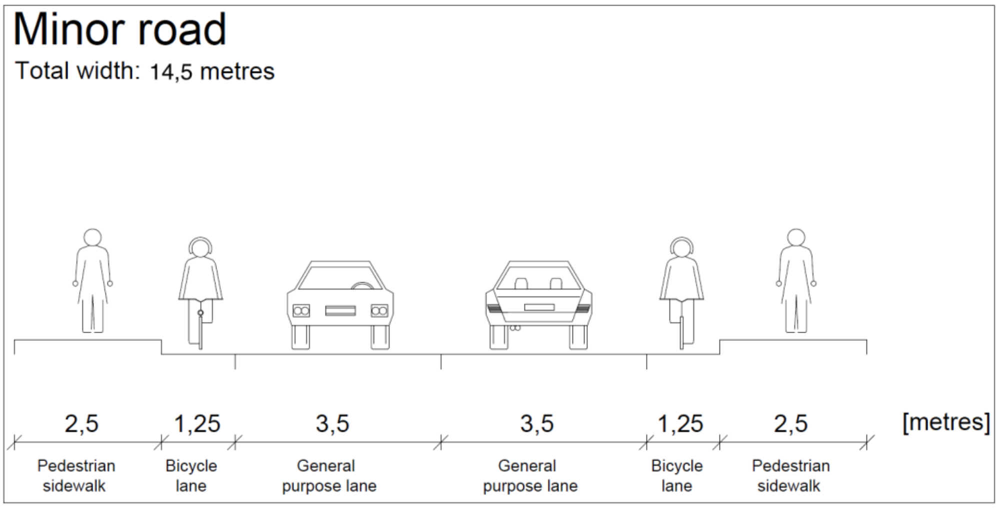

Figure 15: Cross section of the minor road.
[Figure made in AutoCAD]

Figure 15 shows cross section of minor roads approaching the throughabout. Total width is 14,5 metres before the transformation associated with the throughabout. At pedestrian and bike crossings, splitter islands are established. The splitter island is widened in front of the circulatory lane for easy guidance of vehicles, and extended waiting space in front of the busway. The change in cross section of the minor road extends the width by 4 metres, resulting in a total width of 18,5 metres just before the pedestrian and bike crossing.

3.2 Mobility

Mobility describes passage of the throughabout for the different transport groups; public transport, cyclists, pedestrians, and general purpose traffic.

3.2.1 Public transport

Buses drive with absolute priority in dedicated, centred lanes at the throughabout. With intention of improving the public bus service, bus lanes are implied to exclusively serve public buses. Taxis, electrical vehicles, cyclists, and other transport modes currently permitted in public transport lanes in Norway are here excluded from the segregated meridian busway. This reduces delay; increasing efficiency and attractiveness of the public bus service. Additionally, frequencies through conflict points in the circulatory lane are reduced, increasing continuation and flow.

The segregated meridian busway constitutes two conflict points with general purpose traffic. These occur in the circulatory lane, where other traffic must give way for buses. For buses driving from both directions, the first conflict point constitutes a potential collision where vehicles hit the left side of the bus, or buses hit the right side of the vehicle. This occurs in drivers' and buses' direction, respectively, halfway through the passage of the busway. Buses exit the throughabout through the second conflict point. Here, potential collisions are incoming vehicles from the right side, or buses driving into the left side of vehicles. Due to absolute priority, buses are not requisite to decelerate when approaching conflict zones in this design. Hence, cyclists and pedestrians are also to give way for buses. Slow design speed for buses preserve traffic safety for noncompliance of give way rules. Bike and pedestrian crossings of bus lanes are further elaborated in *Chapter 3.2.2* and *Chapter 3.2.3*, respectively.

Buses are provided with absolute priority to avoid delays caused by decelerating and accelerating. As buses are heavy, energy demand for speed adjustments is correlating high. This results in increased motor work and more delay due to slower deceleration and acceleration. For motorised vehicles, speed changes are effortlessly adjusted for drivers by using the brake and gas pedal. For non-motorised transport groups, deceleration and acceleration are performed by human powers. Hence, such speed adjustments require more human effort than motorised traffic, especially for cyclists. Traditionally, pedestrians are given high priority in the road network. The effort of stopping and starting for this transport mode is minimal, and priority is hence given due to time efficiency. Cyclists carry the weight of the bikes, resulting in increased requirement of energy for speed changes. For cyclists, accelerating is the effort. Additionally, cyclists must necessarily step off the bike when stopping, resulting in even more delay. Considering deceleration and acceleration delays with human effort is deliberated to the benefit of buses in this design. As the busway only serves public buses, passage frequencies through bike and pedestrian crossings are small. This means few conflicts, and infrequent need of stopping for these transport groups.

Straight lining the busway result in an optimized crossing regarding travel distance and efficiency. Avoiding turning movements increases passenger comfort, also comfort for the driver; discomfort and ache in shoulders and neck are reported from steering the bus through sharp curves at roundabouts (Giæver and Tveit, 2006, p. 21). Additionally, a straight-lined busway facilitates larger public transport vehicles in the future. Curve radius at roundabouts and throughabouts is a limiting measure for the passage capability of larger vehicles. This design avoids this issue for the public transport service. In Norway, this is of special relevance due to enlarged buses for increased capacity in coming years. E.g.: in the city of Trondheim, new public buses of up to 25 metres length are expected to enter the road network in 2019 (Hvordan blir busstilbudet i 2019?, 2017), compared to todays' longest buses of 18,75 metres (Liste over busser som kjøres på oppdrag for AtB, 2016).

3.2.2 Cyclists

Cyclists are provided with dedicated lanes at the throughabout. A continuous network of visible lanes serve high priority to the cyclists. By absolute priority of buses, cyclists must give way for public transportation, constituting two conflict points. Additionally, eight conflict points occur with general purpose traffic, and eight conflict points with pedestrians. The circulatory bike lane is one-way regulated. Thus, cyclists must merge and adjust to each other at entry of the circulating area. Give way signs in the asphalt are not included for this movement in the experimental design due to assumed merging.

Conflict points between cyclists and general purpose traffic are regulated to benefit cyclists. General purpose traffic must give way to cyclists at all entries and exits of the throughabout. A waiting space of 5 metres is established between bike crossings and the circulatory lane, allowing one personal car to queue up without interrupting the circulating vehicle flow inside the throughabout.

Conflict points between cyclists and pedestrians are regulated to benefit pedestrians. Pedestrian crossings are established in bike lanes at entries and exits of the circulatory bike lane, requiring cyclists to give way. Hence, cyclists must be extra cautious in front of merging with circulating bicycle traffic; preserving traffic safety by increased attention and reduced speed. In the circulating area, there are no conflict points with pedestrians. Cyclists is then to only pay attention to the motorised vehicles.

By absolute priority of buses, conflict points between cyclists and buses are beneficially regulated for buses. Cyclists must give way to approaching buses from both directions, utilizing a waiting space of 3,5 metres in length in front of the busway. Though less is sufficient by current design bicycle length of 1,8 metres (Statens vegvesen (N100), 2014a, p. 151), this waiting space constitute width of bus stops as well; hence 3,5 metres.

The continuous one-way regulated bicycle network constitutes defined movements for cyclists at the throughabout. Distances for right-, straight-, and left turns are respectively associated with entries from the major and minor road.

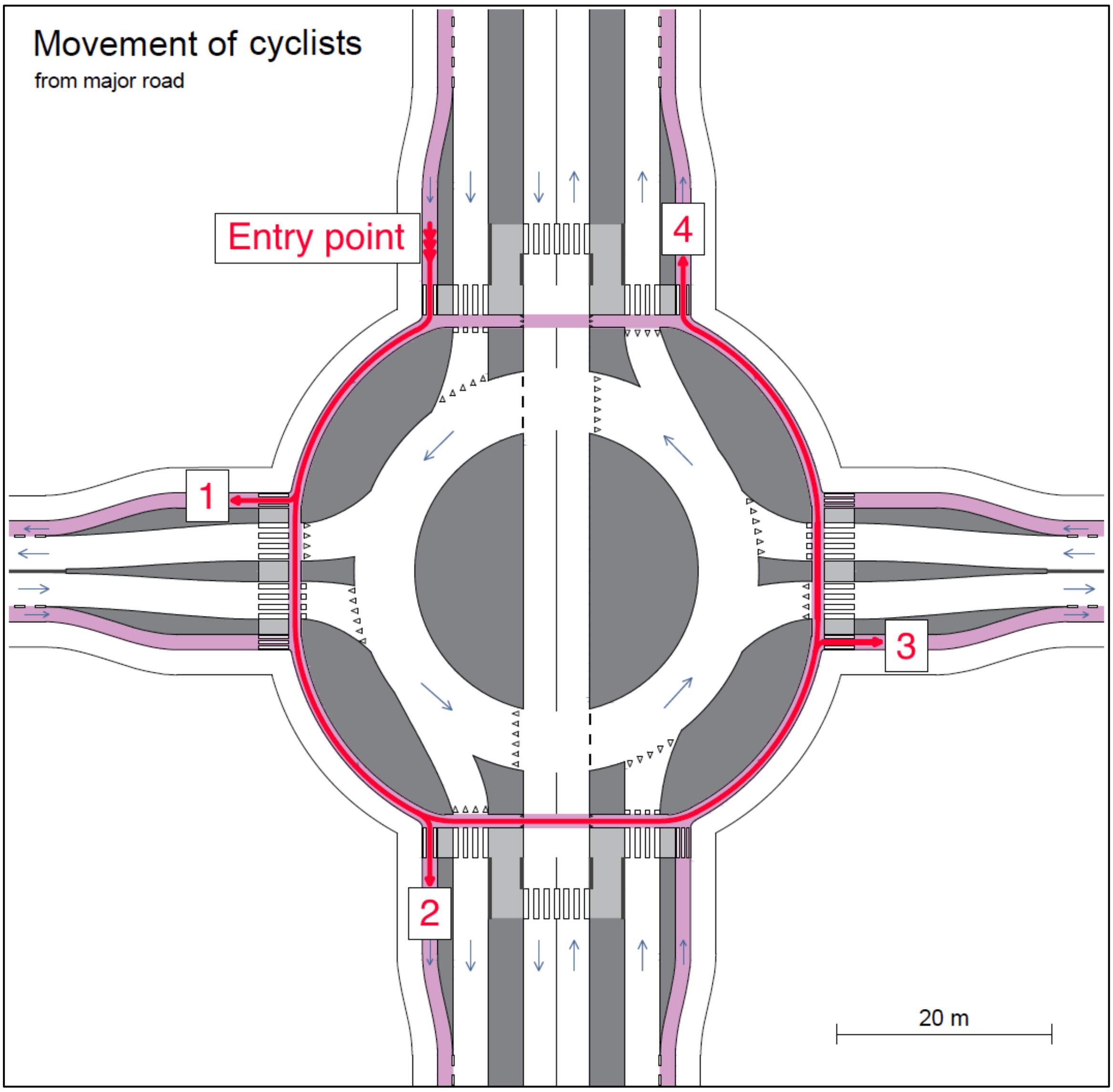

Figure 16: Bicycle movements with approach from the major road.
[Figure made in AutoCAD]

Figure 16 shows right-, straight-, left-, and return movement at the throughabout for cyclists coming from the major road. For a right-turn movement, cyclists merge with circulating bicycle traffic before crossing the pedestrian crossing on the way out. Straight movements have one additional merging point with incoming cyclists from the minor road. Left turn and return movement require crossing of the busway. Hence, cyclists must necessarily stop for present buses, causing delays for the cyclists. At crossings over all other lanes with motorised traffic, vehicles are regulated with give-way rules, resulting in no other stops for cyclists. Performing left turn or returning movements can also be executed by stepping off the bike and use pedestrian crossings. Especially for return movements, distances are largely reduced by using these crossings; numbers are presented in *Table 8*.

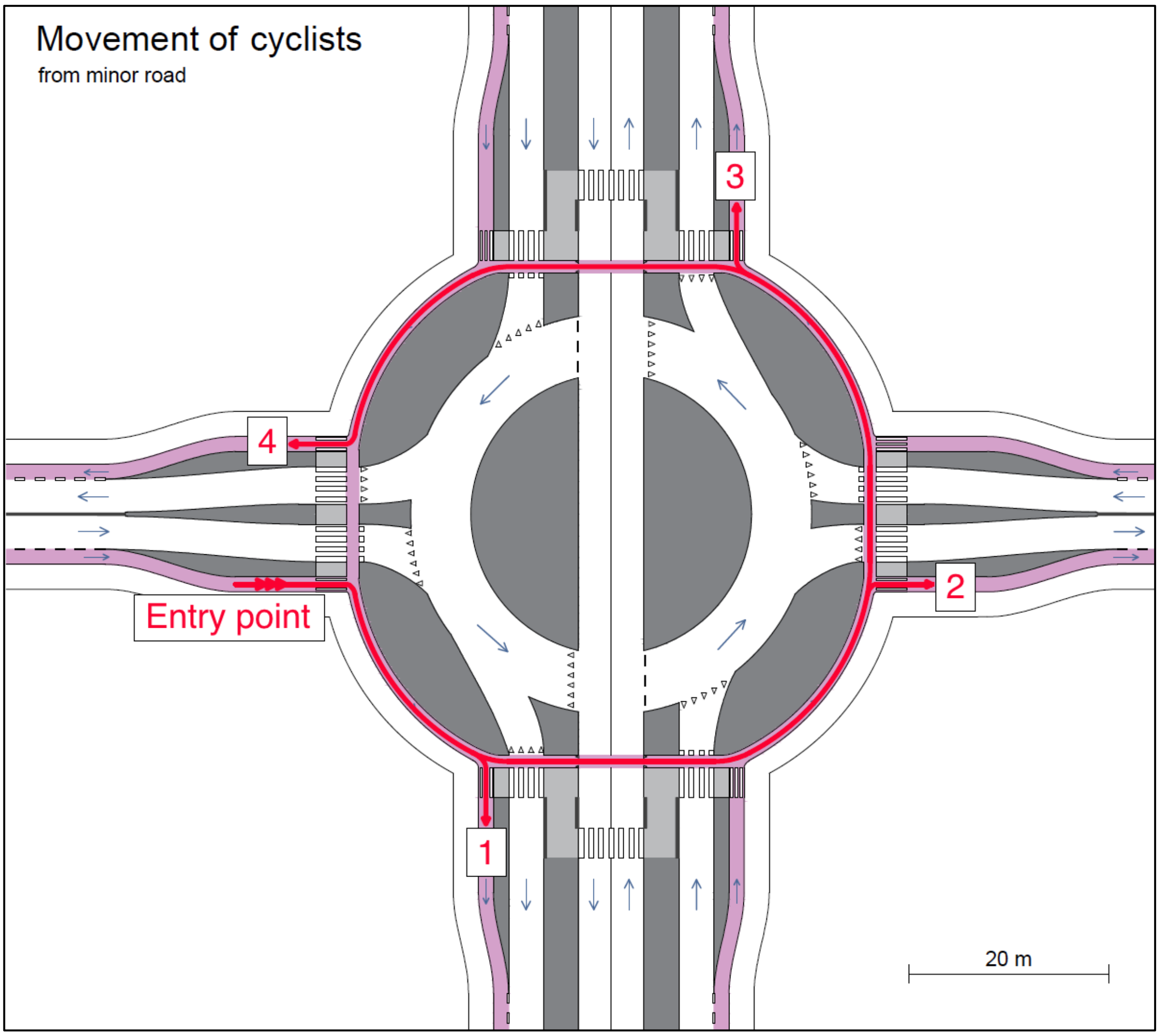

Figure 17: Bicycle movements with approach from the minor road.
[Figure made in AutoCAD]

Figure 17 shows right-, straight-, left-, and return movement at the throughabout for cyclists coming from the minor road. Straight- and left- turning movements conflict with the busway, resulting in stops for cyclists by presence of buses.

Respective distances and estimated travel time for different turning movements with approach from major and minor roads are presented in *Table 8*. Assumed bike speed is 18 km/h for all movements as basis for estimated travel time. Interruption from other traffic is not considered.

Table 8: Distances and estimated travel time for bicycle movements at the throughabout

	From major roads		**From minor roads**	
	Distance	Travel time	Distance	Travel time
1 – Right turn:	24 m	4,8 sec	24 m	4,8 sec
2 – Straight movement:	61 m	12,2 sec	73 m	14,6 sec
3 – Left turn:	106 m	21,2 sec	110 m	22,0 sec
4 – Return: *(alternative by pedestrian crossing):*	144 m *(25 m)*	28,8 sec -	157 m *(15 m)*	31,4 sec -

White background colour: no conflict with bus lanes
Yellow background colour: conflict with bus lanes

Table 8 shows distance and travel time for different bicycle movements at the throughabout. Regardless road of approach, uninterrupted straight movements take less than 15 seconds when biking. Return movements are more than twice that time. As pedestrian crossings constitute considerable shorter distances, these movements are more likely to be performed by the cyclists. Additional to reduced length, travel time is assumedly reduced.

Performing left turns anticlockwise by pedestrian crossings and the pedestrian sidewalk reduces distances with approximately 40 metres with approach from major road, and 50 metres from minor road. Bus lanes are not avoided by performing crossings as a pedestrian, and speed is reduced as walking is slower than walking. Both ways of performing left movements are permitted, and does not constitute big disadvantages for other traffic groups. The widened gap of 1,5 metres between bike lanes and general purpose traffic in front of crossings consider this movement. Cyclists crossing as pedestrians are provided with an additional gap before the crossing to aware motorised drivers of the cyclists' decisions; preserving traffic safety and easier passing of the crossings for general purpose traffic.

Described movements with respective distances applies for the specific experimental design shown in *Figure 12*. These movements and values changes for implementation of two-way regulated connecting bike paths with the circulating area.

3.2.3 Pedestrians

Pedestrians are provided with a segregated network and high priority throughout the design area. Traditional sidewalks are established along roads, dedicated for pedestrians. At roads with low traffic volumes, pedestrian crossings are not necessary, see *Meeting log 2* in *Attachment 3*. As this design is assumed to be implemented at crossroads with higher traffic volumes, crossings are a necessity; hence, present in this design. At crossings of general purpose lanes and bike lanes, pedestrians are given full priority. At the public transport lane, pedestrians are regulated to give way for buses.

Pedestrian crossings are assembled with bike lanes. The circulatory bike lane is inside the pedestrian walking area, reducing the number of conflict points with cyclists to a minimum. At these conflict points, cyclists are regulated to give way. With bike lane width of 1,25 metres, this order constitutes small delays for pedestrians, while cyclists are provided with rapid headway. Bike and pedestrian crossings are withdrawn 5 metres from the circulatory traffic lane; enough space for queueing up one design personal car without disturbing other traffic (Statens vegvesen (N100), 2014a, p. 129). Extending this designated waiting space for general purpose traffic increases distances and delays for pedestrians at the throughabout. This is a disadvantage as walking is a slow transport mode; reducing the attractiveness. A waiting space for general purpose traffic between the bike and pedestrian crossing was also considered for the design in an earlier stage. This was avoided by same reasons; distances and delay for pedestrians. General purpose traffic would then firstly focus on cyclists and secondly on pedestrians. Instead, they are required to focus on both simultaneously. In Norway, assembled bike and pedestrian crossings are wide spread in use. Observing both simultaneously is hence not considered a problem.

Pedestrian and bike crossings are equally levelled with other traffic in this design. Elevating these crossings was considered in an earlier stage of the design process. The advantage is reduced speed for general purpose traffic, improving safety of the crossing transport modes. This will negatively affect general purpose traffic which are already given reduced priority. Providing a rapid exit of the circulatory lane is desired due to potential clogging issues at the throughabout.

A pedestrian waiting space is recommended for crossings spanning over roads with more than 8 metres of width (Statens vegvesen (V127), 2014f, p. 29). The traffic island should constitute an undisturbed waiting area of minimum 2 metres; enough space for facilitating stops of pedestrians with strollers and wheelchair users (Statens vegvesen (N100), 2014a, p. 151). Waiting spaces are implemented on all roads due to the width of major road and already presence of a splitter island on the minor road. Length of waiting area over minor road entries are 2 metres, and 3,5 metres on the major road due to shared width with bus stops. 3,5 metres also fulfils the requirement of 2,5 metres free space between fences; from the NPRA guide handbook (Statens vegvesen (V129), 2014g, p. 75).

Crossing public transport lanes with absolute priority has been an enduring challenge for this design during the process. This has been a challenge at earlier presented Hillevågsveien in *Chapter 2.1.2* as well. By discussion with Helge Ytreland (NPRA), see *Attachment 3*, occurring challenges at Hillevågsveien were presented; relevant and transposable for the experimental design. Based on this discussion, the following solution is proposed:

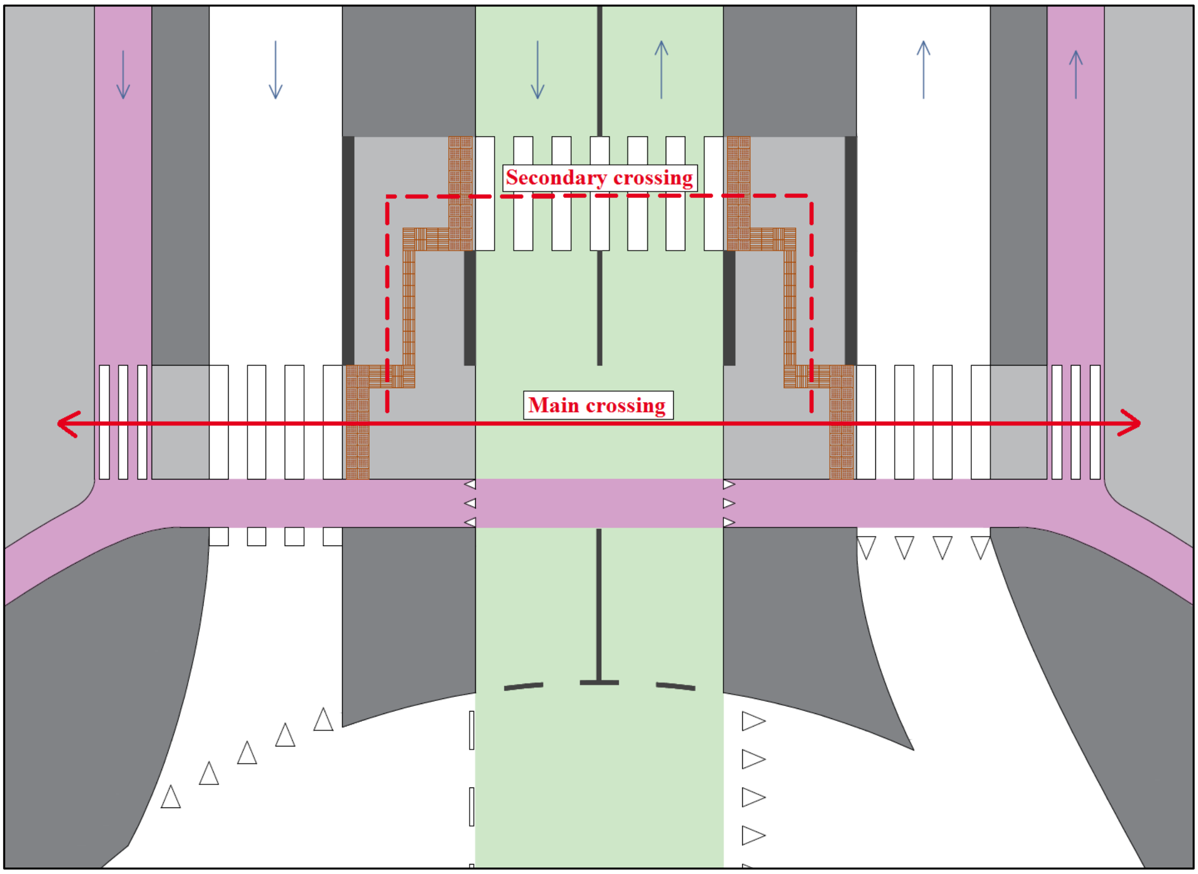

Figure 18: Pedestrian crossings over major road.
[Figure made in AutoCAD]

Figure 18 shows pedestrian crossings over public transport lanes, general purpose traffic, and bike lanes. With approach from the sidewalk, pedestrians cross the bike lane firstly. Cyclists are regulated to give way for pedestrians; causing a speed reduction for cyclists before entering the circulatory bike lane.

The bike lane and general purpose lane is separated by a pedestrian waiting space. Traditional zebra stripes are implemented over the general purpose lane where motorised traffic must give way for pedestrians. This applies for general purpose traffic from both sides. As pedestrian and bike crossings are adhered side by side, vehicles must detect both transport modes at crossing.

Proposed crossing of the busway is untraditional to the current road network in Norway. Pedestrians are usually regulated with highest priority. The absolute priority of buses in this design results in pedestrians to give way. After crossing the general purpose lane, pedestrians are provided with a waiting space of 3,5 metres before the busway. At this point, there are two options of crossing; *main* and *secondary* crossing from *Figure 18*.

The main crossing is assumed to serve most pedestrians. Openings in circumferential fences, terminated lane separating road markings in the busway, and traffic signs visually present the crossing area. Traffic signs regulate and inform pedestrians of the crossing as zebra stripes are not implemented. Zebra stripes are avoided to prevent confusion of pedestrians, preserving traffic safety. Gradually lowering the pavement to the busway for guidance was considered earlier; avoided due to traffic safety as well. This prevents round and circular elements from rolling onto the busway, and incautious entry of the conflict zone. Hence, waiting spaces associated with bus lanes are equally levelled with surrounding motorised lanes. Approaching buses with speeds of 40 km/h constitute risk of severe accidents. Leading pedestrians directly into the lane is hence not desired, especially regarding children. Hence, a secondary crossing is established. The traffic sign should instruct pedestrians to cross the busway when vacant, and give way whenever a bus is present.

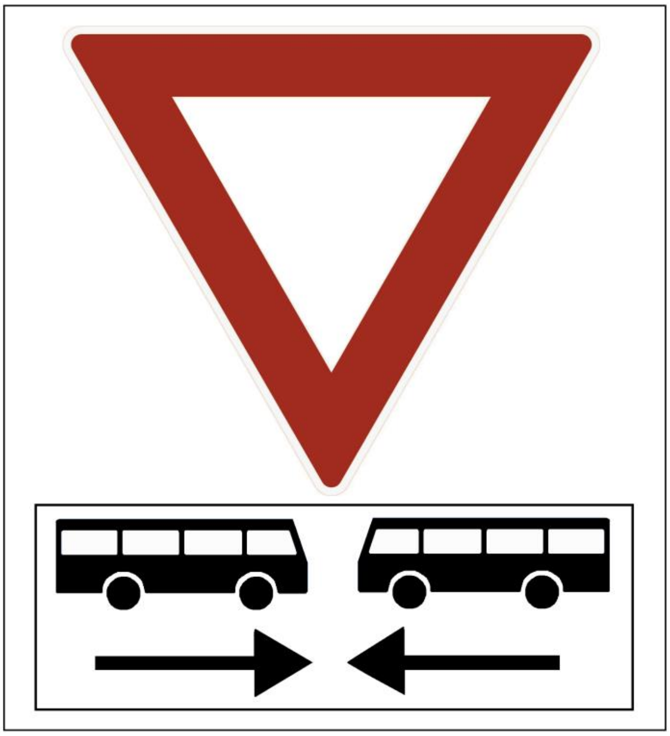

Figure 19: Traffic sign for pedestrians crossing the busway.
[Figure made in Paintbrush]

Figure 19 shows a suggested traffic sign for pedestrians crossing the busway, consisting of one give way sign and one additional plate. The give way sign is *202 Vikeplikt* from the Norwegian Public Roads Administrations handbook (Statens vegvesen (N300), 2014c, p. 87). The additional plate below does not yet exist, but compliant with *826 Sykkeltrafikk i begge kjøreretninger* in the same handbook. Sign 826 is also used as an additional plate to the give way sign, and regulates traffic to give way for cyclists coming from both directions. Hence, a similar sign is proposed with displayed buses on the plate instead of bicycles.

An additional text-displaying traffic sign will increase pedestrians' understanding of the crossing; e.g. *Give way to buses – Cross when vacant*. As this is a new type of crossing, supplementing information is desired to avoid confusion; preserving traffic safety.

The secondary crossing is mainly established for visually impaired pedestrians. In an interview with Helge Ytreland (NPRA), see *Attachment 3*, these have experienced problems crossings segregated meridian busways. Standing in between the noise from four different motorised traffic lanes makes detection of buses difficult, and causes disorientation. Additionally, guide dogs are trained to cross traffic lanes over zebra stripes. Hence, tactile paving is implemented to guide visually impaired pedestrians to the secondary crossing. As this crossing is signalised, the tactile paving leads to the call box (Statens vegvesen (N100), 2014a, p. 77). Signal phase should not interrupt buses in the public transport lane. Hence, green signal should only be provided when buses are not present.

Universal design is considered with both pedestrian crossings. The main crossing is not signalised to reduce delays for most pedestrians. Pedestrians uncomfortable with unsignalised crossings can also use the signalised secondary crossing.

3.2.4 General purpose traffic

The experimental design serves high priority of buses, cyclists, and pedestrians; negatively affecting general purpose traffic. Both enter and exit of the circulatory lane requires crossing of pedestrian and bike crossings with higher priorities. Additionally, general purpose traffic must give way in the circulatory lane for approaching buses.

Pedestrian and bike crossings are regulated with give way rules for general purpose traffic. After the bike crossing, a waiting space of 5 metres is established before entering the circulatory lane. Due to giving way for vehicles in the circulatory lane, this waiting space allows queueing of one design personal car without affecting other traffic.

In the circulatory lane, vehicles move in clockwise direction by traditional roundabout rules for right-handed driving. In front of the busway, another waiting space of 5 metres is established for queueing of one design personal car. Give way markings are withdrawn 0,5 metres from the busway to establish an additional safety zone between queueing vehicles and buses. Lane width just before this waiting space is widened, allowing other vehicles to exit the circulatory lane concurrent with minimum one personal car queueing in front of the busway. The width of the circulatory lane might facilitate more than one car queueing while others exit the circulatory lane, depending on driving behaviour and acceptance. This waiting space is established in front of both conflict points with the busway inside the throughabout.

General purpose traffic must give way for another bike and pedestrian crossing exiting the throughabout. Another waiting space of 5 metres is established in front of this crossing. Give way markings are withdrawn 0,5 metres from the bike lanes to establish an additional safety zone between general purpose traffic and cyclists.

Established waiting spaces makes driving easier for general purpose traffic throughout the throughabout. This requires focus on pedestrians and cyclists firstly, then circulating traffic in the circulatory lane, bus traffic in busway if crossing, then pedestrians and cyclists again before recurring to a regular, segregated lane. This prevents observation of several traffic groups simultaneously, preserving traffic safety due to easier passing of conflict points. The only exception from traditional roundabouts in Norway is the penetrating busway in the circulatory lane with give way regulations. This is not completely unfamiliar as trams go through several roundabouts today. The main difference are traffic rules where trams have higher priority, see *Attachment 2*.

Waiting spaces of 5 metres facilitate queueing of one design personal car of 4,8 metres (Statens vegvesen (N100), 2014a, p. 129). These waiting spaces fall short for longer vehicles, resulting in disturbed traffic. Queueing of larger vehicles or several personal cars in front of the circulatory lane result in obstruction of pedestrians and cyclists. These transport groups can share the assembled crossing area of 4,25 metres; not considerably impacting traffic flow and capacity. Obstructing traffic behind waiting spaces in the circulatory lane have greater consequences. This prevent other general purpose vehicles from exiting the circulatory lane. Hence, clogging inside the throughabout is more likely to occur.

Expanding the circulatory lane into two lanes reduces clogging problems. Two lanes increase space for vehicles to pass queueing vehicles; improving capacity and traffic flow. One circulatory lane is chosen by traffic safety measurements. Lane changing inside the throughabout requires focus on other general purpose vehicles, abating focus on the conflict point with buses. At this design, these conflict points are of special importance due to the severity of collisions and unfamiliarity. Hence, one circulatory lane is chosen, but with the possibility of exiting the throughabout for queueing of minimum one personal car.

The experimental design is constructed to facilitate larger vehicles at the throughabout. As all dimensions to a similar design are not provided by the NPRA handbooks, Helge Ytreland (NPRA) was asked for feedback from drivers with large vehicles at comparable Hillevågsveien in Stavanger, see *Attachment 3*. Currently, there have not been reported any negative feedback from truck drivers in Hillevågsveien.

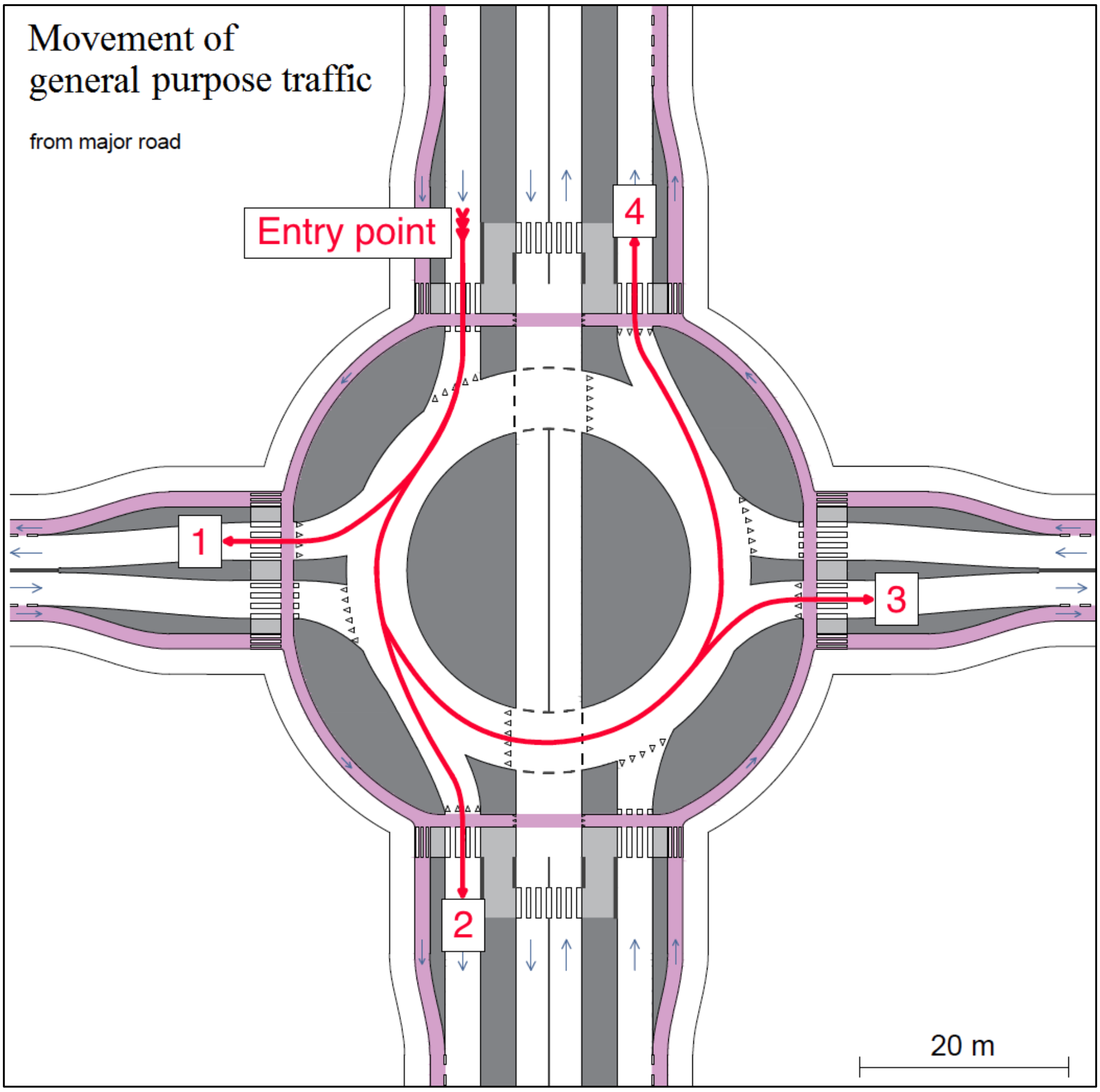

Figure 20: Movements of general purpose traffic with approach from the major road. [Figure made in AutoCAD]

Figure 20 shows right-, straight-, left-, and return movements at the throughabout for general purpose traffic coming from the major road. Right- and straight movements are not in conflict with the busway. Most general purpose traffic is assumed to go straight as this movement continue the major road. Left turns to the minor road and rare return movements require one crossing of the busway.

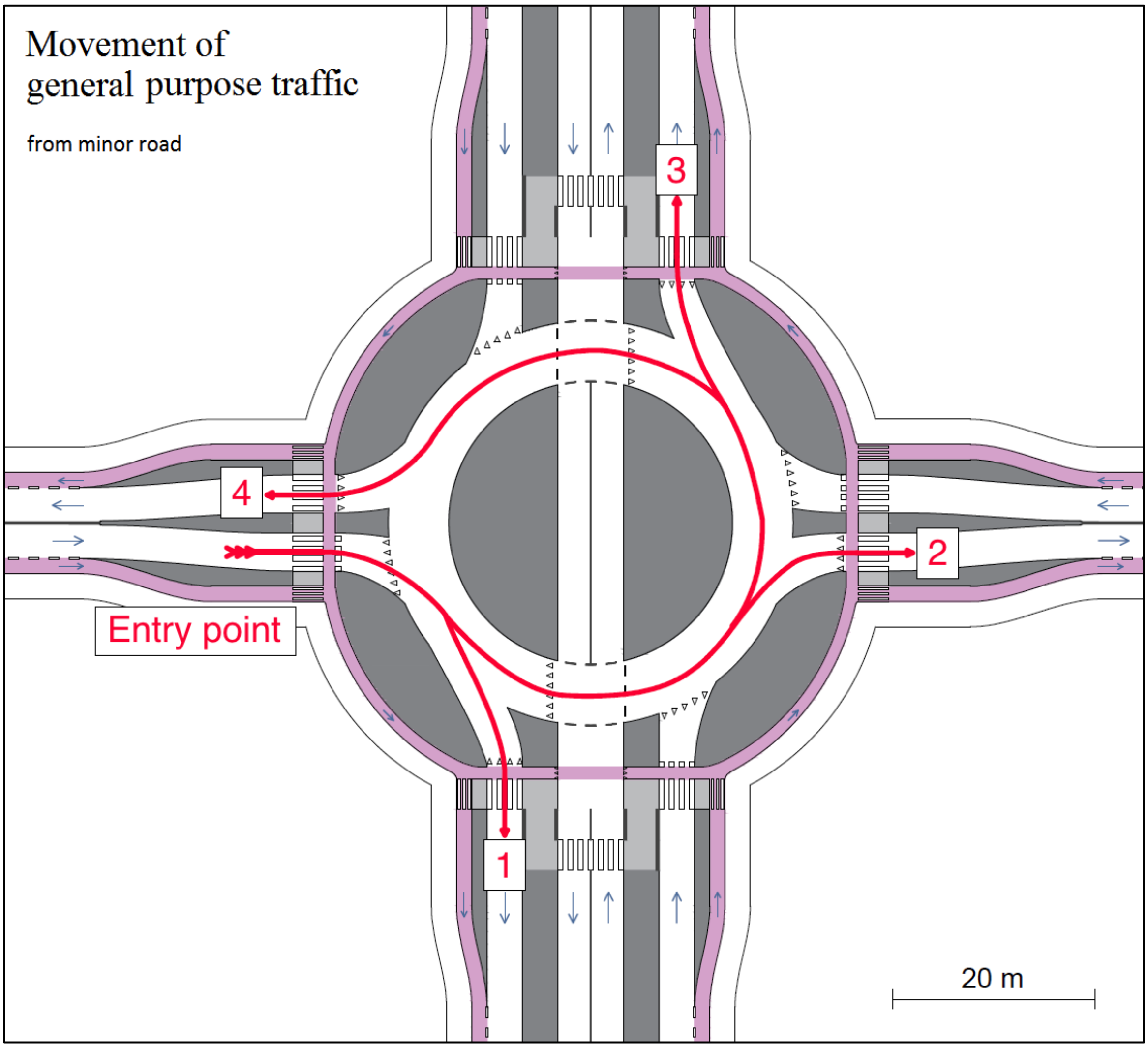

Figure 21: Movements of general purpose traffic with approach from the minor road. [Figure made in AutoCAD]

Figure 21 shows right-, straight-, left-, and return movements at the throughabout for general purpose traffic with approach from the minor road. Right turns are not in conflict with the busway, constituting one of the major movements. As most traffic is assumed to enter the major road, left turn is the other major movements. Both left turns and straight movements require one crossing of the busway. The rare return movement to and from the same minor road requires two crossings of the busway.

3.3 Design speeds

Design speeds are set to 40 km/h for all motorised traffic. This is decided based on meetings with competent professionals, see *Meeting log 1* and *Meeting log 2* in *Attachment 3*, and in cooperation with supervisor Arvid Aakre.

(Frøyland et al., 2016, p. 7) states design speeds at different BRT systems around the world, and traditional speed limits on roads just outside city centres. Design bus speeds of 40 and

50 km/h are commonly used in these areas; providing efficient transportation while preserving high level of traffic safety. (Frøyland et al., 2014, p. 13) recommends design speed of 40 km/h for other motorised traffic, ensuring safe crossing of the non-motorised transport modes.

High bus speeds increase efficiency of the transport mode. Additional to traffic flow and capacity, design speed also impacts geometry and safety. Based on current NPRA handbooks, design speed of 40 km/h for general purpose traffic requires less area at the throughabout than 50 km/h due to geometry requirements. For buses, design speed does not necessarily require a larger throughabout; dependant on sight conditions. Regarding traffic safety, collisions with buses at conflict points will be more severe with higher speeds. High speed also result in less time for other traffic to detect buses. Considering safety issues with the efficiency of the bus service is of great importance.

Throughabouts are rare in Norway. By the time this report is written, there are no unsignalised meridian opened roundabouts with passing buses. In Bergen and Oslo, there are a few throughabouts with trams passing straight through. Due to the unfamiliarity, a conservative design speed is chosen. For buses, the speed limit can be adjusted close to conflict points, resulting in minimalized delay. Design bus speed through intersections might be increased in the future if this solution gets more familiar.

3.4 Bus stops

Bus stops are not drawn in the experimental design in *Figure 12* as principles are in focus. Area for bus stops are allocated between bus lanes and general purpose lanes on the major road on both sides of the throughabout. Bus stops with centred public transport lanes require users to cross a general purpose lane for accessing the bus service.

(Statens vegvesen (V123), 2014e, p. 13) recommends placement of bus stops after intersections. Thus, approaching buses will go straight through conflict points before entering the bus stop. Minimalized bus stop time is desired for an effective bus service, but stop time is highly dynamic due to many factors; e.g. number of on- and off-boarding passengers, wheel-chair users, people with disabilities, children, payment system, questions for the driver, etc. Bus stop time is not affecting other traffic groups for implemented bus stops after conflict points, eliminating hesitation of other drivers. This is of special importance for the experimental design as intersections with crossing buses in the circulatory lane is not a commonly known solution; causing extra insecurity for traffic at the throughabout.

Required width and length of kerbside bus stops are minimum 2,5 metres and 20 metres, respectively (Statens vegvesen (N100), 2014a, p. 130). Bus stop length of 20 metres accommodate one bus at the stop. Extending the length for simultaneously serving several buses is easily implemented with the experimental design. Width of 2,5 metres facilitates wheelchair users and winter maintenance with traditional snowploughs (Statens vegvesen (V123), 2014e, p. 23). Based on a meeting with Steinar Simonsen (NPRA), see *Attachment 3*, the width was decided to be widened to 3,5 metres. This fulfils the temporary requirement of bus stops to the upcoming BRT-system of "Superbuss" in Trondheim in 2019 (Superbuss – Prosjekteringsanvisning for stasjoner; utkast, 2017, p. 7). Width of 3,5 metres accommodates a bus shed, free passage zone of 2 metres, and a safety zone for side mirrors of incoming buses. Additionally, further passage along the bus stop away from the throughabout is prohibited. Hence, both enter and exit of the bus stop is one-way regulated; facilitated with this width.

Bus stops should not be closer than 5 metres in front of, or less than 1 metre behind a pedestrian crossing (Statens vegvesen (N100), 2014a, p. 130). Hence, bus stops are established behind pedestrian crossings by minimal distance to reduce walking distance to the bus stop. Assumedly, there is no need for separating the bus stop from the bus lane, resulting in a kerbside stop. This eliminates geometric delay for the buses, and takes up less area in the design.

Implementing bus stops just after conflict points require buses to slow down over pedestrian crossings and intersections with the circulatory lane, at least the last conflict point. Speed reduction over these conflict points preserves traffic safety, and makes it easier for other traffic to navigate through the throughabout.

Bus stops are accessed by using same pedestrian crossings as major road crossings. Shared space serves several purposes and reduces required area. Proposal bus stops at the throughabout are shown in *Figure 22*.

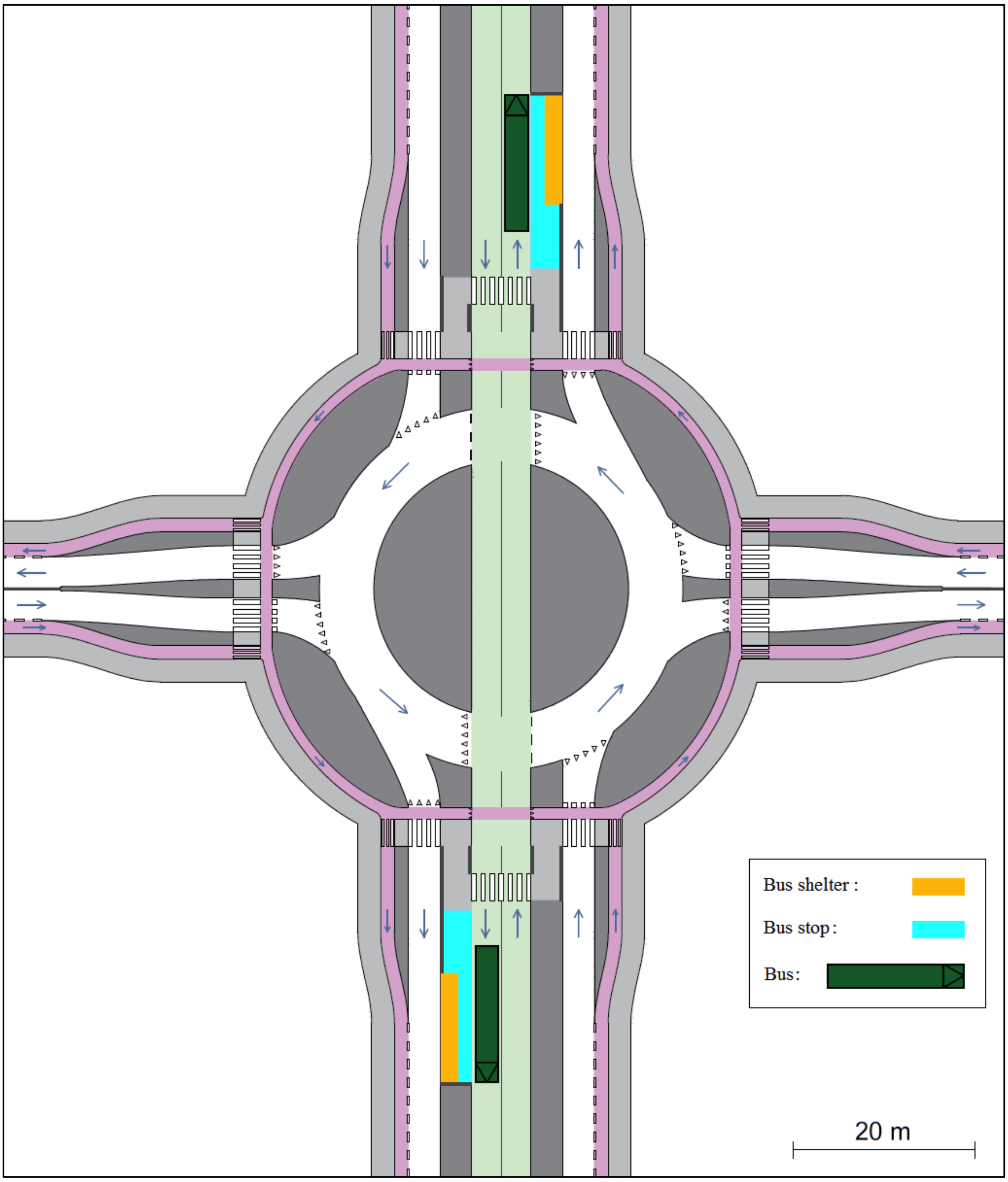

Figure 22: Bus stops in the experimental design.
[Figure made in AutoCAD]

Figure 22 shows implementation of bus stops after conflict points in the experimental design. Though principles are in focus, dimensions are based on the upcoming BRT-system of "Superbuss" in Trondheim in 2019 (Superbuss – Prosjekteringsanvisning for stasjoner; utkast, 2017). Bus stops of 3,5 x 20 metres are established after signalised pedestrian crossings on both sides of the throughabout with bus shelters of 1,95 x 12 metres. Fences displayed in bold black colour circumference the bus stop; preventing further passage away from the throughabout. Bus stops are not drawn in detail with tactile pacing and warning lines, but shows required area and principles.

During the design process, an alternative to bus stops after conflict points was establishing bus stops on the same side of the throughabout. The main advantage is improved access between the two bus stops, which is an inconvenient manoeuvre with the final design. Main reasons for establishing bus stops after conflict points are previously described traffic safety issues, and that the major road serves buses going strictly in north- and southbound directions. It is assumed that the major road does not serve numerous bus lines. Hence, users are not changing buses here for changing bus lines. Line changes are assumed to take place at other customised bus stops, or hubs.

4. METHOD

Method considers how the experimental design is analysed, and input data for obtaining best possible result. As this chapter also includes data and process, a separate data chapter is not included. In the scientific article, data and method are two separate chapters as input data are briefly listed. Discussion of method, process and input parameters are assembled in this chapter.

Implementing a new design in the road network induce changes in current traffic situation and driving behaviour. Observing changes is of importance regarding capacity, behaviour, and traffic safety. The experimental design aims for improved traffic flow for buses and cyclists, without causing excessive inconvenience for other traffic groups. Additionally, high level of traffic safety is to be preserved. Resulting changes can be retrieved by testing the scenario in full-scale, small-scale a model, test sub-parts of the design, or use traffic software to simulate and analyse. In this report, assessments of the design are based on quantitative output data and simulations with data programs.

4.1 Data programs

Occurring effects in new designs can be observed by data models. Data programs constitute visual and quantitative analyses of a theoretical implementation. (Aakre, 2016b, p. 13) states advantages with usage of data tools in traffic assessment. Analysing new road geometries by software is often less time consuming than implementing a full-scale test, and often less expensive. Also, it retains the experiment in a controlled environment without interrupting existing traffic. Evaluating the design in a safe, controlled environment is of special importance as this design is not yet existing in the current road network.

Traffic software create a simplified situation of reality, though several programs consider different driving behaviours. Additional to previously described advantages, traffic assessment by data tools have associated downsides (Aakre, 2016b, p. 14). Being a simplification of reality, calibration and validation is desired for valid output. Additionally, data modelling can be more time- and cost consuming than other assessment methods, also executional demanding. Several traffic situations demand extensive and detailed input data; challenging to retrieve. Also, misuse of modelling programs is a possible factor, especially relevant for this thesis as the author have meagre experience with such data tools. Thus, close monitoring with supervisor Arvid Aakre is engaged; an experienced professional for traffic assessment with several data tools.

Data tools operating on micro- or mesoscopic levels are preferable as the road design to be investigated is of relatively small size. There exist several programs applicable for such analyses; e.g. *CORSIM, PARAMICS, SIMTRAFIC, SYNCHRO, CAPCAL,* etc. *SIDRA INTERSECTION* and *AIMSUN* are programs the supervisor of this thesis have immense experience with; suited for analysing, calculate, and simulate effects. Another microscopic program; *VISSIM,* is also applicable. VISSIM has a more developed bicycle model compared to AIMSUN, but the integration between vehicles and pedestrians is less complex (Uteng and Taylor, 2015, p. viii). Due to a greater network of experienced persons with AIMSUN and SIDRA INTERSECTION, VISSIM is not used.

SIDRA INTERSECTION implies to be especially suited for simple analyses of intersection designs without complicated geometries, and AIMSUN for intersections with untraditional geometries (Røys, 2015, p. iv). Hence, SIDRA INTERSECTION is used for analysing only the conflict point between buses and general purpose traffic, and AIMSUN for the full design with all transport groups interacting. Analyses and simulations constitute an important basis for weighting the design with varying traffic situations regarding traffic volumes and behaviour.

4.1.1 Calibration and validation

Calibration and validation ensures that utilized data constitute models comparable to real situations. Calibration is adjustment of parameters for attaining realistic results, and validation is comparison of results to other independent data sets.

Calibrating models require comparable data sets, constituting a basis for adjusting parameters to meet a realistic situation. Validating model results require external, independent sets of results. Validation is most qualifiable when comparing to similar traffic situations. Model results can then be approached to realistic data by calibration and validation each iteration until sufficient compliance.

Validating new designs are challenging as data from an equal situation are not retrievable. Some designs can be validated to some extent by other proportionate traffic situations, while other designs are not comparable with current road network. Validation of the experimental design is difficult as the design is not found other places. Segregated meridian busways through the central island of roundabouts exists, though not many countries have such throughabouts. Also, a continuous network of cyclists around roundabouts exist, but not found in combination with a throughabout.

A comparable data set to the experimental design was not found. Observations from unsignalised throughabouts in Oslo was unsuccessfully inquired from the Norwegian Public Roads Administration and the company administrating all public transport in Oslo *Ruter AS*. Hence, calibration and validation of the experimental design are not performed in this report. Parameters are adjusted to meet a realistic situation, but results are not compared for ensuing parameter optimisation.

4.2 SIDRA INTERSECTION

SIDRA INTERSECTION is a program that was first introduced in 1984 as SIDRA; *Signalised & unsignalised Intersection Design and Research Aid* (Akçelik and Associates Pty Ltd, 2016). The disclosed acronym explains the essence of the program; a tool for analysing both signalised and unsignalised intersections. The program has been under constant development since the beginning, with latest version being SIDRA INTERSECTION 7.0.7. The newest version available at the University's computer labs is SIDRA INTERSECTION 7.0.5; hence utilized version in this thesis.

In the following, relevant information about the program for this thesis is described. This is based on the user guide (Akçelik, 2017); advised to read for supplementing information.

The program is analytic and deterministic, meaning no randomness in the program for set conditions. Mathematical equations are computed identically and parameters do not vary with different runs. Hence, one output is produced per initial state. SIDRA INTERSECTION allows modelling with different vehicle types; e.g. light vehicles, heavy vehicles, buses, bicycles, trams etc., but calculations are based on groups of vehicles. Due to equal behaviour per vehicle group, it operates on a mesoscopic level; meaning in between micro- and macroscopic.

Output data are based on Origin-Destination movements and provides information of capacity, timing, and performance. Capacity and timing include delays, queue lengths, and stop rate. Performance includes operation costs, fuel consumption, and emission models based on local parameters and conditions. As this report focus on traffic management; capacity and timing are considered. Results are displayed both in picture and graph form by the individual movements or different movement groups. To obtain these data, several parameters are decided. Firstly, geometry is set with type of intersection or roundabout, and number of lanes of the different entries. Input data related to a signalised or unsignalised design is then decided, followed by vehicle and driving behaviour parameters.

Gap acceptance is defined by *critical time gap* and *follow-up headway* for vehicles in the program, relevant at conflict points with give way regulations. The program uses *SIDRA Standard (Akçelik M3D)* as default Gap acceptance.

In SIDRA INTERSECTION, total delay is measured by two different delays; *geometric* and *stop-line* delay. Geometric delay is the additional time spent driving through an intersection area caused by the geometric design. This is due to necessary speed reduction. Presence of other vehicles does not affect geometric delay. Stop-line delay is delay caused by other vehicles at the intersection due to giving way and standing in queue. These two delays constitute the total delay for affected vehicles; *control delay* in SIDRA INTERSECTION.

Observed queues are measured in two different ways; *back of queue* and *cycle-average queue*. *Back of queue* is a measure of potential queue at end of longest occurring queue per cycle. *Cycle-average queue* is the average queue occurring in the system. (Akçelik, 2017, p. 474) describes an approximate relation between simulated average *back of queue* and *cycle-average queue* at roundabouts. The relation is a linear formula: $y = 2{,}6007x - 0{,}3766$, where y represents average *back of queue*, and x represents *cycle-average queue*.

Optionally, queues are measured with a quantile. Thus, extreme queues during the model run are ignored. Hence, most frequently occurring queues are in focus. A quantile of 95 % is used as a default value in the program, generally considered good for design purposes (Akçelik, 2017, p. 368).

Average delay per vehicle is calculated in the program by dividing total delay on number of vehicles; relatable measure for drivers in the system. Average delay can be measured for specific lanes or the whole system.

4.2.1 Objectives

SIDRA INTERSECTION is used for analysing conflict points in the circulatory lane between general purpose traffic and buses. This gives an indication of occurring queues and delays by different volumes of general purpose traffic and bus frequencies. *Back of queue*, *cycle-average queue*, and *average delay per vehicle* are investigated. One conflict point is modelled in SIDRA INTERSECTION; northern conflict point with income general purpose traffic from right side.

The circulatory lane is exposed to queues due to absolute priority of buses at the throughabout. Hence, investigating conflict points in the circulatory lane are of interest. Though SIDRA INTERSECTION facilitate modelling with pedestrians, conflict points only concern motorised vehicles; buses and general purpose vehicles.

4.2.2 Data and process

Modelling this conflict point in the experimental design requires input parameters of traffic, driving behaviour, and geometry. Data and process in SIDRA INTERSECTION is described in this subchapter. Program parameters not mentioned in the following are used with default values.

The conflict point is constructed by creating a give way regulated intersection with one lane crossing a two-lane major road. The single lane cross the two-lane busway by approach from the right side, compliant with both conflict points in the circulatory lane at the throughabout. Lane width, directions, and movements are set in *site inputs*.

Transport modes are allocated to associated lanes by editing “Movement Classes”. Only buses are inserted for the busway. For the circulatory lane, both light and heavy vehicles are inserted.

(Statens vegvesen (N200), 2014b, p. 209) states design values of percentage heavy vehicle share on different road types in Norway. The handbook states a heavy vehicle share of 10 % on feeder roads; suitable road type for the experimental design. Hence, a heavy vehicle share in the circulatory lane for general purpose traffic is set to 10 %. Remaining 90 % constitute light vehicles.

Dimensions of vehicles are used with default values in SIDRA INTERSECTION. Adjustments are not made as the purpose of the model is giving a rough indication of occurring queues. *Vehicle length* and *queue space* are shown in *Table 9*.

Table 9: Vehicle lengths and queue spaces in SIDRA INTERSECTION

	Vehicle length *[m]*	**Queue space** *[m]*
Buses	10	13
Light vehicles	4,5	7
Heavy vehicles	10	13

Vehicle lengths and *queue spaces* are shown in *Table 9*. *Queue space* describe the space between queueing vehicles in front and behind, including vehicle length. As queues only occur in the circulatory lane, *queue space* is excessive for buses.

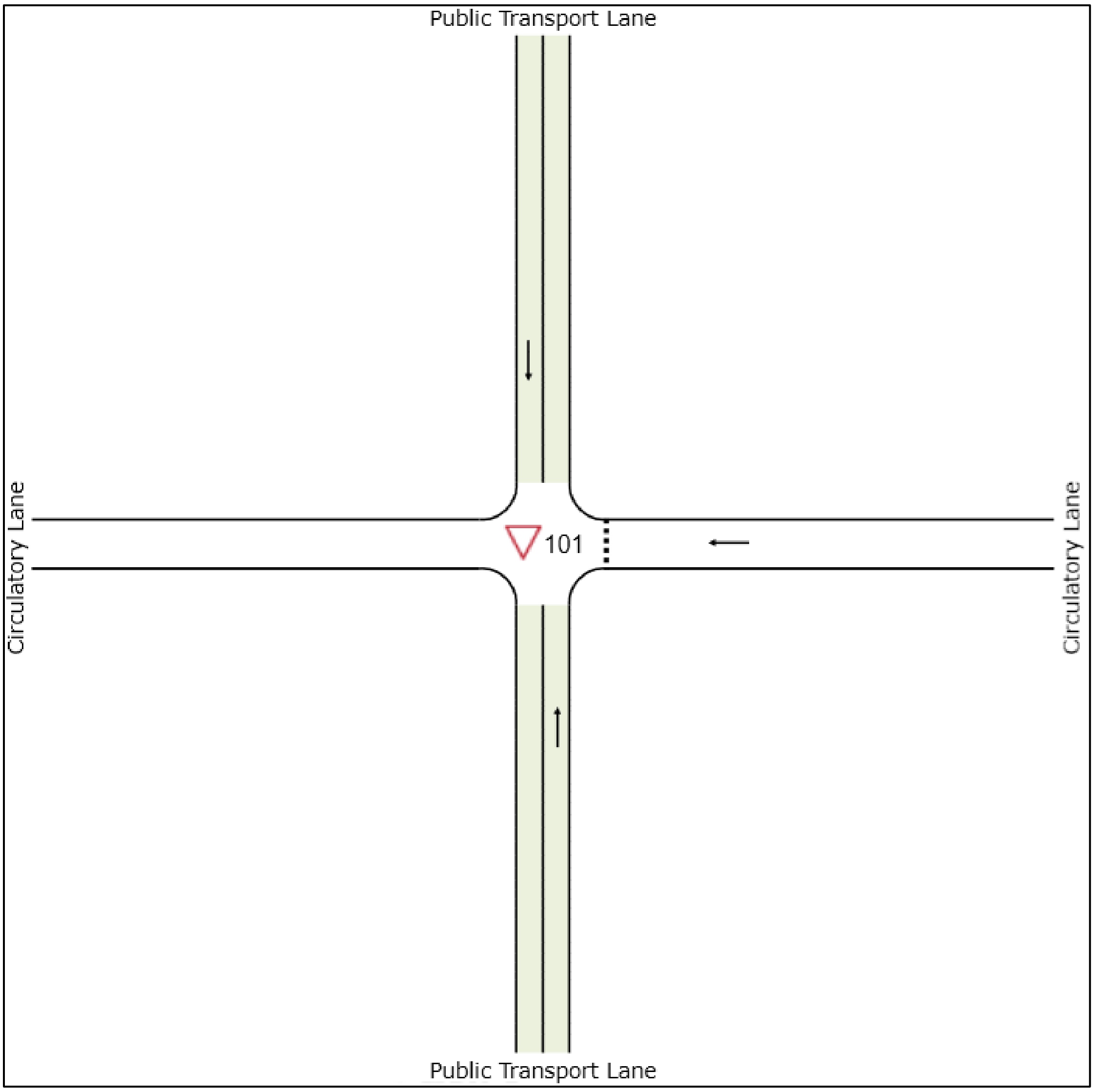

Figure 23: Model area in SIDRA INTERSECTION 7.0.5.
[Source: screen dump from the program]

Figure 23 shows a screen dump of the model in SIDRA INTERSECTION. The public transport lane is highlighted with green colour. The circulatory lane is regulated to give way for approaching buses. Direction arrows display traffic movements.

Bus lanes are designed with a speed limit of 40 km/h at the throughabout, see *Chapter 3.3*. Buses are assumed to maintain this speed due to absolute priority; hence, bus speed is set to 40 km/h. Chosen bus speed in the program does not consider bus stops after conflict points. Suggested bus stops in *Chapter 3.4* result in a reduced speed over conflict points, especially the last conflict point. Reduced bus speed increases passing time, resulting in longer delays for general purpose traffic.

The speed of general purpose vehicles is likely to vary due to differences in driving behaviour, entry points, and traffic volumes. Approach speed in front of the bus lane is set to 25 km/h, though a more dynamic speed profile is assumed.

Two Way Sign Control calibration (TWSC) is excluded for the circulatory lane. Thus, values of gap acceptance can be specifically defined. Hence, calibration parameters for determining *critical time gap* and *follow-up headway* are not included. As buses are provided with absolute priority, *critical time gap* and *follow-up headway* are not relevant for bus lanes.

Critical time gap and *follow-up headway* for light vehicles are set to 5,0 and 3,0 seconds, respectively. These values are calibrated for heavy vehicles in the program with a factor of 1,5. As the design does not yet exist, experienced values cannot be retrieved. Hence, *critical time gap* and *follow-up headway* is estimated in cooperation with supervisor Arvid Aakre. Assumed average driving behaviour is based on values at roundabouts in the 6'th Edition of the Highway Capacity Manual (Spack, 2017). The manual describes *critical time headway* instead of *critical time gap*, resulting in a larger value than the equivalent *critical time gap*. For one approaching lane and one circulating lane, *critical time headway* is 4,99 seconds in the manual. In comparison, *critical time gap* is assumed to be 5,0 seconds for vehicles in the investigated design; larger equivalent value for *critical time headway*. *Follow-up headway* is increased from 2,609 to 3,0 seconds. Values in the Highway Capacity Manual apply for traditional roundabouts. As users are not familiar with the experimental design, more conservative values are assumed. 10 % heavy vehicles and 90 % light vehicles in the circulatory lane constitute an average *critical time headway* and *follow-up time* of 5,25 and 3,15 seconds, respectively.

Peak Flow Factor considers changes in flow over periods. *Peak flow* includes an increased traffic volume over a *Peak Flow Period*. *Peak Flow Period* is set to 30 minutes in the model of the modelling time of 60 minutes. For the circulatory lane, a peak flow factor of 95 % is included, resulting in 5 % more general purpose vehicles per scenario. Bus lanes are assumed to serve evenly distributed traffic by scheduled public buses. Hence, *peak flow factor* is not included for the public transport lane.

Quantitative investigation of the conflict point is done by testing different flow frequencies of buses, and vehicles in the circulatory lane. Flow frequencies are listed *Table 10* and *Table 11*.

Table 10: Tested flow frequencies in the public transport lane

Buses per hour *[bus/h]*	***Average bus frequency***
20	*180 sec*
40	*90 sec*
80	*45 sec*
120	*30 sec*
160	*22,5 sec*
200	*18 sec*
240	*15 sec*

Table 10 shows tested bus frequencies in the model. Values represent passage frequency at the crossing; hence, alternating movements from both sides. Thus, bus lanes are

allocated with half the flow per approaching bus lane in the program. Lowest tested frequency is one bus every 180 seconds. Highest frequency is one bus every 15 seconds.

Table 11: Tested flow frequencies in the circulatory lane

Vehicles per hour *[veh/h]*	***Passage vehicle frequency***
300	*12,0 sec*
350	*10,3 sec*
400	*9,0 sec*
450	*8,0 sec*
500	*7,2 sec*
550	*6,5 sec*
600	*6,0 sec*

Table 11 shows tested vehicle frequencies approaching the conflict point. This traffic stream approaches from one side, and is tested with an interval of 50 veh/h per scenario. Lowest tested frequency is one vehicle every 12,0 seconds. Highest frequency is one vehicle every 6,0 seconds.

4.3 AIMSUN

AIMSUN is an acronym for *Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks*; established in 1989 as GETRAM. The program can operate on microscopic and mesoscopic levels, also perform hybrid simulations (Transport Simulation Systems, 2016). Analysing individual vehicles and their interactions is of interest for the experimental design. Hence, microscopic operations are performed in this thesis. AIMSUN provides visual presentation when running the model. This enables observation of individual driving behaviour, effects, and visual validation of the model. AIMSUN 8.2.0 is the latest version; utilized in this report.

In the following, information about the program relevant for this thesis is described. This is mainly based on Kristoffer Røys' Master's thesis (Røys, 2015, p. iv). Additionally, AIMSUN 8.2 User's Manual is used; advised to read for supplementing information (Transport Simulation Systems, 2017).

AIMSUN is a stochastic model; results differ with different model runs due to inclusion of variations. Movements vary by mathematical equations for the individual vehicles, and parameters vary by set deviations within maximum and minimum values. As results differ, several replications should be performed for valid results. Necessary number of replications for obtaining results of an average situation vary for different models. Replications should propose a clear trend in a normal distribution with an acceptable confidence interval.

Main elements in AIMSUN models are sections, nodes, intersections, roundabouts, and centroids. Sections are lanes with defined traffic directions; straight or curved. Nodes are established where several sections meet, and drivers must make a progressive section choice. Hence, nodes constitute intersections and roundabouts. Optionally, nodes can be established as a *yellow box*. Without a yellow box, drivers will follow the vehicle in front, resulting in queueing inside the node. This is prevented by establishing a yellow box. Vehicles are then not permitted to enter the intersection area; allowing other movements to happen without being blocked by queueing vehicles. Centroids generate and retract traffic to and from the model of different transport modes. Additionally, there are several other elements in the program; e.g. detectors, signal systems with custom-made control plans of phases, variable message signs (VMS), etc.

Traffic volumes and movements are inserted by Origin-Destination matrices or allocating specific volumes to the outer parts of the constructed road network. With Origin-Destination matrices, choice of direction at crossroads are set in matrices with associated volumes. By allocation of traffic volumes from outside the network, direction choices are not pre-set; hence, chosen during the simulation.

Variations during model runs are optionally pre-set in the program. A similar function to "Peak Flow Factor" in SIDRA INTERSECTION is not found in AIMSUN. Hence, effects of rush hours are investigated by making several matrices. Matrices can be customised or multiplied by a multiplication factor in the program for step-wise volumes and movements.

Vehicle movements depend on *global parameters*, *section parameters*, and *vehicle parameters*. As AIMSUN is time-stepped, these parameters impact movements per *simulation step* (Δt). One simulation step calculates and aggregates one situation into another, with set time interval between each simulation step. Chosen time interval impact the model largely as change in behaviour and reaction relies on simulation steps. Behaviour is constant until new calculations take effect by a new simulation step.

Global parameters affect all transport modes in the network regardless position; e.g. simulation step. Other global parameters are queue up speed, leaving speed, reaction time while driving and at stops, lane changing parameters, etc.

Section parameters consider parameters to different sections; e.g. speed limit, accepted speed over yellow box intersections, slope, etc. This impact vehicles when entering new sections with new parameter values.

Vehicle parameters describe properties of the vehicles in the model; e.g. length, width, maximum desired speed, maximum acceleration and deceleration, speed acceptance, etc. Parameters are set by mean values, optionally with deviations, minimum and maximum values to include variation for transport groups. Different transport modes have separate sets of vehicle parameter values.

AIMSUN's *Give Way Model* regarding driving behaviour is based on gap acceptance. Vehicles approaching a junction must make the decision of crossing the conflict zone or not based on acceptable gap and risk. The decision depends on position, speed, and acceleration of the approaching vehicle and other close by vehicles with higher priority. The program calculates whether the vehicle will accept to cross or not by listed parameters in *Table 12*.

Table 12: Parameters in AIMSUN's Give Way model

Parameters in the Give Way model
• Maximum Give Way Time • Initial Safety Margin • Final Safety Margin • Initial Give Way Time Factor • Final Give Way Time Factor • Visibility To Give Way • Visibility Along Main Stream

Maximum Give Way Time describes stop time before drivers reduce gap acceptance to a minimum for entering a conflict area. Long stop times result in acceptance of smaller gaps as drivers get more aggressive.

Initial Safety Margin is the time gap drivers need for accepting entry of a conflict zone. The value is based on time gap between the driver's vehicle and conflicting vehicle after theoretically entering the conflict area. Initial safety margin applies for vehicles newly arrived at the junction.

Final Safety Margin is the smallest time gap drivers accept between its vehicle and the conflicting vehicle for entering the conflict zone. This time gap applies for vehicles exceeding maximum give way time.

Initial Give Way Time Factor is a dimensionless factor constituting waiting time at stop before drivers accept smaller gaps when multiplied with *maximum give way time*.

Final Give Way Time Factor is a dimensionless factor constituting additional waiting time at stop before drivers accept the smallest gap when multiplied with *maximum give way time*.

Visibility To Give Way is the distance in front of a junction where vehicles start to use the Give Way model; called "Give Way model application zone".

Visibility Along Main Stream is the distance a vehicle has for observing approaching vehicles on a crossing road with higher priority. Vehicles on the high priority road outside this zone are not considered by the give way regulated vehicle at the junction as they are not within sight.

AIMSUN 8.2.0 facilitates modelling with all relevant transport modes for the experimental design; buses, general purpose vehicles, cyclists, and pedestrians. Cyclists and pedestrians are new features in AIMSUN. These transport modes are not yet fully developed; e.g. not visualised in 3D simulations in utilised version. Optionally, *Legion* can be bought and used as an established, additional software for pedestrian modelling. Legion is not used in this thesis.

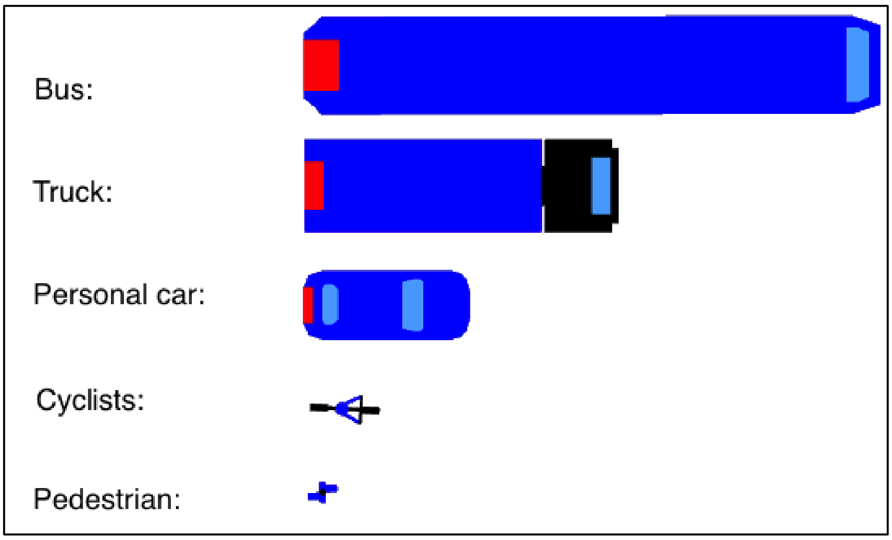

Figure 24: 2D presentation of transport modes in AIMSUN 8.2.0.
[Source: edited screen dump from the program]

Figure 24 shows the 2D presentation of different transport modes in AIMSUN: bus, truck, personal car, cyclist, and pedestrian. Varying sizes of occurring vehicles, cyclists, and pedestrians are implementable in the program for adaption to realistic situations.

Buses can be allocated to dedicated routes in the network. Bus routes are established with appertain bus stops, associated departure times, and frequencies. Stop time at bus stops are defined, optionally with deviation. Departure time from centroids can also be set with a deviation.

Most parameters in AIMSUN are set with a mean value. Optionally, deviations, minimum and maximum values are added to include random behaviour and dimensions for realistic variety. Deviations are mostly included based on a truncated normal distribution between set minimum and maximum values.

Output data are based on the full network, sections, lanes, turns, and nodes. Optionally, results are also displayed by detectors or defined routes. AIMSUN investigates flow, speed, density, travel time, delay, queue lengths, stop time, number of stops, total distance travelled, and total travel time. Results are displayed by specific or all transport modes.

4.3.1 Objectives

AIMSUN is used for analysing the full design with all transport modes interacting. This gives an indication of occurring delays and acceptable traffic volumes for respective movements of different transport groups.

Chosen traffic volumes constitute a basis for assessment of the experimental design. As principles of a new design is investigated, an initial state is to be established for further work and development; aimed in this thesis. AIMSUN allows modelling of the full experimental design with all relevant transport modes. This constitute an important basis for investigation of effects and occurring interactions.

4.3.2 Data and process

Data used for modelling and simulations in AIMSUN is described in the following. Parameters in the program not mentioned are used with default values.

Model of the experimental design is by best efforts drawn to geometric conformation with the detailed drawing in *Figure 12*. AIMSUN does not support equally detailed drawing; hence, geometric tricks are used to adjust the model to best extent.

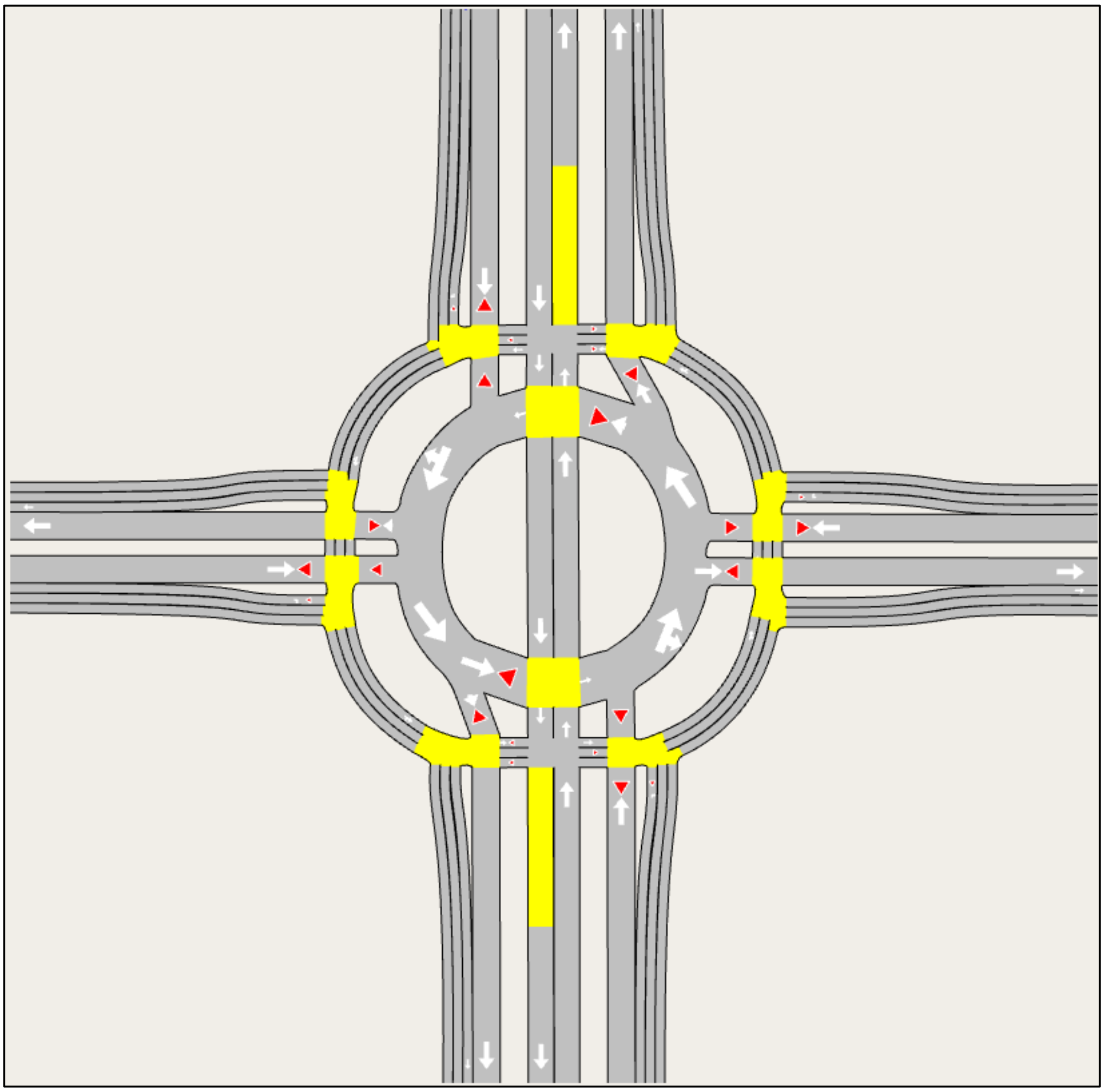

Figure 25: Model area in AIMSUN 8.2.0.
[Source: screen dump from the program]

Figure 25 shows a 2D-drawing of the model in AIMSUN. Conflict points are featured in the figure as connected major and minor roads are longer than displayed 40 metres; 100 metres in the model. Yellow colour displays both yellow box nodes and two bus stops. The two bus stops are established in public transport lanes outside circulating traffic. Yellow boxes are established for preventing queueing inside the nodes blocking other traffic. Yellow box speeds are used with default values for general purpose traffic, and by speed limit for buses.

Established bus stops constitute a reduction in speed through the last conflict point in the circulatory lane, and last bike and pedestrian crossings. Though deviation is included for public transit lines, tested bus frequencies never exceed bus stop capacity of one bus. Time at bus stop is set to 25 seconds, with deviation of 5 seconds.

As sidewalks are not one-way regulated, two lateral lanes are established for facilitating both directions of pedestrian movements. Outer lanes facilitate anticlockwise movements, and clockwise in inner lanes. Hence, the full network is used, and roads are crossed from both sides.

Road types in the model are adjusted to conform with desired speeds, lane widths, breaking intensity, and gap acceptance of different transport modes. Road types are customised by creating copies of existing road types, and adjust parameters. Maximum speed, lane width, breaking intensity, and original road type are shown for adjusted road types in *Table 13*. Gap acceptance by *Initial Safety Margin*, *Final Safety Margin*, *Initial Give Way Time Factor*, *Final Give Way Time Factor*, *Visibility To Give Way*, and *Visibility Along Main Stream* are shown in *Table 14*.

Table 13: Adjusted road types in AIMSUN

Utilized road type *(name in AIMSUN)*	**Original road type**	**Max. speed** *[km/h]*	**Lane width** *[m]*	**Breaking intensity**
A-Bus Lane	Tram	40	3,25	High
A-General Purpose Lane	Secondary	40	3,5	Regular
A-General Purpose Lane (Wait-space)	Secondary	30	6,0	Regular
A-Bike lane	Cycleway	15	1,25	Regular
A-Pedestrian area	Pedestrian Area	6	1,25	Regular

Table 13 shows adjusted road types in AIMSUN. Road types are allocated to each transport mode, except for general purpose traffic. General purpose traffic is customised at waiting spaces in the circulatory lane; *A-General Purpose Lane (Wait-space)*, where maximum speed and driving behaviour are adjusted. *A-General Purpose Lane* is used at other general purpose traffic segments as road type. In the circulatory lane, segments are widened to widths of 6 metres.

Bus lanes are adjusted to *high* breaking intensity due to assumed efficient operation for improved bus service. This has an impact of speed and travel time over last conflicts point related to breaking in front of the bus stop.

As segments are one-directional in AIMSUN, two sidewalks are modelled with half the width to facilitate both directions. Hence, sidewalks are 1,25 metres wide per direction.

Table 14: Gap acceptance in AIMSUN

Road type	**Initial safety margin** *[sec]*	**Final safety margin** *[sec]*	**Initial give way time factor**	**Final give way time factor**	**Visibility to give way** *[m]*	**Visibility along main stream** *[m]*
A-Bus Lane	3	1	1	2	25	60
A-General Purpose Lane	3	1	1	2	30	60
A-General Purpose Lane (Wait-space)	3,5	1,5	1	2	30	60
A-Bike lane	3	1	1	2	50	144
A-Pedestrian area	3	1	1	2	50	8

Table 14 shows gap acceptance by road types in the model. *Initial safety margin* and *final safety margin* are conservatively adjusted for waiting spaces in the circulatory lane; *A-General Purpose Lane (Wait-space)*. Hence, drivers require longer gaps for crossing.

General purpose traffic is distributed with 10 % heavy vehicles and 90 % light vehicles as lanes are assumed to be associated with feeder roads (Statens vegvesen (N200), 2014b, p. 209). Default values of "truck" are used for heavy vehicles in AIMSUN. Other transport modes are adjusted to meet Norwegian standards (Statens vegvesen (N100), 2014a, p. 151-154).

Table 15: Dimensions of transport modes in AIMSUN

	Length *[m]*				**Width** *[m]*			
	Mean	*Deviation*	*Min.*	*Max.*	Mean	*Deviation*	*Min.*	*Max.*
Buses	15	-	-	-	2,55	-	-	-
Light vehicles	4,8	*1,3*	*3,5*	*5,2*	1,8	*0,1*	*1,7*	*1,9*
Heavy vehicles	8	*2*	*6*	*10*	2,25	*0,2*	*2*	*2,8*
Cyclists	1,8	-	-	-	0,75	*0,1*	*0,65*	*0,85*
Pedestrians	0,4	*0,2*	*0,3*	*0,8*	0,7	*0,1*	*0,5*	*1,0*

Table 15 shows lengths and widths of transport modes in the model by mean value. Additionally, deviation, minimum and maximum values are included for variations. Dimension of buses are set without deviation as the busway is assumed to serve uniform public buses. Motorcyclists are not thoroughly considered, but included as a simplification by minimum value and deviation of light vehicles.

Origin-Destination movements of the different transport modes are defined by associated centroids connected to lanes. In this model, centroids generate and retract travelers from outside the network to and from dedicated lanes.

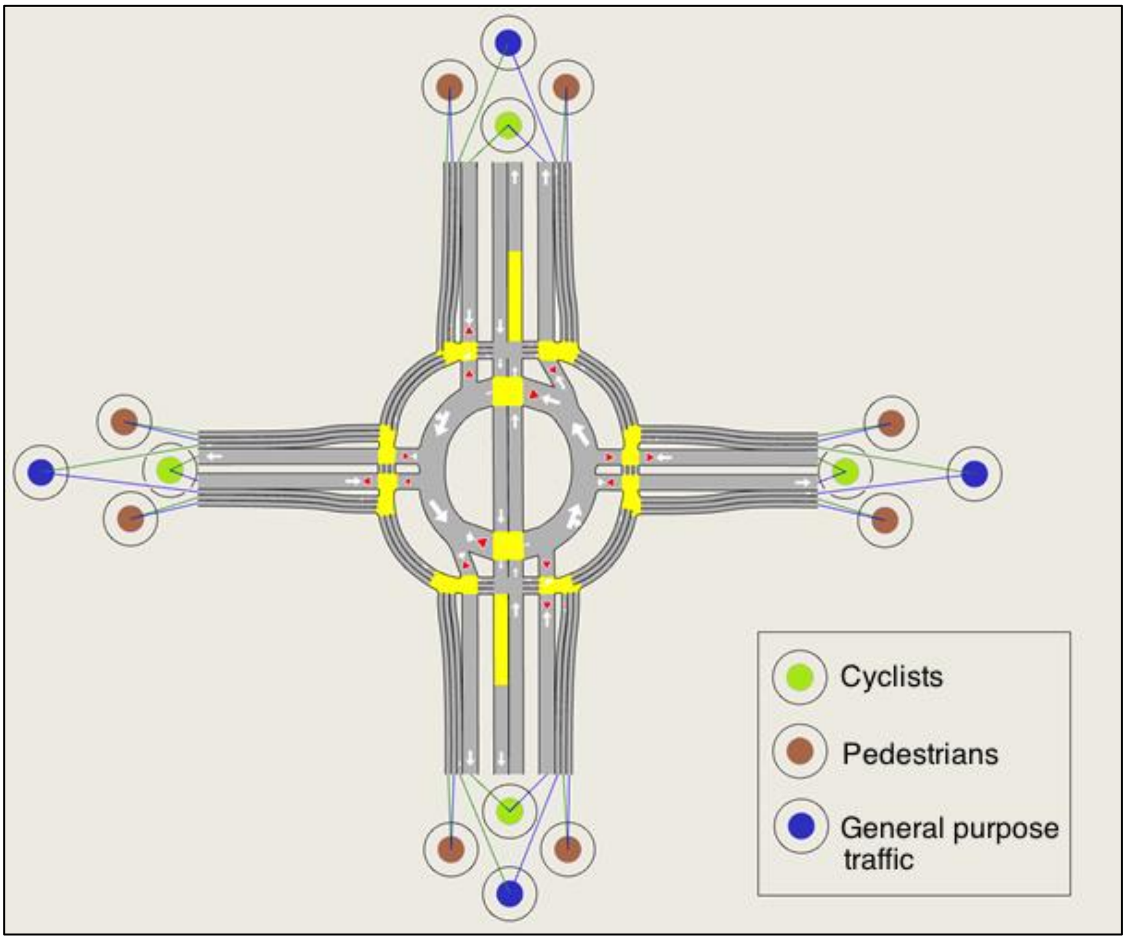

Figure 26: Placement of centroids in AIMSUN.
[Source: edited screen dump from the program]

Figure 26 shows centroids in the model for generating and retracting traffic of different transport modes. Centroids are not used for buses as bus departures are defined by *Public Transit Plans* in the program. As a simplification, bike and pedestrian movements associated with bus stops are not considered in the model.

Scenarios are investigated by alternating flows of general purpose traffic, buses, and cyclists/pedestrians. Cyclists and pedestrians are assembled as a simplification to reduce quantity of scenarios; rational as presence of these transport modes are often related. Each transport mode is modelled with three different flow intensities; *low*, *intermediate*, and *high*.

Table 16: Bus frequency intensities in AIMSUN

	Low	**Intermediate**	**High**
Bus frequency, per lane	10 bus/h	15 bus/h	30 bus/h
Departure interval, per lane	6 min	4 min	2 min

Table 16 show tested bus frequencies; *low*, *intermediate*, and *high* flow intensity. Values apply per lane, constituting a total bus frequency at the throughabout of 20, 30, and 60 buses per hour. This means an average passage through each conflict point every 3, 2, and 1 minute, respectively.

Buses are included by *Public Transit Plans* per lane in the program. Bus departures are set with a deviation of 20 seconds per line for all scenarios. Time at the bus stop is set to 25 seconds, with deviation of 5 seconds.

Movements of general purpose traffic will vary largely from site to site. As principles of the experimental design are investigated, a percentage distributed scenario is defined. This is used as basis for further assessment with varying traffic volumes by different flow intensities. Though symmetrical approaches and departures from major and minor roads are utilized, values are based on Hillevågsveien, Stavanger (Bråtveit, 2016, p. 39). Total approach from major and minor roads in the model conform sufficiently; 77,8 % and 22,2 %, respectively.

Table 17: Flow intensities of general purpose traffic in AIMSUN

Movement	**Low** *[veh/h]*	**Intermediate** *[veh/h]*	**High** *[veh/h]*	***Percentage distribution***
Approach from each major road:				
Straight movement	312	415	518	*74 %*
Left turn	50	67	84	*12 %*
Right turn	50	67	84	*12 %*
Return	8	11	14	*2 %*
SUM:	*420*	*560*	*700*	*100 %*
Approach from each minor road:				
Right turn	48	64	80	*40 %*
Straight movement	22	29	36	*18 %*
Left turn	48	64	80	*20 %*
Return	2	3	4	*2 %*
SUM:	*120*	*160*	*200*	*100 %*
TOTAL:	**1080**	**1440**	**1800**	

Table 17 shows general purpose traffic volumes for different movements by flow intensities. All flow intensities are equally distributed in percent for each movement, with varying volumes. *Low* flow intensity constitutes 25 % less vehicles than *intermediate*, and *high* 25 % more. Volumes are allocated to 90 % light vehicles and 10 % heavy vehicles in Origin-Destination-matrices in AIMSUN. As subdivisions result in decimals in matrices, some cells are adjusted in the program by symmetry.

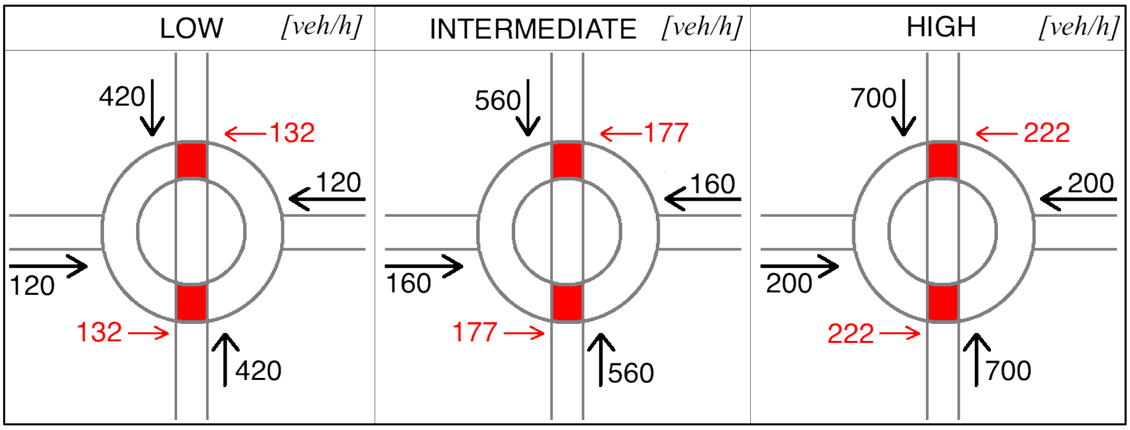

Figure 27: Approaching volumes and crossings of conflict points in the circulatory lane. [Figure made in Paintbrush]

Figure 27 shows approaching volumes of general purpose traffic at entries, and number of vehicles crossing conflict points in the circulatory lane. 25 % of all vehicle movements at the throughabout cross the busway in tested scenarios.

Table 18: Flow intensities of cyclists in AIMSUN

	Low *[cyclists/h]*	**Intermediate** *[cyclists/h]*	**High** *[cyclists/h]*
To/from same centroid	5	6	7
To/from different centroids	15	23	31
TOTAL:	**200**	**300**	**400**

Table 18 shows flow intensities of cyclists in AIMSUN. *Low* flow intensity is defined as 200 cyclists per hour, 300 cyclists/h as *intermediate*, and 400 cyclists/h as *high*. Some cyclists enter and leave by the same road, while most bike to and from different connecting entries.

Table 19: Flow intensities of pedestrians in AIMSUN

	Low *[ped/h]*	**Intermediate** *[ped/h]*	**High** *[ped/h]*
To/from same road	2	3	4
To/from all other centroids	6*	12	18*
To/from same centroid	-	-	-
TOTAL:	**300**	**600**	**900**

*Selected Origin-Destination-cells adjusted in the program to match total pedestrian flow

Table 19 shows pedestrian flows for different flow intensities in AIMSUN. 600 pedestrians per hour are defined as *intermediate* state, with 50 % reduction as *low*, and 50 % increase as *high*. Two centroids are placed at each connecting road; one per two-way sidewalk. No pedestrians are generated to enter and depart from the same centroid as this movement is not realistic. Some pedestrians cross roads for leaving by the same road. Most pedestrians enter and depart from centroids at different connecting roads.

Modelled scenarios run over 60 minutes with a *warm-up time* of 10 minutes. *Warm-up time* changes initial state from no traffic in the model to a filled-up network by set traffic volumes. This makes output data more realistic as delays are not reduced by absence of other traffic in the first minutes of the model run.

5. RESULTS

Results considers output data from models in SIDRA INTERSECTION and AIMSUN. In the scientific article, *back of queue; in vehicles* is presented from SIDRA INTERSECTION. *Back of queue; in metres* is included in this report, together with *cycle-average queue length* and *average delay per vehicle*. In AIMSUN, occurring delays and associated mean queue for different scenarios are investigated. Delays are elaborated in the scientific article, and mean queue in this report. Deviation is included for mean queue for considering variations at different traffic scenarios.

5.1 SIDRA INTERSECTION

Different flow frequencies of buses and general purpose traffic constitutes a 7x7 matrix with 49 different combinations and results per output parameter.

Back of queue is presented by number of vehicles in the scientific article as the most useful performance measure due to short dedicated waiting spaces for circulating traffic (Akçelik, 2017, p. 473). *Back of queue* measures number of potential vehicles from the stop line to the last vehicle affected by the queue. Hence, it is not a measure of vehicles present in the queue, but relative queue capacity. As queues are generated and resolves in cycles, *back of queue* is measured each cycle. With a 95 % quantile, displayed values are not exceeded 95 % of the time. *Table 20* shows *back of queue* in metres.

Table 20: Back of queue [m] at conflict points in circulatory lane.

QUEUE 95 % BACK, CIRCULATORY LANE [m]							
	300 veh/h	**350 veh/h**	**400 veh/h**	**450 veh/h**	**500 veh/h**	**550 veh/h**	**600 veh/h**
20 bus/h	10,1	12,5	15,3	18,4	22,0	26,3	31,4
40 bus/h	10,4	12,9	15,7	19,0	22,7	27,1	32,4
80 bus/h	11,1	13,8	16,8	20,2	26,8	36,8	49,5
120 bus/h	11,9	14,7	20,4	27,7	36,7	47,9	62,3
160 bus/h	13,2	18,6	25,0	33,0	42,9	55,6	72,4
200 bus/h	15,9	21,6	28,7	37,5	48,8	63,6	84,3
240 bus/h	18,1	24,4	32,2	42,2	55,4	73,8	101,7

Occurring *back of queues* span between 10 and 100 metres for the different scenarios. As the conflict point is unsignalised, rapid cycles allow some *back of queue* due to rapid queue dissolution. *Back of queue* increases for increased vehicle and bus flow, with greater intervals at larger flows. Lower traffic volumes in the circulatory lane allow higher bus frequencies, up to a certain point. For circulating traffic volumes of 500 veh/h and up, even the smallest tested bus frequency cause a *back of queue* more than 22 metres. The most frequent bus departure of one bus every 15 seconds. This is an extreme value; causing 73,8 metres *back of queue* for circulating flow of 550 veh/h, and 101,7 metres for 600 veh/h.

Back of queue is related to *cycle-average queue*. *Cycle-average queue* is the average number of queueing vehicles each cycle, also relevant for assessment of traffic efficiency at conflict points in the circulatory lane. (Akçelik, 2017, p. 473) states a relation by a linear regression line for simulated situations: $y = 2{,}6007x - 0{,}3766$, where y is *back of queue*, and x is *cycle-average queue*. Based on this relation, *cycle-average queues* are displayed in *Table 21*. Results are coloured by degree of severity; *green* as not severe, *yellow* as intermediate, and *red* as severe.

Table 21: Cycle-average queue [veh] at conflict points in circulatory lane.

CYCLE-AVERAGE QUEUE, CIRCULATORY LANE [veh]							
	300 veh/h	**350 veh/h**	**400 veh/h**	**450 veh/h**	**500 veh/h**	**550 veh/h**	**600 veh/h**
20 bus/h	0,6	0,8	0,9	1,1	1,3	1,5	1,7
40 bus/h	0,7	0,8	1,0	1,1	1,3	1,5	1,8
80 bus/h	0,7	0,8	1,0	1,2	1,5	2,0	2,6
120 bus/h	0,8	0,9	1,2	1,5	2,0	2,6	3,3
160 bus/h	0,8	1,1	1,4	1,8	2,3	3,0	3,8
200 bus/h	1,0	1,2	1,6	2,0	2,6	3,4	4,4
240 bus/h	1,1	1,4	1,8	2,3	3,0	3,9	5,3

Legend: ≥ 1,0 veh | 1,1 - 2,0 veh | > 2,0 veh

Cycle-average queues of one vehicle or less is classified as not severe; assumed to not cause blockage of other traffic in the circulatory lane. This is related to the designated waiting space; designed for queueing of one design personal car. As traffic lanes are widened before the waiting space and at exit of the circulatory lane, queueing of an additional general purpose vehicle is provided without blocking the exit. As this is not intuitive, queues longer than one vehicle will most likely result in a more interrupted flow, displayed with yellow colour an intermediate state. More than 2 vehicles in *cycle-average queue* is set as severe.

Average delay per vehicle is the total delay in the lane divided by all adhered vehicles during the model run. Results from different traffic combinations are displayed in *Table 22*.

Table 22: Average delay [sec/veh] at conflict points in circulatory lane

AVERAGE DELAY, CIRCULATORY LANE [sec/veh]							
	300 veh/h	**350 veh/h**	**400 veh/h**	**450 veh/h**	**500 veh/h**	**550 veh/h**	**600 veh/h**
20 bus/h	0,2	0,2	0,2	0,3	0,3	0,3	0,3
40 bus/h	0,4	0,4	0,5	0,5	0,6	0,6	0,7
80 bus/h	0,8	0,9	1,0	1,1	1,3	1,8	2,3
120 bus/h	1,3	1,4	1,8	2,2	2,7	3,3	4,0
160 bus/h	1,9	2,3	2,8	3,3	4,0	4,8	5,8
200 bus/h	2,8	3,3	3,9	4,5	5,4	6,5	8,1
240 bus/h	3,7	4,3	5,0	5,9	7,1	8,7	11,3

Table 22 shows that low bus frequencies do not considerably impact different circulating traffic flows. Though more vehicles result in increased delay, higher vehicle volumes constitute more units to divide total delay by.

5.2 AIMSUN

Results in AIMSUN are based on 27 different scenarios at the throughabout. Volumes are varied by three different intensities of bus traffic, general purpose traffic, and assembled cyclists and pedestrians. Output data are produced by average values of 10 replications per scenario, assumed to give adequate results. As principles with the experimental design are investigated, number of replications does not constitute any weakness with results.

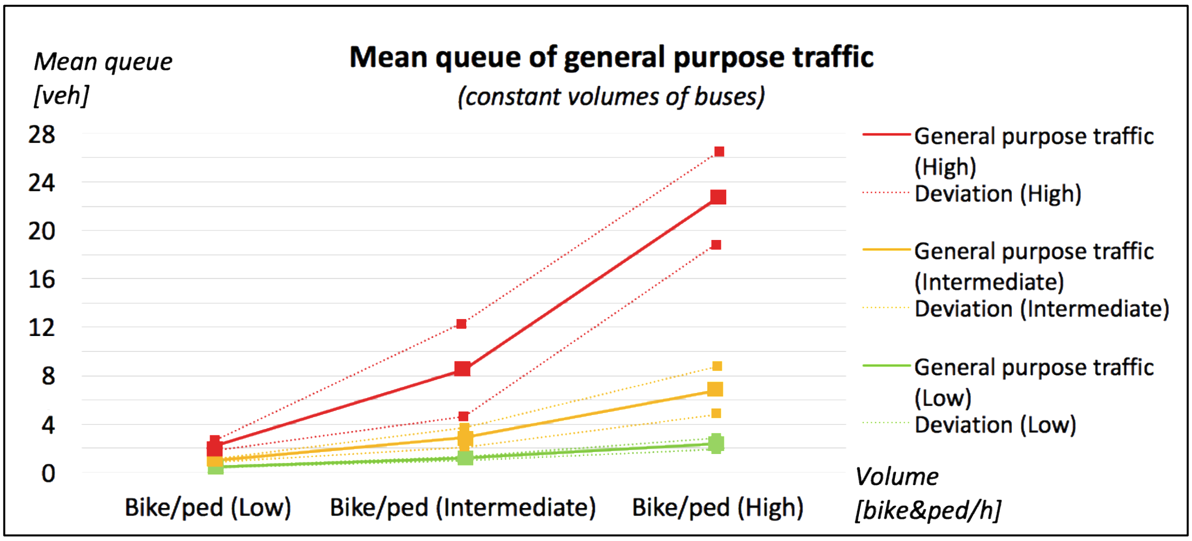

Figure 28: Mean queue [veh] of general purpose traffic with varying cyclist and pedestrian volumes. Values from AIMSUN

Mean queue in *Figure 28* shows occurring queues in the model measured in *vehicles*. *Mean queue* is directly related to *delays*; displayed in the scientific article. *Figure 28* is included to show deviation at different volumes of general purpose traffic, cyclists and pedestrians. Deviating values from average *mean queue* lines in the figure show the amplitude of variations; e.g. greater deviations mean that drivers are more likely to differ largely from average *mean queue*.

At low volumes of cyclists and pedestrians, *mean queues* are low. Deviations are also low; for all flow intensities of general purpose traffic. Deviations are more significant at scenarios with higher cyclist and pedestrian volumes. An additional trend is more deviation for longer *mean queues*; higher up on the y-axis. Low flow intensity of general purpose traffic result in low *mean queues* in all scenarios of different cyclist and pedestrian volumes. Associated deviations per scenario are low. This means that it is unlikely that drivers vary largely from *mean queue*.

6. DISCUSSION

Discussion considers the experimental design and results from data programs. The four research questions, presented in *Chapter 1.3*, are used as basis for discussion. Last three research questions are mainly elaborated in the scientific article; supplemented in this report. As the full design with all transport modes interacting is investigated in AIMSUN, these results are mostly considered. The first research question is discussed in the following, though most design elements in the experimental design are already considered in *Chapter 3*. This chapter also includes discussion of maintenance and winter road management, area use, and current laws for future implementation.

The experimental design is derived from solutions of other existing intersections, roundabouts, and throughabouts. Though there are different ways of serving high priority solutions for public transport, cyclists, and pedestrians, selected designs are utilized for improving today's situation in Norway. The initial state of two roads connecting is resolved by roundabout elements instead of a crossroad. This is to reduce conflict points, see *Figure 2*, and provide seamless driving without signal control. Avoiding signal controlled intersections prevent red time delays, and improves performance at low traffic volumes (Bernetti et al., 2003, p. 16).

Centred and kerbside public transport lanes have both positive and negative aspects, discussed in *Chapter 2.1*. Centred public transport lanes are used for facilitating meridian segregated lanes through the central island; throughabout. Based on observed tram movements at such throughabouts in Oslo, France, etc., this design provides improved priority of buses. Straight movements eliminate geometric delay. No signal controlling result in no control delay, and absolute priority by regulation excludes traffic delay. Hence, there is no delay for buses at the throughabout. This improves public bus efficiency to the fullest, resulting in a more attractive service.

Tested bus frequencies in AIMSUN vary between 1 minute, 2 minutes, and 3 minutes per bus over conflict points. Depending on implementation sites, these values might be too large or too small, but constitute a basis for scenarios. (Frøyland et al., 2016, p. 6) have investigated bus frequencies at different BRT-systems. The report describes a departure frequency of 8 buses/h per direction both in Hillevågsveien, Stavanger and in Almere, Netherlands. This is per route; hence, multiplied with number of bus routes with equal service level. The report also describes a required departure frequency of 7 buses/h or more for a high standard system from a Swedish BRT-guide. Tested bus volumes up to 30 buses/h/direction in AIMSUN is therefore designed to serve several bus routes.

An attractive bus service relies on several factors. Conforming arrival time to schemed bus timetable is an important factor for users. If buses arrive simultaneously at the throughabout, general purpose traffic might also be negatively impacted. Crossing conflict points in the circulatory lane takes less than 2 seconds for design personal cars driving at constant speeds of 25-30 km/h. Acceleration and deceleration result in increased crossing time. Full stop due to presence of a bus reduces crossing time significantly. If another bus is following closely, general purpose vehicles might necessarily wait even longer, increasing risk of larger queues and blocking of exits in the circulatory lane. Additionally, several buses at bus stops might cause blockage of the busway for other traffic behind the bus stop. Therefore, punctuality of the bus service is important. *Intelligent Speed Adaption* (ISA) is a tool that can be used to prevent such problems. This support bus drivers' compliance with the speed limit, and makes bus driving more uniform between bus stops. There are several other intelligent tools available for supporting evenly distributed arrival times of buses.

A continuous bicycle network at the throughabout improves priority of cyclists. Unlike today's typical designs in Norway, dedicated bike lanes are provided at entry, through conflict points, and at exit of the throughabout. Kerbside bike lanes along approaching roads are separated from motorised lanes at the throughabout with defined and visible conflict points at crossings. Additionally, bike lanes are coloured, making biking easier and safer due to improved visibility to cyclists and of cyclists. Give way regulations result in a seamless flow, and no control delay by red time. Cyclists are provided with high priority, but not absolute as they must give way for approaching buses when crossing major roads.

Today's high priority of pedestrians is preserved in the experimental design. As with cyclists, pedestrians are regulated with higher priority than general purpose traffic, but must give way for approaching buses. Unsignalised crossings are traditionally most beneficial for pedestrians, except for trams. In the experimental design, priority of pedestrians is reduced by the busway. By tested frequencies in AIMSUN of a bus once a minute or rarer, this does not constitute considerable delays for pedestrians. Apart from giving way to buses in bus lanes, pedestrians are provided with a familiar network with highest priority at all other crossings.

Cyclists and pedestrians have longer distances with a circulatory lane design for most movements compared to a more compressed solution. Circulating bicycle traffic is assumed to serve a steadier flow with such design. Additionally, biking is assumedly easier and comfortable, preserving traffic safety. Delays are assumed to be minimally increased.

Absolute priority of buses, and high priority of bicycles and pedestrians impact general purpose traffic. General purpose traffic sees most delay in the network with lowest priority.

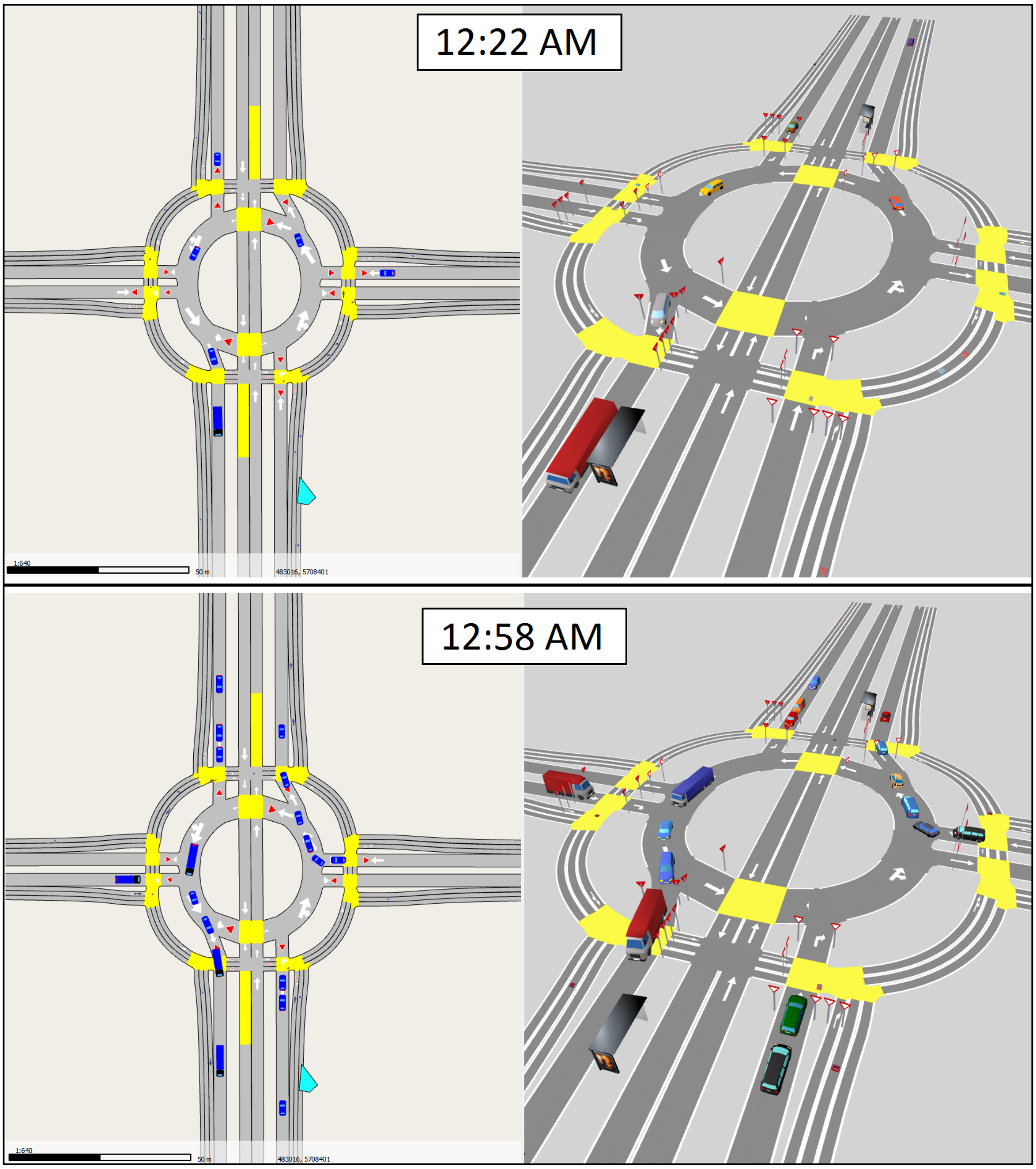

Figure 29: Variation in traffic situation during a scenario in AIMSUN.
[Source: screen dump from the program]

Figure 29 shows traffic situations at two different times during one simulation in AIMSUN. These two situations are displayed to observe differences and variations in occurring queues during one model run, displayed both in 2D and 3D. The two upper pictures show few vehicles in the network, and uninterrupted flow. The two pictures below show a more congested network at another time during the simulation. Displayed scenario consider intermediate flow intensities of all transport modes. It is important to acknowledge that "intermediate" is a relative term in this thesis, not an absolute measure.

Intermediate flow intensities of all transport modes in *Figure 29* result in an average delay per general purpose vehicle of 62,3 sec/km, see results in the scientific article. As the two lower pictures in the figure display one of the longer queues observed during a simulation, this number might be misguiding. 62,3 seconds/km gives the impression of more than one minute delay in the network. As the unit is time delay per kilometre, length of approaching roads affect this value considerably. Delays occur at conflict points; hence, no delays after last conflict points in the model. Connected entries and exits are 100 metres in the model. This result in 200 metres driving additional to movements in the circulatory lane. 62,3 seconds of delay is therefore 4-5 times higher than actual delay in the network.

The delay measure in AIMSUN calculates the additional time it takes to pass the network compared to undisturbed movements. Design speeds allocated to different sections might be too high, resulting in increased delays. E.g. speed in the circulatory lane of 30 km/h for general purpose traffic might be unrealistically high for certain movements.

Described aspects explain some of the strengths with simulations. From *Figure 29*, it is visually obvious that delays are not severe with displayed worst case scenario in the two lower pictures.

Level of service (LOS) is a typical measure used for considering traffic conditions. LOS is alphabetically ranked from A (best) to F (worst), most often based on delays or queues. In SIDRA INTERSECTION, LOS is based on delay. The greatest occurring delay of 11,3 seconds per vehicle on average in the model is the only scenario ranked as LOS B. All other scenarios result in LOS A from the program. These rankings are not valid as SIDRA INTERSECTION display LOS rankings for roundabouts. The model in SIDRA INTERSECTION is only considering one conflict point; hence, ignoring all other potentially delaying conflicts at a roundabout. General purpose traffic will see more delay in the full system by longer *back of queues* as exits will be blocked in the circulatory lane.

With lowest priority, general purpose traffic is delayed at several places in the network. In the AIMSUN model, general purpose traffic is additionally delayed due to unrealistically even distribution of pedestrians throughout the network. Results show that volumes of cyclists and pedestrians have a significant impact on delays of general purpose traffic. Though this report focus on at-graded intersections, a level separated bike and pedestrian crossing will largely eliminate delays for general purpose traffic at the throughabout.

6.1 Data programs

Assessment of traffic management at the throughabout is based on traffic software. Though used data programs constitute visual and quantitative analyses of a theoretical implementation, there are certain limitations with data tools as models only represent a simplification of reality. Other advantages and disadvantages are mentioned in *Chapter 4.1*. Strength and weaknesses with AIMSUN and SIDRA INTERSECTION are described in the scientific article.

Traffic software require calibration and validation for attaining comparable results to a real situation. Comparable data sets are needed for performing calibration and validation. This constitutes a challenge with new designs as experienced data do not exist. A similar solution to the experimental design is not found to the full extent in the current road network, though elements are known. Data from throughabouts with passing trams in Oslo was sought without success. In Netherlands, several circulatory bike lanes exist, but not in combination with a throughabout or give way regulated crossings where motorised traffic is given higher priority. As comparable data sets are not retrieved, calibration and validation of models are not performed. Input parameters are still thoroughly considered, elaborated in *Chapter 4.2.2 and 4.3.2*.

Gap acceptance at the throughabout is difficult to predict as the design is unfamiliar to users. Chosen values for gap acceptances are decided in cooperation with supervisor Arvid Aakre. In SIDRA INTERSECTION, gap acceptance is based on roundabouts in the 6'th Edition of the Highway Capacity Manual (Spack, 2017). In AIMSUN, default values from the program are used, with a conservatively adjusted gap acceptance in front of conflict points in the circulatory lane for general purpose traffic. Gap acceptance is likely to vary for drivers in the circulatory lane. Some drivers might be unaffected of a new intersection design, while others drive much more defensive with associated higher gap acceptance. As users gets more used to the design, gap acceptance is likely to be reduced over time (Spack, 2017).

Gap acceptance is included differently in the two programs. *Critical time gap* and *follow-up time* constitute gap acceptance in SIDRA INTERSECTION. In AIMSUN, gap acceptance is allocated to sections instead of vehicles. This results in equal gap acceptance for all vehicles on sections in AIMSUN, in contrast to different gap acceptances of light and heavy vehicles in SIDRA INTERSECTION. Parameters for gap acceptance in AIMSUN are based on theoretical gaps at the conflict point if entering the conflict zone. This justifies equal gap acceptance for light and heavy vehicles in AIMSUN.

SIDRA INTERSECTION is used for investigation of occurring queues and delays at conflict points in the circulatory lane. Tested flow intensities are much higher than in AIMSUN. As the model is limited to one conflict point, other movements at the throughabout are not affected by queues in the circulatory lane. Including other movements of general purpose traffic at the throughabout will result in larger delays as long queues in the circulatory lane will cause blockage of exits. High flow frequencies are tested to display delays caused by solely circulating traffic over the busway. As most movements are not crossing bus lanes, tested frequencies are probably unrealistically high.

The model in AIMSUN considers the full design with all transport modes interacting. By visual verification during simulations, most movements went as intended. Queue capacity in front of bus lanes without disturbing other traffic have been discussed previously in this report. During simulations, up to two personal cars were observed queueing in front of the busway while other vehicles exited the circulatory lane simultaneously. Some undesired occurrences were also observed. During random simulations, buses occasionally reduced speed in front of conflict points with general purpose traffic. As buses are not delayed in the design, this is ignored, but it also impacts general purpose traffic. As buses use longer time over the crossing, waiting time is increased for general purpose traffic in front of the conflict points. This results in increased delays for general purpose traffic.

Another observed irregularity was pedestrians ignoring other traffic. Mostly, all transport modes behaved as regulated in the model.

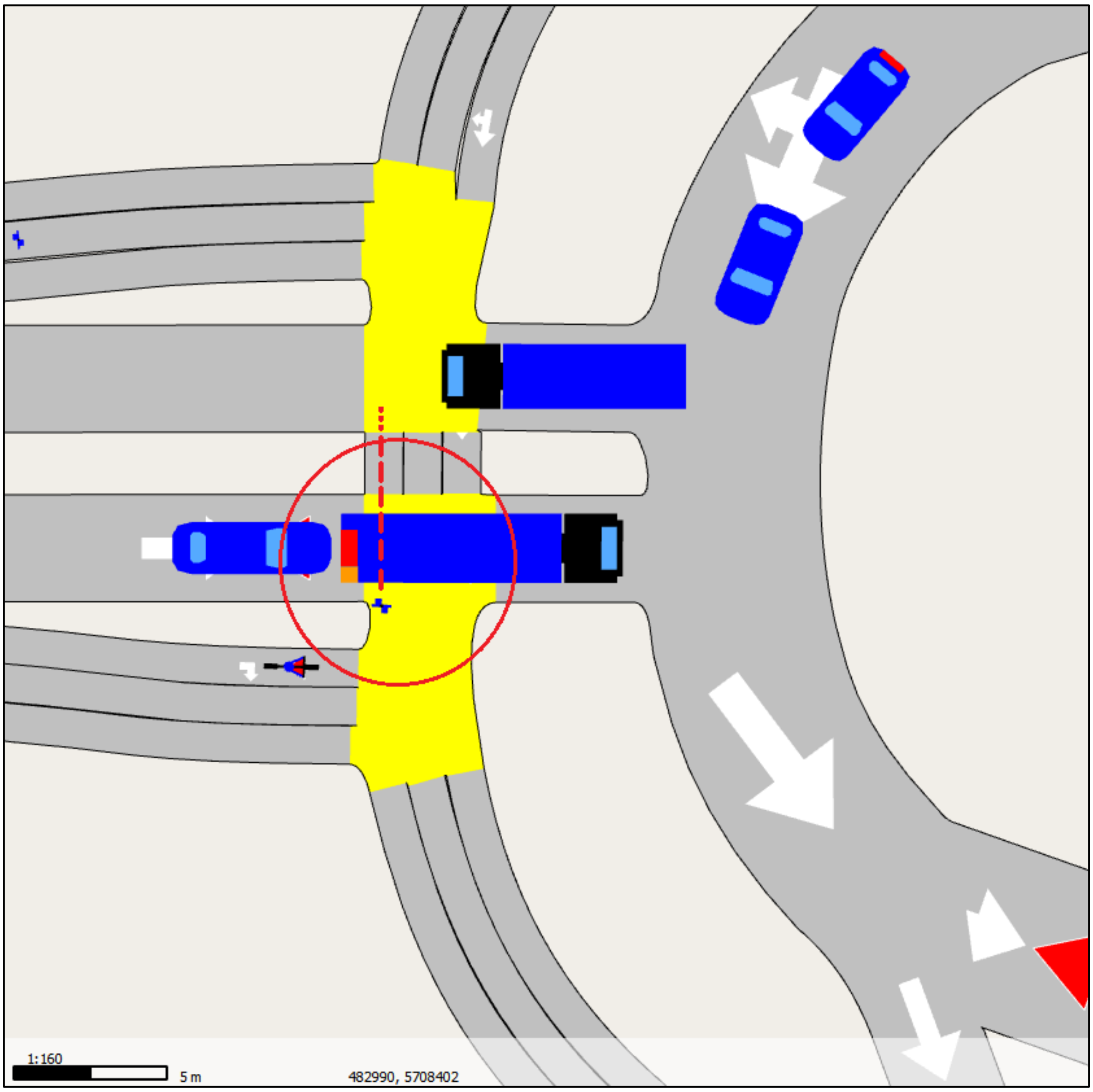

Figure 30: Pedestrian ignoring other traffic during a simulation in AIMSUN. [Source: screen dump from the program]

Figure 30 shows a screen dump from AIMSUN during a simulation. The truck in front of the circulatory lane was waiting until acceptable gap with circulating traffic. At stop, the pedestrian crossed straight "through" the truck. This also occurred over bus lanes, where pedestrians ignored approaching buses. Crossings of general purpose lanes with standstill traffic is not an unrealistic movement, and not obedience of traffic rules. Such crossing over the busway is more severe. These movements occurred rarely, but is not an intended move.

Pedestrians and cyclists are newly featured in AIMSUN. This might cause some irregularities and bugs in the program. E.g. pedestrians were only occasionally displayed in 3D-simulations. They were not displayed as pedestrian, but as downscaled personal cars. Cyclists were never displayed in 3D-simulations, only in 2D.

Certain preset Origin-Destination movements of cyclists in AIMSUN are not likely to occur in a real situation. Cyclists performing left turns will most likely use pedestrian crossings instead of taking the long detour in the one-way regulated circulatory bike lane, discussed in *Chapter 3.2.2*. Additionally, some cyclists were set to perform returns. As cyclists are only using bike lanes in the model, cyclists do not use pedestrian crossings. Thus, set bicycle movements result in a higher number of cyclists in the bike lanes compared to a real situation.

6.2 Traffic safety

Traffic safety must be considered with new designs to gain knowledge about dangerous situations and prevent accidents. The experimental design is not found to the full extent other places, though most elements are known. Unsignalised conflict points in a circulatory lane are not found with passing buses, but is used several places for trams. Data on accidents at such throughabouts in Oslo was unsuccessfully inquired by contacting the Norwegian Public Roads Administration and the company administrating all public transport in Oslo: *Ruter AS*. *Report 519* by the Norwegian Public Roads Administration have examined these throughabouts; stating that there have been relatively few accidents (Frøyland et al., 2016, p. 13). Density of accidents involving pedestrians are relatively equal for centred and kerbside public transport lanes, based on specific site analyses in Oslo and Trondheim. Additionally, the report states that there are little comparative data on accidents at different BRT-systems, but traffic safety seems to be better preserved with a well-designed BRT-system.

The throughabout in Hillevågsveien, Stavanger is signalised at entries for all traffic when presence of buses. Though this leads to no traffic over conflict points in the circulatory lane, general purpose traffic and cyclists are delayed largely. As entries are signalised, several movements not in conflict with the busway are also regulated to stop; not desired. A middle way is establishing traffic lights in the circulatory lane in front of conflict points. Thus, movements not in conflict with bus lanes can flow uninterrupted for unblocked exits. Observing traffic signals in the circulatory lane is a challenge as general purpose traffic have many things to focus on at the throughabout.

Conflict points in the circulatory lane are important elements regarding traffic safety. Buses driving in 40 km/h enter with a 90-degree angle on general purpose vehicles; potentially causing severe accident. Hence, highlighting these conflict points are of special importance.

One measure is highlighting the busway with coloured pavement. Bus lanes are drawn with green colour in this report's figures; a suggestion for making the busway more visible. This makes it clear where buses travel, similar to red coloured bike lanes in Norway today. As it is currently expensive to colour asphalt, an alternative is only colouring conflict points.

Figure 31: Coloured asphalt at conflict points in Melbourne, Australia.
[Source: Google Maps – street view]

Figure 31 shows coloured asphalt at conflict points between trams and general purpose traffic in Melbourne, Australia. Tram lines are not highlighted with coloured asphalt to the full length, only conflict points in the circulatory lane. In Melbourne, red asphalt is used for conflict points with public transport, and green colour for bike lanes. In Norway, red colour is used for bike lanes. Public transport lanes have no colour designated, but green is a possible alternative in contrast to existing red coloured asphalt.

Another measure for highlighting conflict points is elevating bus lanes. In addition to improved visibility, drivers will feel the busway when crossing. As with speed bumps over pedestrian crossings, general purpose traffic will see the elevated busway as something deviating from the normal, resulting in increased focus and somewhat increased threshold for entering the conflict zone.

Traffic signs can also highlight conflict points in the circulatory lane. One possibility is establishing a dynamic sign displaying which direction the next bus is approaching from. This increases awareness of drivers, reducing a focus point in the circulatory lane. This is desired as general purpose drivers have several other things to focus on when driving through the throughabout. Implementing such a traffic sign close to the conflict point constitutes another focus point; hence, might be counter-productive. If this sign is placed further away, the next bus might pass before drivers arrive at the conflict point. Especially if there are queues. Thus, drivers might ignore the actual direction of an approaching bus. Establishing a sign displaying both direction of bus approach and estimated arrival time eliminates this scenario. Exact design of such a traffic sign is not examined in this Master's thesis; hence, mentioned in *Chapter 8*.

In *Chapter 3.2.3*, a give way sign for pedestrians was suggested associated with the main crossing over bus lanes. Additional to an informative traffic sign, the text can also be implemented in the pavement. This increases awareness of the untraditional crossing of the busway. Including information of approaching speeds of 40 km/h for buses can be added to gain knowledge for pedestrians. This raise awareness of possible impact severity, and increases focus and respect of the crossing.

Zebra stripes are not implemented at main pedestrian crossings of the busway. This would make the crossing more visible, and conforming with today's standard of crossing roads. As the crossing in the experimental design is unsignalised, pedestrians would have higher priority than buses if zebra stripes were implemented, by current traffic rules. Thus, zebra stripes are avoided. Additionally, zebra stripes will lead pedestrians into the conflict point with less attention to approaching buses. Impacts between buses and pedestrians are severe; hence; intendedly avoided.

An issue with main pedestrian crossings is sight when presence of buses at bus stops. As the crossing is unsignalised, pedestrians cross the busway when vacant. A standstill bus at bus stops will obstruct pedestrian sight lines for a bus coming from the opposite direction. This could lead to pedestrians entering the conflict zone without observing an approaching bus in 40 km/h from the right side. General purpose traffic might also be affected by this in front of conflict points in the circulatory lane. If this is an issue, bus stops can be established further away from the throughabout.

Universal design is considered throughout the experimental design. This makes the throughabout more accessible, and preserves traffic safety. Drawings in this Master's thesis do not include all details for a future implementation, but main elements are included. Tactile paving at pedestrian crossings is of special importance; included in *Figure 18*.

6.2.1 *Maintenance and winter road management*

Maintenance and winter road management is of special importance with the experimental design to avoid confusion at the untraditional throughabout. Hence, a consistently clean and easy understandable design is desired.

Regarding traffic safety; coloured, partly coloured, or elevated public transport lanes have been discussed. For elevated bus lanes, it is important to not gap separate the public transport lanes and the circulatory area regarding snowploughing. Snowploughs in the circulatory lane will face difficulties with such edges. Hence, elevated lanes must be even.

In Norway, road markings are usually established by thermoplastics or paint. Thermoplastic road markings are durable to cyclic loads, but exposed to scraping from snowploughs as it is elevated from the road. Visibility of give way markings in front of crossing bus lanes inside the circulatory lane is important to inform general purpose drivers of regulations with approaching buses at high speeds. Traditionally, thermoplastics are used as road markings when constructed, and paint for further maintenance. Paint is cheap and easy to apply. It is also equally levelled with the asphalt, but not as durable. An alternative is investing in a more durable marking with reduced need of future maintenance. Less maintenance of road markings reduces inoperative time of the throughabout, and less maintenance costs. Instead of using thermoplastics or paint, milling give way markings in the pavement and replace them with white-coloured asphalt could be done at construction. Making these give way markings equally unicoloured as thermoplastics or paint might be a challenge. Hence, traditional road markings might be applied on top of the white asphalt. White-coloured asphalt as base preserves traffic safety as scraped markings on top still shows give way markings to some extent.

6.3 Area use

Final geometry of the experimental design should be accustomed to circumstances at the site of implementation. Though the design is presented with specific geometry, changes can be made both for increased and reduced area use. Geometry of the experimental design is described in *Chapter 3.1*.

Area inside crossings related to the throughabout constitute an area of 2786 m^2 over 57x59 metres, shown in *Figure 13*. Reducing this area is not desired as it facilitates movements of all transport groups. Reducing inscribed circle diameter will impede larger vehicles, and sharpening bike lane curves constitute less fluent pattern for cyclists. Connecting entries outside this 57x59 metre area have greater potential of area adjustments.

Major and minor roads are drawn with 28 and 14,5 metres of width, respectively, before changed cross sections at the throughabout. For the major road, bus stop width of 3,5 metres facilitates today's standard of upcoming "Superbuss" in Trondheim, Norway. Defined as a kerbside bus stop, this area can be reduced to 2,5 metres (Statens vegvesen (N100), 2014a, p. 130). Alternatively, the two bus stops can be assembled to one centred bus stop facilitating on- and off-boarding for both directions. *Figure 32* shows an implemented centred bus stop in Quito, Ecuador, facilitating both directions.

Figure 32: One centred bus stop in Quito, Ecuador.
[Source: Google Maps – street view]

The dual-purpose bus stop in *Figure 32* reduces cross section width. This design requires changes in current geometry of the experimental design, but is implementable. Negative effects are an additional crossing of traffic lanes for accessing the bus stop. Additionally, reduced road width close to the throughabout is excessive as entry and exit of the circulatory lane are preferably widely separated. Hence, such a bus stop is not examined in the experimental design, but is an alternative at sites with area issues.

At the end of bus stops furthest away from the throughabout, separating centred bus lanes with general purpose traffic by 3,5 metres does not serve any purpose. Reducing this area to 0,5 metres result in a new cross section width of 22 metres, presented in *Figure 33*.

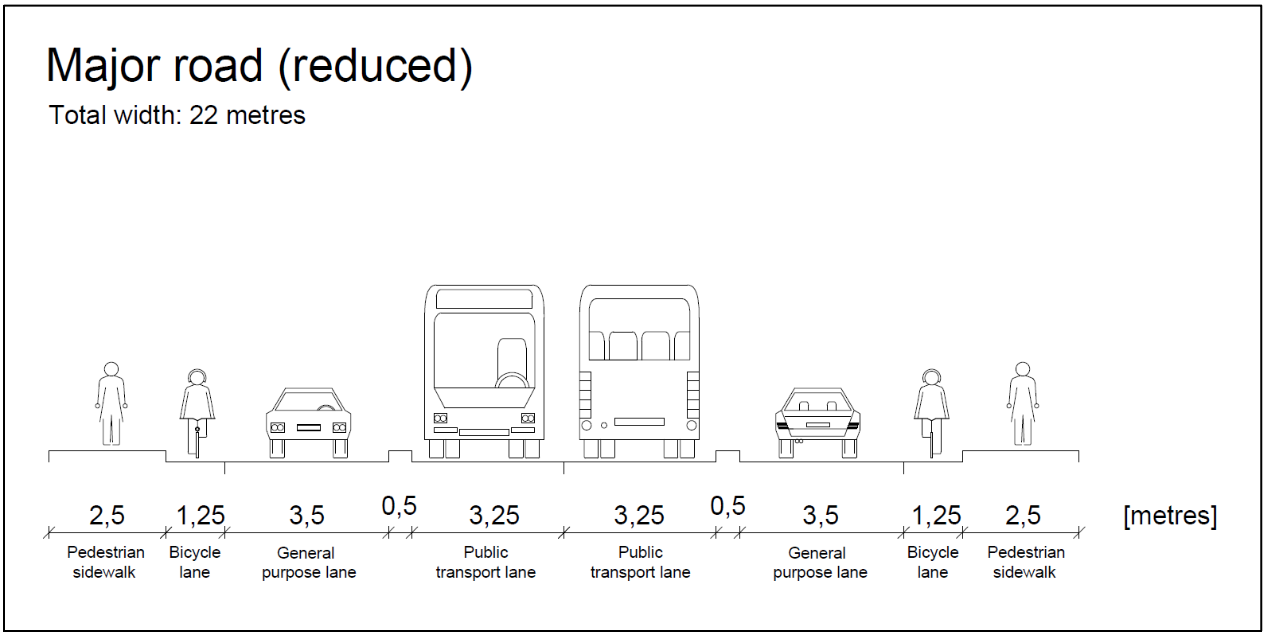

Figure 33: Reduced cross section of major road.
[Figure made in AutoCAD]

Area outside the throughabout might still not be sufficient for such road widths as shown in *Figure 33*. For additional width reduction, separating spaces of 0,5 metres can be abolished. This results in no physical separation of dedicated bus lanes with general purpose traffic, constituting an increased risk of confusion or non-compliance of dedication to public transport. Another alternative is reducing the major road to a two-lane road. This is an option with area or economic issues, and preferably low general purpose traffic volumes. Hence, buses and general purpose traffic share lanes until the two-lane road transforms into a four-lane road. At this point, buses are regulated to enter the centred public transport lane and general purpose traffic to drive in kerbside lanes. This is not desired as priority of the bus service is reduced, but an option for prioritizing buses at intersections.

Bike lanes along major and minor roads are drawn one-directional. For abundant area at entries, bike lanes can be expanded into two-directional, constituting an increase in cross section widths. Geometric adjustments are required at entries and exits for improved movements onto the one-directional circulatory bike lane at the throughabout. Approaching bike lanes in the present experimental design are drawn to facilitate entry and exit of one-directional bike lanes.

6.4 Current laws

The experimental design is not found to the full extent in Norway, nor in other countries. In this subchapter, the design is discussed related to current laws for implementing such a design in Norway.

Geometry of the experimental design is mainly based on the Norwegian Public Roads Administration's handbooks. Design geometry preserves functionality for traditional traffic as turning movements are equally facilitated to traditional roundabouts. Some parameters are not found in handbooks due to geometric irregularities of an opened central island with waiting spaces in the circulatory lane, and centred bus lanes going through.

Kerbside public transport lanes are most common in Norway and used as basis for public transport lanes in current handbooks. Today, segregated meridian busways must be exempted via application and approval (Statens vegvesen (V123), 2014e, p. 46).

Throughabouts exist in Norway. Two serve passage of buses at Hillevågsveien in Stavanger, and remaining serve trams. In Hillevågsveien, throughabouts also act as full-scale experiments as these are the first implemented with buses going through the central island. Hence, solutions are conservative; e.g. signalising all entries to exclude other traffic from the circulatory lane when presence of buses. Though conservative solutions, throughabouts in Hillevågsveien have required several applications and approvals for exemptions. The unsignalised experimental design is likely to meet even more adversities.

Current laws differentiate traffic rules for buses and trams. All users of the road network must give way and if necessary stop for trams (Statens vegvesen (2016)). Similar rules do not apply for buses. Lower deceleration results in longer stopping times for trams. Hence, other traffic is obliged to give way; preserving traffic safety and improving headway of trams by increased priority. The absolute priority is excepted at throughabouts where trams are regulated by traffic signs to give way at entry for other traffic. The high priority is regained at the exit of the throughabout. See *Attachment 2* for current tram rules in Norway. Buses will benefit from obtaining a similar juridical priority as trams. With the modern way of thinking bus priority in Norway; *plan tram - use bus* (Frøyland et al., 2014, p. 7), a more efficient public transport service with improved acceleration and deceleration is promoted. Normally, investment costs are also much lower for bus systems than trams.

In addition to public buses, public transport lanes in Norway also serve other buses, taxis, electrical vehicles, hydrogen vehicles, motorbikes, mopeds, and bikes. For improved priority of the public bus service and reduced frequency through conflict points, other transport groups should be excluded. By now, there exist no traffic signs in Norway dedicating lanes only for buses. A bus symbol is used on the traffic sign for public transport lanes; *508 Kollektivfelt* (Statens vegvesen (N300), 2014c, p. 92), but this permits other mentioned transport groups as well.

Implementing traffic signs for circulatory bike lanes at roundabouts have been a challenge in Norway, see meeting with Helge Ytreland (NPRA) in *Attachment 3*. This is related to placement of traffic signs to preserve acceptable sight conditions, and type of signs by today's catalogue. Though it currently is a challenge in Norway, circulatory bike lanes have already been implemented in the Netherlands. These designs have not met much dissatisfaction or trouble to the authors knowledge.

(Statens vegvesen (N302), 2015, p. 76) display road markings of crossings between general purpose traffic and assembled bike and pedestrian crossing with higher priority. In addition to give way markings in front of the bike lane away from the junction, white, quadratic boxes are established between give way markings and the bike lane. These are excluded in the experimental design as bike lanes are already easily visible by coloured paving. Approaching the junction from the side road, give way markings in the pavement are implemented in front of the zebra crossing in handbook N302. These are excluded in the design as unsignalised zebra crossings already regulates pedestrians to right-of-way; by §9.2 in *Regulations relating to pedestrian and vehicle traffic* (Trafikkregler, 2004). Eliminating unnecessary elements in the pavement is of interest to keep a simplistic and easily understood road network; reducing risk of confusion for drivers. This makes driving easier by requiring less focus on pavement markings, preserving traffic safety and comfort for drivers.

7. CONCLUSION

Conclusion is based on research questions, presented in *Chapter 1.3*. Last three research questions are mainly concluded in the scientific article, supplemented in the following.

Objective of this Master's thesis is investigating a way to increase priority of bicycles and public transport at intersections, while preserving traditionally high priority of pedestrians. A new intersection design facilitates this, with absolute priority of buses, and high priority of cyclists and pedestrians. The intersection design is acknowledged as a "throughabout" as lanes penetrate the central island of a traditional roundabout.

Buses are given absolute priority in dedicated lanes straight through all conflict zones at the throughabout. Conflicts are not signalised to reduce delay for other traffic, except for two secondary pedestrian crossings. Secondary pedestrian crossings are established for mainly serving visually impaired pedestrians. Thus, not used by most pedestrians. These crossings are signal controlled by red signal when presence on buses, and green signal when vacant. Buses are therefore unaffected of the secondary pedestrian crossings.

Unsignalised bus lanes result in no control delay. Geometric delay is avoided by straight lining the meridian segregated busway at the throughabout. With highest priority over conflict points, buses are neither delayed by other traffic. The centred busway with absolute priority and no delays is a significant improvement from today's traditional termination of kerbside public transport lanes at intersections in Norway.

Priority of cyclists is improved by a circulatory bike lane mostly separated from other traffic. The circulatory bike lane is continuous and one-way regulated, serving a steady flow of bicycles with defined movements. The circulatory lane design result in somewhat longer distances for most movements of cyclists and pedestrians, but with minimal delay. As buses are provided with absolute priority, both cyclists and pedestrians must give way for approaching buses. At all other crossings, cyclists and pedestrians have highest priority. Pedestrians are regulated with highest priority at conflict points between cyclists and pedestrians.

Absolute priority of buses, and high priority of cyclists and pedestrians negatively impact general purpose traffic. General purpose traffic sees most delay at the throughabout with lowest priority in the network. By tested scenarios in traffic software, different volumes of buses with absolute priority does not considerably impact other transport modes, neither for general purpose traffic. Intermediate flow intensities of all transport modes showed through simulation an acceptable traffic situation regarding delays and mean queues. For general purpose traffic, this meant a delay of 62,3 sec/km, and 2,9 veh in mean queue. Higher volumes of general purpose vehicles had a significant impact on general purpose traffic. Higher volumes of cyclists and pedestrians also impacted general purpose traffic, and cyclists and pedestrians as well. Tested flow intensities; *low*, *intermediate*, and *high*, are relative terms, but constitute a basis for investigation of occurring effects.

Presented throughabout design is assessed by traffic software; a simplification of reality. Investigated scenarios give an indication of occurring queues and delays for selected traffic volumes and associated movements. This thesis constitutes a basis for further investigation and development of the design.

8. FURTHER WORK

The experimental design consists of mostly known elements in today's road network. Though throughabouts and circulatory bike lanes exists, they are not found assembled into one intersection design. Pedestrian and bicycle crossings over the busway are innovative in the experimental design. Due to no experience, these solutions should be thoroughly examined regarding functionality and traffic safety.

In this Master's thesis, the experimental design is presented and elaborated to the author's best extent within limits of intended work load. Still, there are several aspects with the design to be further investigated. Effects of different solutions for colouring public transport lanes should be assessed. Other measures for highlighting conflict points in the circulatory lane should also be investigated; e.g. elevated public transport lanes. Though signal controlled conflict points will increase delay for general purpose traffic, it is of interest to compare effects with the unsignalised experimental design regarding traffic safety.

Analyses and assessment of the design performed in this Master's thesis constitute a basis for further investigation. Several scenarios are tested in traffic software, but with limited variations due to work load. Greater variation should be further investigated. Additionally, effects of peak hours are of interest as provisional scenarios are modelled with constant traffic volumes. Results from traffic software in this thesis give an indication of occurring delays per transport mode for a theoretical implementation.

Traffic safety is difficult to examine based on data tools. In traffic software, behaviour is based on mathematical formulas and theoretical conflict points, with limited inclusion of individual variations. Thus, models run seamlessly, excluding several human factors. In *Chapter 6*, new traffic signs were discussed to increase traffic safety at the throughabout. These traffic signs, displaying direction of approach for buses and estimated arrival time, should be further investigated and developed for serving the purpose intended.

Proposed traffic sign over main pedestrian crossing, see *Chapter 3.2.3,* is also a new traffic sign. Traffic signs, text in pavement, and other aspects with pedestrian and bike crossings over the busway should be thoroughly analysed as a new type of crossing in today's road network.

A complete implementation of traffic signs at the experimental design is not considered in this Master's thesis. Helge Ytreland (NPRA) stated that traffic signs at circulatory bike lanes have been a challenge to establish in Norway, see *Attachment 3*. Though this is a current challenge in Norway, circulatory bike lanes have been implemented several places in the Netherlands. These designs have not met noteworthy dissatisfaction or trouble to the authors knowledge.

Emergency vehicles are not considered in this Master's thesis. Whether these should use centred bus lanes or general purpose lanes are not investigated or decided.

By limitations to the thesis, a bus service along the major road is considered. Investigating designs serving high priority of buses from all directions is also of interest based on principles from this thesis' throughabout design.

9. EPILOGUE

This Master's thesis is written entirely by Øyvind Høsser; both process report and scientific article. Models in traffic software are also made by the author, but revised and discussed with supervisor Arvid Aakre. Arvid Aakre has been an important collaborator by excellent support during the process. Arvid Aakre has contributed with professional input, revised several parts of the text, and participated during the whole process. In the scientific article, Arvid Aakre contributed by choosing which results to present for an improved outcome of the article.

Personally, this Master's thesis has been challenging, but an interesting experience. The subject was interesting to me already last autumn, and great motivation has been an important factor for the final product. Spending such amount of hours on one thing have been a challenge, but a valuable experience.

As the experimental design is not found to its full extent today, data was not found for comparison or experienced values. Collecting relevant input parameters was also occasionally a challenge, but resolved sufficiently for ample results. Additional to parameters in NPRA handbooks and other articles, values of circulatory bike lane widths and vehicle speed in the circulatory lane were inquired by contacting professionals. Though these values were never collected, results are based on other ample input parameters. As principles are in focus with this Master's thesis, exact values are not necessarily required. The personal experience with collecting relevant input parameters have been challenging, yet interesting.

Hopefully, this Master's thesis will be useful for others. There are still several aspects to be further assessed and considered. Seeing a future implementation of the experimental design or similar would be personally very rewarding.

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PART II – SCIENTIFIC ARTICLE

PRIORITIZING BICYCLES AND PUBLIC TRANSPORT AT INTERSECTIONS

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Abstract

Traffic growth result in capacity challenges and increased pollution; locally and globally. Increasing attractiveness of public transport, biking, and walking is desired, as acknowledged environmentally friendly and passenger efficient transport modes. This article considers a new, unsignalised intersection design with absolute priority of public transport and high priority of cyclists and pedestrians. Assessment is based on models and analyses performed in traffic software; *SIDRA INTERSECTION* and *AIMSUN*. Models show that the absolute priority of buses throughout the design is not significantly impacting other traffic, for tested flow frequencies. Buses pass the intersection in the fastest way possible due to no geometric delay, or necessary speed reduction caused by other traffic. Cyclists and pedestrians are provided with high priority, and small delays. Traffic safety is discussed in the article, intendedly preserved. This constitutes a basis for further investigation and development of the design.

Keywords: *priority, public transport, bicycle, intersection, roundabout, throughabout, delay*

1. INTRODUCTION

1.1 Background

In Norway, dedicated public transport lanes and bike lanes are expediently provided at uninterrupted road stretches in major cities. At intersections, these dedicated lanes are often terminated, leaving buses and cyclists to mixed traffic. The abolished priority constitutes an inconvenience regarding efficiency and continuity, as well as traffic safety for cyclists. Additionally, by objectives in the *National Transport Plan* (NTP) of Norway (Meld. St. 26 (2012-2013)), the attractiveness of public transport, cyclists, and pedestrians must be improved. Improving attractiveness can be done by increasing efficiency through priority, especially at intersections.

1.2 Scope limitations

Bus is featured as the main public transport mode in this article as the most frequently used public transportation service in Norway (Statistisk sentralbyrå, 2016). The article considers at-grade junctions with one major road going through. Hence, buses enter and exit the intersection along one axis. Two other roads connect, resulting in a four-armed intersection.

1.3 Experimental design

There are different measures for streamlining the passing of public transport and cyclists at intersections. Varying traffic conditions require individual solutions to achieve the objectives of implementing changes. Traditionally, signalised priority has been a popular method through active or passive signalising. There are other ways as well; in this article, a new design is created.

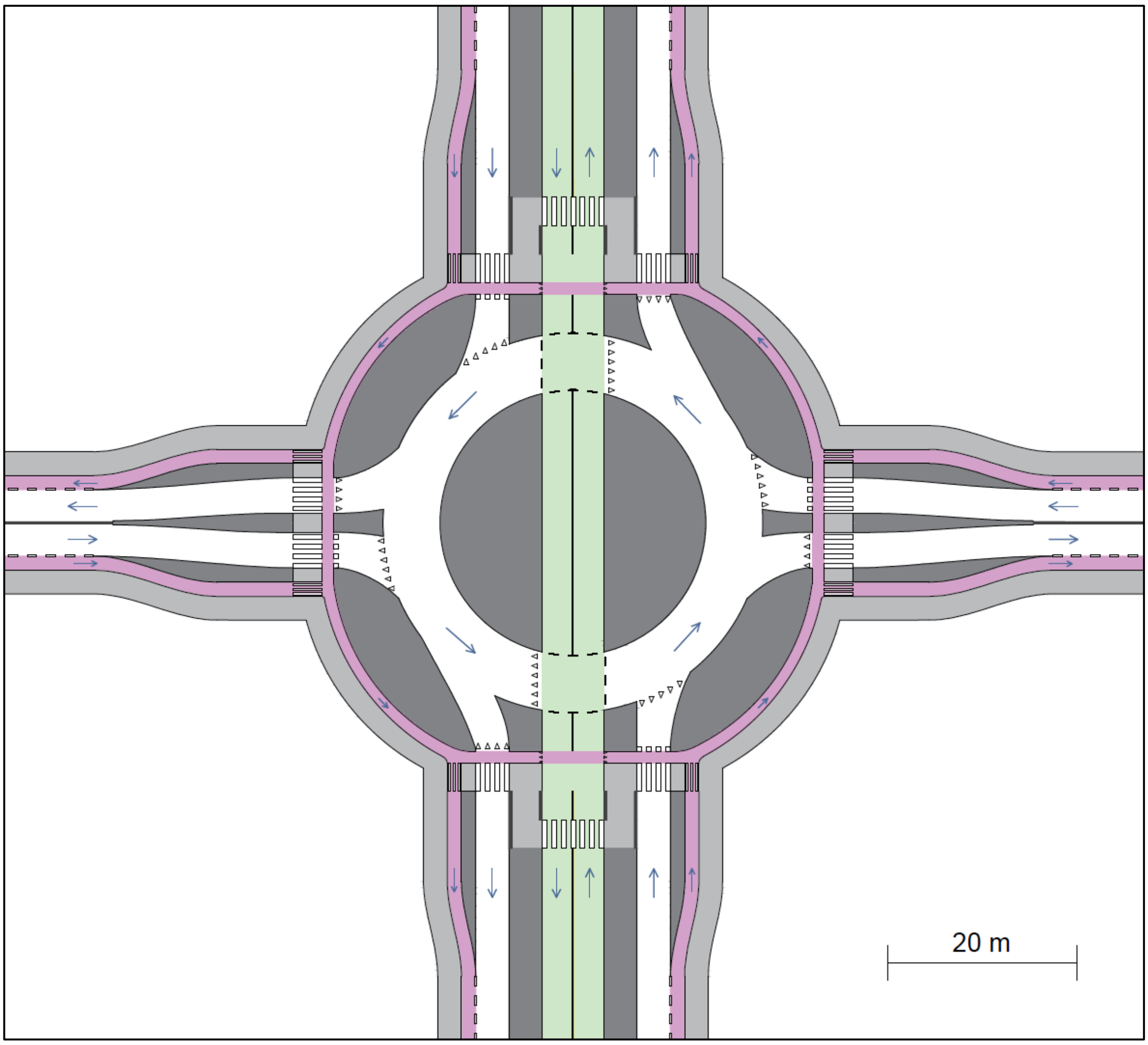

Figure 1: Experimental design; "throughabout"

Figure 1 shows main principles of the experimental design further analysed in this article. It is acknowledged as a "*throughabout"* in the following due to segregated meridian public transport lanes going through the central island; *green* colour. Priority of public transport and cyclists are improved by absolute priority of public transport in separated lanes, and a continuous bicycle network; *red* colour. The throughabout is not signal controlled.

Table 1: Main geometry of the experimental design

Geometric parameters and values	
Diameter of central island	28 m
Inscribed circle diameter	40 m
Width of circulatory lane	6,0 m
Width of bus lane	3,25 m
Width of general purpose lane	3,5 m
Width of bike lane	1,25 m
Width of pedestrian sidewalk	2,5 m

Fundamental geometry parameters and values are shown in *Table 1*; facilitating trucks.

Dedicated public transport lanes are segregated in the middle of the road, resulting in no turning movements for buses when passing the intersection. The straight-lined driving pattern and absolute priority provides ultimate efficiency; no geometric-, control-, or traffic delay. Traditionally, pedestrians have been most prioritized in urban areas in Norway. This design provides high priority of pedestrians, but whenever a bus is present, pedestrians are regulated to give way. The main pedestrian crossing is unsignalised in a straight line from crossings of general purpose lanes. A signalised, secondary crossing is established for visually impaired pedestrians. Green signal is provided when buses are absent. As heavy vehicles use much more time and energy on stopping and accelerating, pedestrians must wait the few seconds it takes for the public transport vehicle to pass.

Cyclists are provided with a continuous, dedicated bike network inside the pedestrian area and outside the motorised vehicles. Compared to traditional mix of cyclists and other traffic due to termination of bike lanes, traffic safety should be improved. The priority is also improved as all motorised vehicles must give way except public transport.

1.4 Task description

This design aims for high priority of public transportation, cyclists, and pedestrians. Further investigations are based on quantitative analyses and visual simulations, raising three research questions to the design:

- Which traffic volumes constitute a tolerable delay with the design?
- How does the design affect different transport groups?
- How is traffic safety preserved?

2. METHODOLOGY

2.1 Analysing method

The design is analysed by traffic software; *SIDRA INTERSECTION* and *AIMSUN*. SIDRA INTERSECTION is an analytical program on a mesoscopic level, and AIMSUN performs simulations on a microscopic level. Using traffic software allows visual and quantitative analyses of a theoretical implementation by observing occurring effects. Additionally, it retains the experiment in a safe, controlled environment without interrupting existing traffic; of special importance as the design is not yet familiar in current road network.

In SIDRA INTERSECTION, conflict points in the circulatory lane with the busway are investigated. One conflict point is modelled into an intersection with give way-rules for circulating traffic. Occurring *back of queues* 95 % of the time for various bus flows and general purpose traffic are investigated. *Back of queue* measures length from the stop line to the last vehicle affected by the queue. This gives an indication of which traffic volumes the lanes can retain for an accepted queueing in the circulatory lane.

In AIMSUN, the full design is investigated with the interaction of all transport groups. This provide quantitative values of acceptable volumes for the different transport modes, and visual observation of traffic management and driving behaviours. The design is modelled with three different levels of traffic volumes by the different transport groups; *low*, *intermediate*, and *high* volumes. Variations between buses, general purpose traffic, and non-motorised traffic constitute three 3x3 matrices of results per output parameter.

2.2 Strengths and weaknesses with SIDRA INTERSECTION and AIMSUN

SIDRA INTERSECTION is a deterministic program; results are equal per model run by constant use of mathematical equations and input parameters. Unrealistic exclusion of variations constitutes a weakness with the program. AIMSUN is a stochastic model. Hence, variance is included by differences in driving behaviours, vehicle sizes, and arrivals in the model. Several replications are required for calculating average result values for a scenario.

Modelling roundabouts in AIMSUN has associated challenges: driving behaviour at the roundabout, driving in the circulatory lane, merging at exits, and gap acceptance from different directions (Aakre, 2016, p. 47). These factors are not realistically developed in AIMSUN 8, constituting weaknesses with modelling the experimental design.

AIMSUN does not support detailed drawing of models. Thus, the design cannot be recreated precisely. Inaccurate adjustments can be performed as lengths are displayed for sections, but angles and exact curves cannot be set. As the model will not conform fully with the design, occurring behaviour should be observed during simulations for verification.

AIMSUN allows visualisation in both 2D and 3D. This is a strength with the program as occurring situations, behaviours, and eventual errors in model runs can be observed. SIDRA INTERSECTION does not support visualised model runs.

3. DATA

All scenarios run over 60 minutes. In AIMSUN, a warm-up time of 10 minutes is included for filling up the network before results are produced. As the experimental design is assumed to be implemented mainly at feeder roads, general purpose traffic is distributed with 10 % heavy vehicles and 90 % light vehicles in both programs (Statens vegvesen (N200), 2014b, p. 209).

3.1 SIDRA INTERSECTION

Due to symmetrical experimental design, conflict points in the circulatory lane are investigated by modelling one crossing between buses and general purpose traffic. The two-lane busway constitutes a total width of 6,5 metres, with a 6-metre-wide circulatory lane crossing nearly perpendicular. General purpose traffic is regulated with traffic signs to give way for approaching buses from both sides. Further data is listed in *Table* 2.

Table 2: Data in SIDRA INTERSECTION

Parameter	Bus lane	General purpose lane
Vehicle type	Bus: 100 %	LV: 90 %, HV: 10 %
Speed	40 km/h	25 km/h
Critical time gap	-	LV: 5,0 sec, HV: 7,5 sec
Follow-up headway	-	LV: 3,0 sec, HV: 4,5 sec

LV = Light vehicles, HV = Heavy vehicles

Critical time gap and follow-up headway are calibrated for heavy vehicles with a default factor of 1,5 due to lower acceleration compared to light vehicles. Average values for general purpose traffic are 5,25 and 3,15 seconds, respectively.

Peak flow factor of 95 % over 30 minutes are included for realistic variations of flows in the model. Tested bus and general purpose traffic flows are presented in *Table 3*.

Table 3: Traffic flows in SIDRA INTERSECTION

Bus frequency	Vehicle frequency
1. 20 bus/h	1. 300 veh/h
2. 40 bus/h	2. 350 veh/h
3. 80 bus/h	3. 400 veh/h
4. 120 bus/h	4. 450 veh/h
5. 160 bus/h	5. 500 veh/h
6. 200 bus/h	6. 550 veh/h
7. 240 bus/h	7. 600 veh/h

3.2 AIMSUN

The model in AIMSUN is made to the author's best extent to geometrically comply with the experimental design. *Yellow boxes* are established at intersections associated with bus lanes, cyclists, and pedestrians to prevent undesired blockage. *Road types* are adjusted for conforming speeds, lane widths, and gap acceptance.

Parameters for *gap acceptance* are used with default values, except at waiting spaces in the circulatory lane for general purpose traffic. *Initial safety margin* and *final safety margin* are conservatively set at 3,5 and 1,5 seconds, respectively.

Due to Norwegian conditions, transport modes are adjusted to national design dimensions (Statens vegvesen (N100), 2014a, p. 151-154). Deviations are included for variations.

Bus stops are included in the model, resulting in a reduced bus speed over last conflict points. Bus stop capacity of one bus is never exceeded by departure frequencies, bus stop time, and deviations. Traffic is generated by symmetrical movements during all model runs.

Table 4:Traffic volumes of transport modes for different flow intensities in AIMSUN

Flow intensity	**Buses *(both lanes)***	**General purpose traffic**	**Cyclists and pedestrians**	
Low	20 bus/h	1080 veh/h	200 cyclists/h	300 ped//h
Intermediate	30 bus/h	1440 veh/h	300 cyclists/h	600 ped//h
High	60 bus/h	1800 veh/h	400 cyclists/h	900 ped//h

Table 4 shows volumes of the three different transport groups constituting different scenarios in AIMSUN; buses, general purpose traffic, and cyclists and pedestrians. Cyclists and pedestrians are assembled as a simplification with most movements entering and exiting different connecting roads. Bus flows are generated to and from both lanes by a 50/50 percentage allocation. Deviation of 20 seconds per departure is included.

General purpose traffic is equally distributed in percent for all flow intensities. 59,1 % drive to and from major roads, and 4,4 % drive to and from minor roads. Of these, 2 % enter and exit by the same entry. 18,7 % of drivers go from major roads to a minor road. 17,8 % exit a major road with approach from a minor road. This constitutes 77,8 % approaching from major roads, and 22,2 % approaching from minor roads.

4. RESULTS

4.1 SIDRA INTERSECTION

Different traffic flows constitute 49 combinations, presented in a 7x7 matrix. *Table 5* shows occurring *back of queue* with 95 % quantile of time. Due to queue spillback into adjacent lanes and short waiting spaces in front of bus lanes, *back of queue* is a more relevant measure than *cycle-average queue* (Akçelik, 2017, p. 473). Results are coloured to degrees of severities. *Green* is defined as not severe; assumed no blockage of other movements.

Table 5: Resulting back of queue with 95 % quantile in SIDRA INTERSECTION

QUEUE 95 % BACK, CIRCULATORY LANE [veh]							
	300 veh/h	**350 veh/h**	**400 veh/h**	**450 veh/h**	**500 veh/h**	**550 veh/h**	**600 veh/h**
20 bus/h	1,3	1,6	2,0	2,4	2,9	3,5	4,1
40 bus/h	1,4	1,7	2,1	2,5	3,0	3,6	4,3
80 bus/h	1,5	1,8	2,2	2,7	3,5	4,8	6,5
120 bus/h	1,6	1,9	2,7	3,6	4,8	6,3	8,2
160 bus/h	1,7	2,4	3,3	4,3	5,6	7,3	9,5
200 bus/h	2,1	2,8	3,8	4,9	6,4	8,4	11,1
240 bus/h	2,4	3,2	4,2	5,6	7,3	9,7	13,4

< 2,5 veh   2,5 - 4,0 veh   > 4,0 veh

Results in *Table 5* show that 16 of 49 scenarios have less than 2,5 vehicles in average *back of queue*. This serves a continuous flow at the throughabout, equal to maximum 1 vehicle in *cycle-average queue* (Akçelik, 2017, p. 473). Increased general purpose traffic and bus flows cause more delay by greater *back of queues*. 13 scenarios are of intermediate state, and 20 scenarios severe of all tested scenarios.

4.2 AIMSUN

Flow intensities of the different transport modes constitute 27 different scenarios. The model in AIMSUN is investigated by occurring delays in *seconds per kilometre*.

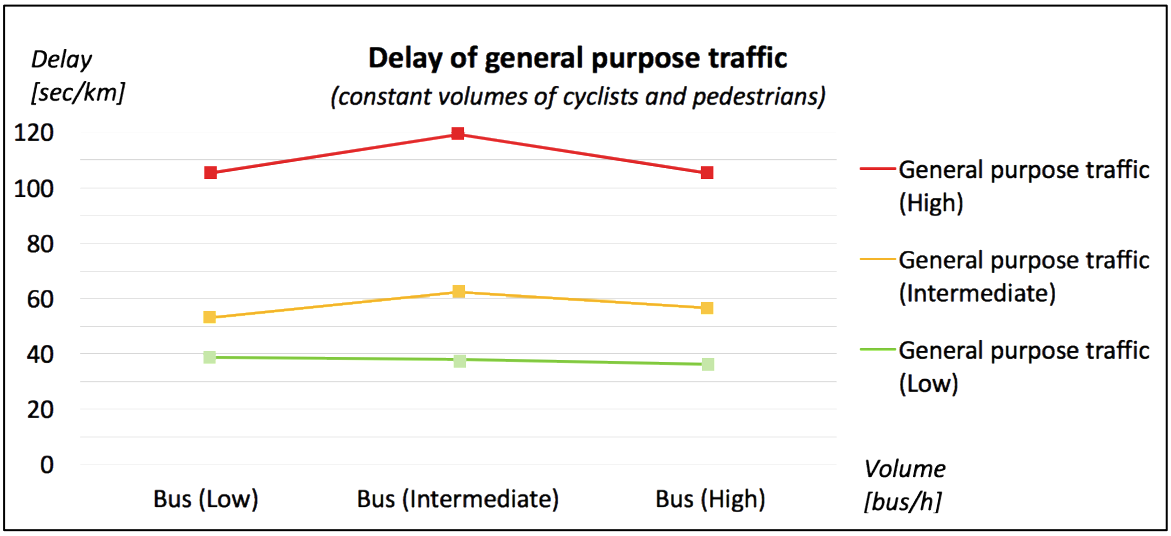

Figure 2: Delay of general purpose traffic with varying bus volumes. Values from AIMSUN

Figure 2 shows delay of general purpose traffic at three different bus volumes; *low*, *intermediate*, and *high* intensities. Relations between these volumes are unknown; linearly presented in all figures. The coloured lines represent different flow intensities of general purpose traffic. Cyclists and pedestrians are modelled with intermediate volumes.

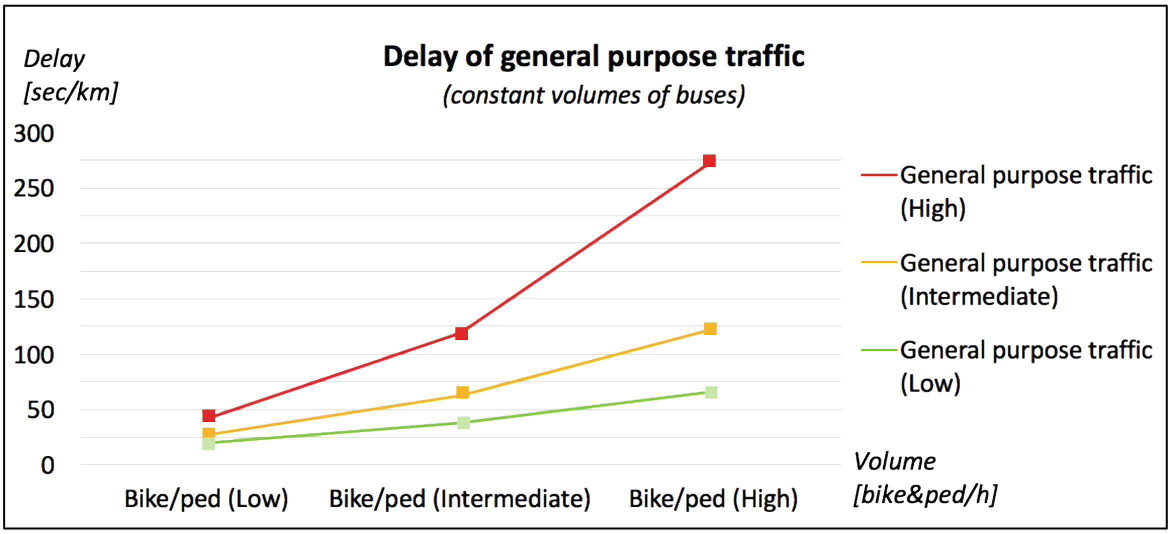

Figure 3: Delay of general purpose traffic with varying cyclist and pedestrian volumes. Values from AIMSUN

Figure 3 shows delay of general purpose traffic by varying volumes of cyclists and pedestrians. Buses are modelled with intermediate departure frequency in all scenarios.

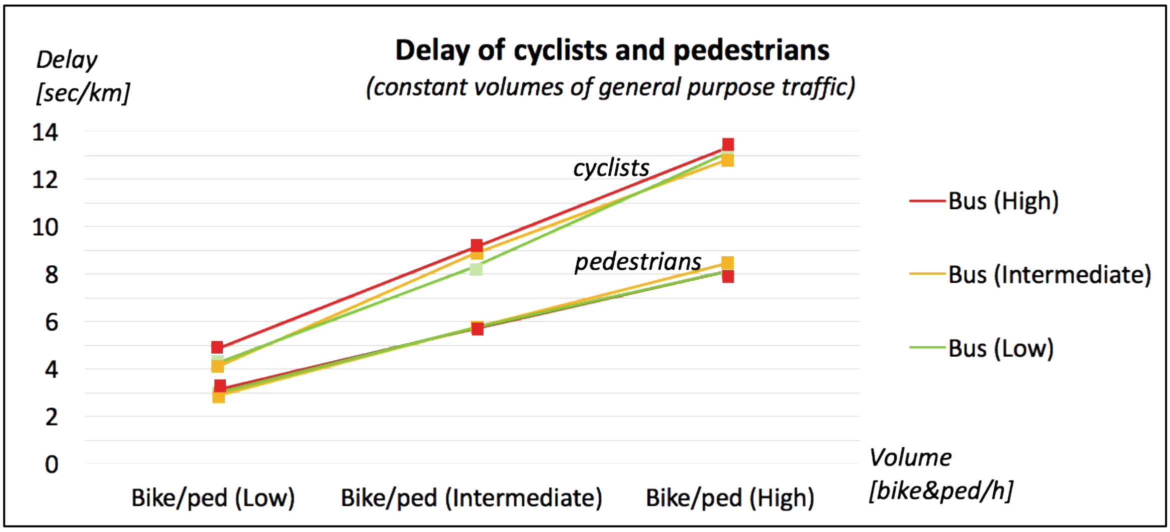

Figure 4: Delay of cyclists and pedestrians with varying cyclist and pedestrian volumes. Values from AIMSUN

As cyclists and pedestrians are required to stop for approaching buses, associated delays are presented for different bus volumes in *Figure 4*. The three upper lines show delay of cyclists. Scenarios deviate relative to each other by less than a second per cyclist and pedestrian flow intensity. The three lower lines represent pedestrians. As values are approximately equal each scenario for pedestrians, these lines are very close in the diagram. General purpose traffic is modelled with intermediate flow intensity in all scenarios.

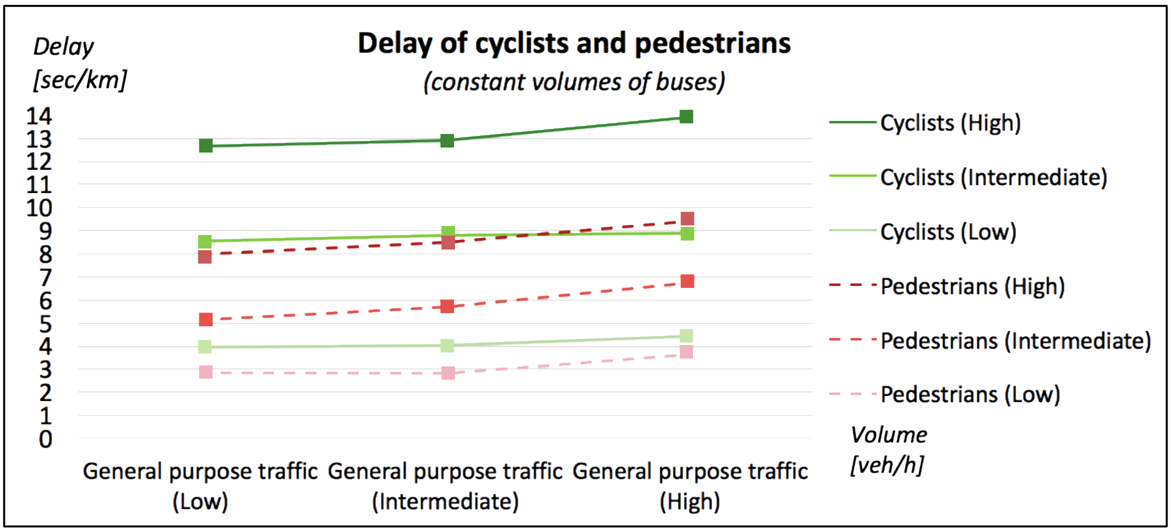

Figure 5: Delay of cyclists and pedestrians with varying general purpose traffic volumes. Values from AIMSUN

Figure 5 shows delay impact of cyclists and pedestrians by different flow intensities of general purpose traffic. Buses are modelled with intermediate departure frequency.

Results show that a segregated meridian busway through the central island does not cause considerable inconveniences for other traffic. Horizontal lines with small deviations in *Figure 2* show that buses do not affect general purpose traffic. Vertical gaps between lines show that flow intensities of the transport mode impact delays. Additionally, bicycle and pedestrian volumes contribute to increased delays for general purpose traffic, shown in *Figure 3*. *Figure 4* shows that cyclists and pedestrians are rarely affected by different bus flow intensities. Delay lines are approximately equal for cyclists and pedestrians, varying by flow intensity of own transport modes. *Figure 5* shows that general purpose traffic volumes slightly increase delays for cyclists and pedestrians. Pedestrians are slightly more affected than cyclists at low and intermediate flow intensities of general purpose traffic; barely noticeable by circa 1 second per kilometre in relative deviation. Hence, delay of transport modes at the throughabout are mainly affected by respective flow intensities by used values. Buses are not delayed in any scenario by absolute priority at all conflict points.

5. DISCUSSION

Data models allow observation of theoretical effects and driving behaviour. Chosen traffic volumes constitute a basis for assessment, though volumes and movements will vary from site to site. *Low*, *intermediate*, and *high* flow intensities are defined as basis for scenarios; not absolute values. Scenarios form relative measures for specific movements and volumes.

Several input parameters in models are debatable, constituting uncertainties with output data. Parameters of gap acceptance in both programs are mainly used with default values, and more conservative for general purpose traffic in the circulatory lane. Drivers are assumed to act more conservative at a new design in the road network, though actual behaviour could differ. Gap acceptance might be even more conservative, or not changed at all. Increased gap acceptance is included in both programs as an assumption. Over time, gap acceptance is likely to be reduced as drivers get more used with the design (Spack, 2017).

In SIDRA INTERSECTION, bus speed is set to design speed of the lane. Bus stops after conflict point result in reduced bus speed over the crossing, not considered in the model. This result in longer crossing time for buses; increased delay of general purpose traffic. Circulating speed in front of the conflict point is set to 25 km/h. This speed varies with entry point and behaviour; hence, more dynamic than set value.

Tested scenarios of circulating flows in SIDRA INTERSECTION vary from 300 to 600 veh/h; 600 veh/h equals one vehicle passing every 6 seconds. Such values of flow intensities in the experimental design are not likely as most movements are not in conflict with bus lanes. Additionally, *peak flow factor* is included, increasing total flow of general purpose traffic. Large circulating flows result in considerable *back of queues* with only 20 bus/h, see *Table 5*. Bus frequencies are also unrealistically high in this model. Highest bus frequency in AIMSUN is 60 bus/h compared to 240 bus/h in SIDRA INTERSECTION. Such high bus frequencies will cause problems for general purpose traffic. Additionally, bus stops require large capacities.

In AIMSUN, variations due to peak periods are not included. As a simplification, the secondary, signalised crossing, and pedestrian and bicycle movements to and from bus stops are also excluded. Ignoring bus stops, delay of general purpose traffic is reduced as these lanes are crossed for access of bus stops. AIMSUN generates pedestrian departures relatively evenly; hence, not in groups. As pedestrians tend to move in groups, this cause more delay for general purpose traffic and cyclists, not conforming to a real situation. Delays in AIMSUN presented in *sec/km* constitute 4-5 times as many seconds as delay in the network. Movements in the model are 200-250 metres as connecting entries and exits are drawn with lengths of 100 metres.

Pedestrians make route choices based on set Origin-Destination movements between centroids, and shortest way in AIMSUN. As pedestrians are regulated with anticlockwise movements in outer lanes and clockwise in inner lanes, geometry impacts route choice. With one path shorter than another, only one route is followed. This impact certain movements unrealistically.

The circulatory lane is widened in front of conflict points and at exits. Thus, an additional vehicle to the vehicle using the waiting space can queue up in the circulatory lane, allowing others to exit simultaneously. This occurred in AIMSUN, observed during simulations; reducing delays of general purpose traffic. Though this worked out for two personal cars, other movements were not executed correctly in the program. Transport groups did not always obey traffic rules, and buses sometimes unintendedly slowed down in front conflict points.

Tested bus flows are not causing problems with the secondary, signalised crossing in the design. As this crossing is assumed to mainly facilitate visually impaired, green time portion must be sufficient for safe crossing. Hence, high bus frequencies should be avoided.

Calibration and validation of models are not performed due to incomparable data sets. Data from other throughabouts with penetrating trams and buses were sought without success. "Traditional" roundabouts do not give comparable values; hence, not used. As principles with the design as investigated, traffic management is assessed by defined scenarios as a basis. Analyses give indications of occurring delays and effects, a basis for further investigation.

Traffic safety issues are raised with new designs. Not familiar with the situation, users might be confused or feel unsafe. Give way regulated conflict points in the circulatory lane are of special interest as least acknowledged element in today's road network. The situation can be improved by different measures. Highlighting bus lanes with coloured asphalt makes conflict points more visible. This guide both buses and other traffic over conflict points, and makes observation of approaching buses easier. Bus lanes can be coloured throughout the full design, or over conflict points. Another potential measure is elevating bus lanes from the circulatory lane. This increase drivers' awareness and focus over the busway. These conflict points are of special interest as severe accidents can occur with approaching buses in 40 km/h, and impact angles of 90 degrees.

Conflict points with the busway are important to highlight, though these are not the most frequent movements. Continuation of the major road throughout the design area requires no crossing of bus lanes for general purpose traffic or cyclists. Entering the major road from minor roads by right turns are also not in conflict with bus lanes.

A throughabout in Hillevågsveien, Stavanger have signal controlled entries for other traffic when presence of buses. Traffic signals also obstruct movements not in conflict with the busway; hence, not an optimised solution. Instead of give way signs, signalising conflict points in the circulating area are considered. Due to longer delays by red signal time, this solution is avoided. Crossing the busway is not assumed to be problematic with several similar solutions of passing trams at throughabouts in Norway today.

Traffic safety for pedestrians and cyclists at crossings of the busway is considered by three crossings serving different purposes. Cyclists are regulated to give way to buses with a separate path for crossing. Safe and uninterrupted waiting spaces of 3,5 metres are established between motorised lanes. Though less length is sufficient (Statens vegvesen (N100), 2014a, p. 151), this is also intended to facilitate the width of a bus stop further away from the throughabout. Pedestrians are provided with two crossings of the busway. The main crossing is unsignalised alongside the bicycle crossing, serving most pedestrians. By absolute priority of buses, pedestrians are regulated to give way. The second crossing is signalised, separated from the main crossing. This crossing is proposed for providing safe crossing of visually impaired pedestrians by red signal time when presence of buses, and green signal time when vacant. Tactile paving should be implemented for guidance. This crossing can also serve other pedestrians. Tactile tiles are not included in the principle drawing in *Figure 1*.

6. CONCLUSION

Buses have no delays due to absolute priority: no delay caused by other traffic, signal control, or geometrically as buses move in straight line through the central island. Cyclists are given high priority in the network as delays are small. Though delays are small, the withdrawn circulatory bike lane constitute longer movements compared to a more compressed design. Delays for pedestrians are also small; thus, today's high priority is preserved. Cyclists and pedestrians must give way for buses in the bus lanes, but provided with highest priority elsewhere in the network at all other crossings. Cyclists and pedestrians are mostly impacted by respective volumes at the throughabout. General purpose traffic is least prioritized in this design; worst impacted transport mode. Volumes of general purpose traffic impact most, and higher frequencies of cyclists and pedestrians. Certain movements of general purpose traffic must cross the busway by giving way to buses; an issue regarding traffic safety.

Based on tested scenarios with defined volumes and movements; cyclists and pedestrians are rarely affected by other transport modes, and buses not affected at all. General purpose traffic sees most delay in the network with lowest priority. By *back of queue* results over conflict points, buses do not severely impact general purpose traffic until 400 veh/h. Larger flows result in problematic queues; blockage of other traffic. Such large volumes of general purpose traffic are improbable as not an assumed frequent movement at the throughabout. Results from AIMSUN show that tested bus frequencies do not impact general purpose traffic, though lower frequencies are tested compared to SIDRA INTERSECTION. Flow intensity of general purpose traffic causes most delay to itself, and some delay from high volumes of bicycle and pedestrian traffic. Intermediate volumes of cyclists and pedestrians do not cause severe changes in impact of general purpose traffic; 300 bike/h and 600 ped/h, respectively. Cyclists and pedestrians are not notably impacted by general purpose traffic; mainly impacted by respective volumes. By tested scenarios in AIMSUN, different volumes of buses are not affecting other transport groups.

As traffic software is used as method for assessment, consideration of traffic safety is limited. Discussion of assumed occurrences are based on other observed situations as elements are known from elsewhere. Crossings between general purpose traffic and buses constitute most exposed conflict points, though these are not frequent movements. Give way regulated crossings are not assumed to be a problem between these transport modes. General purpose drivers are considered by separating conflict points from each other, thus; focusing on one conflict point at a time. This preserves traffic safety for all transport modes at the throughabout. Unsignalised crossings over the busway for pedestrians and cyclists can lead to severe impacts with buses. Traffic safety is preserved by low bus speeds of 40 km/h, designated crossings with an additional signalised crossing, waiting spaces, and universal design.

Assessment of the design is solely based on traffic software; a simplification of reality. Hence, more analyses should be performed by larger scaled models with close monitoring. This article constitutes a basis for further investigation and development of the design.

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PART III – ATTACHMENTS

PART III – Attachments consist of three enclosed attachments, and five digital attachments.

List of enclosed attachments

List of digital attachments

- ExperimentalDesign.pdf
- AIMSUN_OutputData.xlsx
- AIMSUN.ang
- SIDRAINTERSECTION_OutputData.xlsx
- SIDRAINTERSECTION.sip7

ExperimentalDesign.pdf shows the experimental design in vector graphics, drawn in AutoCAD.
AIMSUN_OutputData.xlsx includes selected output data from AIMSUN, presented in an Excel-file. These data are used as basis for result figures from the program.
AIMSUN.ang is the file from AIMSUN of the model used for investigation of the full experimental design with all transport modes interacting.
SIDRAINTERSECTION_OutputData.xlsx includes selected output data from SIDRA INTERSECTION, presented in an Excel-file.
SIDRAINTERSECTION.sip7 is the file from SIDRA INTERSECTION of the model used for investigations of the conflict points in the circulatory lane.

Attachment 1

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Text of the Thesis

MASTER DEGREE THESIS

Spring 2017
for

Øyvind Høsser

Prioritizing bicycles and public transport at intersections

BACKGROUND
This Master's thesis is the final submission for a Master's degree in the Civil Engineering programme at the Norwegian University of Science and Technology (NTNU).

By current National Transport Plan of Norway; NTP 2014-2023, all future traffic growth is to be taken by public transport, biking, and walking. As dedicated public transport lanes and bike lanes are often terminated at intersections, priorities are abolished by mixed traffic. This result in disadvantages and delays. Increasing attractiveness through improved priority and efficiency of these transport modes is basis for this thesis.

TASK
Objective of the thesis is investigating a way to increase priority of bicycles and public transport at intersections. The task is divided into four parts:

1. State of the art. The candidate shall give a brief description of current priority of public transport, bicycles, and pedestrians in Norway. Elements regarding associated priorities shall be discussed with main focus on public transport. Assessment and elaboration of different existing designs gain knowledge both for the candidate and readers of the Master's thesis.
2. An intersection design with increased priority of bicycles and public transport should be presented, based on State of the art. Pedestrians shall be considered; not exposed to unnecessary large delays.
3. The candidate shall use two data tools for assessment of the design. SIDRA INTERSECTION and AIMSUN should be used for modelling parts or the full network, with focus on traffic management. Traffic management is also basis for a scientific article. An introduction to mentioned traffic software and description of most relevant parameters is expected to be included.
4. The experimental design and results from traffic software should be assessed. Additionally, traffic safety should be considered. Analyses and assessment should be reflected in a summary, and conclusion.

Weighting of different parts is decided between the candidate and supervisor.

Research questions:

1. Which design improvements at intersections facilitate increased priority of public transport and cyclists in Norway, preserving high priority of pedestrians?
2. Which traffic volumes constitute a tolerable delay with the new design?
3. How does the design affect different transport groups?
4. How is traffic safety preserved with this design?

General about content, work and presentation

The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords (template on: http://www.ntnu.no/bat/skjemabank)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- The main text.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the same points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in “Writing Reports” by Øivind Arntsen, and in the departments “Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave” (In Norwegian) located at http://www.ntnu.no/bat/studier/oppgaver.

Submission procedure

Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

The master thesis will not be registered as delivered until the student has delivered the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable. See http://www.ntnu.no/bat/skjemabank for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". The document is found on the NTNU HMS-pages at http://www.ntnu.no/hms/retningslinjer/HMSR07E.pdf

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Startup and submission deadlines
Startup and submission deadlines are according t o information found in DAIM.

Professor in charge: Arvid Aakre

Contact at the Norwegian Public Roads Administration: Malin Bismo Lerudsmoen

Department of Civil and Transport Engineering, NTNU
Date: 15.01.2017, (revised: 09.06.2017)

Arvid Aakre

Professor in charge (signature)

Attachment 2

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Current tram rules in Norway

Current tram rules in Norway

Current tram rules in Norway are retrieved from the Norwegian Public Roads Administration's websites; available at: http://www.vegvesen.no/trafikkinformasjon/Lover+og+regler/Trafikkregler/Vikeplikt+og+trikk (accessed 01 June 2017)

Paragraph §10 nr.2 states the current tram rules of Norway, legitimate as of 1'th of June 2017. The paragraph is also translated to English by the author of this report.

§10 nr.2 (original):
"Trafikant skal gi fri veg og om nødvendig stanse for sporvogn og for jernbanetog".

§10 nr.2 (translated by author of this report):
"All users of the road network must give way and if necessary stop for trams and trains".

The Norwegian Public Roads Administration provides complementary information about trams in traffic:

- Other traffic is obliged to give way to trams as trams require longer stopping time due to lower deceleration speed
- Pedestrians must give way for trams, also at unsignalised crossings
- By traffic signs, trams must give way to other traffic when entering a roundabout. When exiting the roundabout, other traffic must give way to the trams.

Attachment 3

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Meeting logs

Meeting log 1 – Malin Bismo Lerudsmoen and Silje Hjelle Strand
Meeting log 2 – Helge Ytreland
Meeting log 3 – Steinar Simonsen

Meeting log 1 – Malin Bismo Lerudsmoen and Silje Hjelle Strand

Date: 17.02.2017
Attendees: Malin Bismo Lerudsmoen (NPRA), Silje Hjelle Strand (NPRA), Øyvind Høsser
Place: Brynsengfaret 6A, 0667 Oslo, Norway

A meeting was held on 17'th of February 2017 at the Norwegian Public Roads Administration's workplace in Oslo. Both Malin Bismo Lerudsmoen and Silje Hjelle Strand have buses, cyclists, and pedestrians as focus area. Additionally, Malin Bismo Lerudsmoen is external professional contact for this thesis. The essence of the interview is described briefly in the following.

During the meeting, the design was discussed in an early stage. During the meeting, several aspects of the provisional design was discussed, and potential issues were raised.

The main outcome of the meeting was an extended understanding of current parameters in the handbooks, perspective on the provisional design, and supply of two relevant reports published by NPRA; *report 312* and *report 519*. Additionally, problems regarding bus stops in the middle of the road were discussed. This resulted in a solution where the bus shelter blocks further pedestrian passage, also entry of the bus stop from other side.

The speed of the buses through the conflict points was also discussed; preferably high. Regarding traffic safety, it was limited to 40 or 50 km/h. Ultimately, 40 km/h was considered an applicable design speed to preserve traffic safety with a new design.

Meeting log 2 – Helge Ytreland

Date: 27.02.2017
Attendees: Helge Ytreland (NPRA), Øyvind Høsser
Place: By phone call

The 27'th of February 2017, a meeting was held by conversation through a phone call. Helge Ytreland has been one of the key persons working with the throughabouts in Hillevågsveien, Stavanger. He works in the department of *planning and management* in Stavanger. The essence of the interview is described briefly in the following.

During the meeting, occurring situation and aspects with Hillevågsveien were discussed. Most prominent:

Signalising vs. give way regulation: Current rules for buses and trams in the national road network are different by today's rules. Hence, give way markings have been implemented inside the throughabout for the buses. The obstruction of vehicles performing turning movements not in conflict with the busway is caused by having signalised entries. The obstruction problem is due to shortage of area outside the throughabout as more lanes cannot be established.

Circulatory bike lane: Circulatory bike lanes were brought up as a subject, though it is not present at Hillevågsveien. Helge Ytreland stated that establishment of traffic signs for circulatory bike lanes at roundabouts have been a challenge in Norway.

Pedestrian crossings: At roads with low traffic volumes, designated pedestrian crossings are not necessary. Making the design in Hillevågsveien suitable for blind people has been a challenge. Visually impaired pedestrians experience confusion in between the four different traffic lanes. Additionally, guide dogs are trained to cross traffic lanes over zebra stripes. Straight pedestrian crossing or staggered pedestrian crossing over the traffic lanes have been considered, with the outcome of avoiding straight crossing for preserving higher level of traffic safety due to not running straight over.

Reported feedback from larger vehicle: There have not been reported any discontentment from larger vehicle drivers.

Additionally, Helge Ytreland provided registered traffic volumes over a rush hour of general purpose traffic at the throughabout at one registration the 13'th of October 2015. These data have been utilized as basis for modelling in AIMSUN.

Meeting log 3 – Steinar Simonsen

Date: 06.03.2017
Attendees: Steinar Simonsen (NPRA), Øyvind Høsser
Place: Prinsens Gate 1, 7013 Trondheim, Norway

A meeting was held on 06'th of March 2017 at the Norwegian Public Roads Administration's workplace in Trondheim. Steinar Simonsen is an engineer with many years of experience and knowledge about buses, cyclists, and pedestrian. The essence of the interview is described briefly in the following.

During the meeting, aspects with the busway and the bicycle network were discussed. Provisional 2,5 metres bus stop width was discussed, with the outcome of a widened bus stop to make the design applicable for the coming BRT-system of "Superbuss" in Trondheim in 2019. An associated report with background information about this system was provided; *Superbuss – Prosjekteringsanvisning for stasjoner; utkast*. By the time of the meeting, the report was not yet published, but permitted for use in the Master's thesis with ensuing publication.

Steinar Simonsen approved a bike lane width of 1,25 metres in the circulating area for one-way regulated biking.