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Norwegian University of
Science and Technology

# Improved Cycle Facility Design at Intersections

**Miroslav Vasilev**

Civil and Environmental Engineering
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Supervisor: Kelly Pitera, BAT

Norwegian University of Science and Technology
Department of Civil and Transport Engineering

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF CIVIL AND TRANSPORT ENGINEERING

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| Name: Miroslav Veselinov Vasilev | | | | |
| Professor in charge/supervisor: Kelly Pitera | | | | |
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Abstract:

The Norwegian transportation authorities have the ambitious goal of improving cycle infrastructure in order to increase the share of cycle commuters. This project was undertaken to find design solutions for cycle facilities that terminate at intersections.

Two sites with existing but discontinuous cycle facilities in Trondheim, Norway were used as a case study – a roundabout and a signalized regular intersection. An extensive literature review of best practices from around the world was carried out to provide different design solutions. Video recordings and on-site observations were carried out to gather data which was afterwards analyzed to get a better understanding of the behavior and interactions of the traffic users at intersections.

Based on the results of the analysis, two solutions were suggested as being appropriate for the roundabout: Raised crossing at the approaches and Separate cycle paths in the inside of the roundabout. The proposed design implementations for the regular intersections were: Cycle lanes through the intersection, Advanced Stop lines and Cycle paths with sidewalk.

Although the above solutions were based on the best international practices and the specifics of the studied sites, their expected positive effects cannot be guaranteed. That is why a before-and-after study is highly recommended in the case of their actual implementation.

Keywords:

| |
|---|
| 1. Cycle facility design |
| 2. Discontinuity |
| 3. Intersection |
| 4. Roundabout |

# MASTER DEGREE THESIS

SPRING 2014

for

Miroslav Vasilev

# Improved Cycle Facility Design at Intersections

**BACKGROUND**

Two-thirds of bicycle accidents in Norway, including over half of the cycling-related deaths and severe injuries, occur at intersections. Bicycle facility discontinuities (for example, a bike lane ending) where bicyclists have to merge with motorized traffic are of concern, especially in city areas where limited space constrains the designs. Improving bicycle facility design at these locations may not only reduces accidents, but also improve cyclists' comfort, which may influence people's decisions to cycle. Improving cycle facilities at intersections is important and timely given the desire to increase the bicycle mode share in Norway, as well as in many other countries.

**TASK**

The objective of this thesis is to develop alternative intersection designs for two intersections with existing, but discontinuous bicycle facilities.

**Description of task**

The assignment subtasks shall include:

- Conduct literature review of current research on discontinuities of cycle facilities (background), and cycle facility intersection design (possible solutions)

-- Develop and conduct a study/survey to better understand the movements of bicyclists at study intersections

- Develop intersection improvement suggestions (including drawings) that allow for safe and efficient bicycle mobility.

- Provide general recommendations for bicycle facility intersection 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.

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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.

On submission of the thesis the candidate shall submit a CD with the paper in digital form in pdf and Word version, the underlying material (such as data collection) in digital form (e.g. Excel). Students must submit 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.

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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**
The work of the task starts 27 January 2014.
The paper is to be delivered at the latest in DAIM by 23 June 2014.

**Professor in charge: Kelly Pitera**

Department of Civil and Transport Engineering, NTNU
Date: 04.02.2014

Kelly Pitera

# PREFACE

The purpose of this study was to provide design solutions for discontinuous cycle facilities at intersections and roundabouts. It is part of a broader research track aimed at the improvement of urban bicycle facilities in response to the growing cyclist volumes in Norway. The other areas that this research track investigates are the sizing of bike facilities and the design of shared use lanes. No dedicated funding was required by the current study.

The study focused on two intersections in Trondheim, Norway. A thorough literature review was carried out to investigate design improvements from other countries. On-site observations were carried out to gather data needed for the analysis of the traffic patterns at the studied intersections. Several design solutions for accommodating cyclists at the study intersections were suggested.

# ACKNOWLEDGEMENTS

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# SUMMARY

The purpose of this project is to suggest improvements of the design of existing but discontinuous cycle facilities at intersections. A vast literature review was undertaken to examine design solutions from other countries. Two intersections in Trondheim, Norway were used as a case study – a roundabout and a signalized regular intersection. Study of the traffic on these intersections was carried out which involved two methods of observation. The first one was manual data collection on-site which involved measurements of the geometric features of the intersections, traffic flow counts and registration of different information about the behavior of traffic users. A Surveyor's wheel was used for the geometric measurements and specially developed observation forms consisting of different questions about the cyclists were used for the traffic flow counts and the behavior studies. The second method of observation involved video recordings of the studied intersection which were later examined to gather more information about both motorized and un-motorized traffic users. Additional data about the traffic volumes and accident history of the studied intersections were acquired from the web page of the Norwegian Public Roads Administration.

Several solutions for the improvement of the cycle facilities on the studied intersections were suggested based on the investigated design practices from all over the world and on the analysis of the collected data. The facilities recommended for the roundabout were: Raised crossings at the approaches and Separate cycle paths. The design solutions for the regular intersection involved: Cycle lanes through the intersection, an Advanced Stop line, a Cycle path with sidewalk and a Raised crossing at one of the intersection's arms. Drawings of the suggested design improvements were prepared.

General recommendations about the cycle facility design at intersection in Norway were also given with the precaution that in-depth before-and-after studies should be part of any implementation projects in order to be able to track the actual efficiency of the chosen measures.

# 1. INTRODUCTION

Developed countries all over the world have been making serious efforts at reducing the negative human impact on the environment. Motorized vehicles traffic is one of the main sources of detrimental emissions and hence it offers a huge potential for improvement. A policy accepted worldwide to diminish these emissions is to enhance the development of sustainable means of transportation such as: public transport, bicycling and walking. Cycle commuting in particular has proved to be quite beneficial both environmentally and socially.

Norway, as a country where the growing urban population puts demand on the transport system, faces the challenges of meeting the needs of different transport users. The Norwegian National Transportation Plan stated that the traffic growth in cities should be taken by public transport and soft modes, including bicycling. To accommodate the growing number of cyclists in already congested cities, it is important to consider both how new infrastructure could be designed, as well as how existing infrastructure could be better utilized.

Important parts of the infrastructure are intersections due to the capacity problems that they pose and the considerable number of bicycle accidents that occur there. Moreover, there are challenges in relation to discontinuities of cycle facilities at intersections which were only addressed by a few studies. Improving bicycle facility design at these locations may not only reduce accidents, but also create a comfortable environment for cyclists, which may encourage more people to use cycling as a means of transport.

The task of this project is the provision of design improvements of terminating cycle facilities at two study intersections. A thorough literature review is carried out to find the best design solutions from other countries. A survey is developed and conducted to better understand the movements of bicyclists at the study intersections. However the methodology doesn't involve in-depth statistical analysis. Its purpose is to improve the general understanding of the behavior of the different transport users at the intersections.

Based on the design practices from other countries and on the analysis of the survey's results several design solutions for the studied intersections are proposed.

# 2. LITERATURE REVIEW

## 2.1. Discontinuities

There are numerous studies on the safety effects of on-street cycle facilities such as cycle lanes, while literature on bicycle facility discontinuities are scarce even though this is a highly important matter. Cycle lanes provide a comfortable and relatively safe accommodation for riders commuting in the urban environment but a very common situation in many modern cities is when a lane is ended or interrupted abruptly. This is the case at many intersections where the lane ends forcing cyclists to merge with motorized traffic through the junction without having any dedicated facility,often reducing their subjective perceptions of safety. A literature review of current research on discontinuities of cycle facilities and cycle facility intersection design was carried out to better understand the scope of the problem. While there is limited literature on cycle facility discontinuities, the importance of continuity in cycle networks is commonly discussed.

A report by a Scientific Expert Group of the OECD Road Transport Research Programme (1998) presented a review of the current safety situation of vulnerable road users in OECD Member countries. Based on a problem-oriented approach, the report identified the major safety problems faced by vulnerable road users taking into consideration their social, regulatory and physical environments. It provided an overview of their mobility patterns and accident characteristics based on available travel surveys and national statistics. The review of current experience in policies aimed at the protection of vulnerable road users took into account recent evaluation results of some safety measures which although not entirely new, tend to get more and more widely used. Problems that still call for adequate improvements were the basis for exploring prospective measures. Based on research and experience documented, the Group gave recommendations which mostly apply to urban policies and the urban environment. One of the recommendations concerned the design of space for pedestrians and cyclists. The Group formulated some criteria that should be followed when designing the space allocated to pedestrians and cyclists for their movements. One of the criteria was that continuity should be provided by properly connecting links of the networks and avoiding detours and sudden changes in traffic conditions.

In order to develop sound policies that advocate the use of bicycle transport, a literature study was undertaken by Heinan et al (2010) to examine the main factors for commuting to work. One of the factors they focused on was the built environment and more specifically on the continuity of bicycle infrastructure (either separate lanes or marked sections on roads where a bicycle facility is provisioned throughout the route).They considered this aspect to be significant as the existence of section of a route which doesn't provide cycle facilities could deter some people from cycling.

Stinson and Bhat undertook a study (2003) to assess the significance of the determinants of commuter cyclists' route choice preferences. They investigated route-level and link-level factors. A stated preference survey was conducted over the Internet to gather data. The information was used for estimation of empirical models. According to Stinson and Bhat, route-level factors refer to those characteristics that are most essential when accumulated over the whole route. These determinants include travel time, bicycle facility continuity (which accounts for interruptions in cycle facilities such as junctions), and delays due to traffic controls. Stinson and Bhat considered a total of eleven link and route attributes for the purpose of their survey. The interpretations of most of the factors they used were quite comprehensible, except for facility continuity. They defined a bicycle facility as being 'continuous' if the bike facility was available along the whole route without interruptions. A bicycle facility was defined as 'discontinuous' if there was no bicycle facility for at least 25 percent of the route (i.e., the rider would have to share a traffic lane with motor vehicles for 25 percent or more of the route). It was found that bicycle commuters generally prefer continuous facilities to interrupted ones and the availability of a continuous bicycle facility is much more important on arterial streets in comparison to residential streets. It was hypothesized that this is because facility discontinuities can present a higher safety risk on carriageways with higher levels of traffic.

In a follow-up study (2005), Stinson and Bhat investigated the differences in cycle route preferences of cyclists with different level of experience in bicycle commuting to work (or school). They classified the commuters into three different categories based on their reported experience and interest level in bicycle commuting, and estimated individual binary logit models for each category. The three categories were: experienced in bicycle commuting, inexperienced bicyclists who have an interest in considering commuting by bicycle in the future and inexperienced bicyclists who have no interest in commuting by bicycle. The data used in the analysis were gathered by Stinson and Bhat through a survey administered over the Internet. The survey asked several questions about the participant's commute patterns in addition to a series of stated preference questions which inquired data on the respondent's route choice in a modeling framework. The results quantitatively showed the differential importance of each route determinant to individuals of each level of experience. It was found that discontinuity of bicycle facility negatively impacts the route selection of both experienced and inexperienced riders. It was also found that inexperienced cyclists appear to value continuity slightly higher than experienced users, though the difference was not statistically significant.

To get a better understanding of the discontinuities of on-street bicycle lanes in cities, Krizek and Roland (2005) undertook a study of 30 sites in and around the city of Minneapolis, Minnesota. They investigated cyclists' perceptions of comfort when they encounter different discontinuities and estimated the strength of explanatory factors affecting their perceptions by analyzing the results of a survey of cyclists. The research focuses mostly on intersections, from the point of view that they are the transition from where on-street cycle lanes are available to where they don't exist. The authors measured the physical characteristics of the chosen discontinuities, including measures of the street width, number of adjoining traffic lanes, traffic volumes, parking availability, the direction of adjacent traffic, side of the road of the bicycle lane, and other physical attributes. They also administered a stated preference survey in which cyclists were asked to rate their level of comfort while riding through each of the discontinuities.

Questions about cyclists' socio-demographic characteristics and cycling experience were added in the survey.

The authors categorized the discontinuity sites in three different groups: left-handed losers, intersection inconsistencies, and lapsing lanes, based mainly on physical characteristics, traffic volume, and presence of a major junction.

'Left side losers' represents discontinuities where bicycle lanes, being on the left side of the street, compel the cyclists to cross over lanes of traffic to continue moving on the right side of the street when the facility is terminated (Fig. 1).

Fig. 1. – Examples of left side losers[1]

The group of 'intersection inconsistencies' consists of discontinuities where the bicycle lane is terminated because of a huge junction (Fig. 2). In such cases the cycle lane is usually on the right-hand side of the road but dissipates after the intersection because of many reasons such as automobile parking, a street with a different layout or not enough space.

Fig. 2. – Examples of intersection inconsistency[2]

The third category – 'lapsing lanes' – are those that usually terminate under relatively favorable conditions and provide wide enough lanes to ride in mixed traffic (Fig. 3).

To get a better notion of the numerous determinants leading to different levels discomfort, the authors utilized multi-variate modeling. At the end it was concluded that lanes that end on the left side of the street, increased distance of crossing intersections, the presence of parking after the discontinuity, and increased width of the curb lane all raise the level of discomfort for the cyclist.

This study focused attention on discontinuities by addressing especially on the worst ones. It also devised a way of categorizing them which would help planners by giving them a better understanding of the cycle facilities they manage. The research also utilized a methodology that could be easily implemented to settings in other urban areas such that the

[1] Source: Figure 2 in (Krizek and Roland, 2005)
[2] Source: Figure 3 in (Krizek and Roland, 2005)

most dangerous discontinuities could be prioritized in capital improvement plans to alleviate their detrimental effect.

Fig. 3. – Examples of lapsing lanes[3]

As intersections are the most difficult design challenge for planners and being the place where the majority of bicycling-related accidents occur, the following part of the literature review considers different solutions for riders at junctions.

[3] Source: Figure 4 in (Krizek and Roland, 2005)

## 2.2. Design Solutions

Different design solutions from all over the world, aimed at improving the design of cycle facilities at intersections, are presented. They were found after an extensive literature review of current research.

### *I. Solutions for crossings*

Separate cycle paths are recognized for being safe along continuous sections of roads but conflict situations with motorized vehicles occur at the to intersections between cycle paths and streets. For example, most of the bicycle-motor vehicle crashes in the Netherlands occur in urban areas at unsignalized priority intersections, where an arterial road crosses a local road. Over ninety-five percent of these are failure-to-yield accidents (Schepers, J. et al, 2011). There are various designs of crossing facilities and this creates lack of informity in both cyclists and drivers. Layout of crossing provisions should be easily comprehensible by all traffic users. For example when cyclists and pedestrians have the right of way on a crossing of a carriageway, this should be properly indicated.

A study of nearly two hundred bicycle-car accidents in four Finnish cities found that the most frequent accident type at bicycle crossings was when a driver turning right and a bicyclist coming from the driver's right along a cycle track (Räsäsen and Summala, 1998). Only 11 percent of the motorists noticed the rider before the collision, while 68 percent of cyclists saw the motorized vehicle. Ninety-two percent of cyclists who noticed the driver thought that he would yield as required by the law.

Similarly Danish studies of conflict situations at priority intersections where a car driver failed to yield to a cyclist who had priority over the motorist showed that a common reason for these collisions is that the driver didn't see the cyclist even though he had been looking in the direction where the rider was (Herslund and Jørgensen, 2003). These types of accidents are known as "looked-but-failed-to-see". In a study based on 10 self-reported near accidents, Herslund and Jørgensen (2003) found that when experienced drivers search for other road users, they usually unconsciously concentrate on the locations where other motor vehicles are. It was hypothesized that this is a factor in accidents where bicycles were overlooked.

One way to increase traffic safety of both cyclists and pedestrians is to provide them with elevated crossings at intersections between streets and cycle tracks. There are two major types of raised crossings for urban areas according to (Furth et al, 2011) which are very popular in the Netherlands – Exit Construction and Speed Tables.

According to Dutch regulations unsignalized crosswalks are prohibited where the speed limits exceed 60km/h so raised crossings aren't applicable on 70+ kph roads in the Netherlands. Passing through a raised crossing with higher speeds could send the driver out of control. Underpasses and overpasses are the preferred solution on Dutch 70+ kph roads (Furth et al, 2011).

# EXIT CONSTRUCTION

Exit Constructions are used at unsignalized priority intersections between an arterial street, with an outside parallel cycle track, and a local street. Exit Constructions are designed to provide a safer passage for cyclists and pedestrians over the side street without changing grade (Fig. 4). They are supposed to enforce lower speeds for traffic on the intersecting carriageway.

Fig. 4. – Exit Construction[4]

In the Netherlands they are mainly used for bike paths that run alongside 50 kph roads, where they intersect with 30 kph local roads. According to the Dutch regulations the ramp of Exit Construction should be at a grade of 15-25% (Furth et al, 2011).

The dimensions for Exit Constructions applied in the Netherlands are shown on Fig. 5 (CROW, 2007). The variables on the drawing mean: 'w' – is the width of the sidewalk and/or cycle track being crossed, 'b' – is variable and the width is chosen by the engineer, and 'a' – a ramp width of 50 to 80 cm. The steeper the grade of the ramp is, the closer to a complete stop the motorized vehicle will make which increases the safety effect for cyclists (Furth et al, 2011).

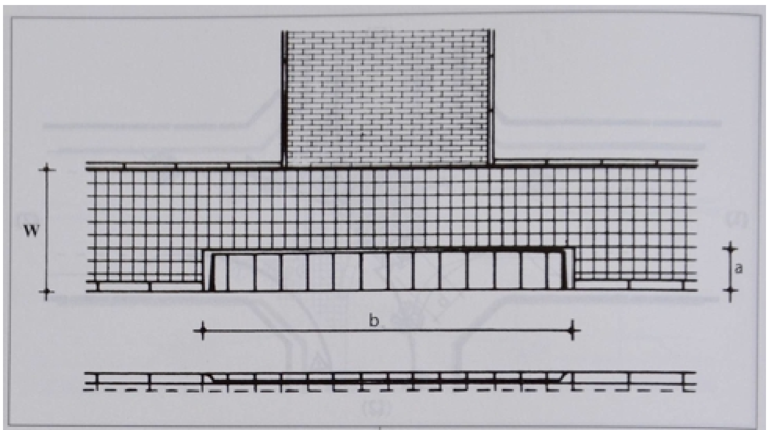



Fig. 5. – Exit Construction[5]

[4] Source: (Furth et al, 2011)
[5] Source: CROW Design manual for bicycle traffic

During their observation of raised crossings in the Netherlands, Furth et al (2011) noticed that buses were not impeded from normally passing through these facilities. In Delft Exit Construction style crossings with a grade of 25 percent are used on many bus routes (Fig. 6). To be able to go over it public transport buses should significantly reduce their speeds which has a positive effect on cyclists' safety.

Fig. 6 – A bus slows down to safely negotiate its way over an Exit Construction[6]

Many studies from around the world evaluated the benefits of Exit Construction and some of them are presented below.

Summala et al (1996) undertook a study of bicycle-motor vehicle accidents at non-signalized T-intersections in the City of Helsinki similar to previously described studies. It was found that the main crash type was that where a cyclist comes from the right on the major street and the motorist is turning right from the minor street. The study put to a test a hypothesis that motorists turning right concentrate on the vehicles coming from the left – as those approaching from the right pose no threat to them - and fail to see the cyclist from the right early enough. This was done by analyzing drivers' scanning behavior at two T-intersections. Two hidden video cameras were used, one to record the head movements of the approaching drivers and the other one to measure speed and distance from the cycle crossroad. The findings were in accordance with the accepted assumptions – the motorists turning right scanned the right leg of the T-intersection less frequently and later than did drivers turning left, suggesting that motorists use a visual scanning method which focuses on more frequent and important threats but neglects visual information on less urgent threats.

The second part of the study examined different solutions to improve the drivers' visual search behavior. It was found that speed reducing facilities such as speed bumps and elevated bicycle crossings and stop signs, placed in advance of the intersection were effective at changing drivers' visual search patterns in relation to cyclists approaching from the right.

A study undertaken by Leden et al (2000) developed a mathematical risk model to assess the safety effect of a new layout of a cycle crossings. The design involved raising the crossings and painting them in a bright color. It was found that as a result of the implementations, motorists' speeds decreased as expected. Nevertheless, it was hypothesized that the positive effect of the reduced speeds was to a certain extent counteracted by the

[6] Source: (Furth et al, 2011)

increased bicycle speeds. However, the safety per cyclist was still improved by roughly 20 percent mainly due to the growth in cycle flow. It was hypothesized that bicycle flow increased due to the new design of the crossings as cyclists found them to be safer and time saving.

Gårder et al (1998) developed a before-and-after methodology to estimate the effect on cyclists' safety of raising urban cycle crossings by 4 to 12 cm. Four of all 44 reconstructed intersections in Gothenburg were studied in detail. All the cycle paths run parallel to arterial streets and the raised crossings were all across minor streets (Fig. 7). Before the implementation, bicycle paths had ended with short ramps or curb cuts at each cross street, and cyclists had used conventional crossings. Gårder et al used information on accidents from hospital-reported database for the period 1988-1996. Broad cycle flow counts were performed at two of the sites and at two control sites for two weeks before the implementation and two weeks after. Study of the safety perceptions of the cyclists at the intersections before and after the implementations was also undertaken. A survey on bicyclists' safety was sent to 22 experts from different countries. Video recordings were also applied to gather information on cyclists' behavior.

Fig. 7. – Raised crossing[7]

As a result of the before-and-after study it was found that 50 percent more cyclists used the paths after the implementation of the raised crossings. It was also found that the safety per bicyclist was improved by around 20 percent because of the increase in bicycle traffic and with another 10 to 50 percent due to the improved design. Application of statistical methods showed that the highest probable consequence of an elevated cycle crossing is a risk reduction of approximately 30 percent compared with the before situation with a standard cycle crossing.

The effects of the implementation of new layout of cycle crossings in Lund, Sweden were assessed in a research which utilized literature studies, accident analysis and observational studies (König, 2006). The design of the new facilities involved elevation of crossings and red-grey coloring (Fig. 8.). Two pairs of junctions were chosen as study sites – each of them consisting of one reconstructed and one control intersection. The observational studies involved speed measurements, behavior studies, conflict studies and interviews. It was found

[7] Source: Figure 1 in (Gårder et al, 1998)

that after the implementations the speed of the motorists was reduced and cyclists became more self-confident. This was due to the perception of cyclists that they had priority in combination with their uncertainties related to the yielding regulations. This context was generated by a partly unconscious interpretation of the construction with its characteristic elements.

It was concluded that this kind of layout for crossings had the potential to improve cyclists' total traffic safety. One possible approach towards achieving the above was to visualize the right of way regulation – by traffic signs at the cycle paths, for example.

Fig. 8. – Colored and raised cycle crossing[8]

A study undertaken by Schepers et al (2011) examined the safety of cyclists at unsignalized priority intersections within urban areas. The main point of interest was the connection between the design features of the junctions and bicycle-motor vehicle crashes. During a four-year period of observation of the study intersections, 339 failure-to-give-way collisions with cyclists were registered. As a result of the study it was found that the most efficient way to enhance the safety of cyclists at intersections is the implementation of speed-reducing facilities for drivers leaving or entering the main road, such as raised crossings.

Fig. 9. – Well marked, reddish colored, raised bicycle crossing[9]

[8] Source: (König, 2006)

It was also found that safety is increased where the cycle track approaches are placed between 2 and 5 meters away from the main carriageway. Unexpectedly, it was found that "well marked" and reddish colored cycle crossings were related to greater risk (Fig. 9). According to Thomas (2013) a major drawback of this study is that it wasn't a before-and-after evaluation which makes it possible that these sites had already had safety issues prior to the implementations.

As a whole, the papers reviewed show that Exit Constructions have a positive effect on cyclists' safety, due to the reduced motorists' turning speeds and their increased awareness of approaching cyclists.

## SPEED TABLE

The other type of raised crossing is Speed Table (Fig. 10). They are flat-topped speed humps long enough for the entire wheelbase of a passenger car to rest on top. Speed Tables are applied when a cycle track or a pedestrian sidewalk intersects with a carriageway at a right angle. They are applied in order to lower motorists' speeds on streets where cyclist and pedestrian movement occurs, regardless of who has right of way (Furth et al, 2011). Street markings are used to show the driver that there is elevation. Brick or other textured materials increase visibility, and may enhance safety and speed reduction. According to (Furth et al, 2011) in the Netherlands Speed Tables are applied even when the cyclists do not have priority on the cycle track just to enhance the safety of the self enforcing traffic calming.

Fig. 10. – Speed Table[10]

Furth et al (2011) examined an example of a speed table on a main cycle route near the city of Delft (Fig. 11.). When initially constructed, the intersection was a raised crossing with yield sings for motor vehicles, giving priority to bikes. Unfortunately, there were accidents after the implementation, which required further changes.

[9] Source: Figure 1 in (Schepers, J. et al, 2011)
[10] Source: (Furth et al, 2011)


Fig. 11. – Speed Table in Delfgauw (a Dutch village)[11]

Stop signs, which are very uncommon in the Netherlands, were implemented as a supplementary measure to discourage motorists from speeding through the intersection.

According to (Furth et al, 2011) Speed Tables can be implemented on a variety of locations – from the largest cycling paths to simple pedestrian crossings, at the discretion of the engineer. The most common locations for Speed Tables on 30kph roads, were perpendicular cycle tracks, providing access to public facilities and commercial areas.

The examples that Furth et al (2011) encountered, varied in their width. Occasions where a cycle track narrowed for a raised crossing were rare. The horizontal part of the crossing was usually 1,5 to 3 meters wider than the cycle track (or combined cycle track and sidewalk). This increased safety because the motor vehicles could slow down before reaching the cycle track, not at its edge. Due to the relatively low grade of the ramps (5-10%), it was possible for the cars to pass through these facilities, whenever no cyclists were present, without lowering their speed too much.

In the Norwegian traffic regulation there is a section called System changes which describes crossings between cycle paths and roads. According to Håndbok 233 (2014) a system change is a type of facility where pedestrians or cyclists change to another type of facility. It is stated that frequent changes on a route can be a huge challenge, especially for cyclists and should be avoided. It is also stated that system changes should preferably be located at intersections. A system change on a section of a road is shown on Figure 12. According to Håndbok 233 (2014) these facilities should be highlighted in such a way as to be visible for cyclists, motorists and other road users. Crossings should be signposted and supplemented with road markings. It is noted that a possible solution is to elevate the crossings. These treatments are intended to increase the attentiveness of traffic users and to enhance speed reduction.

[11] Source: (Furth et al, 2011)

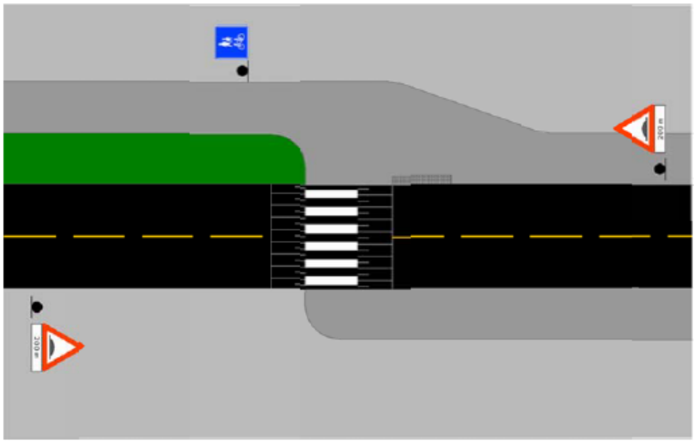


Fig. 12. – Crossing between mixed traffic and foot- and cycle path[12]

Raising the crossings between cycle tracks and roadways is a proven means of increasing their visibility, which leads to a reduction of motor vehicles' speed and improvement of their visual scanning and ultimately increasing safety.

[12] Source: Figure 3.18 in (Håndbok 233, 2014)

# *II. Solutions for roundabouts*

The main advantages of the roundabout are that it favors fluid mobility and enhances traffic safety. Intersections of this kind have better capacity and a quicker traffic interchange because users don't need to stop at signals. One of the safety benefits of the roundabout is that vehicles negotiate their way through these intersections in lower speeds and thus the severity of the accidents is reduced. Another safety feature is that many of the usual conflict points are omitted (such as left turns in countries where the traffic moves on the right side of the rode).

In general, numerous international studies have concluded that the safety effect of the conversion of a regular intersection into a roundabout is undoubtedly positive. In a before-after study of 23 newly constructed roundabouts, in the U.S., a highly significant reduction of 40 percent for all crash severities combined and 80 percent for all injury crushes were estimated (Bhagwant et al, 2001). Even higher reductions of 90 percent were observed in the numbers of fatal and incapacitating injury crushes. According to Crow (2007) the single-lane roundabout is the safest type of intersection.

While the overall safety effects are positive, when it comes to accidents involving vulnerable road users, such as cyclists, the effect of roundabouts is uncertain. Numerous studies have proven that there is a greater risk of cyclist injury accidents at roundabouts in comparison to other types of intersections. Large, unsignalized, multilane roundabouts are usually the riskiest and the most intimidating for cyclists (Holland, R., 2009). A before-and-after study was carried out of injury accidents involving bicyclists on 91 roundabouts in Flanders-Belgium (Daniels et al, 2008). They found that the conversion of intersections into roundabouts inside build-up areas increased the number of injury accidents involving bicyclists by 48%. For accidents causing fatal or severe injuries inside built-up areas, an average increase of 77% was found. Hels and Orozova (2007) explained this with the fact that orientation in a roundabout is more difficult for all road users than in an ordinary junction. They also claim that passing through a roundabout is physically more demanding due to the circular deflection of the road and (given the difference in speed between motorized vehicles and bicyclists) this may increase the number and proportion of one-cyclist accidents.

At the same time quite the opposite results were found in the Netherlands. In a before-and-after study of 201 newly built roundabouts a 47% reduction in accidents and a 71% reduction in casualties of accidents involving cyclists was observed (Schoon and van Minnen, 1994). The study also examined the safety of effect of three different treatment designs for cyclists: a) - a separate cycle path, b) - a cycle lane on the roundabout and c) – no specific engineering measure. In examining the three cycling solutions the roundabout with cycle path becomes clearly preferable at higher traffic (8000 vehicles/day) and cycle intensities.

Because of the discrepancy seen in the presented findings I hypothesize that the influence of the conversion of an intersection into a roundabout on cyclists' safety depends on the country it is taking place. Countries have their own experience in the provision of cycle facilities and the behavior of transport users is also different in each one of them.

The heterogeneity in the results of the safety performance of particular roundabouts or particular group of roundabouts can be partly explained by chance factors and by some structural difference between locations (Daniels et al, 2010). Studies have tried to relate the level of safety for cyclists at roundabouts to special cycle facilities at roundabouts.

A widely debated issue throughout the world is the choice of the different design solutions to accommodate bicyclists in roundabouts. There are many different views on the safety effects of the available solutions. There are four main design practices which are commonly applied:

1. Mixed traffic;
2. Cycle lanes;
3. Separate cycle track;
4. Grade separated roundabouts.

## MIXED TRAFFIC

The implementation of the first solution does not require any additional facilities since cyclists are considered to have the same rights as the motorized vehicles (Fig. 12). Riders follow the same yielding rules when they enter, negotiate their way through the circulatory area and leave the roundabout. When cyclists enter the roundabout they should give way to the circulating vehicles.

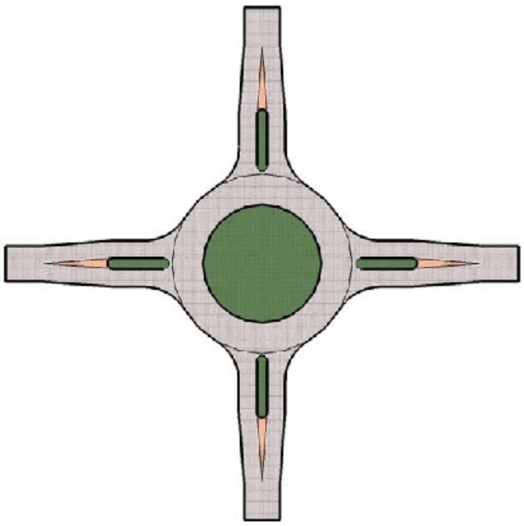


Fig. 12. - Roundabout with mixed traffic[13]

When riding within the circulatory area of the roundabout exiting vehicles should yield to parallel circulating vehicles.

According to the Norwegian regulations (Sykkelhåndboka 233) when there are cycle lanes on the approaches of the roundabout they have to be truncated 5 to 10 meters before the give-way line or immediately before the pedestrian crossing. Bicycle lanes in the exits start right after the roundabout or after the pedestrian crossings. In this way, the roundabout is a mixed traffic solution.

When cycle tracks are separated from the motorized traffic along the arms of the intersection cyclists are usually led onto the roadway via ramps or lowered curbs and mixed

[13] Source: Figure 1 in Daniels et al (2009)

with the other traffic users before the roundabout. After leaving the roundabout cyclists are led out of the roadway.

The mixed traffic solution is recommended up to a roundabout intensity of approximately 6,000 pcu/day (CROW, 2007). According to this design manual any cycle facilities along the roundabout's arms at 20 to 30 meters before the roundabout should be tapered/truncated. The advantage of this solution is that cyclists remain in motorists' field of vision (CROW, 2007).

Another modification of this design solution is to add advisory pavement markings or 'sharrows' in the traffic lanes of the approaches and in the circulatory area of the roundabout to enhance mixing between the modes (Wilke et al, 2014). An example of this variation is shown in Figure 13. According to Wilke et al, there is strong evidence that such markings can be effective and are recommended where speeds are equitable. They have found that cycle lanes on the approaches should terminate some distance behind the holding line where speeds are low. It is advisable in such cases that the width of the approach lanes does not exceed 3.0 meters so that the drivers do no attempt to enter the roundabout alongside cyclists (Wilke et al, 2014).

Fig. 13. – Roundabout with advisory lane markings[14]

## CYCLE LANES

The second possible design solution for accommodating cyclists in roundabouts is to provide cycle lanes inside the roundabout next to the traffic lanes (Fig. 14). These lanes are situated on the outer side of the circulatory area of the roundabout. They are segregated from the traffic lanes only by a marked white lane, small physical element or a slight grade separation. They can also be colored differently or a different cover of the asphalt pavement can be applied to mark them.  Colors which are most often used to differentiate cycle lanes inside the roundabouts are red, blue and green. A variance of this design solution is roundabouts where cycle lanes are differently colored but not separated from the carriageway by a line marking. This facility is called 'cycle suggestion lane'. Cyclists are not are not obliged to use the cycle lane and may use the carriageway but this option is still categorized as a roundabout with cycle lanes. (Daniels et al, 2009).

Roundabout with cycle lanes are used mainly in some European countries and in UK. Some road controlling authorities in Australia and New Zealand have followed their example and implemented bicycle lanes too (Wilke et al, 2014).

[14] Source: Figure in Wilke et al (2014)

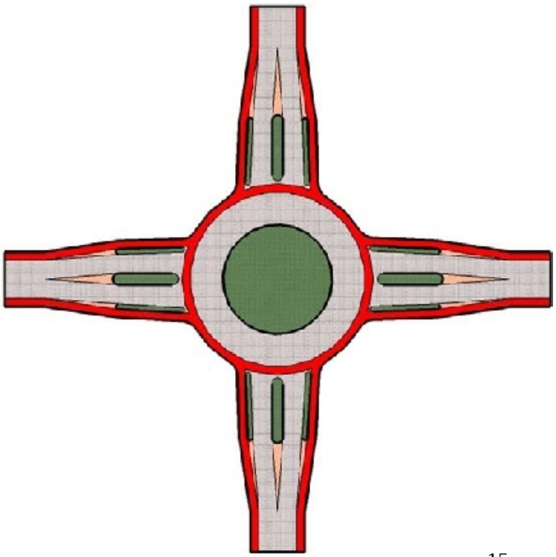


Fig. 14. - Roundabout with cycle lane.[15]

Brilon claims in his paper on roundabouts in Germany that: ‘cycle lanes at the peripheral margin of the circle are not allowed since they are very dangerous for cyclists. According to him up to a traffic volume of 15,000 veh/day, cyclists can be safely accommodated on the traffic lane without any additional facilities. When the traffic volume is higher than that, he recommends the use of separate cycle tracks (Brilon, W., 2005).

Designs which utilizes cycle lanes within the circulatiory area are not recommended by CROW (2007). According to this design manual, at relatively quiet roundabouts, up to 6,000 pcu/day, no additional facilities for cyclists are needed. Exceptions to this rule are the cases where cycle facilities would contribute for a better fit with the connecting roads. A separate cycle track is a preferable solution in such occasions.

The United Kingdom also has experience in constructing roundabouts with cycle lanes. This design is said to be used successfully at Heworth Green, north-east of York city centre, where a continental-style roundabout providing designated lanes for cyclists was created in 2001 (Fig. 15). York City Council (Holland, R., 2009) describes the continental-style roundabouts (also known as compact roundabouts) as having tighter geometry than the typical UK roundabout and being more cycle-friendly as motorized transport users are not expected to try to overtake cyclists on the circulatory area because of its limited width. An overrun apron around the central island is provided to reduce the area used by cars by increasing the island’s effective diameter, while at the same time allowing larger vehicles to negotiate their way through the junction. According to Holland (2009) roundabout such as the one at Heworth Green should be applied at locations where many cycle routes intersect at a roundabout. The roundabouts should be comprised of wide cycle lanes, a reduced circulatory area width, tight geometry, and a smaller outside diameter than conventional roundabouts. Separate cycle lanes are provided for cyclists who intend to leave the roundabout on the next exit and thus helping drivers to realize which way cyclists are going. Cyclists are only positioned close to the perimeter when they intend leaving at the next exit – otherwise, they are positioned away from the perimeter (Holland, 2009). This roundabout, also known as ‘magic roundabout’ has been given a Prince Michael International Road Safety Award in

[15] Source: Figure 2 in Daniels et al (2009)

2003. Having in mind the design of this roundabout it can be hypothesized that placing cycle lanes in a roundabout should only be done if the geometry of the intersection is changed in a way that it reduces the speed of the motorized transport users.

Fig. 15. – Continental-style roundabout with cycle lanes at Heworth Green in York, UK

When it comes to the Norwegian road traffic regulations it is clearly stated that there should not be constructed separate bicycle lanes through roundabouts (Håndbok 233, 2014).

## SEPARATE CYCLE TRACK

The third design solution for accommodating bicyclists in roundabouts is to provide a segregated cycle track outside the perimeter of the roundabout. There is a clearly stated preference for this design practice throughout the world because of its proven safety effects for cyclists.

On such roundabouts cyclists approach, circle around and leave the roundabout using a dedicated bicycle tracks at a distance of more than one meter from the roundabout. Usually there is a pedestrian sidewalk that runs parallel to the cycle track. Different color of the pavement is used to distinguish the cycle track. The only conflict points between the cyclists and the motorized vehicles occur where the cycle track crosses the arms of the roundabout. There are two different options when arranging the priory rules on these crossings. One of them is to give priority on the cyclists coming on the track over the vehicles approaching or exiting the roundabout (Fig. 16a). This corresponds to the popular tendency to give right of way to the traffic which circulates on the roundabout. This solution is usually implemented with a circulatory shape of the cycle track around the roundabout to provide for a convenient and fast passage for cyclists. This is the recommended solution for roundabouts situated inside built-up areas since it corresponds with the cycle-friendly policy (CROW, 2007).

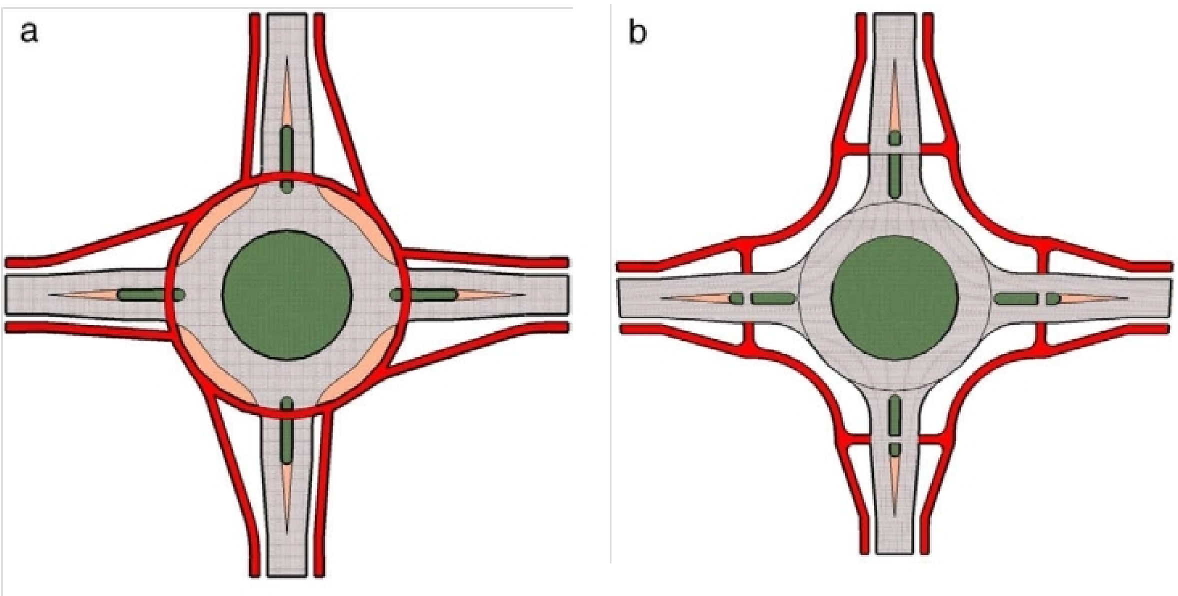



Fig. 16 – Roundabouts with cycle track: a) Priority to bicyclists. b) No priority to bicyclists.[16]

When designing the solution with no priority to cyclists the shape of the cycle tracks has to contribute to speed reduction as it is shown in Figure 16b. This kind of roundabouts is recommended for use in rural areas, where motor vehicles approach with considerably higher speeds. As a result of these recommendations, made by CROW, cyclists don't have priority on nearly all rural roundabouts in the Netherlands, while having right of way on 60 percent of the urban roundabouts (SWOV, 2012).

Dijkstra (2005) studied the safety effects of both priority rules for roundabouts with cycle tracks in the Netherlands. To do this he made an estimate of the number of urban roundabouts having segregated cycle tracks and the number of registered casualties of cyclists on these roundabouts. This study clarified what the result would have been if the priority rule on all urban roundabouts with a dedicated cycle track had been the same: either all cyclists 'with priority' or all without priority'. As a result of these hypothetical scenarios there were an 'extra' 52-73 injured a year in the case of 'with priority'.

According to SWOV (2012) the advocacy of giving cyclists priority on urban roundabouts that CROW insists on has got nothing to do with safety, but is motivated by mobility reasons in favor of the bicycle.

As it was noted earlier cycle lanes within the roundabout are not a preferred solution in the Netherlands. On busy roundabouts, with more than 6000 pcu/day, the use of separate cycle track is preferred (CROW, 2007). In this design manual it is also stated that the following principles apply to cycle facilities:

- the attentiveness of the bicyclists must be enhanced by the design of the cycle track;
- the place where cyclists cross the roadway must be evident and clear enough;
- near the location where cyclists cross the roadway they must be clearly visible for drivers.

[16] Source: Figure 3 in Daniels et al (2009)

When a one-way cycle track is designed around a roundabout there is a drawback concerning cyclists who intend to turn left. In such cases they are obliged to turn right on the cycle track and cross two of the approaches to the roundabout before getting to the arm they need (concerning four-armed roundabouts). This detour can be omitted by the provision of a two-way cycle track which on the other hand creates different problems. Two-way cycle tracks crossing the approaches would mean that drivers should expect cyclists from both directions and because of this consideration tracks of this kind are avoided (CROW, 2007). If this solution is applied it is strongly recommended that the crossings between the cycle track and the approaches are elevated and properly designed, signposted and marked to draw maximum attention from drivers to the cyclists coming from both sides (CROW, 2007). According to the Dutch design manual implementing cycle tracks in two directions with right of way is not a preferable solution.

According to the Norwegian regulations the AADT volumes, when the possibility of leading the cycle traffic off the roundabout should be considered (8000 pcu/day), are higher than these stated in the Dutch manual (Sykkelhåndboka, 2013). The solution which is recommended by the Norwegian Handbook is foot- and cycle path outside the carriageway around the roundabout (Fig. 17). The crossings between the path and the approaches should be preferably 10 to 15m and minimum 5 m away from the roundabout. In urban areas it is recommended to add a pedestrian crossing close to the roundabout, 5 m from the roundabout, if the speed limit is below 45 km/h. This minimum distance allows for a car waiting between the give way line and the crosswalk[17].

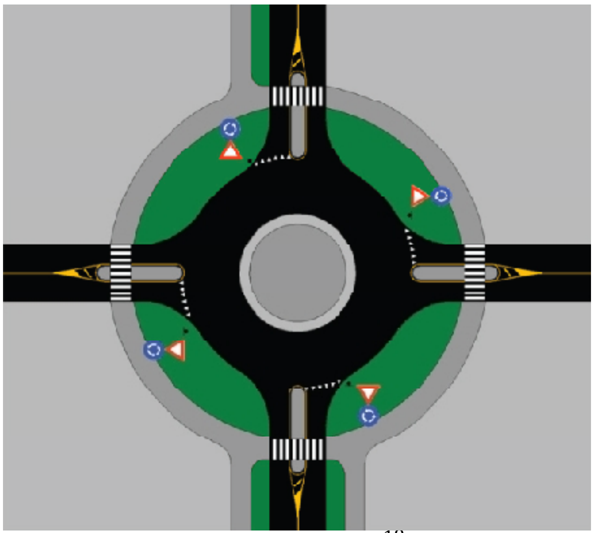


Fig. 17. – Foot- and cycle path[18]

[17] Translation from Norwegian

[18] Source: Figure 4.20 in Sykkelhåndboka, 2013

## GRADE SEPARATED ROUNDABOUTS

The forth design solution for accommodating cyclists in roundabouts is called ‘grade separated roundabout (Fig. 18). This design allows cyclists to pass under the approaches of the roundabout and thus avoiding any conflicts with the motorized traffic.

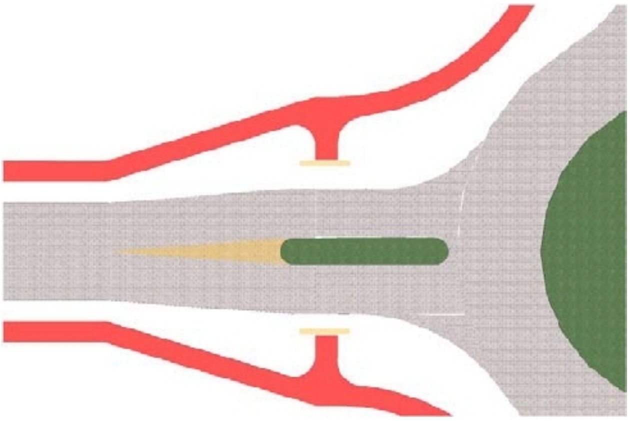


Fig. 18. – Roundabout with grade-separated cycle path[19]

## COMPARISON BETWEEN THE DIFFERENT DESIGN PRACTICES FOR ROUNDABOUTS

Schoon and van Minnen (1993) did a study of 201 newly built roundabouts in the Netherlands. They found that roundabouts with a cycle lane provision within the circulatory area resulted in more fatalities of riders than mixed traffic. They have also discovered that roundabouts with segregated cycle tracks had fewer accidents than roundabouts with mixed traffic for AADT volumes more than 12,500.

For sites with AADT less than 7,500 the number of accidents where cyclists were involved was similar for those providing cycle lanes and those with mixed traffic. Sites with segregated cycle tracks resulted in a smaller number of conflicts than those with cycle lanes and those with mixed traffic.

Daniels et al (2009) performed a before-and-after study of injury crashes with bicyclists at 90 newly constructed roundabouts in Flanders, Belgium. The studied roundabouts included nine sites for mixed traffic, 40 equipped with designated cycle lanes within the circulatory area, 38 with the separated cycle tracks outside the carriageway and three roundabouts with the grade-separated solution. They found that roundabouts with bicycle lanes performed worse compared to the other design types (mixed traffic, separate cycle tracks and grade-separated cycle paths).

A Danish researcher (Lund, 2008) examined motor drivers’ behavior towards cyclists circulating in roundabouts in urban areas with or without cycle facilities using driver simulator. Seven roundabout designs (as equal as possible) with different type of cycle facilities in the approach and in the circulation area were tested. The driving adjustments of the test driver to circulating bicyclist were measured in terms of approaching speed, eye gazing and time distance to the point of conflict. The time distance showed how close the road

[19] Source: Figure 4 in Daniels et al (2009)

users were when passing each other in the conflict point and the time they had to react to each other if an accident would happen. The circulating cyclist rode in the middle of the cycle facility at roundabouts with cycle facilities and in the middle of the road in sites without cycle facilities. An eye tracker showed that the motorist needed 3,1 seconds to detect a cyclist riding on the bicycle lane or track while it took him 2,5 seconds to notice a cyclist when cycle provisions were not available. It was also found that the motorist spent more time looking at the cyclist when there were no cycle lanes in comparison to the scenarios where cycle lanes were provided. The results of this study indicate that drivers are more attentive to circulating cyclists when no cycle facilities are provided.

Sakshaug et al (2010) undertook a study to find out what roundabout design is safer for cyclists – using separated cycle tracks or integrating cyclists with motorized traffic. Two roundabouts situated in Lund, Sweden, which represented each of the two possible designs, were selected. Quantitative and qualitative methods in traffic conflict, interaction and behavioral studies were used to investigate how interactions and conflicts differ between the different roundabout designs. Field studies and automated video detection of the two intersections were applied. It was found that the roundabout with mixed traffic is more complex and with a higher number of serious conflicts and interaction types. The yielding situations in the separated roundabout turned out to be more uncertain, leading to a lower yielding rate to cyclists and a lower trust in the other road user's willingness to yield.

Austroads, The Association of Australian and New Zealand Road Transport Authorities undertook a study to collect unbiased proof of the effectiveness of cycle lanes within roundabouts and their approaches with the final goal of helping the establishment of policy and design recommendations for their next guidebook (Wilke, 2014). First, they performed a wide review on the current literature available on the topic which concluded that roundabouts with cycle lanes are internationally regarded as having unfavorable safety effect on bicycle traffic users. The review also showed that the most common cyclist injury accident type was when a motorized vehicle entering a roundabout fails to yield to a circulating cyclist. Cyclists' lateral tracking was investigated at eight urban roundabouts to find out that riders move closer to the centre of the traffic lane along the circulatory area. It was stated that on sites where cycle lanes were provided in most cases bicyclists did not use them. Wilke et al have also found that the existence of cycle lanes on the circulatory carriageway may serve to discourage lane sharing. They measured the speed of approaching motorized vehicles and found them to be surprisingly similar. It was also found that modifications of roundabouts such as horizontal and vertical deflection or limited visibility to the right, could be used to reduce vehicle speeds to an equitable speed of desirably 25 km/h which would gain enough time for drivers to scan for conflicting movements. This extra time would probably reduce accidents between motorized and non-motorized vehicles. One of the conclusions that can be drawn out of this study is that roundabout design should either provide equitable speeds or incorporate segregation of bicycle traffic on dedicated tracks. It was also found that lane markings which motivate riding on the traffic lanes can be useful and is advisable on site where speeds are equitable. Cycle lanes should be truncated before the give way lines where speeds are low.

A study undertaken by Møller and Hels (2008) investigated the cyclists' perceived risk in specific situations, determinants influencing the perception of risk and cyclists' knowledge about traffic rules regulating the interaction between road users in roundabouts. One thousand and nineteen cyclists aged 18-85 participated in the study. Interviews were conducted in five Danish roundabouts to gather data. One of their findings was that the level of perceived risk was considerable higher in roundabouts without a cycle facility than in roundabouts with a cycle facility. It was found that car traffic volume influences the perception of risk, but the influence decrease as the bicycle volume increases. The majority of cyclists (66-67%) claimed that reducing the number and speed of the cars in the roundabout would improve bicycle safety. Eighty-two percent of the cyclists interviewed in a roundabout without a cycle facility claimed that building a cycle facility would reduce the accident risk in the roundabout.

As a conclusion concerning the design of cycle provisions at roundabouts it can be said that all studies clearly point out that the separation of the cycle traffic on dedicated tracks is the solution that results in the lowest number of casualties. When it comes to the choice between cycle lanes and mixed traffic most of the findings show that the roundabouts provisioned with cycle lanes within the circulatory area clearly perform worse than those with mixed traffic.

## *III. Solutions for regular intersections*

### CYCLE LANES THROUGH INTERSECTIONS

Bicycle lanes have a positive effect on cyclists' safety as they provide a separation between them and motorized vehicles. Nevertheless, motorists often don't know that they must give way to riders when crossing a bicycle lane (Hunter et al, 1999).

At huge junctions, on-street cycle lanes are dashed in order to lead cyclists through the intersection (Fischer et al, 2010). A dashed line is supposed to identify the zone of potential conflict from turning vehicles and straight-travelling riders (Faichney, 2002). This kind of pavement treatment was implemented for example in Osnabruck, Germany as it is shown in Figure 19.

Fig. 19. – Dashed cycle lane in Osnabruck, Germany[20]

In many countries throughout the world colored pavement markings are used as a continuation of the cycle lanes through intersections. The most universally applied colors for this purpose are blue (in Denmark), red (in Germany, Switzerland, the Netherlands, Sweden, Denmark, Belgium and others), yellow (in Switzerland), and green (in Germany and France) (Hunter et al, 1999). These kinds of roadway treatments are aimed at providing guidance for cyclists through complex intersections and to make turning or passing drivers aware they are crossing a bike lane (Fischer, 2010). An example of colored bike lane in Winterthur, Switzerland is shown on Figure 20.

[20] Source: Figure 29 in (Fischer, 2010)

Fig. 20. – Colored bike lane[21]

A report undertaken by Hunter et al (2009) studied the influence that green lane markings together with signing applied in a cycle lane weaving area near a right-turn-only lane next to intersections have on the behavior of traffic users. The study involved videotaping and comparison of behavior of bicyclists and motorists before and after the implementation of the fore-mentioned measures in sites situated in St. Petersburg, Florida.

It was found that considerably more drivers gave way to cyclists after the improvements took place. It was also observed that more motorists signaled when they wanted to turn right. A positive change in the behavior of cyclists was also noted – considerably more cyclists scanned for motorist moving around them. They have also found a reduction in conflicts though it was not statistically significant. A noteworthy finding of Hunter et al was that a considerably higher number of cases of motorists were giving way to cyclists, which corresponded to the results of the study of blue lane treatment in Portland, Oregon.

The use of blue cycle lanes at intersections was introduced by the Municipality of Copenhagen and applied in 1981 for the first time (Fig. 21). The aim was to put stress on areas of potential conflicts between motorists and riders. Nowadays blue cycle lanes are used mainly in Denmark (Jensen, 2008).

[21] Source: Figure 28 in (Fischer, 2010)

Fig. 21. – Intersection in Copenhagen with four blue cycle crossings[22]

Blue cycle lanes were also implemented in US cities to decrease the number of accidents. A study was undertaken by the city of Portland, Oregon, to estimate the safety effects of this innovative provision for cyclists. Ten conflict areas in Portland were marked with blue thermoplastic paint and an accompanying “Yield to Cyclist” sign between 1997 and 1999. The chosen crossings were all at sites where cyclists ride straight and the drivers cross the bicycle lane in order to exit a roadway, enter a right-turn lane, or merge onto a street from a ramp (Fig. 22.). The University of North Carolina Highway Safety Research Center (HSRC) evaluated the gathered data (Hunter et al, 2000). Analysis of video recordings was applied which concluded that most of the behavior changes were positive. A major increase in the number of drivers who gave way to riders and slowed or stopped before crossing the blue colored lanes was found. It was also observed that a higher number of cyclists followed the blue cycle lane. At the same time it was found that due to these facilities fewer cyclists were turning their heads to scan for traffic or using hands to indicate their turning direction. Hunter et al hypothesized that this was due to the reduced cyclists’ perception of risk because of the blue crossings. Most of the surveyed traffic users felt that blue cycle crossings increased safety. It was concluded that blue cycle crossings should continue to be used and evaluated in bicycle-motor vehicle conflict areas.

[22] Source: Fig. 1. in Jensen, 2008

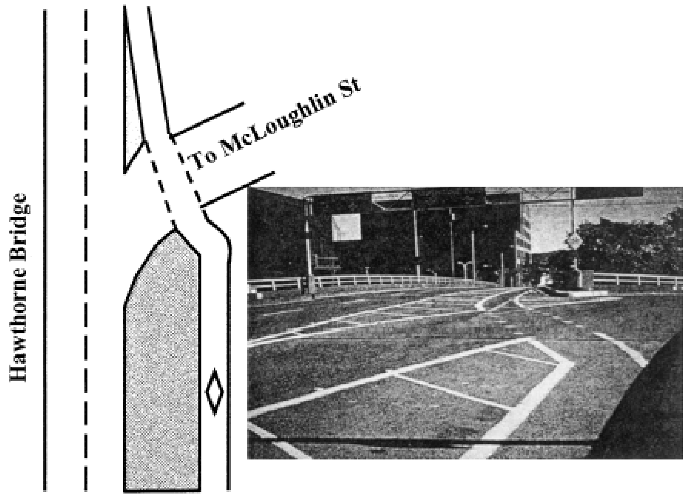



Fig. 22. - Bicyclists continuing on Hawthorne Avenue veer to left, while motorists exiting Hawthorne Avenue onto McLoughlin Street veer to right and cross conflict area (outlined by dash striping).[23]

Hunter et al (1999) explained the reason for marking pavement in blue in conflict areas in US cities. They pointed out that the other colors had conflicting meanings throughout the American transportation system. For example yellow is used for centerline stripes and red and green had specific meanings too: red signifying ‘do not go here’ and green signifying ‘go’. Blue was only meant to suggest parking stalls for disabled.

Another reason for the use blue color, given by Hunter et al (1999), was that many people have a limited ability to differentiate colors. It is difficult for them to recognize red, green and other colors. On the other hand in low light and wet conditions, blue showed up relatively well.

In a study prior to the start of the project of Hunter et al (1999), Bicycle Program Staff had presented the color options to many local community groups in Oregon and Washington. It was agreed upon by everybody that blue is the most suitable color which was another reason stated by Hunter et al (1999).

In Montreal cycle paths were colored in blue to lead cyclists through intersections at five different sites (Fig. 23). In a study by Pronovost and Lusginan (1996) it was observed that cyclists showed a greater obedience to stop signs and were stricter in following the cycle track. This led to a decrease in the accidents involving riders (Pronovost and Lusginan, 1996).

[23] Source: Figure 2 in (Hunter et al, 2000)

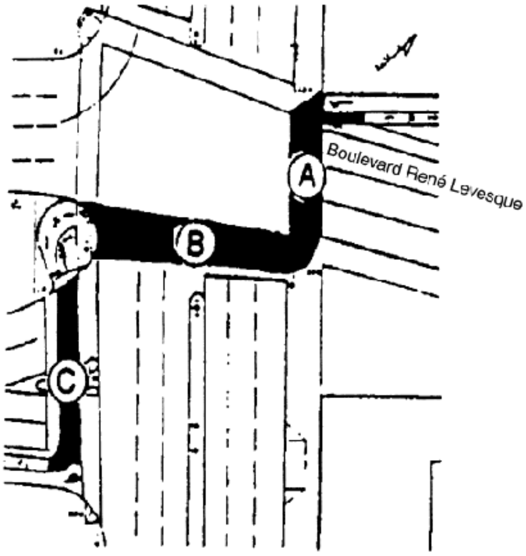



Fig. 23. – Colored bicycle crossing in Montreal[24]

A before-and-after accident and injury study of applying blue cycle lanes in 65 signalized intersections was carried out to examine road safety and perceived risk of cycle facilities in Copenhagen taking into consideration changes in accidents trends, traffic volume and regression-to-the-mean effects in the before period (Jensen, 2008). It turned out that the safety effect is directly related to the number of blue cycle lanes in the intersection. Jensen (2008) found a 10% decrease in accidents at signalized junctions where only one blue cycle crossing had been marked. At the same time marking two or four blue cycle lanes increased the number of accidents by 23% and 60%, respectively. The safety effect is caused by the reduced number of accidents with pedestrians, bicyclists and moped riders that are 'directly influenced' by the blue cycle lanes.

It was also found that the safety benefit of one blue cycle crossing is increasing with the reduction of the size or the traffic volume of the studied intersection. This was explained with the fact that the directly influenced accidents make up a higher percentage of accidents in a small intersection compared to large intersections, and that the safety benefit on directly influenced accidents is greater at small intersections. Jensen (2008) concluded that when there is more than one blue cycle lane in the intersection, the warning message seems to be neglected and it leads to a riskier behavior. It was speculated that too many blue cycle lanes resulted in drivers paying too much attention on the pavement or cyclists and neglecting the traffic signals. Based on the findings of the study a recommendation was made to mark only one blue cycle crossing where vulnerable road users are involved in accidents. The blue cycle lane should be marked at the crossing where the most accidents have occurred (Jensen, 2008).

According to the reviewed studies colored cycle lanes through intersections exert positive effect on the safety of riders through intersections.

Another solution for cyclists at intersections suggests a different opinion on cycle lanes at intersections comparing them with wide curb lanes. This facility is a lane situated on the outer side of a road next to the sidewalk which is wide enough to be used by both a cyclist and a motorist. According to Wayne Pein (2000) a bicycle lane only adds to complexities at junctions and roads in general, while a wide curb lane doesn't. He exemplifies this using a

[24] Source: Pronovost and Lusignan, 1996

scenario where a bicyclists that wants to turn left at a junction provisioned with a bicycle lane tends not to merge to the left far enough in advance or at all. Another problem situation is when motorists turning right across a bicycle lane. In such cases drivers can improperly wait to allow bicyclists to overtake on their right and by doing so they cut off following vehicles and forming puzzling situation for cyclists. A bicycle lane encourages cyclists to overtake motorists on the right side and to go to the front of the queue. According to Wayne Pein (2000) this is very dangerous and leads to many right hook collisions (Fig. 24). Wide curb lanes also enable bicyclists passing on the right side, but it is not as formally regulated as with cycle lanes.

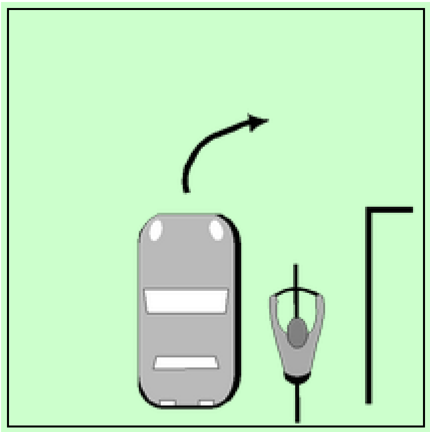


Fig. 24. – Right hook

## ADVANCED STOP LINES

Introduced for the first time in the Netherlands, Advanced Stop Lines are widely considered to be an inexpensive and at the same time highly advantageous solution for cyclists negotiating their way through signalized junctions. Variations of this treatment are also implemented in other Northern European countries, in Australia and New Zealand, in Taiwan, in Canada and in some US cities.

Their design is intended to place cyclists ahead of motorists during red signal allowing them to enhance their conspicuity being in the direct field of vision of drivers and to acquire a more comfortable position for taking turns. An additional stop line, dedicated to cyclists is situated right behind the crosswalk while the traditional stop line for motorists, is pulled back from the intersection. The area between the two stop lines is approximately 5 meters deep and is called an ASL reservoir (or a bike box) and is usually is marked with a bike symbol on the pavement (Fig. 25). A feeder lane or a gate is provided for them to reach it when a queue of vehicles is formed. The pavement on the reservoir and the lead-in area is sometimes colored in green, red or blue to increase the attentiveness of the traffic users and to reduce the encroachment by motorists. When cyclists are ahead of the other traffic at red signal they are given the opportunity to leave the intersection first when the signal changes. This allows them to avoid the danger of being hit by right turning vehicles when moving straight ahead or by straight moving vehicles when turning left. This makes the solution extremely valuable where there are frequent turning conflicts. A solution, practiced a lot in the Netherlands, is to install a separate signalization or cyclists so that they can have earlier green signal. Another positive feature of positioning cyclists in front of the motorized vehicles is that riders are given the opportunity to wait without being directly exposed to the exhaust fumes.

Fig. 25. – Full width ASL[25]

The first ASLs in the United Kingdom were implemented in Oxford in 1984 and then in Newark and Bristol in an effort to enhance the safety for cyclists at signalized junctions. Below is given a characterization of different design variations of Advanced Stop Lanes outlined in (Atkins Services, 2005).

The traditional design of an ASL reservoir covers the full width of the lane (or lanes) approaching the junction (as shown in Figure 26). There is a variation of this layout where the reservoir covers only part of the approach which is known as a Part-Width Reservoir (Fig. 8). The positive features of this variation of this solution are:

- Reduced encroachment of the area by vehicles;
- Reduction of the used space;
- Discouragement of bicyclists from taking risky maneuvers in the off-side of the carriageway when they are not necessary.

Fig. 26. - Part Width ASL[26]

The conventional access to an ASL reservoir is executed by an advisory or mandatory feeder lane (Fig. 9).

[25] Source: Figure 1 in (Rodgers, 2005)
[26] Source: Figure 2 in (Rodgers, 2005)

Fig. 27. – Mandatory feeder lane[27]

If the space is limited and a feeder lane can't be installed, a stub feeder lane or 'gate' can provide access into the ASL reservoir. Gates are diagonal access markings (Fig. 28).


Fig. 28. – A gate and a Virtual Cycle Lane[28]

Stubs are very short feeder lanes (few meters) (Fig. 29). According to (Atkins Services, 2005) full feeder lanes should normally be provided whenever possible.

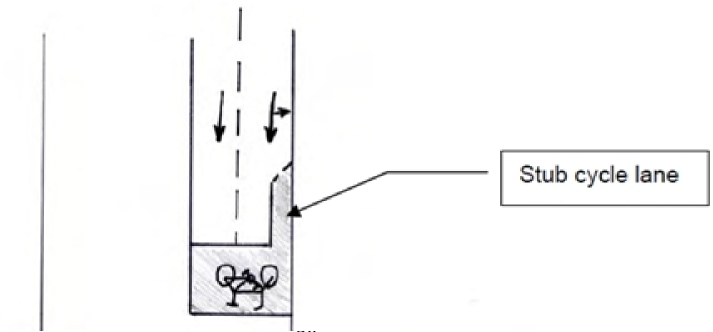



Fig. 29. – Stub cycle lane[29]

[27] Source: Figure in (TRL, 1996)
[28] Source: Figure 3 in (Rodgers, 2005)

[29] Source: Figure 2.1 in (Atkins, 2005)

Another design treatment is the colored surfacing in lieu of cycle lanes or a Virtual Cycle Lane (shown in Fig. 10). Colored surfacing is applied in different situations without cycle lane markings. This solution used to lead cyclists through their intended route and to draws motorists' attention on cyclists and thus to reduce the number of conflict situations. It is a preferred solution when a lane is not wide enough to accommodate an advisory or a mandatory cycle lane (Atkins Services, 2005).

There is a wide range of studies undertaken around the world to assess different aspects of the use of Advanced Stop Lines.

The research study by Atkins (2005) (one of the world's leading engineering consultancies), examined in a before-and-after study the described innovative types of cycle facilities. Atkins focused on ASLs implemented at sites situated along two roads in London. The new facilities were installed during the summer of 2004 and the survey was carried out between November 2004 and January 2005. Video recordings were made at 10 intersections to collect data, including two control sites. More than one of the facility variations were incorporated at most of the selected junctions. It was concluded that relatively few cyclists used the bike boxes (both the standard design and the experimental layouts) in the way they were meant to be used. It was observed that only 25 percent of the bicyclists arriving at a red signal waited in the bike box. The rest of them were waiting before the bike box or crossed all (or part of) the intersection during the red phase. It was also found that motorcyclists were entering at least half of the bike box area during 60 percent of time and the car traffic was doing so 14 percent of the time. There were cases (only with full-width reservoirs) when motorcyclists obstructed the bicyclists from using the bike boxes.

Different conclusions were drawn for each of the cycle infrastructure improvements by Atkins (2005). Some of the findings are mentioned below. It was found that Part-width reservoirs didn't have capacity problems and were subjected to less encroachment by motorized vehicles compared to full-width bike boxes. When it comes to the Virtual cycle lanes it was concluded that they allow the provision of a cycle facility in traffic lanes as narrow as 3 meters (with 1,2 meters for the virtual feeder lane and 1,8 meters for the general traffic lane). It was found that the higher the cycle flows were, the less vehicle encroachment into the Virtual cycle lanes is. Atkins (2005) observed that Virtual cycle lanes were providing a better access to bike boxes in comparison with Gate Entries where many bicyclists were unable to get to the reservoir.

Design recommendations were given by Atkins (2005) concerning the cycle facilities and some of them are mentioned below. It was concluded that Part-width reservoirs (boxes) should be provided instead of full-width ones on arms without right turn. It was found that due to the fact that cyclists preferred to wait to the nearside of the bike boxes, the depth of the reservoir (box) is more significant than its width.

It was also recommended Virtual cycle lanes to be provided in addition to gate access on nearside traffic lanes which are between 3 meters and 3,5 meters wide in order to provide a better access to reservoirs.

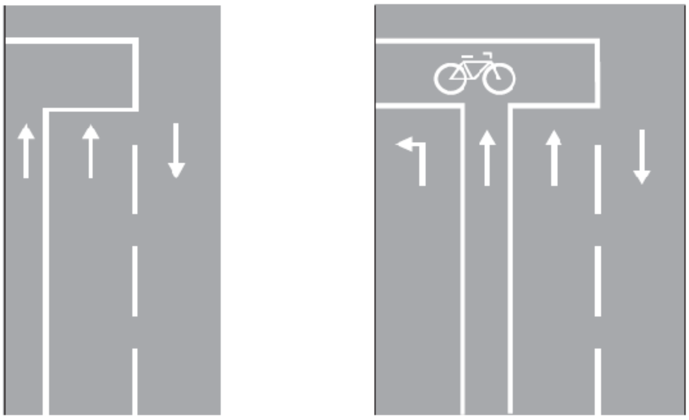
Rodgers (2005) worked on a before-and-after study of cycle provisions along the same two roads in London studied by Atkins (2005). The data that was collected before and after the implementation of the improvements included:

- cycle flows through the intersections;
- travel time for cyclists;
- user's perceptions towards cycling;
- accidents data.

As a result of the surveys it was found that the cycle traffic flows increased with 27 percent in the after period. Cyclists interviewed during the before period pointed out the need for safety and journey time improvements. It was found that in the after period cyclists' satisfaction level increased. Rodgers (2005) found also a decrease in the length of the journeys. It was hypothesized that the implementation of new facilities encouraged less confident cyclists to use the studied routes instead of alternative routes as before. The interviewed users generally thought that their journey time was not changed after the improvements. As a whole they answered that they found the new cycle facilities as useful. Advanced stop line was the facility which was favored the most by cyclists. The study of cyclists' perceptions stressed on the importance of implementing the appropriate new cycle facilities at intersections. Of the surveyed riders, 51 percent stated that cycling after the implementations felt safer, while 45 percent felt that there was no change. Accident data was analyzed for the before period but there wasn't enough accident data available for the period after the installment of the new cycle facilities. Rodgers (2005) recommended the use of the appropriate cycle facilities only after carefully taking into consideration the unique characteristics of the intersections.

To understand more about the effect of Advanced Stop Lines on cyclists' and other traffic participants' behavior at intersections, The London Road Safety Unit commissioned the Transport Research Laboratory (a private company offering a transport consultancy and research service) to conduct a survey at sites in London (Allen et al, 2005). The study assessed the safety at ASL sites using data on casualties before and after the implementation and conflict situations observed at these sites. To do this, a video observation was carried out at 12 sites with ASLs and 2 control sites without ASLs. It was found that at intersections provisioned with ASLs a considerable part of the cyclists (92%) were able to get to the front of the traffic queues during red signal while at the control sites only 62% managed to do that. It was also observed that the number of vehicles that encroached onto the pedestrian crosswalks while waiting at signals decreased. Allen et al (2005) noticed that due to the motorized vehicles' encroachment onto ASL reservoirs and feeder lanes, the effectiveness of these facilities was reduced. The safety at ASL was not conclusively determined by the casualty and conflict analysis because there was a wide variation between sites and further research was needed on this matter.

A study of the effect on capacity of Advanced Stop Lines, was undertaken by Wall et al (2003). A signal-controlled junction modeling computer program was utilized together with before-and-after video surveys. Five different theoretical before-and-after scenarios involving the installment of an ASL with either a nearside or a central cycle lane were studied (Fig. 30).



a) b)

Fig. 30. – Two variations of Advanced Stop Lines: a) ASL with a nearside cycle lane, b)ASL with a central cycle lane[30]

It was found that the implementation of ASLs has no major influence on the capacity of the intersection except in the cases where a traffic lane is removed to provide them. At intersections where a traffic lane was removed a considerable reduction in saturation flow of around 50 percent was observed. It was also found that slight changes (not more than 1-2 seconds) in the inter-green timings may be needed if ASLs are installed.

Loskorn et al (2013) undertook a study to determine the effect of bike boxes (ASLs) on the behavior of bicyclists and motorists. The behavior of 950 cyclists was examined in 2009 by observing two study sites in three different phases: the before period, after bicycle boxes were installed, and after a green marking was implemented inside the box and on the approaching bicycle lane. A positive relationship was found between the predictability of bicyclists' behavior and the increasing percentage of the bicyclists who passed through the intersection. It was observed that the implementation of the boxes strongly stimulated the cyclists to advance in front of queuing motorized vehicles (92 percent of all cyclists) and thus being more visible to them. It was also observed that actually only 20-26 percent of the riders stopped in the bicycle box area after the installation of the bike box marking. The implementation of the green colored pavement inside the bike box area resulted in considerable improvement in bicyclists' behavior, but at a great material cost. It was also observed that many of the drivers encroached the bike box area.

Hunter (2000) undertook a study of an innovative bike box treatment implemented at a busy junction between two one-way streets (Fig. 31.) in Eugene, Oregon in 1998. Video recording was applied to study the operational behavior and conflicts with other transport users. It was found that 22 percent of the cyclists for whom the newly implemented facility was mainly intended (those who came on the left cycle lane and crossed the street to get to the cycle lane on the right side of the street) actually used it. It was hypothesized that the encroachment of the bike box area by motorists resulted in a reduction of its usage by the cyclists. Even though the number of conflicts between cyclists and motorists didn't change significantly after the bike box installment, conflicts were not observed when the new facility was used the way it was designed to be used.

[30] Source: Figure 1 in (Wall et al, 2003)

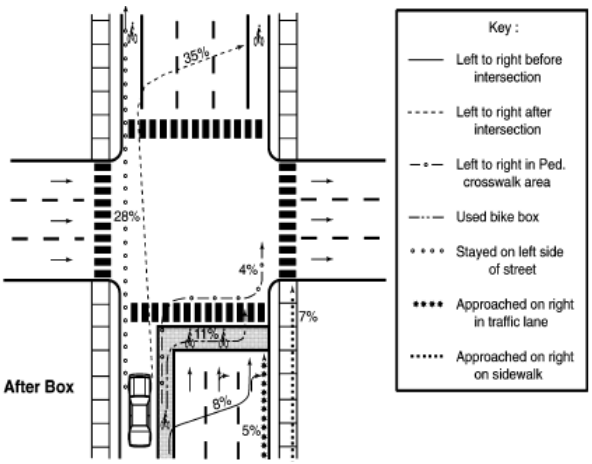


Fig. 31. – Overview of the intersection and bicyclists' maneuvers[31]

A research was undertaken by Newman (2002) to examine the utility of new cycle road markings in Christchurch. The aim of this study was to confirm that the Advanced Cycle Lane (Fig. 32) and Advanced Stop Boxes (bike boxes) enhance both physical and perceptual safety of intersections for cyclists. The investigation focused on three main aspects:

- the safety effect – examination of the accident data in relation to the new markings;
- the perceptions of the people who are supposed to use the implemented solutions;
- study of the behavior of users to find out whether the actions of the users correspond to the expectations.

The study was developed in such a way that each section had its own set of performance standards that the markings needed to achieve.

After the study was completed it was concluded that even though the Advanced Cycle Lanes and ASB (bike boxes) didn't entirely fulfill the stated performance standards set at the beginning of the study, the Christchurch marking standards were appropriate for a following implementation. Evaluation of the different elements of the research showed that the markings have met acceptable performance standards in terms of improved safety. The survey indicated that the performance standards were only partially met as far as riders' and motorists' behavior and attitude towards the use of cycle markings are concerned. Further analysis of the behavior and attitude study showed that the reason performance standards are only partly fulfilled is related to convenience of movement (e.g. vehicles stopping in Advanced Cycle Lanes) and sense of discomfort of use (i.g. vehicles queuing behind cyclists at Advanced Stop Boxes). It was decided that these discrepancies are not severe enough to stop the usage of the new design solutions in Christchurch.

[31] Source: Figure 5 in (Hunter, 2000)

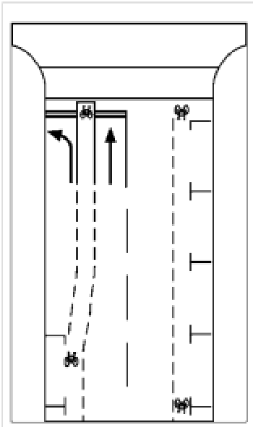


Fig. 32. – Advanced Cycle Lane[32]

Wheeler (1992) examined Advanced Stop Lines for cyclists at signal controlled road junctions in England as part of a research into new design solutions for cyclists. The study junctions were situated in Oxford, Newark and Bristol and all of them had ASLs on one or two of their four arms. The aim was to find out whether the ASLs were being used safely by all road users in order to assess their suitability for a wider use. It was concluded that ASLs helped cyclists to get a better position before taking a right turn (left turns in countries where the traffic moves on the right side of roads). It was observed that more than 75 percent of cyclists used the cycle lane and reservoir (bike box) in a proper way. More than 90 percent of motorists didn't encroach the cycle lane and 82 percent of motorists arriving during the red signal didn't encroach the bike box.

Traffic safety evaluation of engineering measures - Development of a method and its application to how physical lay-outs influence bicyclists at signalised intersections (Linderholm, 1992).

A study undertaken by Linderholm (1992) examined the layout of solutions for cyclists at signalized junctions including use of pulled back stop lines for vehicles (Advanced Stop Lines). Different methods were applied to assess the safety of cyclists: conflict studies to estimate the expected accident frequencies, traffic counts to analyze accident risk, studies of the behavior of road users and the interactions between them and interviews. It was found that due to the implementation of the ASLs the accident risk for cyclists was reduced by around 35 per cent. It was stated that this effect was due to the changed behavior when approaching the junction and when taking left turns. The risk levels for cyclists moving straight into the intersections weren't changed. It was also observed that motorists respected the modified stop lines.

The analysis of a proper accident data can help to reach a conclusion about the effect on safety of cyclists. Five out of the nine described studies utilized conflict studies. Rodgers (2005) assessed accident data for the before period of his study but decided that there was not enough data for the after period so no overall results were given. Allen et al (2005) also couldn't draw any conclusions about the cyclists' safety since there was a wide variation between the studied sites. Newman (2002) concluded that the new markings can be considered effective in terms of safety of cyclists. Hunter (2000) found that no conflicts were observed in the after period when the facility was used the way it was supposed to be used.

[32] Source: (Newman, 2002)

Linderholm (1992) found more specific results for the safety of cyclists – a reduction of accident risk by about 35 percent.

Studies which managed to analyze conflict and accident data and to reach some conclusions show that ASLs exert a positive effect upon the safety of cyclists in signalized intersections.

# 3.METHODOLOGY

## 3.1.Study sites

Two intersections were selected for the study. The study aimed at finding intersections which are used by a considerable amount of cyclist and have existing but discontinuous bicycle facilities. They differ in their engineering solutions, location, traffic type and volumes and the function and the size of their arms. Both of them are situated in Trondheim, a Norwegian town with 180,000 inhabitants and a growing amount of cyclists.

One of the studied crossroads is signalized and will be referred to here as a regular intersection (Fig. 33). There are marked and signposted on-street cycle lanes on approach A (Vollabakken street) that end at the intersection. Advanced stop line, or bike box, is also provided which allows cyclists to stop in front of the other vehicles at the traffic lights. The asphalt cover of the cycle facilities here is colored in red. On approach D (Høgskoleveien) there is a signposted foot- and cycle path on the right sidewalk (when coming towards the intersection). There are no designated bike facilities on the other two approaches.

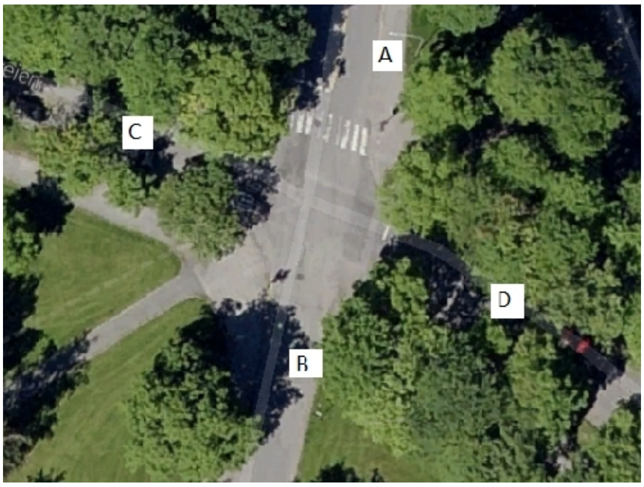



Fig. 33. Overview photo of the regular intersection.

The other intersection is a roundabout. It is bigger in size and has higher traffic volumes than the regular intersection (Fig. 34). On approach A (Strindvegen) there are on-street cycle lanes on both sides of the carriageway which terminate at the roundabout.

There are also on-street cycle lanes on both sides of the carriageway of approach D (Dybdhals veg). Because of a bus stop situated on the right side of the road (when coming towards the roundabout) cyclists are led onto the sidewalk to pass behind it. After the bus stop they are led back to the carriageway via a ramp approximately 50 m before the roundabout. Both cycle lanes on approach D end at the intersection. The described bike facilities on approaches A and D are indicated with interrupted marking line.

There is a bus stop on the right side (when going out of the intersection) of approach B (Torbjørn Bratts veg) situated 20m after the roundabout. After the bus stop the sidewalk turns into a two-way foot- and cycle path designated with a signpost *522 Foot- and cycle path*.

On approach C (Strindvegen) there is a two-way marked cycle path on the left sidewalk (when coming towards the intersection). Cyclists riding in the opposite directions are separated by centre line markings. The cycle path terminates at the roundabout. On the other side of this approach there are no cycling facilities.

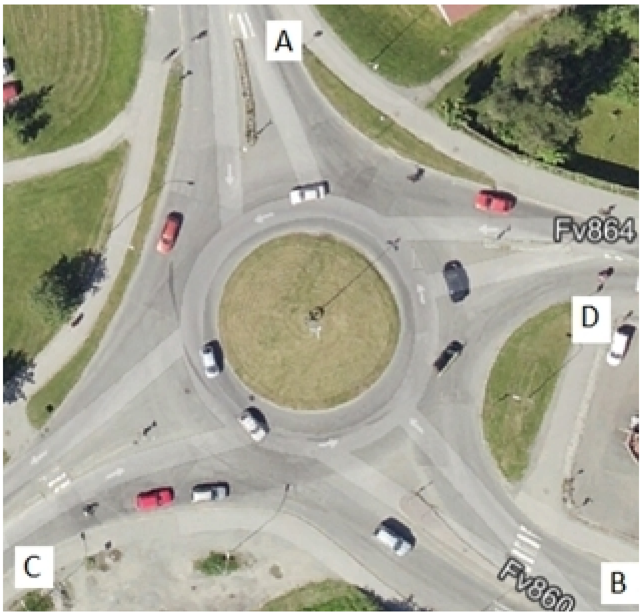


Fig. 34. Overview photo of the roundabout.

## 3.2.Survey Execution

The focus of the research was to examine bicycle lane discontinuities using the two intersections as a case study. Different qualitative and quantitative methods were combined. For the purpose of better understanding the discontinuities at the studied intersections, statistical data was collected. Currently there are modern video collection units which automate the data collection process but for the purpose of this study simple methods which don’t require sophisticated equipment were used.

### *I. Study of bicyclists*

The first data collection effort aimed at investigating the behavior of the cyclists at the intersections and learning more about the traffic. This was done using two methods of observation:

1) Manual data collection on site
2) Video recording

Video recording of the regular intersection was carried out on 13/03/ 2014 from 07:45 to 08:45 covering the morning rush hour. The camera which was used captured a view of the entire intersection that encompasses all four approaches. It allowed an observation of the movements of the cyclists in a following analysis of the video. The data about the riders was collected using a specially developed observation form (Fig. 35). The form consists of questions related to the behavior of the cyclists and their interaction with other traffic participants. The answers were filled in a table given below the questions where every column designates a different cyclist.

It is important to know which arms of the intersection a cyclist uses to pass through it. A simple way to answer this question was devised. The route of each cyclist was traced on a miniature drawing of the intersection provided in the table.

The second question requires information about the exact facilities which each cyclist chooses to use. For the sake of being thorough, all possible combinations of facilities were given as different options to choose from.

The next six questions were observational and designed as yes/no questions. The observational questines and reasoning as to why they were specifically considered are listed below.

3. Do they dismount before crossing?

Motorists are required to stop only for pedestrians using crosswalks. Many cyclists dismount before crossing to easily negotiate their way through intersections. This action also impacts efficiency by slowing down the cyclists movement through the intersection.

4. Do they use the pedestrian crosswalk?

Related to the previous question, cyclists may use the pedestrian crosswalk to move through the intersection. It is expected that cyclists who dismount will use the crosswalk, but not all those who use the crosswalk will dismount,

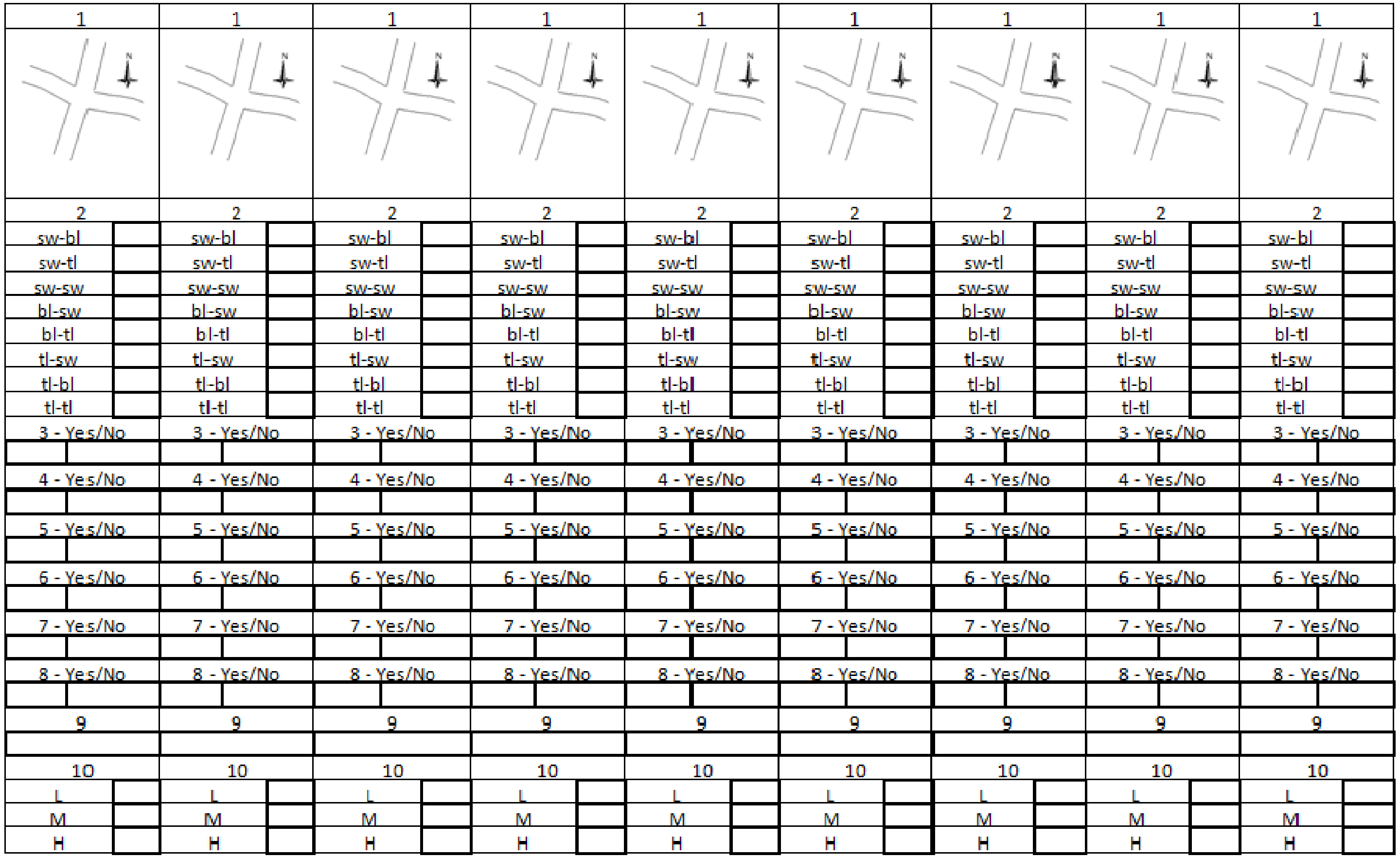
5. Do they take traffic signals into consideration?

Some cyclists infringe the traffic laws by running the red lights when they think that there is no traffic on the transverse street and thus create potential hazardous situations

6. Do they make risky movements?

Although ‘risky’ is a rather relative term, in this study it describes the kind of movements which could lead to conflicts. The following definition of a conflict was used ‘…an observable situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged’ (Sakshaug et al., 2010). Risky movements can also lead to single-cyclist accidents due to speeding or misjudging the condition of the pavement’s surface.

1. Which arms of the intersection do they use?
2. Which facility do they use before and after passing through the intersection:
   - sw - sidewalk; bl - bike lane; tf - traffic lane;
3. Do they dismount before crossing?
4. Do they use the pedestrian crosswalks?
5. Do they take traffic signals into consideration?
6. Do they make risky movements?
7. Do car drivers yield to cyclists?
8. Do pedestrians obstruct the movement of cyclists along the crosswalks?
9. How much time do they spend moving through the intersection?
10. What is the car traffic volume like – light, medium, heavy?



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|---|---|---|---|---|---|---|---|---|
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| 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| sw-bl | sw-bl | sw-bl | sw-bl | sw-bl | sw-bl | sw-bl | sw-bl | sw-bl |
| sw-tl | sw-tl | sw-tl | sw-tl | sw-tl | sw-tl | sw-tl | sw-tl | sw-tl |
| sw-sw | sw-sw | sw-sw | sw-sw | sw-sw | sw-sw | sw-sw | sw-sw | sw-sw |
| bl-sw | bl-sw | bl-sw | bl-sw | bl-sw | bl-sw | bl-sw | bl-sw | bl-sw |
| bl-tl | bl-tl | bl-tl | bl-tl | bl-tl | bl-tl | bl-tl | bl-tl | bl-tl |
| tl-sw | tl-sw | tl-sw | tl-sw | tl-sw | tl-sw | tl-sw | tl-sw | tl-sw |
| tl-bl | tl-bl | tl-bl | tl-bl | tl-bl | tl-bl | tl-bl | tl-bl | tl-bl |
| tl-tl | tl-tl | tl-tl | tl-tl | tl-tl | tl-tl | tl-tl | tl-tl | tl-tl |
| 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No | 3 - Yes/No |
| 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No | 4 - Yes/No |
| 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No | 5 - Yes/No |
| 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No | 6 - Yes/No |
| 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No | 7 - Yes/No |
| 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No | 8 - Yes/No |
| 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| L | L | L | L | L | L | L | L | L |
| M | M | M | M | M | M | M | M | M |
| H | H | H | H | H | H | H | H | H |

Fig. 35. Observation form for the regular intersection.

7. Do car drivers yield to cyclists?

A considerable number of accidents at intersections are defined as vehicle-failed-to-give-way-accidents

8. Do pedestrians obstruct the movement of the cyclists along the crosswalk?

Every once in a while there are pedestrians who would start crossing at the same time and thus occupy the entire width of the crosswalk. In these cases the riders are compelled to slow down or even to get off the bike.

9. How much time do they spend moving through the intersection?

As mentioned previously in question 3, cyclists actions may impact their efficiency in using the intersection, where efficiency is related to the time it takes to move through the intersection. One way of assessing the utilization of the different cycle facilities is to compare the times cyclists spend on each facility when moving through the intersections. Having video recordings at the observers' disposal it is easy for them to determine the exact times.

10. What is the car traffic volume like – light, medium, heavy?

The data collection also considered motorzied vehicle traffic in the intersection. The traffic flow is not steady and its density varies with time. This has to be taken into consideration in order to study the movement of cyclists properly. In the traffic flow theory it is accepted that the maximum density achievable under free flow is the critical density ($k_c$). A way to categorize the traffic volume was introduced dividing it in three different groups:

- Light – when there are no more than three motorized vehicles present at the intersection the moment when a rider goes through the intersection;
- Heavy – when the traffic flow reaches the critical density;
- Medium – when the traffic flow is between the previously described boundaries.

## BICYCLISTS ON THE ROUNDABOUT

When it comes to the roundabout it was not possible to get a proper view over the entire area due to its larger size. Therefore a video recording was not used for registering bicyclists here. In order to study properly the movement of the cyclists on all arms of the intersection manual data collection had to be conducted on site. Two field observers monitored the roundabout on 12/03/14 during the morning rush hour from 07:45 to 08:45 and from 17:00 to 18:00 the same day covering the afternoon rush hour. One of the observers focused on the cyclists coming from approaches A and D and the other registered those coming from approaches B and C. The forms used for the regular intersection had to be modified to allow easier data registration given the fact that the information was filled in manually during the observation. To achieve this goal the number of questions was reduced and the table was adjusted. A drawing of the roundabout which shows all cycle facilities and pedestrian crosswalks was provided on the data collection form. It enabled the observers to register the route that cyclists used, their choice of cycle facilities and whether they moved through the pedestrian crossings. This was done by simply drawing the trajectory of each cyclist on the sketch of the roundabout given in the table (Fig. 36).

The second question required a categorization of the motor vehicle traffic flow using the same approach as it was described for the regular intersection. Another question which was also included here was whether the cyclists get off the bikes.

1.1. Which arms of the intersection do they use?
1.2. Which facility do they use before and after passing through the intersection:
1.3. Do they enter the roundabout?
1.4. Do they use the pedestrian crosswalks?
2. What is the traffic volume?
   - Light; Medium; Heavy;
3. Do they dismount before crossing?

4. Note if you see any of the following situations?
   - There is a near accident situation;
   - A motor vehicle driver fails to yield to cyclist;
   - Pedestrians obstruct the movement of cyclists on the crosswalk and sidewalk;

| 1 | 1 | 1 | 1 |
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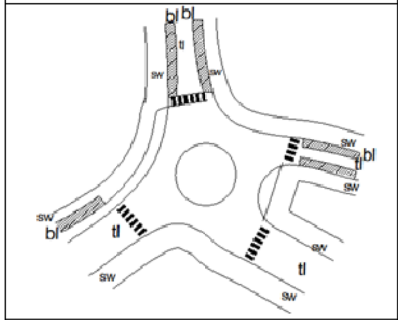
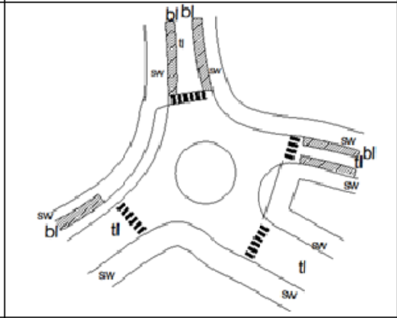
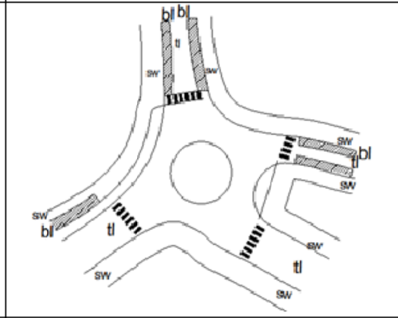
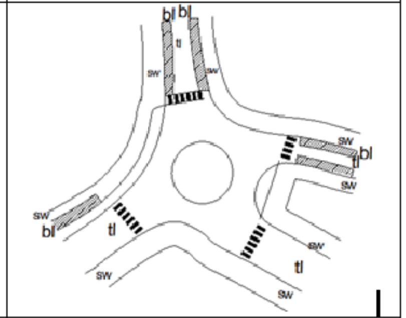
|  |  |  |  |
| 2 | 2 | 2 | 2 |
| LIGHT | LIGHT | LIGHT | LIGHT |
| MEDIUM | MEDIUM | MEDIUM | MEDIUM |
| HEAVY | HEAVY | HEAVY | HEAVY |
| 3 | 3 | 3 | 3 |
| DISMOUNT | DISMOUNT | DISMOUNT | DISMOUNT |
| NODISMOUNT | NODISMOUNT | NODISMOUNT | NODISMOUNT |
| 4 | 4 | 4 | 4 |
| NEAR ACC | NEAR ACC | NEAR ACC | NEAR ACC |
| YIELD | YIELD | YIELD | YIELD |
| OBSTRUCT | OBSTRUCT | OBSTRUCT | OBSTRUCT |

Fig. 36. Observation form for the roundabout

The last question consists of three subsections which were designed as open questions and are supposed to be answered only if one of the described situations occurs. The first subsection directs observers' attention to near accident situations at the intersection. The following definition was accepted to describe such accidents: 'A near-accident is a situation, where road users are less than 1.5 s from a collision but avoid this by evasive maneuvers (Jensen, 2007).

According to a Danish study the most frequent types of police registered bicycle accidents in roundabouts are accidents involving a cyclist circulating in the roundabout and a car that either enters or exits the roundabout (Møller and Hels, 2008). To take this into consideration it has been found as necessary to note in the second subsection every situation in which a car driver fails to yield to a cyclist both inside the roundabout and on its arms.

The third subsection of this question focuses on the interaction between the pedestrians and cyclists on the sidewalks and on the pedestrian crossings. As it was said before riders who use the crosswalks to cross an intersection's arm have to take into consideration the pedestrians. Cyclists also encounter problems when moving on the sidewalks due to pedestrians and this can result in conflict situations. Therefore observers were supposed to register such occasions.

A different observation form was prepared to study the time bicyclists need to go through the intersection using different trajectories (Fig. 37). The same drawing of the roundabout was used to mark the different trajectories of the cyclists. The traffic volume while each one rode through the roundabout was determined according to the already established classification. The time which they spent to go through the different routes was measured with the assistance of a stopwatch. The observation was performed on 14/03/ 2014 from 07:45 to 08:45 during the morning rush hour.

1. What route do they choose?
2. What is the car traffic volume like?
   - Light; Medium; Heavy;
3. How much time do they spend to go through the roundabout?

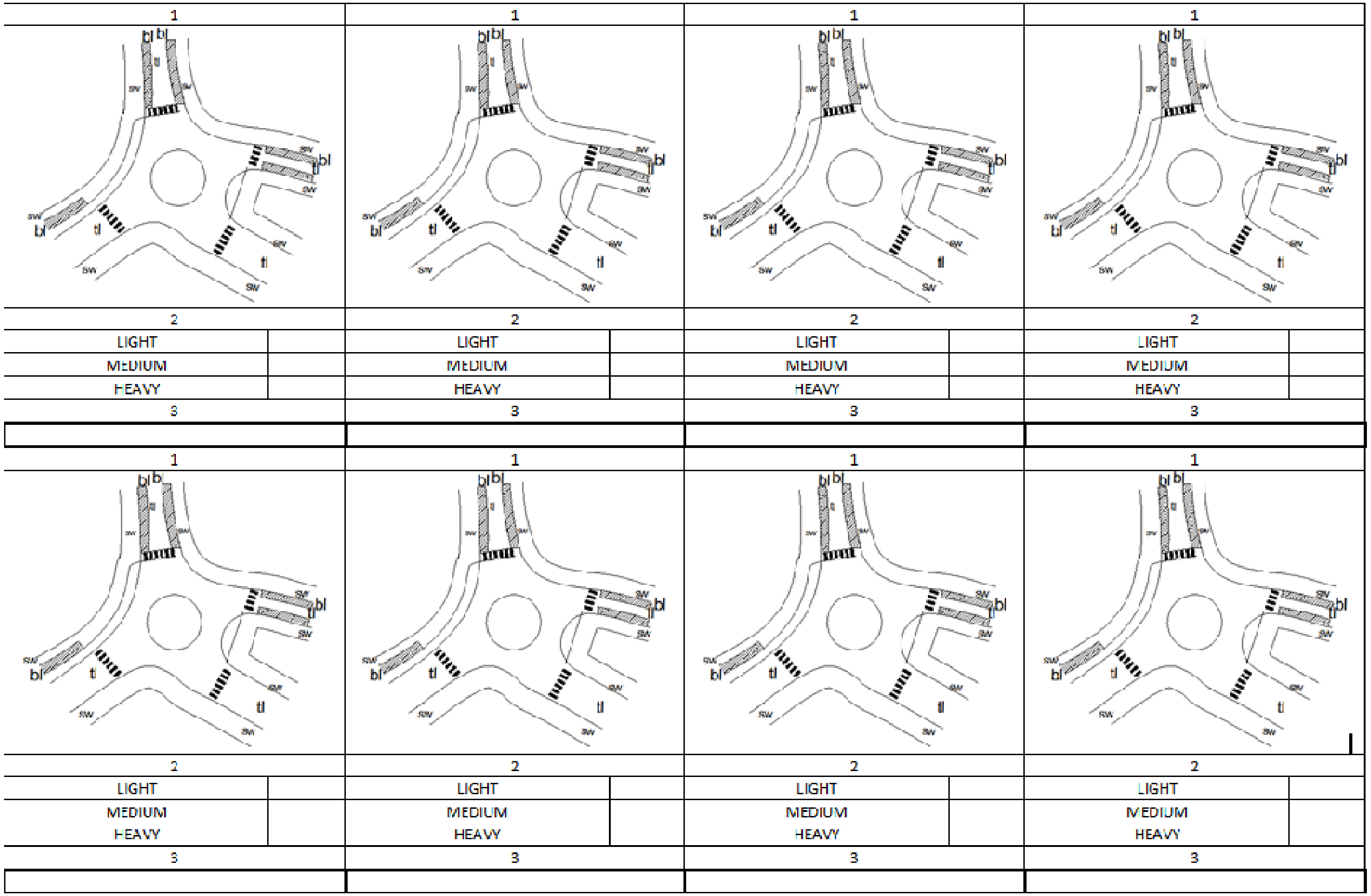



Fig. 37. Observation form for the time measurements

# II. Study of motor vehicles

The AADT volumes on the arms of the intersections were acquired from the Vegkart (www.vegvesen.no/vegkart, 2013), a tools provided by the Norwegian Public Roads Administration (NPRA) which provides various information on roadways in Norway. The percentage of the heavy vehicles is also given there.

Additional study of the motor traffic was executed using video recordings within ths study. The number of left-turn, right-turn and through movements for each arm of the intersections was registered in a following analysis of the recordings.

The video used for registering cyclists on the regular intersection was also used for counting the motorized traffic. Even though video recording was not used for studying cyclists on the roundabout this method was applied for collecting data about the motor vehicles on the roundabout. The video of the roundabout was recorded on the 11/03/ 2014 from 17:00 to 18:00 during the evening rush hour.

# III. Additional data collection

### GEOMETRIC MEASUREMENTS

Most of the geometric features of the intersections such as radii of curves and road widths were acquired from the Vegkart (from NPRA). Other dimensions which are not available there were measured manually using a surveyor's wheel.

### ACCIDENT DATA

With regard to the desired increase in the safety of the cycle facilities an examination of the accidents involving cyclists at two intersections was done. In 1977 the Norwegian Public Roads Administration started cooperation with the Police who provide reports on accidents and the database is updated continuously. Complete information of these accidents is available at Vegkart of  including accident location, date and time, number of injured or killed and other valuable information. This does not include accidents which were not reported to the police.

# IV. Precautions

While collecting the data on-site the observers were exposed to the danger of getting hit by a vehicle. To minimize the risk of incidents, precautions were taken by providing the observers with safety vests. In that way they were easily visible and vehicles were more cautious when passing by them.

The weather conditions had to be taken into consideration when choosing the day for data collection. In case of rain some of the people who usually cycle would shift to another transport mode. It could also be a matter of some difficulty for the data collection. The weather forecast was checked and days shown as having no chance of precipitation were chosen for the survey.

## *V. Difficulties and uncertainties*

Some problems were encountered during the manual data collection on site due to the fact that the flow of cyclists is not regular. At a given moment several cyclists came towards the intersection which made the task of registering them very difficult. Consequently, a few mistakes were probably made in the description of their movements and moreover several cyclists were not registered.

There is one other issue related to the reliability of the collected data that has to be mentioned. The behavior of the cyclists was influenced by the fact that they perceived they were observed. An attempt to avoid this was made by being as unobtrusive as possible during the observation process. (Hvidsten et al, 2008).

# 4.RESULTS

## 4.1.Results for the roundabout

### *I. Features of the area*

The study intersection is a four-legged intersection located two kilometers south of the city center (Fig. 38). Northwest of the roundabout is situated the biggest of NTNU's campuses with around 9300 students. Next to the university are also situated buildings occupied by SINTEF, an independent research institute with around 2000 employees. Southwest of the roundabout is situated the Lerkendal Stadion – Norway's second largest football stadium. Southwards and eastwards of the roundabout are situated mainly residential neighborhoods which consist primarily of low wooden houses and a small commercial area with a restaurant, several small shops and a grocery store. There is a railway stop situated around 100 meters northwest of the roundabout. There are many public transport routes on all arms of the intersection with stops situated 30 to 40 meters from the roundabout. Buses going to and from the airport pass through the intersection.

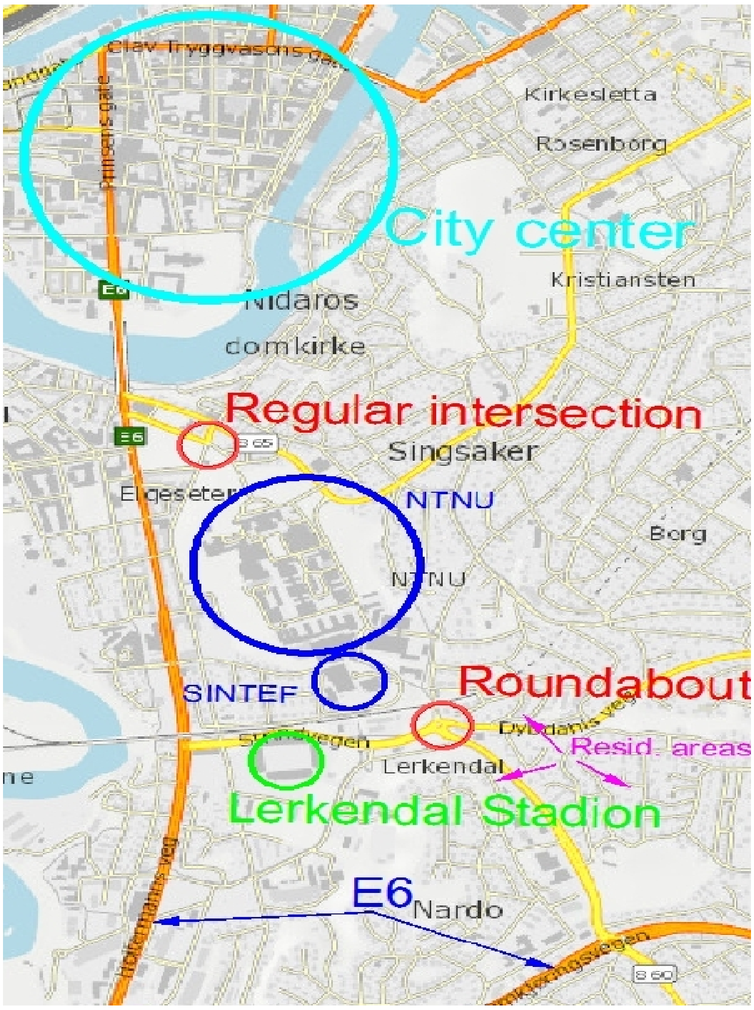


Fig. 38. Map of Trondeheim

Around 600 meters along Strindvegen west there is a connection to Holtermanns veg. Holtermanns veg is part of the European route E6 – the main north-south road in Norway and leads to the center of Trondheim.

The southbound arm of the roundabout (Torbjørn Bratts veg) provides a connection to E6 as well, which is approximately one kilometer south of the intersection.

## *II. Traffic volume*

The AADT volume on Strindvegen north is 11700 and on Strindvegen west is 10300(Norwegian Public Roads Administration). The volumes on approaches B (Torbjørn Bratts) and D (Dybhals) are 15400 and 4400 respectively ( Fig. 39). The percentage of the heavy vehicles on all approaches is the same (10 %). The location of the roundabout next to the university and SINTEF contributes to a great number of soft transport mode users.

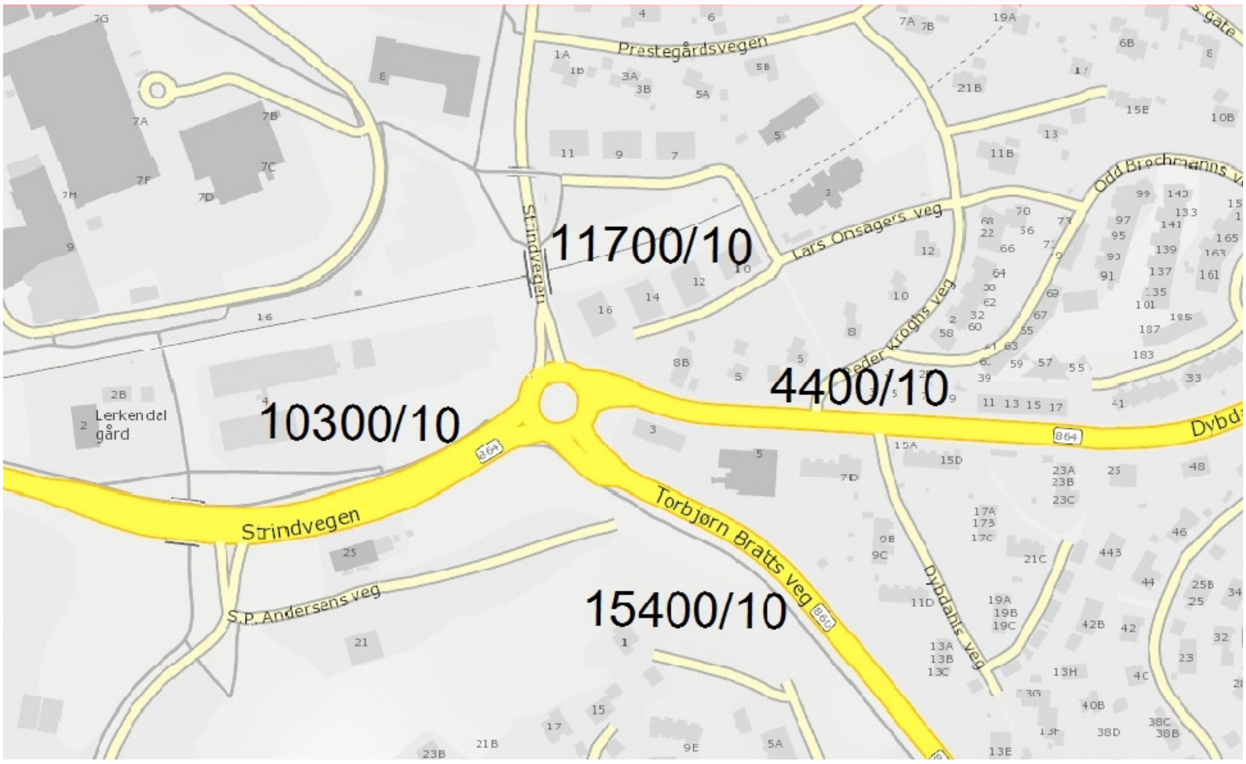



Fig. 39. AADT volumes on the roundabout

## III. *Motor traffic on the roundabout*

The motorized traffic volume during the evening rush hour was registered using video recordings in an additional study. The number of left-turn, right-turn and through movements of the motorized traffic on each arm of the roundabout is shown on Fig. 40.

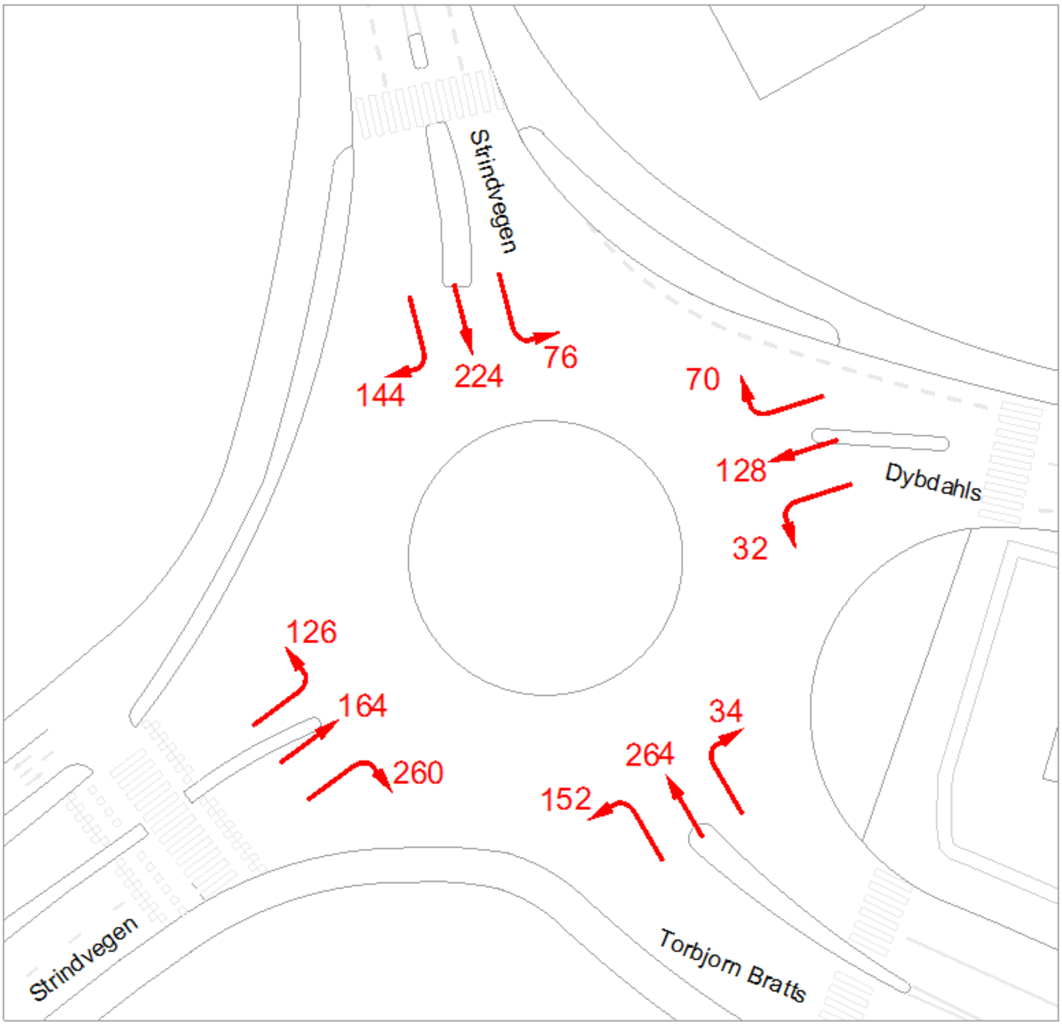



Fig. 40. Motorized traffic volume

## IV. *Accidents*

The Norwegian Public Roads Administration has registered 13 accidents involving cyclists at the roundabout with the earliest accident on record dating back to October, 1994. Unfortunately, due to the nature of accident records, these records are not specific enough to detail the factors and reasons that lead to the different accidents.

# V. *Cyclists on the roundabout*

Altogether there were 382 cyclists registered on the roundabout during the morning and evening rush hours. Sixty-two percent of them were registered during the morning rush hour (between 07:45 and 08:45) and 38% were registered during the evening rush hour (between 17:00 and 18:00) (Table 1). The two periods of observation will be examined separately due to the large discrepancy between them. The university and Sintef which can be defined as trip attractors are situated to the west of the roundabout. On the other hand, residential areas which are trip generators are located to the east (Fig. 41). That is why the traffic flows is in opposite directions during the different times of the day.

Table 1 – Registered cyclists.

| Time period | Number | Percentage |
|---|---|---|
| 07:45-08:45 | 238 | 62% |
| 17:00-18:00 | 144 | 38% |
| Total | 382 | |

The cyclists on the roundabout kept a relatively high speed during the observation periods. This can be explained with the fact that most of them are on their way to or from work.

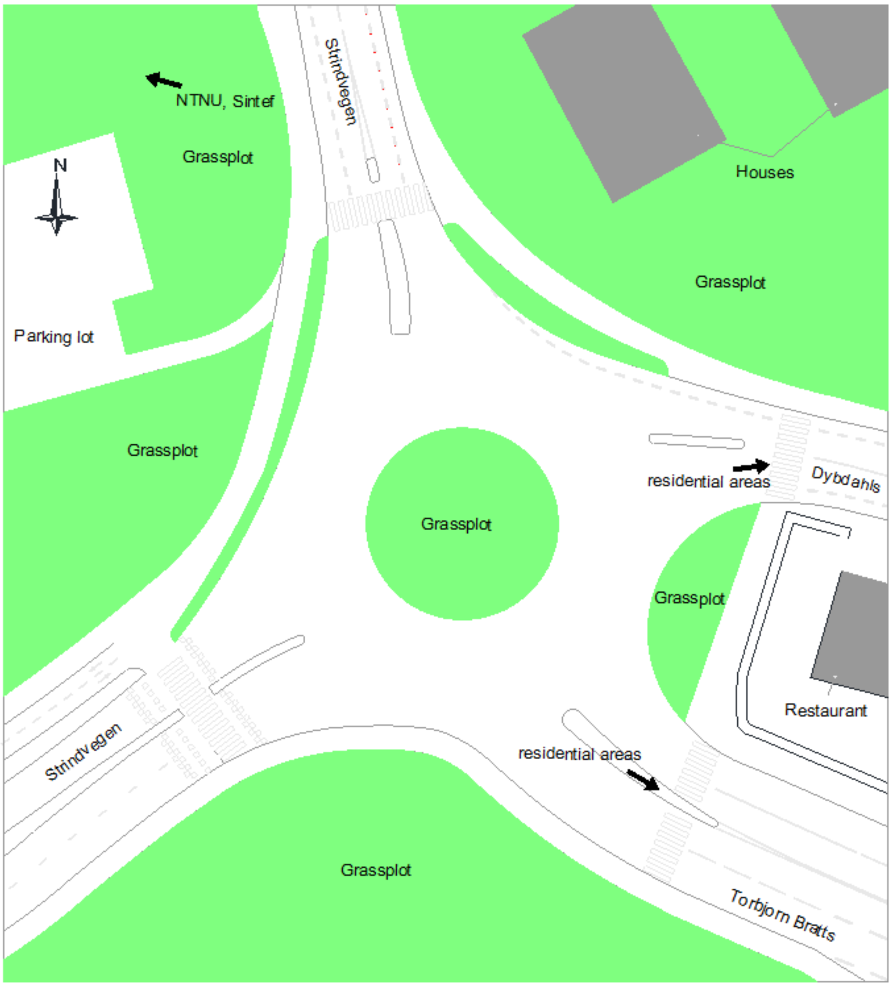



Fig. 41. Map of the roundabout

## CYCLISTS DURING THE MORNING RUSH HOUR

During the morning rush hour there were four main streams of cyclists moving through the roundabout that clearly stood out (Fig. 42). Main stream 1 includes 46 cyclists and they constitute 19% of bicycle traffic on the roundabout during the morning rush hour. Cyclists on this route came from approach B and continued to approach C. Main stream 2 constitutes 22% (52 cyclists) and passes through approaches B and A consecutively. Main stream 3 designates 64 cyclists (27%) moving through approach D and approach A.  Main stream 4 consists of 33 cyclists (14 %) and it passes through approaches D and C. The directions through the roundabout that were followed by the remaining 18% of the cyclists, together with the main streams, are given in Table 2.

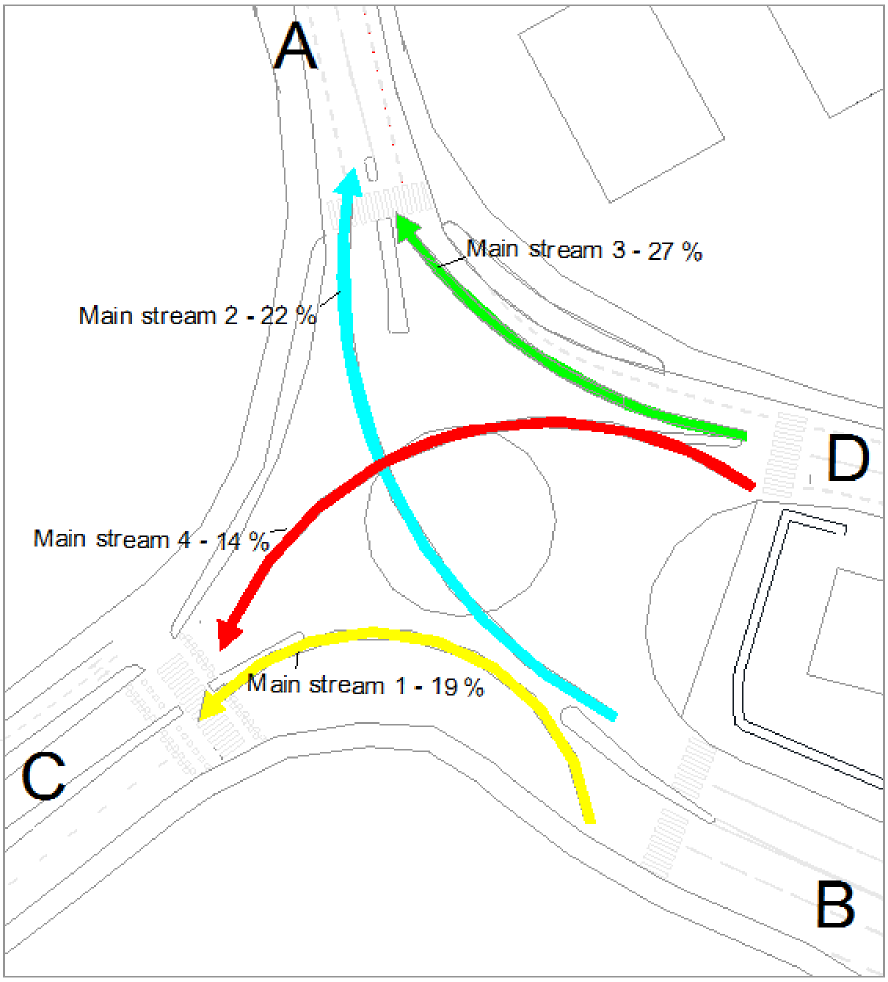



Fig. 42. Main streams during the morning rush hour

The fore-mentioned tendency of trip generation and distribution is clearly seen on the map of the Main streams.

Table 2 – Cyclists on different directions during the morning rush hour.

| Direction | Number | Percent,% |
|---|---|---|
| A-B | 0 | 0 |
| A-C | 0 | 0 |
| A-D | 0 | 0 |
| B-A | 52 | 22 |
| B-C | 46 | 19 |
| B-D | 5 | 2.1 |
| C-A | 16 | 6.7 |
| C-B | 6 | 2.5 |
| C-D | 12 | 5 |
| D-A | 64 | 27 |
| D-B | 4 | 1.7 |
| D-C | 33 | 14 |
| Total | 238 | 100 |

Main stream 1 consists of routes F1, F2, E1, E2 and G1 (Fig. 43). The most used route is E1 which includes cyclists approaching on the left sidewalk of Torbjørn Bratts, continue on the sidewalk through the intersection and then use the pedestrian crosswalk on Strindvegen west to get to the cycle path situated on the right sidewalk (when leaving the intersection). Route E1 is preferred by 65% of the 46 cyclists who use Main stream 1 to pass through the roundabout. This is the shortest way to get to the cycle facility on Strindvegen. Another reason that this route is so frequently used is that it doesn't involve cycling inside the motor-vehicle dominated circulatory area of the roundabout. The other routes are E2 with 15%, F1, F2 and G1 with 7% of the cyclists on Main stream 1 each. The numbers of cyclists on each route are given in Table 3.

Of the cyclists who use Main stream 1, 7% (3 people) are riding on the carriageway and 94% (43 people) on the sidewalks.

Table 3 – Cyclists on Main stream1

| Route | Number | Percent,% |
|---|---|---|
| F1 | 3 | 7 |
| F2 | 3 | 7 |
| E1 | 30 | 65 |
| E2 | 7 | 15 |
| G1 | 3 | 7 |
| Total | 46 | 100 |

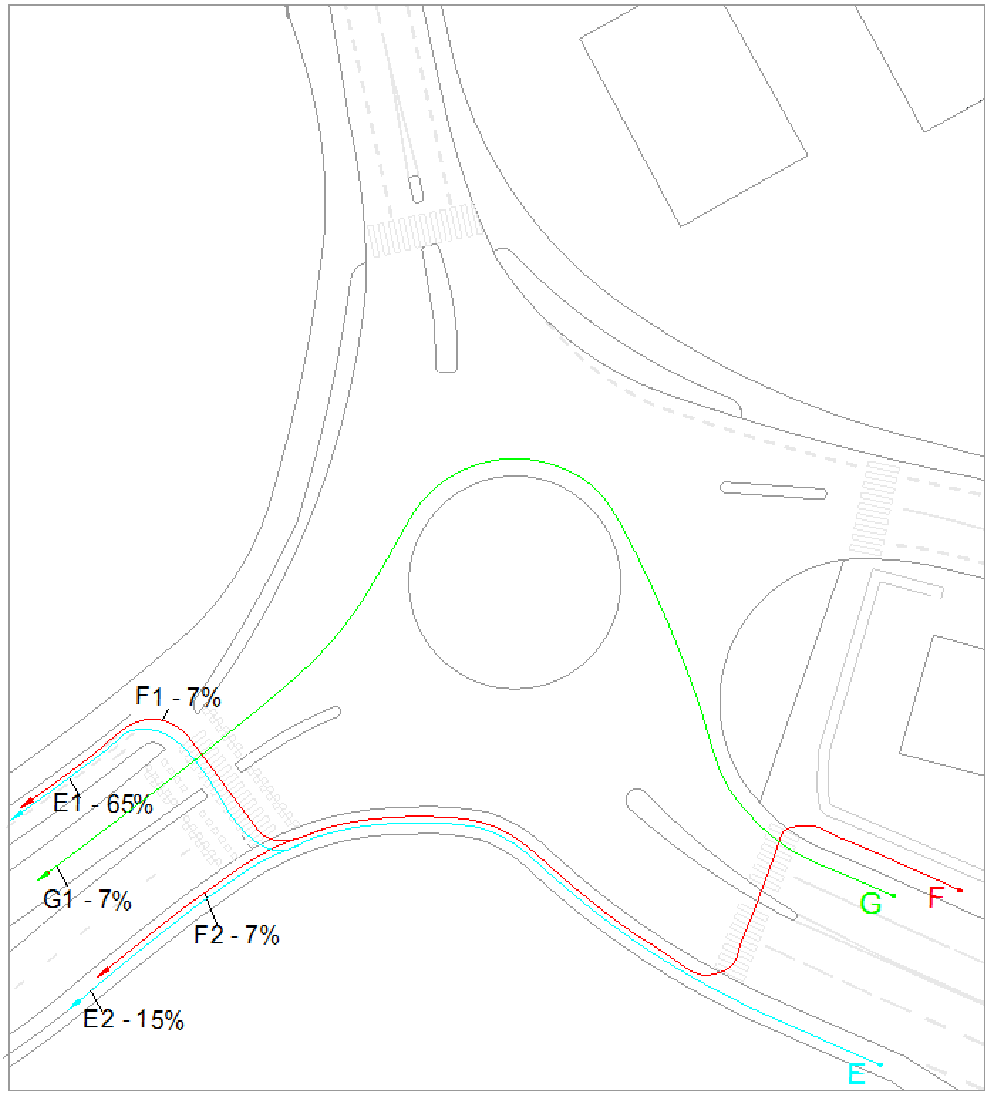



Fig. 43. Routes comprising Main stream 1

Main stream 2 comprises 22% (52 people) of all cyclists riding through the intersection during the morning rush hour. It follows Torbjørn Bratts (southeast of the roundabout) and continues to Strindvegen north which leads to the NTNU's campus. The routes included in this stream are H1, H2, I1, I2, I3 and J1 (Fig. 44).

Most cyclists preferred route H1 (45 cyclists) which constitutes 86% of the cyclists on Main stream 2. Cyclists on this route came from the left sidewalk of approach B. This is due to the fact that this sidewalk transforms into a foot-and-cycle lane 70m before the intersection. A great number of cyclists are heading towards the university and Sintef which are situated to the left of the intersection. So it is understandable that they would like to continue their way on the left sidewalk of Strindvegen north. To get there almost all of them choose route H1as it is the shortest and also requires the crossing of only one approach – Strindvegen west. They cross this street using the pedestrian crossing given there. Only one cyclist used route H2 which requires the crossing of three of the intersections' arms. Only four cyclists (8%) moved through the circulatory area of the roundabout and three of them continued on the cycle lane of Strindvegen north following route I2 (6%). The numbers of cyclists on each route are given in Table 4.

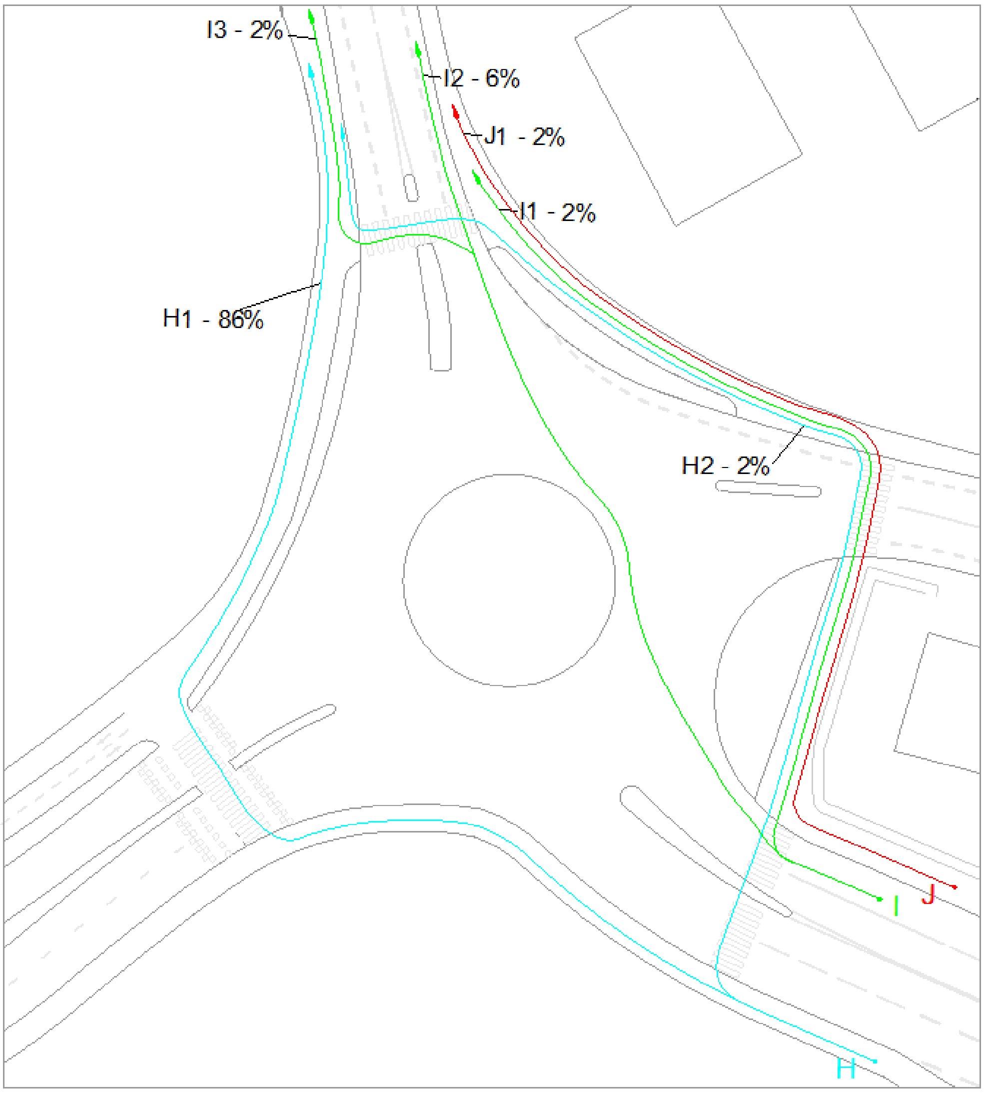


Fig. 44. Routes comprising Main stream 2

Table 4 – Cyclists on Main stream 2

| Route | Number | Percent,% |
|---|---|---|
| H1 | 45 | 86 |
| H2 | 1 | 2 |
| I1 | 1 | 2 |
| I2 | 3 | 6 |
| I3 | 1 | 2 |
| J1 | 1 | 2 |
| Total | 52 | 100 |

Main stream 3 consists of 64 cyclists and constitutes 27% of the morning traffic. It follows Dybhals street and leads to Strindvegen north (Fig. 45). Most of the cyclists who use it are students since there are student villages nearby – Berg - situated next to the roundabout on the right side of Dybhals street (when coming towards the intersection) and Moholt – also not far from here.

The following routes comprise Main stream 3 – K1, K2, K3, L1, L2, L3. Only nine cyclists (14 %) approached the roundabout on the cycle lane of Dybhals street. The other 55 riders came on the right sidewalk of this approach and continued to move on the sidewalk through the roundabout. After that 27 of them crossed Strindvegen north on the pedestrian crossing and continued on the left sidewalk comprising route K1. The reason that so many people changed to the left sidewalk is that most of them would use a shortcut to the university. Another 26 cyclists continued on the right sidewalk of Strindvegen north following the route K3. Only 2 cyclists (3%) who had come from the sidewalk of Dybhals street decided to use the cycle lane on Strindvegen north. Nine cyclists approached the roundabout on the cycle lane of Dybhals street and 7 of them decided to enter the circulatory area of the roundabout. A conclusion can be drawn that in most cases only cyclists who ride on the carriageway (either on cycle lane or traffic lane) are eager to enter the circulatory area of the roundabout. The numbers of cyclists on the different routes are given in Table 5.

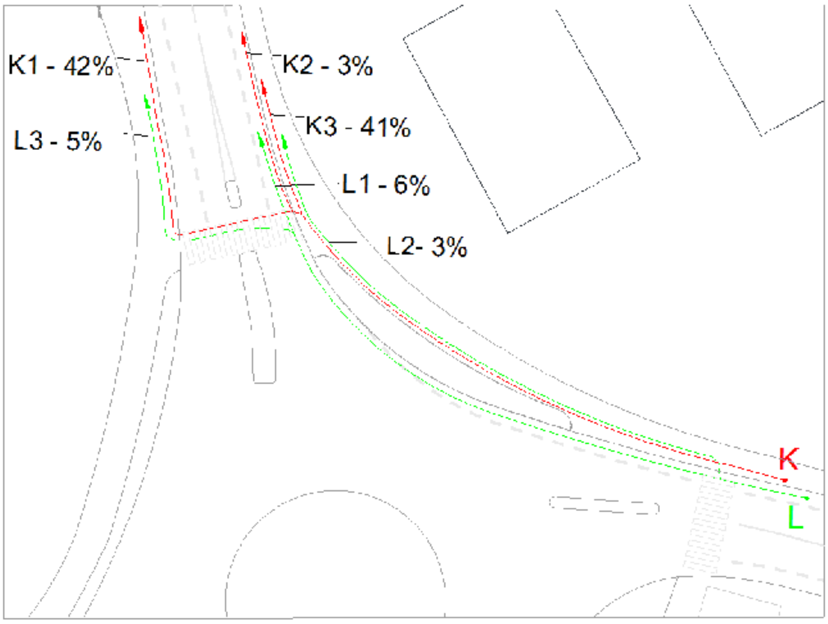


Fig. 45. Routes comprising Main stream 3

Table 5 - Cyclists on Main stream 3

| Route | Number | Percent,% |
|---|---|---|
| K1 | 27 | 42 |
| K2 | 2 | 3 |
| K3 | 26 | 41 |
| L1 | 4 | 6 |
| L2 | 2 | 3 |
| L3 | 3 | 5 |
| Total | 64 | 100 |

Main stream 4 is used by 33 cyclists (14%) (Fig. 46). It follows Dybhahls street and after the roundabout it continues to Strindvegen west. Most of the cyclists used the right sidewalk of approach D when coming towards the intersection (76%). Twenty-four of them continued to ride on the sidewalk to get to the cycle path situated on the right sidewalk of Strindvegen east. To do that, they had to use the pedestrian crossing on Strindvegen north. This is the shortest way to get there and it doesn't involve riding in the circulatory area. The other option to get to the cycle path on Strindvegen east by cycling on sidewalks only is to head southward and cross Dybdahls, Torbjørn and Strindvegen east consecutively. This is rather longer and requires the crossing of three arms so no one did it. Only one cyclist who used route M branched out to route M2 and rode in the circulatory area through the roundabout and then continued on the carriageway of Strindvegen south.

Eighteen percent of the cyclists on Mainstream 4 (6 people) approached the intersection on the cycle lane of Dybdahls street. Four of them chose to move in the circulatory area following route O2 and O3. The above confirms the conclusion that cyclists who approach on the carriageway are more likely to enter the roundabout. The number of cyclists on each route is given in Table 6.

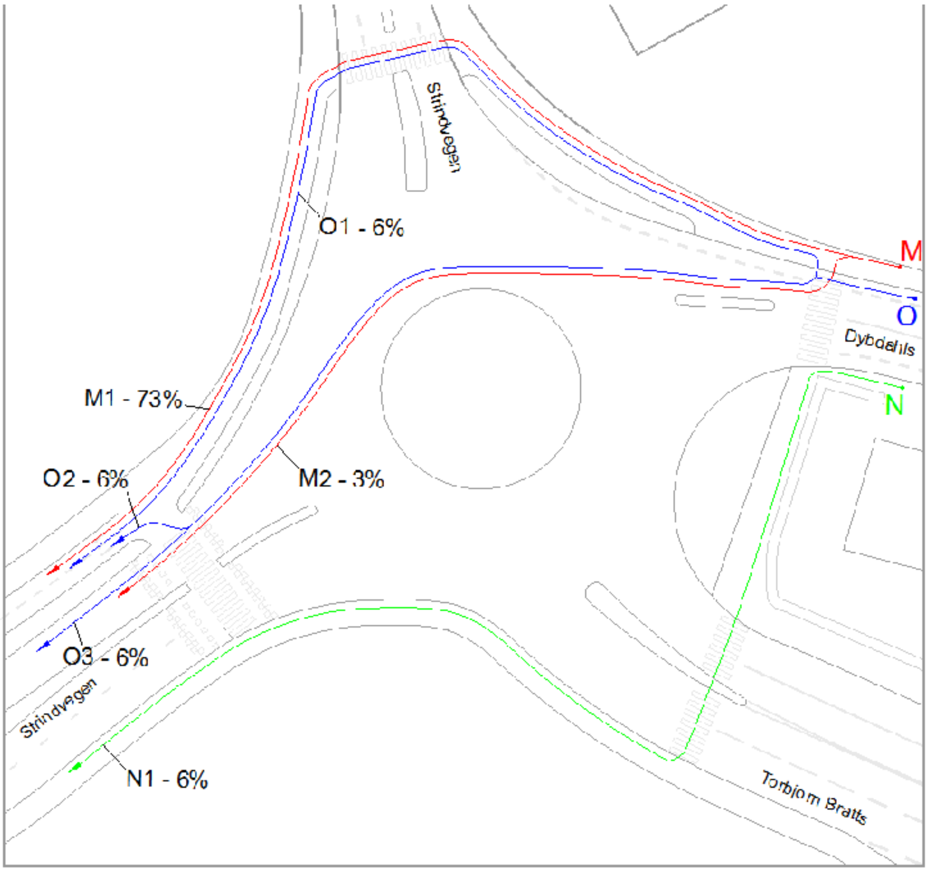


Fig. 46. Routes comprising Main stream 4

Table 6 – Cyclists on Main stream 4

| Route | Number | Percent,% |
|---|---|---|
| M1 | 24 | 73 |
| M2 | 1 | 3 |
| N1 | 2 | 6 |
| O1 | 2 | 6 |
| O2 | 2 | 6 |
| O3 | 2 | 6 |
| Total | 33 | 100 |

During the morning rush hour there was a noticeable decrease in the intensity of the traffic flow which formed two different periods. The first one took place from 07:45 to 08:25 and the second period lasted from 08:25 to 08:45. The traffic during the first period was defined as ‘heavy’ while during the second it was described as ‘medium.’ The number of cyclists registered while the traffic was ‘heavy’ is 176 and cyclists counted during the remaining time are 62. Despite that during the first 40 minutes only 13 cyclists decided to enter the circulatory area of the roundabout while 17 riders entered during the second period (Table 7). This clearly shows that cyclists are influenced by the traffic volume when they decide whether to ride on the carriageway inside or outside the roundabout.

Table 7 – Cyclists who entered the circulatory area of the roundabout.

| Time period | Categorization | Cyclists | Entered circ. area |
|---|---|---|---|
| 07:45-08:25 | Heavy | 176 | 13 |
| 08:25-08:45 | Medium | 62 | 17 |

## CYCLISTS DURING THE EVENING RUSH HOUR

The total number of cyclists during the evening rush hour is 144. The number of cyclists following different directions on the roundabout is shown in Table 8. The four main streams of cyclists riding through the intersection were distinguished (Fig. 10.). Main stream 1 includes 50 cyclists which constitute 35 % of bicycle traffic on the roundabout during the evening rush hour.

Main stream 2 includes 23 cyclists which constitute 16% of bicycle traffic during this period of observation. Cyclists following Main stream 3 are 20 and they constitute 14% of the cyclists during the evening rush hour. Main stream 4 is used by 14 cyclists (10%). Main streams during the evening rush hour are shown in Figure 47.

Table 8 – Cyclists on different directions during the evening rush hour.

| Direction | Number | Percent,% |
|---|---|---|
| A-B | 50 | 35 |
| A-C | 9 | 6 |
| A-D | 20 | 14 |
| B-A | 2 | 1 |
| B-C | 5 | 3 |
| B-D | 1 | 1 |
| C-A | 3 | 2 |
| C-B | 23 | 16 |
| C-D | 14 | 10 |
| D-A | 6 | 4 |
| D-B | 1 | 1 |
| D-C | 10 | 7 |
| Total | 144 | 100 |

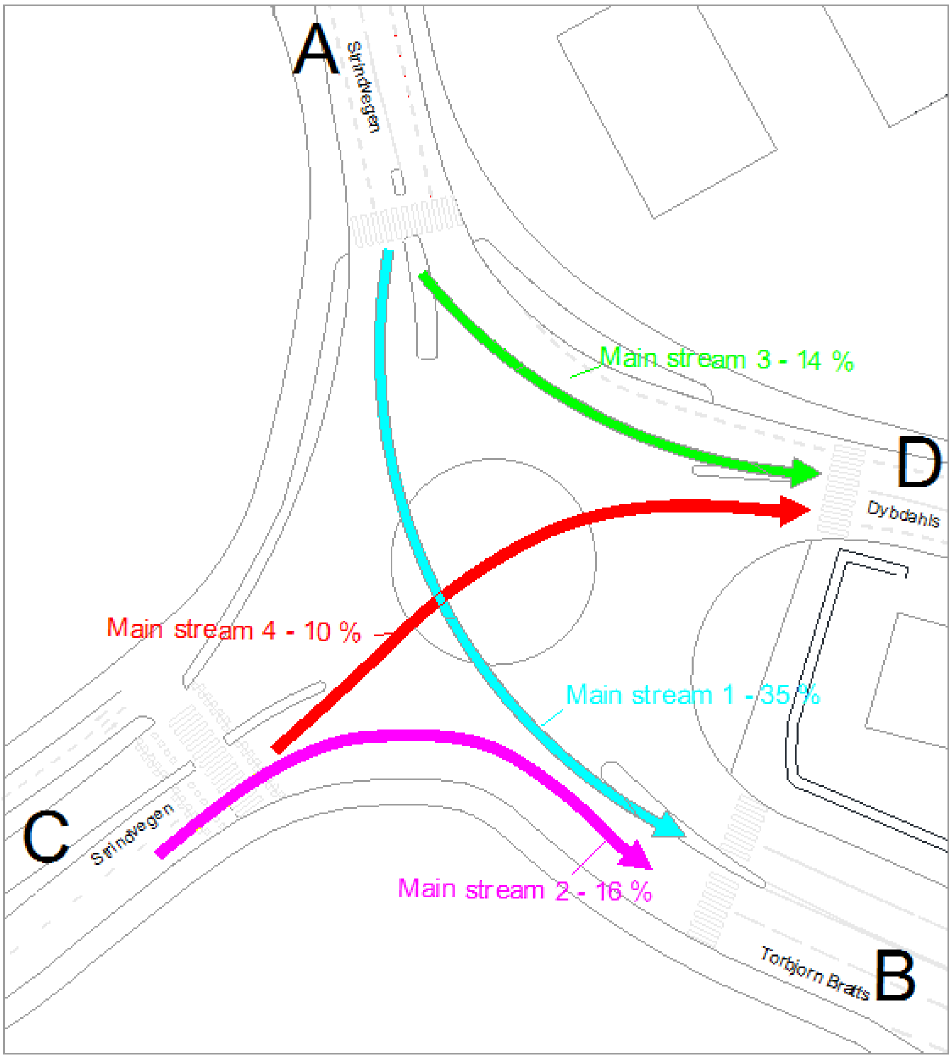


Fig. 47. - Main streams during the evening rush hour

Main stream 1 follows Strindvegen north and leads to Torbjørn Bratts street and consists of the routes: P1, P2, P3, Q1, Q2, Q3, R1, R2 (Fig. 48).

Route Q1 is clearly the busiest one with 22 people (44%). Cyclists on this route move primarily on the sidewalks except when they have to cross Strindvegen east through the pedestrian crossing. This is the safest route since it does not involve entering the motorized traffic and at the same time it is the shortest one. It also leads to the right sidewalk of Torbjørn Bratts (when going out of the roundabout) which turns into a foot- and cycle path - the only facility for cyclists on Torbjørn Bratts street.

Twenty-eight percent of the cyclists on Mainstream 1 entered the circulatory area of the roundabout and all of them initially came from the cycle lane of Strindvegen north. Eight percent of them continued to move on the carriageway of Torbjørn Bratts (route P1) and the other 20% preferred the sidewalk and followed the foot- and cycle path there (route P2). The number of cyclists on each route comprising Main stream 1 is given on Table 9.

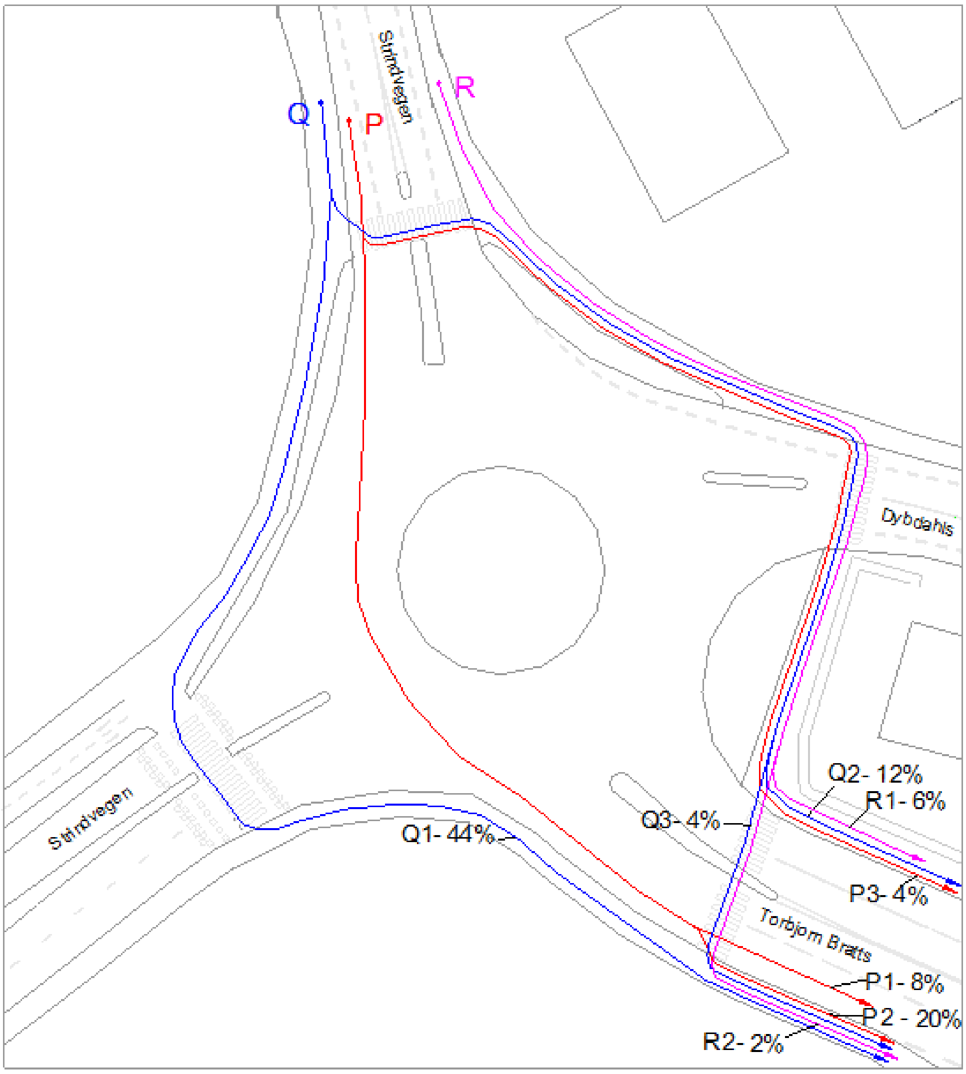


Fig. 48. Routes comprising Main stream 1

Table 9 – Cyclists on Main stream 1

| Route | Number | Percent,% |
|---|---|---|
| P1 | 4 | 8 |
| P2 | 10 | 20 |
| P3 | 2 | 4 |
| Q1 | 22 | 44 |
| Q2 | 6 | 12 |
| Q3 | 2 | 4 |
| R1 | 3 | 6 |
| R2 | 1 | 2 |
| Total | 50 | 100 |

Main stream 2 consists of routes S1, S2, T1, T2. Route S1 was used by 11 people who constitute 48 % of all cyclists on Main stream 2 during the evening observation. It is the route which was used by the biggest amount of cyclists (Fig. 49). This is due to the fact that most of the riders approached the roundabout on Strindvegen west where a two-way cycle path is provided, and then they continued on the sidewalk of Torbjørn Bratts where a foot- and cycle path starts after the bus stop. By following this route cyclists also avoided entering the circulatory area of the roundabout and thus had a safer passage through the roundabout.

Route S2 was used by 9 cyclists who constitute 39 % of the riders on Main stream 2 during the evening rush hour. They followed route S1 up to the crosswalk of Torbjørn Bratts where they crossed and continued on the other sidewalk of the street.

Of all who followed Main stream 2 only three cyclists came on the right sidewalk of Strindvegen west where there are no cycle facilities available. Then two of them continued on the right sidewalk of Torbjørn Bratts to the foot- and cycle path situated there and one cyclist used the pedestrian crossing to get on the left sidewalk of the street (when going out of the roundabout). The number of cyclists on the different routes is given on Table 10.

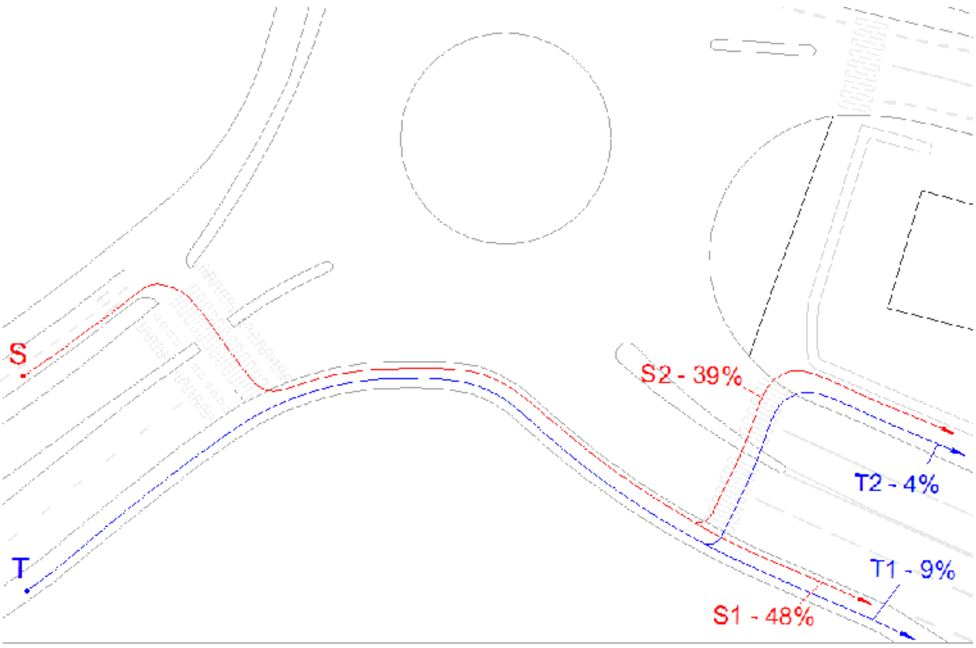



Fig. 49. Routes comprising Main stream 2

Table 10 – Cyclists on Main stream 2

| Route | Number | Percent,% |
|---|---|---|
| S1 | 11 | 48 |
| S2 | 9 | 39 |
| T1 | 2 | 9 |
| T2 | 1 | 4 |
| Total | 23 | 100 |

Main stream 3 consists of routes U1, U2, V1, V2, W1 and W2 (Fig 50). None of the cyclists who followed this stream entered the circulatory area of the roundabout. Sixty percent of them (routes V1 and V2) came on the right sidewalk of Strindvegen north (when moving towards the intersection). Having so many cyclists riding on this sidewalk is largely due to the fact that nearby there is a shortcut to the university that students use when coming back home. To get to Dybhals street they used the pedestrian crossing on Strindvegen north. Half of them decided to continue on the left sidewalk (when moving away from the roundabout) and the other got on the right sidewalk using the crosswalk there. Four cyclists (20 %) approached the intersection on the cycle lane of Strindvegen north but all of them used the pedestrian crossing to get on the left sidewalk (when coming towards the intersection). Four cyclists used routes W1 and W2 approaching on the left sidewalk of the street. As the rest of the riders they continued moving on the sidewalk to get to Dybhals street. Cyclists on the different routes are shown in Table 11.

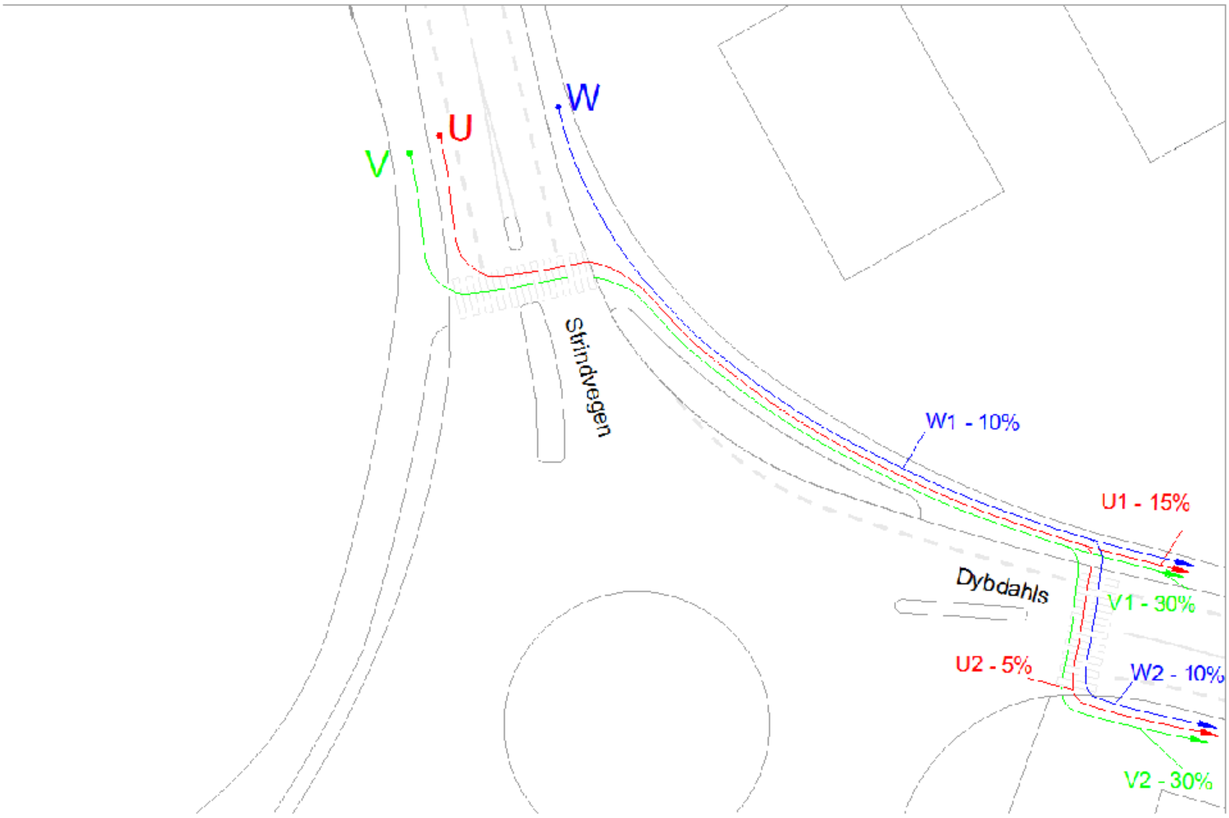


Fig. 50. Routes comprising Main stream 3

Table 11 – Cyclists on Main stream 3

| Route | Number | Percent,% |
|---|---|---|
| U1 | 3 | 15 |
| U2 | 1 | 5 |
| V1 | 6 | 30 |
| V2 | 6 | 30 |
| W1 | 2 | 10 |
| W2 | 2 | 10 |
| Total | 20 | 100 |

Main stream 4 consists of routes X1, Y1, Y2, Y3, Z1, and Z2 (Fig. 60). The number of cyclists on each of these routes is given on Table 12. Only 14% of the cyclists enter the circulatory area of the roundabout (routes X1 and Y2). Route Z1 is preferred by 43% of the cyclists on Mainstream 4 which makes it the most used. This is due to the fact that cyclists who follow it come from the cycle path situated on the left (when approaching the roundabout) sidewalk of Strindvegen west. After the cycle path terminates, the cyclists just continue on the sidewalk, until they cross Strindvegen north on the pedestrian crosswalk given there and then they continue on the left sidewalk of Dybdahls The second busiest route is Y1 which is followed by 4 cyclists (29%). Cyclists on Y1 approach the roundabout on the right sidewalk of Strindvegen and then they use the crosswalk on Torbjørn Bratts veg. From there they get to the right sidewalk of Dybdahls. Each of the routes X1, Y2, Y3, Z2 is followed by only 1 cyclist (7%) respectively.

Table 12 – Cyclists on Main stream 4

| Route | Number | Percent,% |
|---|---|---|
| X1 | 1 | 7 |
| Y1 | 4 | 29 |
| Y2 | 1 | 7 |
| Y3 | 1 | 7 |
| Z1 | 6 | 43 |
| Z2 | 1 | 7 |
| Total | 14 | 100 |

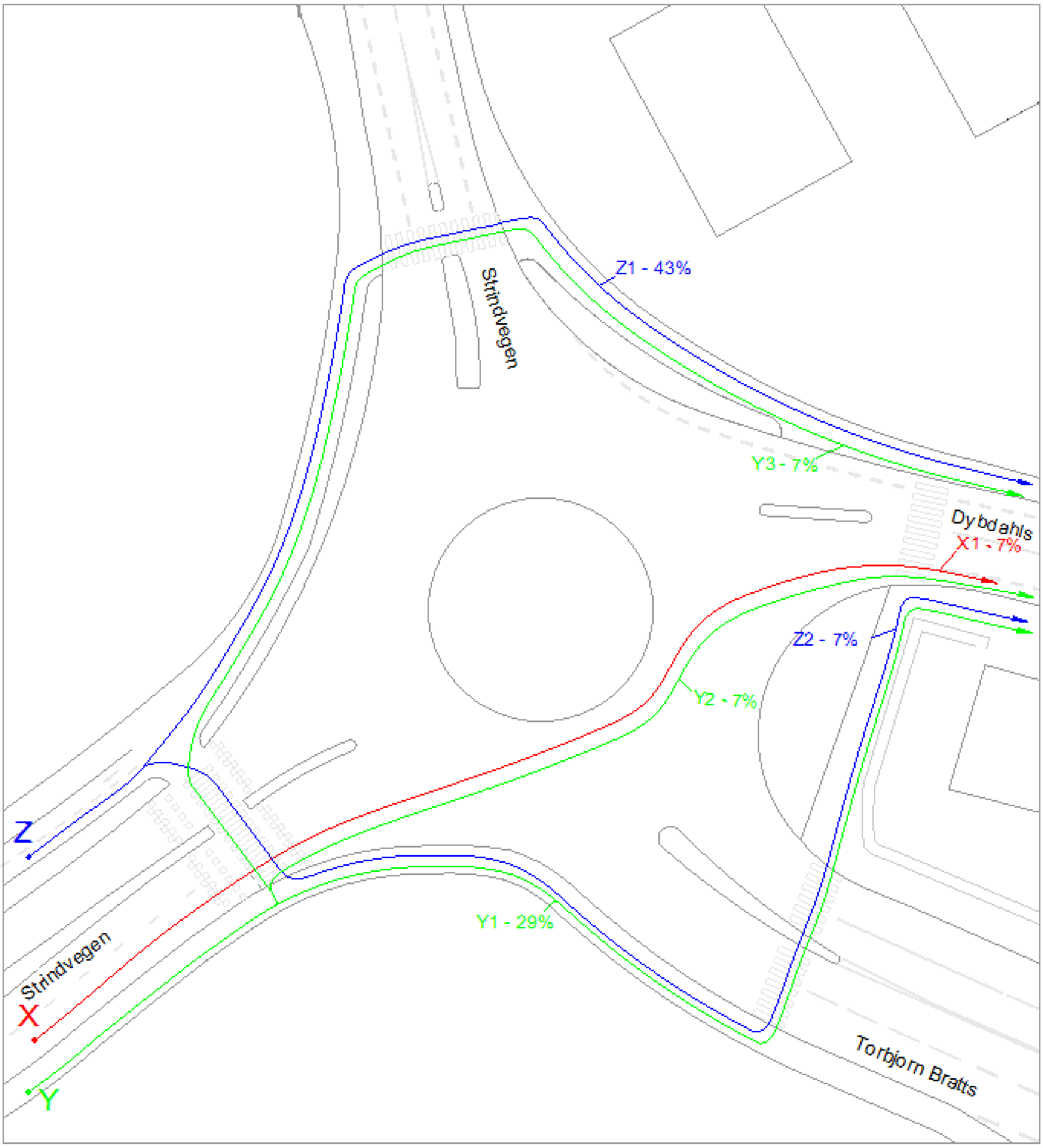


Fig. 60. Routes comprising Main stream 4

There wasn't a noticeable change in the intensity of the traffic flow during the evening rush hour as it was observed during the analysis of the morning rush hour traffic. The density of the traffic flow was alternately described as either 'medium' or 'light'. During the evening rush hour 78% (113 people) negotiated their way through the roundabout while the traffic was described as 'medium'. Of all the registered cyclists during the evening rush hour only 26 entered the circulatory area of the roundabout. A comparison with the riders who did this during the morning observational period is provided (Table 13). Even though more cyclists were registered during the morning rush hour the proportion of those who decided to enter the circulatory area of the roundabout was greater during the evening period of observation when the traffic volume was lower. The above confirms the conclusion that cyclists' perception of risk at roundabouts is influenced by the traffic volume.

Table 13 – Comparison of the cyclists who entered the circulatory area of the roundabout.

| Time | All cyclists | Entered circ. area | % |
|---|---|---|---|
| 07:45-08:45 | 238 | 30 | 13 |
| 17:00-18:00 | 144 | 26 | 18 |

Cyclists in Norway do not have the same rights as pedestrians on zebra crossings. Motorists are only obligated to give way to them if they dismount from their bikes in advance and wheel them through the crosswalk. Cyclists crossing a street have priority only if the sign shown in Figure 61 is provided. During the morning rush hour 161 cyclists used the pedestrian crosswalks to cross the arms of the roundabout. Only 45 (28%) of them got off their bikes before doing that. This can confuse the car drivers and lead to dangerous situations.

During the evening rush hour 103 cyclists used the zebra crossings on the approaches of the roundabout. Only 31 % (32 people) out of them decided to dismount before crossing.

Fig. 61. – Sign giving priority to cyclists crossing a road

Table 14 shows how many times each pedestrian crossing was used by cyclists during both observational periods.

Table 14 – How many times each pedestrian crossing was used

| Crossing on approach | Morning | Evening | Total |
|---|---|---|---|
| A | 61 | 36 | 97 |
| B | 15 | 22 | 37 |
| C | 86 | 50 | 136 |
| D | 6 | 23 | 29 |
| Total | 168 | 131 | 299 |

The average time cyclists spent to pass through the intersection using the circulatory area of the roundabout was 12,25 seconds, while the average time cyclists moving outside the perimeter of the roundabout was 27,01 seconds. Only cyclists that left the intersection on arms that were not adjacent to the arm that they had used to approach the intersection, were registered.

## ADDITIONAL COMMENTS

When registering cyclists following Main stream 4 during the morning rush hour three different cases were observed where the movement of a rider was obstructed. The cyclists rode on route M1 and wanted to use the sidewalk of Strindvegen north . In all of the cases there were too many pedestrians walking on the zebra crossing and they slowed the rider while he wanted to pass through.

Two similar situations were observed on Main stream 3 where three cyclists following route K1 were slowed down when trying to move on the same zebra crossing of Strindvegen north.

During the morning rush hour there were three more registered cases of cyclists whose movement was obstructed by pedestrians. The riders followed route H1 and experienced problems when trying to move on the crosswalk of Strindvegen west.

Two cases of cyclists whose movement was obstructed by pedestrians were observed during the evening rush hour. The riders were following route Q1 when had to slow down because of pedestrians on the crosswalk of Strindvegen west.

A near accident situation was observed during the morning rush hour while registering cyclists on Main stream 2. A cyclist following route H1 approached the crosswalk of Strindvegen west. A car tried to speed out of the roundabout, misjudging the velocity of the bike. The driver had to slam the brakes and the cyclist’s knee barely missed the car’s headlights.

# 4.2.Results for the regular intersection

## *I. Features of the area*

The regular intersection is situated around 200 meters north-west of the biggest of NTNU's campuses – Gløshaugen (Fig. 61). Around 200 meters along Høgskoleveien west there is an intersection with Elgesetergate which leads to the city center. Right next to this intersection is situated the building of the student society in Trondheim - Studentersamfundet. Around 250 meters westwards of the studied intersection is situated St. Olavs Hospital. There are no public transport routes that pass through the intersection.

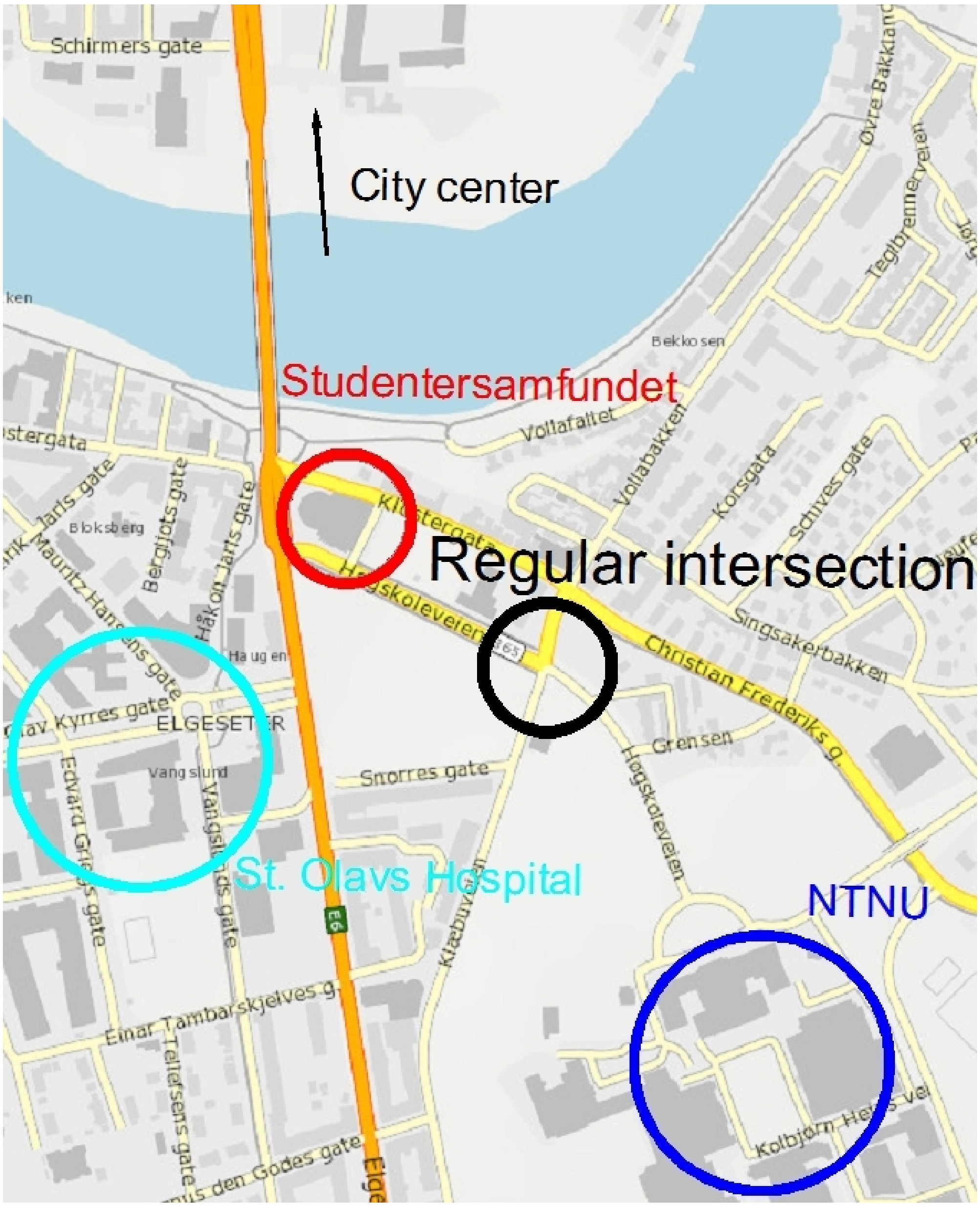



Fig. 61. Map of the intersection's surroundings

There are small public gardens and recreational areas situated south of the intersection. Northwards are situated mainly residential and public buildings and also a restaurant and a grocery shop (Fig. 62).


Fig. 62. Map of the regular intersection

## *II. Traffic volume*

The AADT volumes on the intersection acquired from the web page of the Norwegian Public Roads Administration are given on Figure 63. The volumes on Vollabakken and Høgskoleveien west are 5000 vehicles per day each. The share of heavy vehicles on these streets is eight percent. The volume given for Klæbuveien is 400 vehicles per day, two percent of them being heavy vehicles. There is no information provided for the number of motorized traffic on Høgskoleveien east.

Fig. 63. AADT volumes on the regular intersection

## *III. Motorized traffic*

The results of the additional study of the motorized traffic during the morning rush hour are shown on Figure 64. A total of 398 motor vehicles were registered on the regular intersection during the morning rush hour. In compliance with the data provided by the Norwegian Public Roads Administration most of the motorized traffic was using Vollabakken and Hogskoleveien. A total of 184 automobiles entered the crossroad from Vollabakken. Only 9 vehicles approached the intersection from Klæbuveien and only 11 left it using this arm. The traffic direction which was used the most composed of automobiles that moved on Vollabakken and turned right to Hogskoleveien. The number of vehicles that followed this route is 163 and it constituted 41 % of all the registered automobiles. A total of 248 motorists (62 %) left the intersection on Hogskoleveien west. The number of motorists on different directions is shown on Table 15.

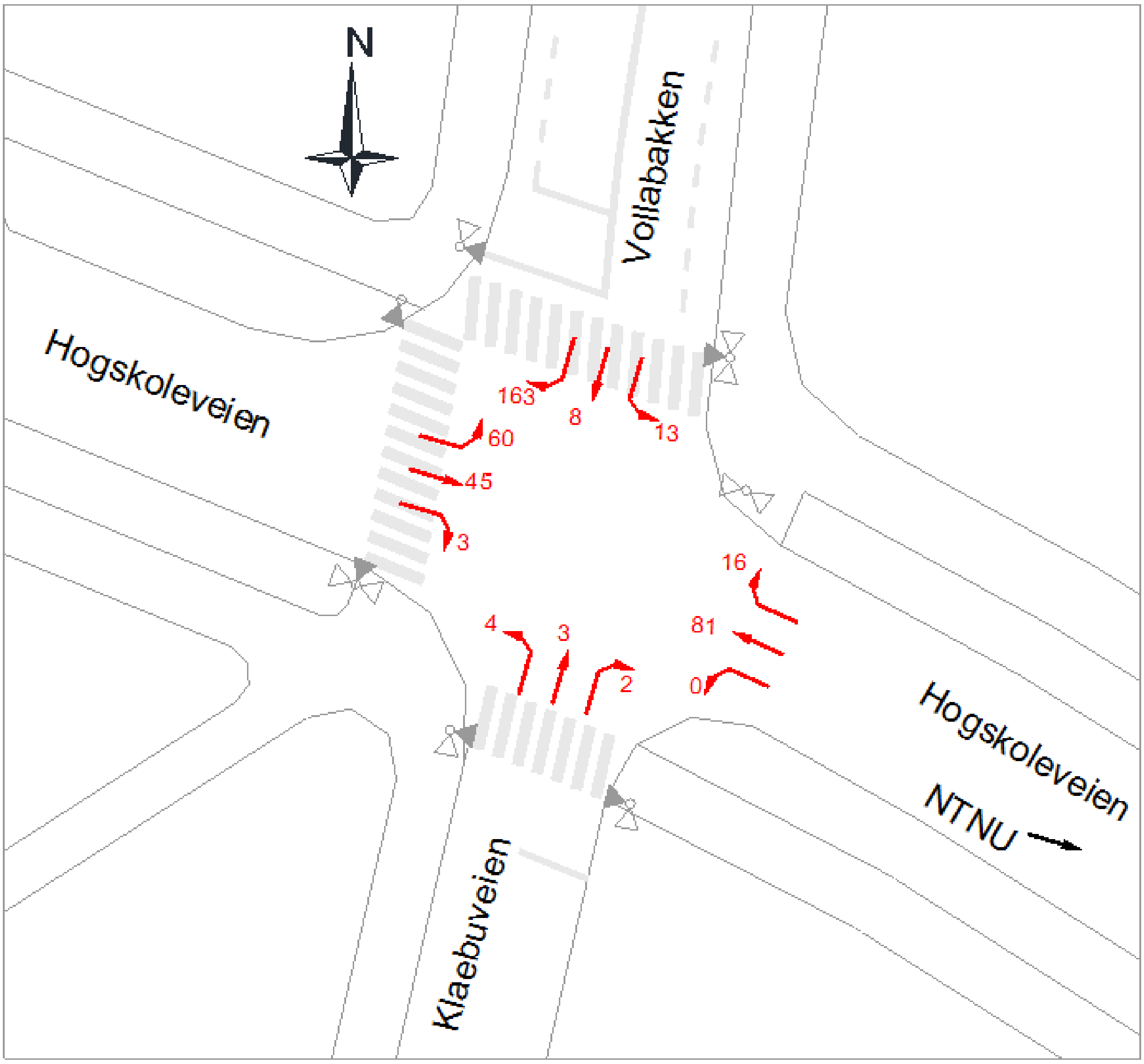



Fig. 64. Motorized traffic volume on the regular intersection

Table 15 – Motorized traffic on different directions

| Direction | Number | Percent,% |
|---|---|---|
| A-B | 8 | 2 |
| A-C | 163 | 41 |
| A-D | 13 | 3 |
| B-A | 3 | 1 |
| B-C | 4 | 1 |
| B-D | 2 | 1 |
| C-A | 60 | 15 |
| C-B | 3 | 1 |
| C-D | 45 | 11 |
| D-A | 16 | 4 |
| D-B | 0 | 0 |
| D-C | 81 | 20 |
| Total | 398 | 100 |

# IV. Accidents

Three accidents involving cyclists were registered by the Norwegian Public Roads Administration with the earliest accident on record dating back to November, 2004.

# V. Cyclists on the regular intersection

During the morning rush hour 215 cyclists were registered on the regular intersection. There were three main streams of cyclists that clearly stood out. Main stream 1 includes 59 people which constitute 27 % of the bicycle traffic registered during the period of observation (Fig. 65). Cyclists on this route came from Klæbuveien and continued straight ahead on Vollabakken.

Main stream 2 is in the opposite direction of Main stream 1 and was used by 35 people which constitute 16 % of the traffic on the intersection. The considerable difference (almost double) in the number of cyclists using these two streams is due to the fact that Main stream 1 leads towards the city center where the transport users head for during the morning rush hour.

Main stream 3 includes 58 people who rode eastwards along Høgskoleveien. The presence of so many transport users riding in this direction can be explained by the fact that Hogskoleveien starts at Elgesetergate and leads to NTNU's campus. Elgesetergate is a main city artery towards the city center while the university is a huge trip attractor for students.

The remaining 30 % of cyclists can be seen in Table 16.

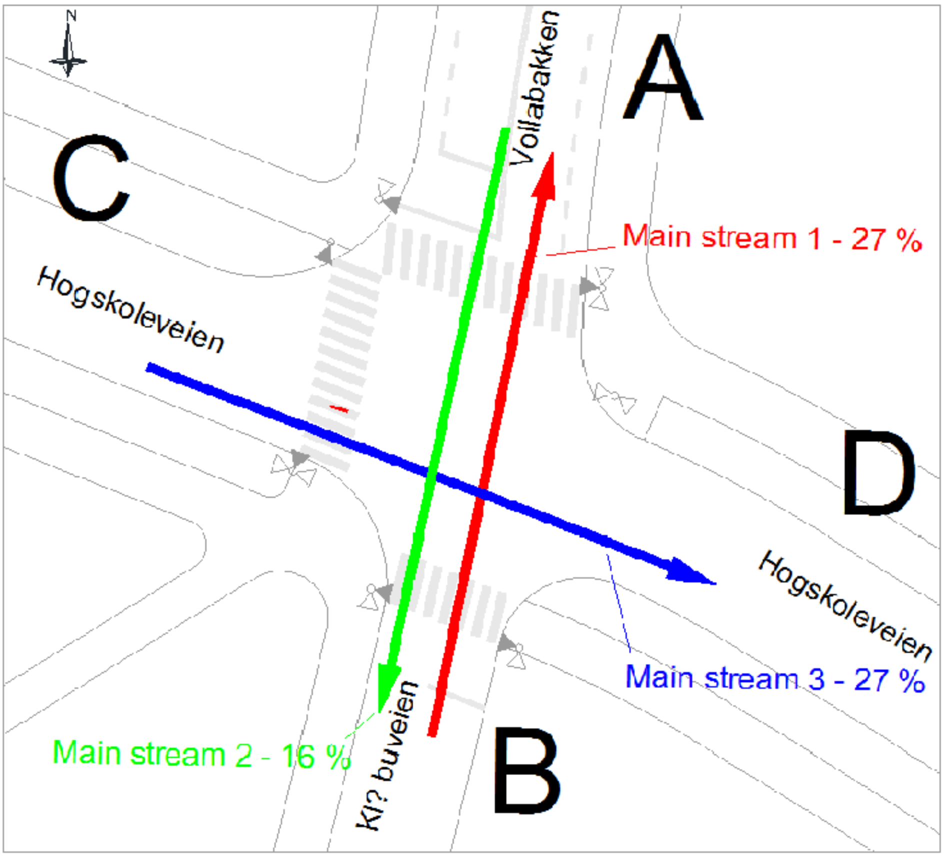



Fig. 65. Main streams of the bicycle traffic

Table 16 – Cycle traffic on different directions

| Direction | Number | Percent,% |
|---|---|---|
| A-B | 35 | 16 |
| A-C | 18 | 8 |
| A-D | 16 | 7 |
| B-A | 59 | 27 |
| B-C | 4 | 2 |
| B-D | 1 | 0 |
| C-A | 0 | 0 |
| C-B | 0 | 0 |
| C-D | 58 | 27 |
| D-A | 2 | 1 |
| D-B | 0 | 0 |
| D-C | 22 | 10 |
| Total | 215 | 100 |

Main stream 1 consists of routes A1, A2, A3 which all start on the carriageway of Klæbuveien (Fig. 66). The fact that they approached the intersection on the traffic lane is largely because the only sidewalk on this arm is on the left side of the street (when moving towards the intersection). Almost all of them 92 % decided to continue straight ahead and use the cycle lane on Vollabakken (Table 2). Four cyclists (7%) decided to get on the right sidewalk of approach A following route A2. One of the cyclists on Main stream 1 (2%) decided first to use the pedestrian crosswalk to get on the southwest sidewalk edge of intersection. From there the cyclist crossed Høgskoleveien using the pedestrian crossing and then continued on the left sidewalk of Vollabakken. The number of cyclists on each route is given in Table 17.

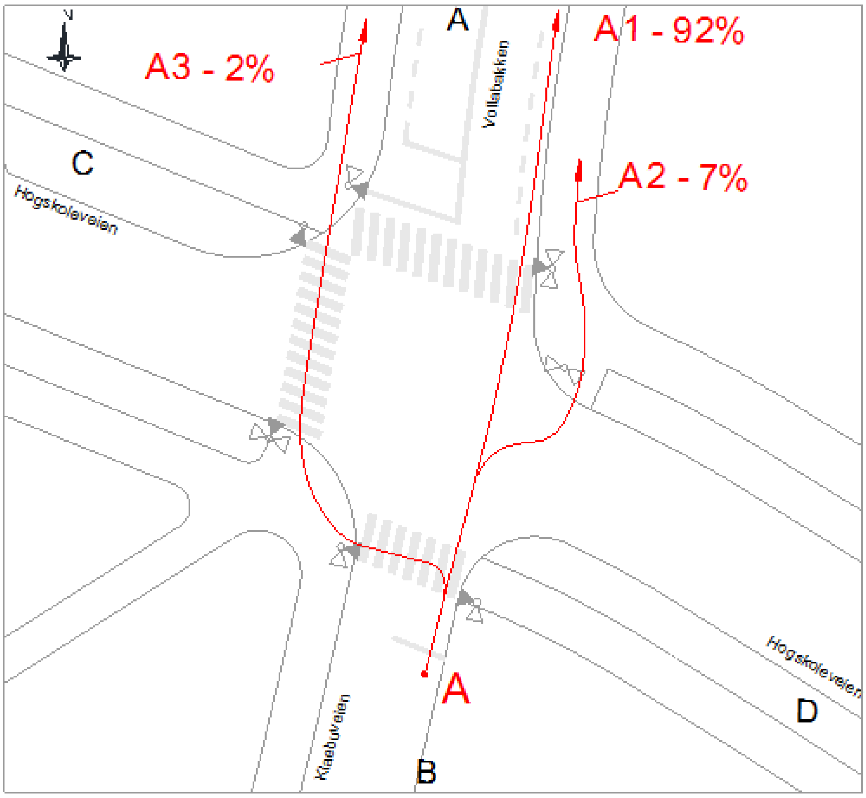



Fig. 66. Routes comprising Main stream 1

Table 17 – Cycle traffic on different routes of Main stream 1

| Route | Enters | Continues | Number | Percentage, % |
|---|---|---|---|---|
| A1 | Traffic lane | Cycle lane | 54 | 92 |
| A2 | Traffic lane | Sidewalk | 4 | 7 |
| A3 | Traffic lane | Sidewalk | 1 | 2 |
| Total | - | - | 59 | 100 |

Main stream 2 consists of routes B1, C1 and C2 (Fig. 67). Cyclists following route B1 approached the intersection on the cycle lane of Vollabakken and continued on the traffic lane of Klæbuveien. It was used by 27 people that constitute 77% of cyclists on Mainstream 2. Cyclists using routes C1 and C2 came on the sidewalk of Vollabakken. Route C1 was used by 7 cyclists (20 %) who proceeded on the traffic lane of Klæbuveien after the intersection. One cyclist (3%) followed route C2 which involves the usage of the crosswalks on Vollabakken and Høgskoleveien consecutively. The number of cyclists on each route are given in Table 18.

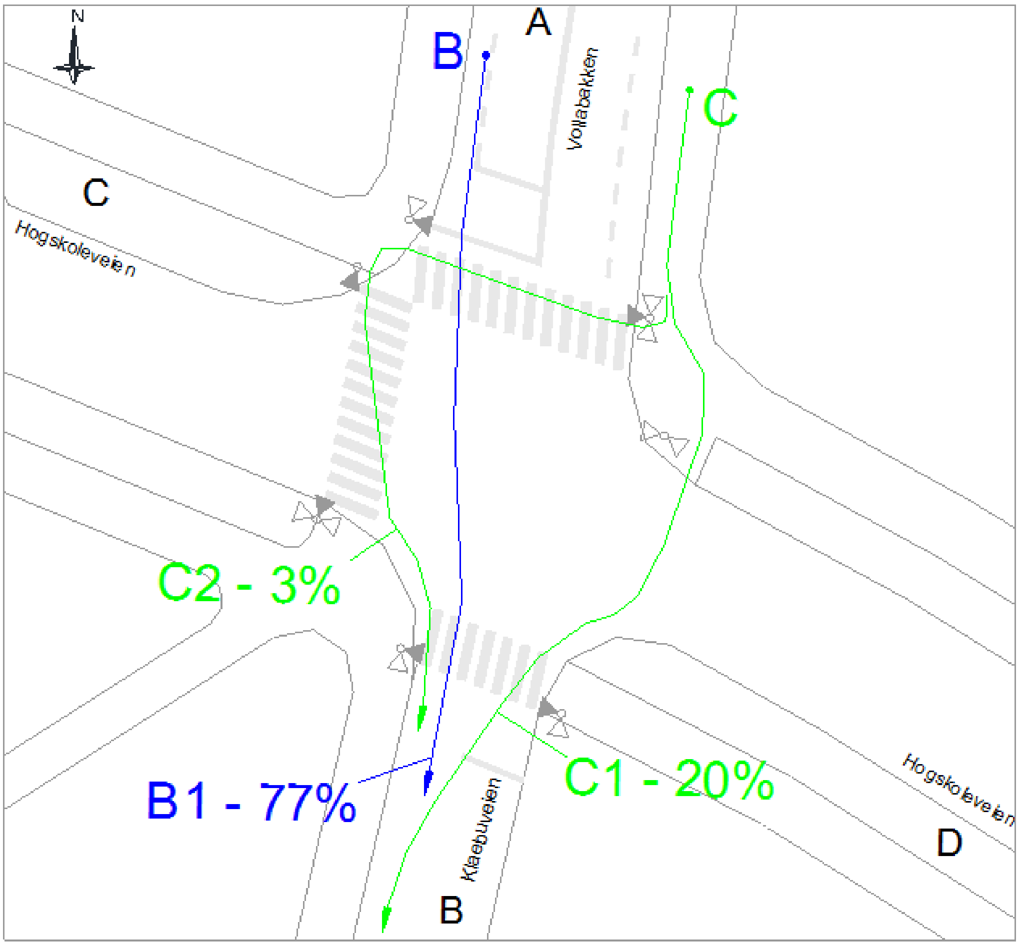



Fig. 67. Routes comprising Main stream 2

Table 18 – Cycle traffic on different routes of Main stream 2

| Route | Enters | Continues | Number | Percentage, % |
|---|---|---|---|---|
| B1 | Cycle lane | Traffic lane | 27 | 77 |
| C1 | Sidewalk | Traffic lane | 7 | 20 |
| C2 | Sidewalk | Traffic lane | 1 | 3 |
| Total | - | - | 35 | 100 |

In Main stream 3 routes D1, D2, E1 and F1 are included (Fig. 68). Routes D1 and D2 start on the left sidewalk of Høgskoleveien west. Route D1 is followed by 46 cyclists (79%) who use the crosswalk on Vollabakken and then continue on the sidewalk of Høgskoleveien east. Cyclists on route D2 used the pedestrian crossings on Høgskoleveien and Klæbuveien consecutively. Only one of the cyclists using Main stream 3 rode on the carriageway of Høgskoleveien which can be explained with the absence of cycle lanes. Route F1 is followed by 5 cyclists who approached on the sidewalk of Høgskoleveien west and then used the pedestrian crossing on Klæbuveien to get to the sidewalk of Høgskoleveien east. The number of cyclists on each of the routes comprising Main stream 3 are shown in Table 19.

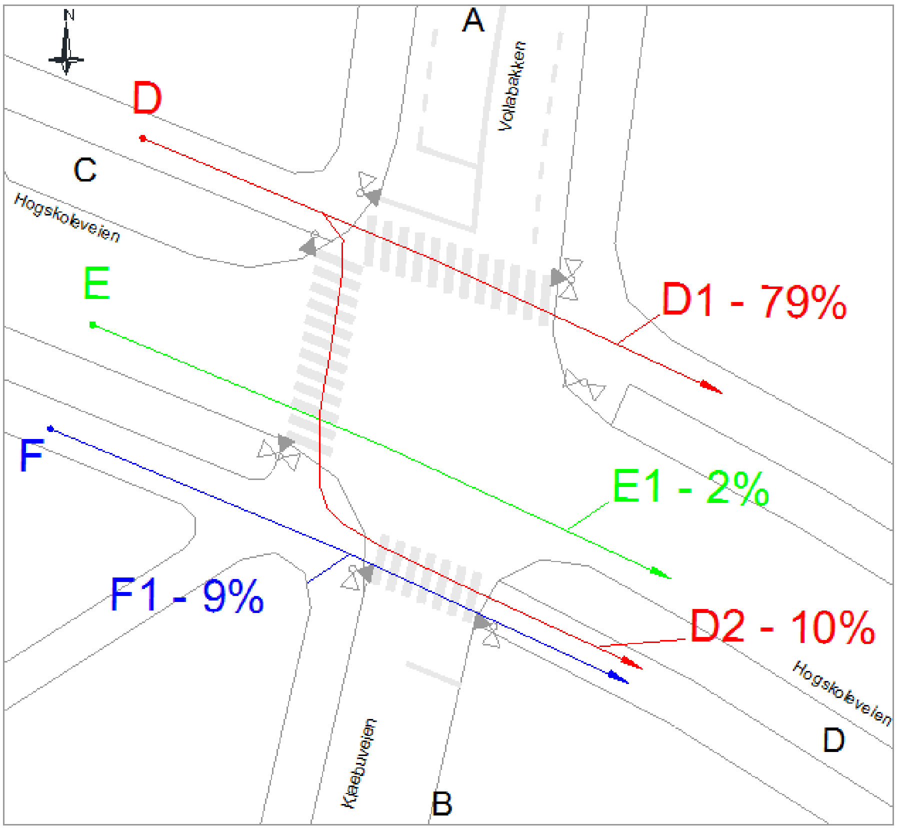



Fig. 68. Routes comprising Main stream 3

Table 19 – Cycle traffic on different route of Main stream 3

| Route | Enters | Continues | Number | Percentage, % |
|---|---|---|---|---|
| D1 | Sidewalk | Sidewalk | 46 | 79 |
| D2 | Sidewalk | Traffic lane | 6 | 10 |
| E1 | Traffic lane | Traffic lane | 1 | 2 |
| F1 | Sidewalk | Sidewalk | 5 | 9 |
| Total | - | - | 58 | 100 |

Another route which is worth mentioning outside the Main streams is G1 which was used by 12 people (Fig. 69). Cyclists who followed G1 came on the carriageway of Høgskoleveien east and then used the pedestrian crossing on Klæbuveien to get on the sidewalk of Høgskoleveien.

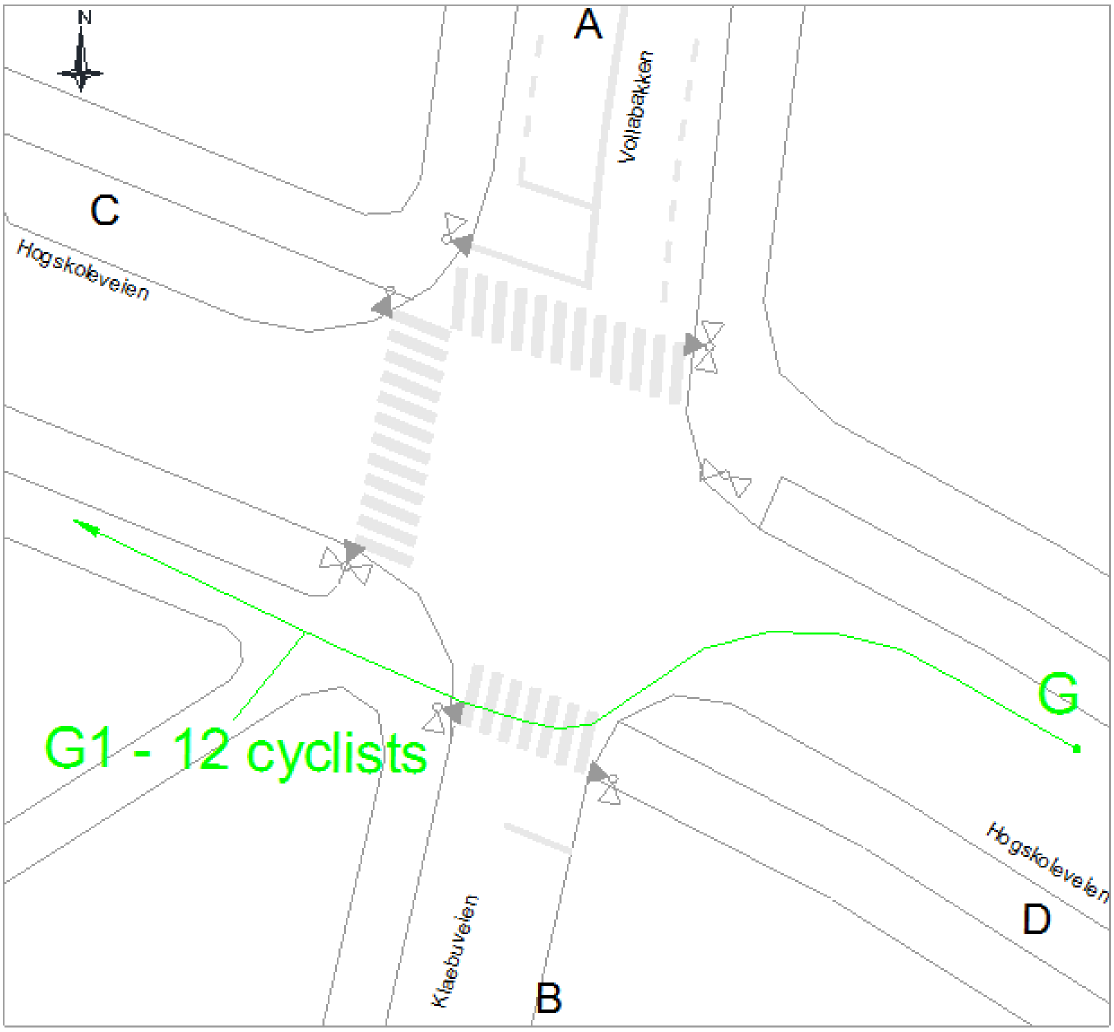



Fig. 69. Route G1

Table 20 shows how many times each of the crosswalks has been used. There isn't a crosswalk on approach D but the number given in the table shows the number of times the approach was crossed where usually a pedestrian crossing is provided. The pedestrian crossings were used by 112 cyclists in total.

Table 20 - how many times each crosswalk was crossed

| Approach | Number |
|---|---|
| A | 70 |
| B | 24 |
| C | 12 |
| D | 6 |

The total number of cyclists dismounting of their bikes is 19. This is 17 percent of all cyclists who used pedestrian crossings. The number of cyclists on main stream roots, who got off their bikes is given in Table 6.

Table 21 – Cyclists who got off their bikes

| Route | Number |
|---|---|
| D1 | 8 |
| D2 | 3 |
| F1 | 3 |
| Other | 5 |
| Total | 19 |

Half of the cyclists (112) took traffic signals into consideration. The number of cyclists on main stream routes who took traffic signals into consideration are shown in Table 7. Almost all but two run the red light when they were sure that nobody is coming along the cross street so these cases weren't considered as being risky. The occasions which were considered to be risky are described below.

A cyclist following route B1 entered in the intersection on red light even though there were cars stuck in a traffic jam. He had to negotiate its way between the cars. The other case was when a cyclist following route A1 entered on red light just before a cyclist coming on his right and they almost collided. There were no cases where a car driver failed to yield to a cyclist. There were three registered cases where a cyclist following route D1 had to slow down because of pedestrians moving along the crosswalk.

Table 22 – Cyclists who took traffic signal into consideration

| Route | Number |
|---|---|
| A1 | 30 |
| A2 | 6 |
| A3 | 1 |
| B1 | 10 |
| C2 | 1 |
| D1 | 37 |
| D2 | 1 |
| E1 | 1 |
| F1 | 3 |
| Other | 22 |
| Total | 112 |

The average time cyclists spent to pass through the intersection on each of the main stream routes is given in Table 23.

Table 23 – Time cyclists spent crossing the intersection

| Route | Time |
|---|---|
| A1 | 4,07 |
| A2 | 6,8 |
| A3 | 8,6 |
| B1 | 5,65 |
| C1 | 4,4 |
| C2 | 23 |
| D1 | 5,2 |
| D2 | 22,4 |
| E1 | 4,5 |
| F1 | 4,13 |

# 5.Analysis and discussion

As it was stated in the literature review, abrupt terminations of cycle lanes affect the route selection of cyclists and can even deter some commuters from cycling (Stinson and Bhat, 2005; Heinan et al., 2010). To better understand the possibilities of enhancing the traffic conditions at discontinuities, two intersections with ending cycle facilities in Trondheim, Norway, were investigated. Through an extensive literature review, different innovative design solutions, applied in developed countries worldwide, were examined. The movements and behavior of cyclists at the study intersections were analyzed to estimate the needs of layout improvements. Previous studies indicate that accidents involving cyclists occur predominantly at intersections. Roundabouts in built-up areas are particularly unsafe compared to other types of intersections accounting for a large number of the registered deaths and severe injuries (Daniels et al., 2008). Thirteen accidents involving cyclists were registered at the studied roundabout, with the earliest accident on record dating back to October, 1994.

Before discussing the results, a few methodological issues should be considered. The current study was carried out over a limited period of time and its main purpose was not an in-depth statistical analysis. It rather aimed at improving the general understanding of the traffic situations and the interactions between cyclists and other transport users at the intersections. The actual implementation of any of the solutions proposed below would require a far more detailed and complicated analysis.

## 5.1.Proposed solutions for improvement of the roundabout

Based on the location and structural properties of the intersection and the observed traffic flows, the following solutions for improvement could be proposed.

### *I. Implementation of Raised crossings*

The main advantages of this type of facility are its low implementation cost and high efficiency. This proposition is also based on the research data which indicated that 85 percent of all registered cyclists during both morning and evening observational periods didn’t enter the circulatory area of the roundabout. Instead, the cyclists preferred to move along the sidewalks and use the pedestrian crosswalks when they needed to cross one of the arms of the roundabout. This led to frequent interactions between pedestrians and cyclists (including a registered near-conflict situation) and also caused delay in the movement of both groups. Introducing elevated facilities to the two most intensively used crossing points would reduce the potential for conflict situations and ease the movement. A considerable enhancement of the safety of both cyclists and pedestrians is also to be expected. It is generally the purpose of all raised crossings to increase the awareness and reduce the velocity of motorized vehicles. This is particularly important at the studied roundabout where the observations revealed a large number of potentially dangerous violations of traffic regulations by cyclists. Only 30 percent of them dismounted their bicycles while moving over the crosswalks, which according to Norwegian traffic regulations does not oblige drivers to yield to them.

The proposed placement of the raised crossing facilities was based on the results of the conducted traffic flow analysis. Figure 70 depicts the roundabout routes, which were followed by a considerably larger number of cyclists than the rest of the routes.

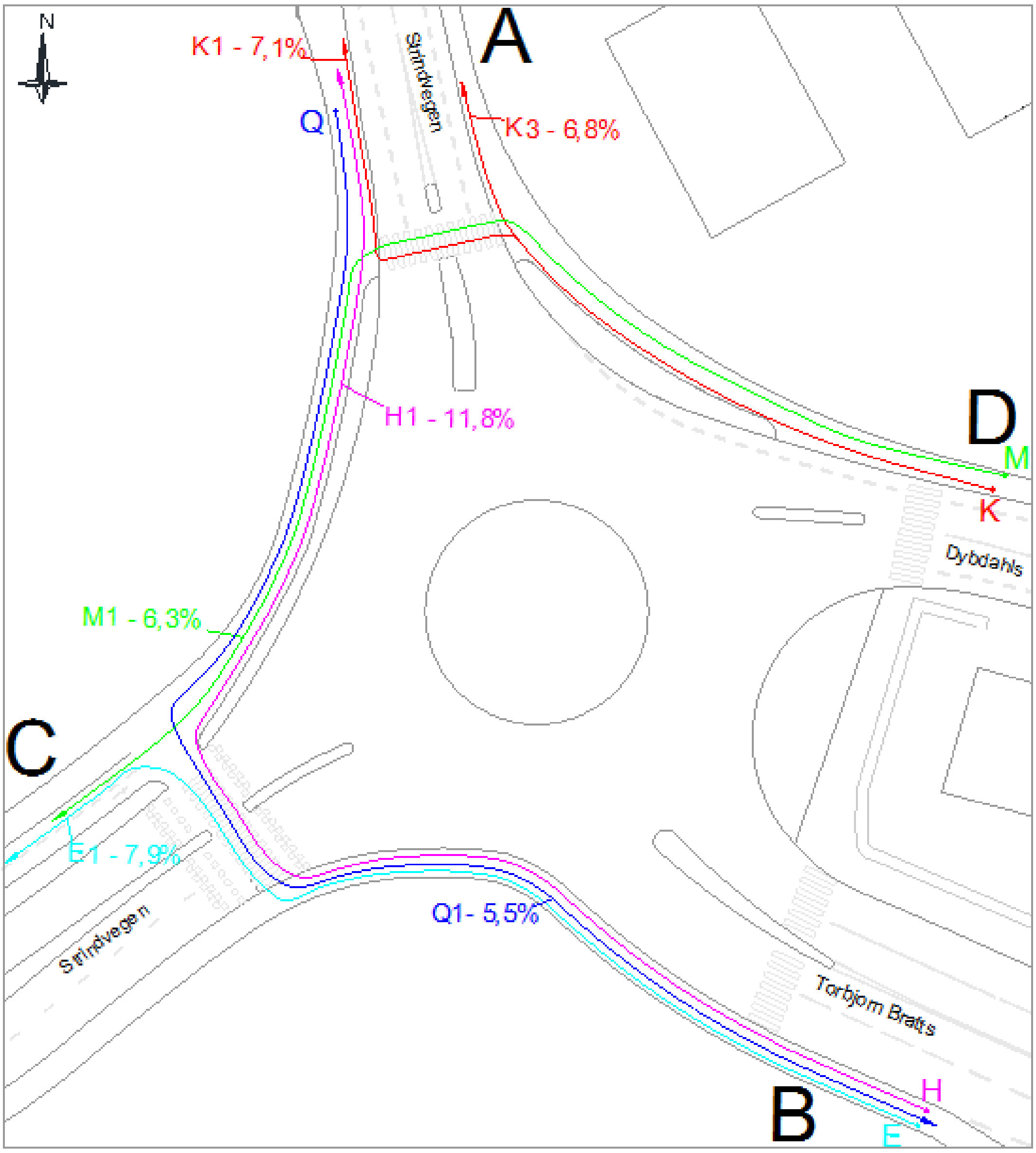


Fig. 70. - Routes followed by the largest number of cyclists

It could be easily noted that the pedestrian crosswalks on Strindvegen north and Strindvegen west were the only corsswalks utilized by the major routes. These two crossings were also used by cyclists following other routes. Table 24 shows how many times each one of the crossings was used.

Table 24. How many times each crossing was used.

| Crossing on approach | Morning | Evening | Total |
|---|---|---|---|
| A | 61 | 36 | 97 |
| B | 15 | 22 | 37 |
| C | 86 | 50 | 136 |
| D | 6 | 23 | 29 |

The excessive usage of the crossings on approaches A and C by cyclists and regular pedestrians slows down the movement of both groups and creates the potential for conflict situations. This exactly is why these two crossings have been chosen to be redesigned into Raised crossings. Additionally, to further improve the throughput, a separate area of crossing dedicated only for cyclists will be provided. It will be placed as an extension of each crossing right next to the zebra marking for pedestrians. The marking of these areas should be similar to the one shown in the Norwegian regulations for crossings between a road and a cycle path with sidewalk (Fig. 71). A zebra-striped path remains as a dedicated crossing for pedestrians while the space for cyclists is signified by small-square markings.

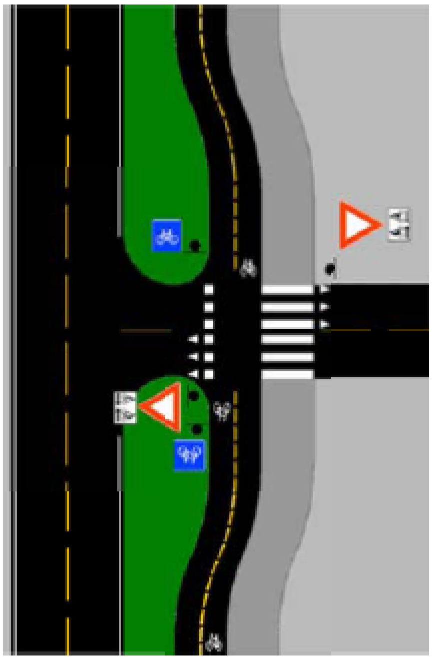


Fig. 71. - Crossing between a road and a cycle path with sidewalk[33]

Another recommended addition to each renewed crossing point is a specific traffic sign (Fig. 72) that would give cyclists the right of priority passage regardless of whether they dismount their bicycles or not. This step is expected to improve the overall safety of cyclists as most of them have been observed to move through the crossings without dismounting anyway. The latter is a safety concern as it is a little known fact that drivers in Norway are not generally obliged to yield to cyclists on a pedestrian crossing unless the cyclists are off their bikes. Using the traffic sign in question would eliminate any confusion and will allow cyclists to cross the arms of the roundabout in a safer and quicker way.

Fig. 72. Traffic sign

[33] Figure 4.14 in Håndbok 233 (2014)

The new layout of the crossing is shown on Figure 73. The width of the crossing for cyclists was chosen from Table 3.2 from (Håndbok 233, 2014). In this table 2,5 metres is the recommended width for a cycle path with 100-300 cyclicsts per hour. The standard width of 3 metres is kept for the zebra-striped path for cyclists. A special triangular marking ('shark teeth') signifies to drivers in both directions that they must yield to cyclists and pedestrians.

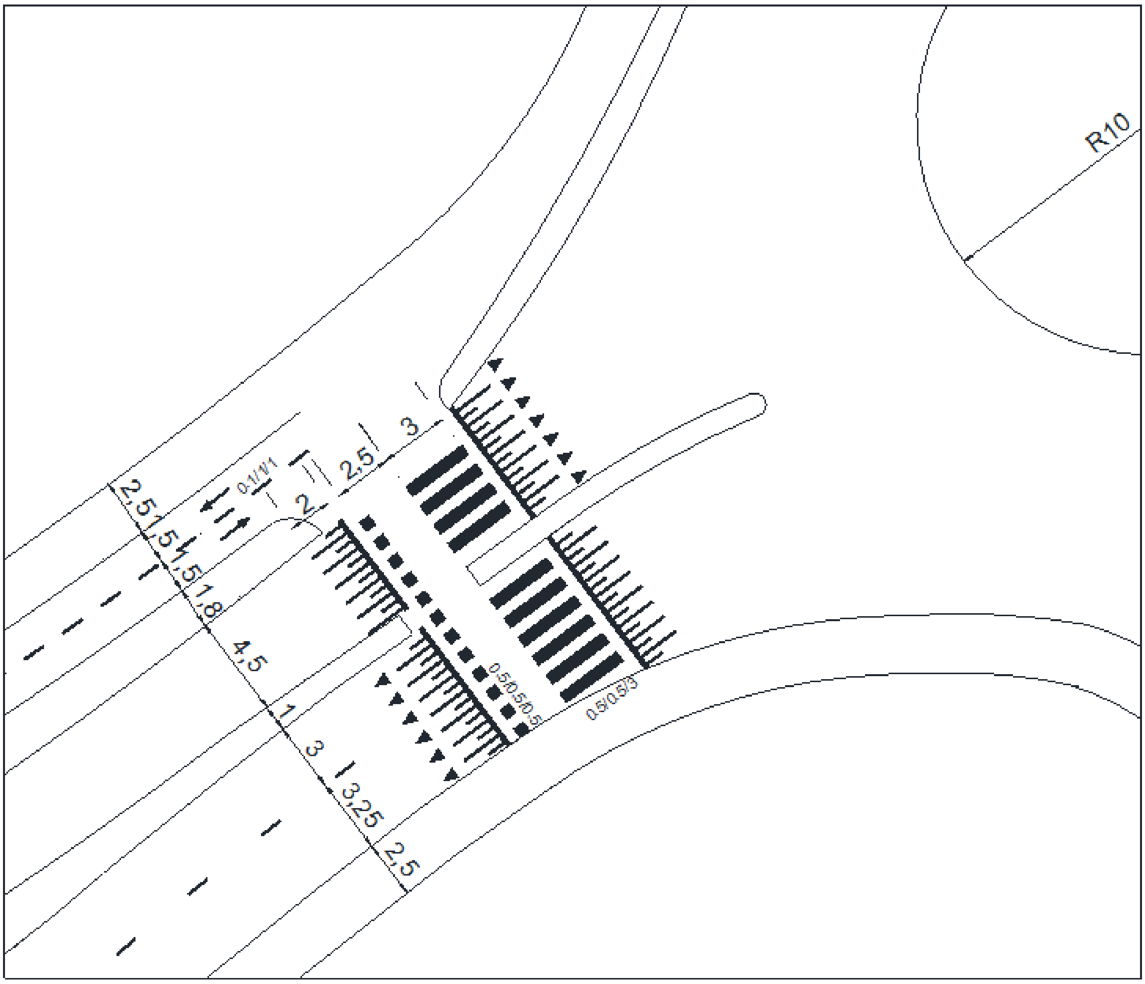



Fig. 73. Raised Crossing on approach C

To make the elevation of the crossing clearly visible, a special marking consisting of alternating longitudinal lines called 'piano keys' will be provided on both sides of the crossing. Similar marking was used to show the elevation of a cycle crossing in a roundabout in Delft (Fig. 74).

Fig. 74. Roundabout with a raised crossing in Delft, The Netherlands

A similar solution is also proposed for approach A (Fig. 75). The only difference is that the zebra-striped crossing and the dedicated cycle area will need to switch places. This is necessary so that the part of the existing median could be used as a refuge island for pedestrians and more complicated reconstruction procedures could be avoided.

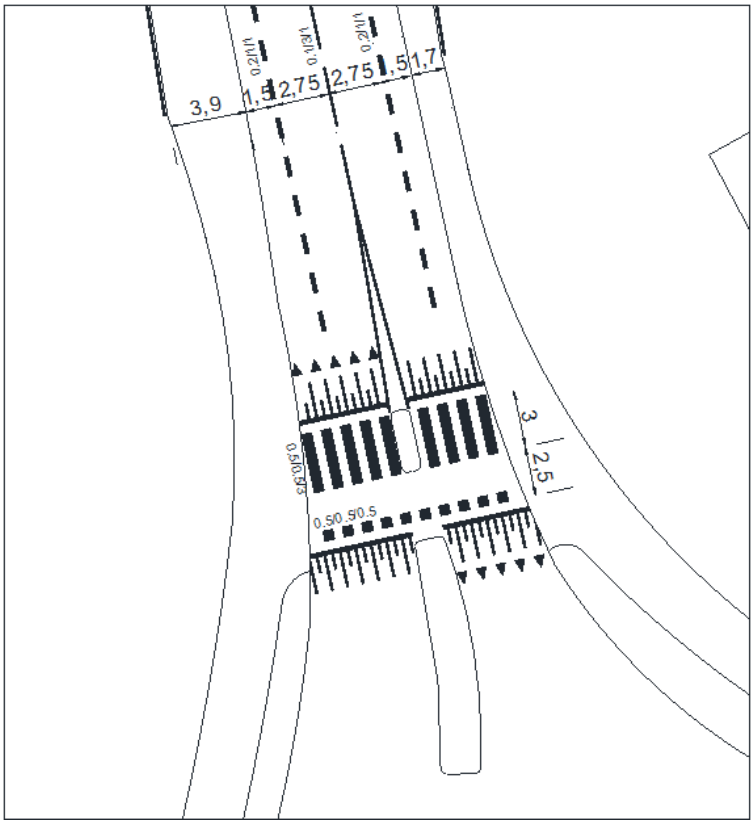



Fig. 75.  - Raised crossing on approach A

The main drawback of the above-proposed solution is the fact that instead of encouraging cyclists to enter the roundabout, it only facilitates their movement through the crossings. In the particular case of this roundabout this should be acceptable due to the monitored traffic flow patterns. Still, a second solution is proposed below to address this drawback and provide a more universal approach that could account for any future changes in the traffic flow situation.

## *II. Implementation of a Separate cycle paths*

Previous studies on cyclists' perception of risk at roundabouts suggested that for the majority of cyclists (66%) the number of cars is related to their level of perceived risk (Møller and Hels, 2008). This finding was supported by the results of the current study, where a relationship was found between the proportion of cyclists, who entered the circulatory area of the roundabout and the number of cars passing through the intersection. Considering the fact that the main Norwegian cities are growing in population, an increase in the number of motorized vehicles could also be expected. This would probably lead to fewer cyclists choosing to enter the roundabout and would generally impede the traffic flow on this junction.

A separate cycle path is an alternative design solution which could allow cyclists to quickly move through the roundabout while feeling safe and not mixing with the motorized traffic. This idea was supported by the study of Møller and Hels (2008) where eighty-two percent of the cyclists interviewed in a roundabout without a cycle facility claimed that building a cycle facility would reduce the accident risk in the roundabout.

As it was concluded in the literature review, the best solution for cyclists in roundabouts is the use of a separate cycle path outside the perimeter of the roundabout as this would result in a smaller number of conflict situations (Schoon and van Minnen, 1993; Sakshaug et al., 2010; Crow, 2007; Daniels et al., 2009). This design is recommended by both the Dutch and the Norwegian regulation. The Norwegian regulation says that when the AADT volumes are above 8000 pcu/day, the possibility of leading the cycle traffic off the roundabout should be considered (Sykkelhåndboka, 2014).

A drawing of the separate cycle path solution is shown on Figure 76. The implementation of the improved design of the roundabout with separate cycle paths would require the use of additional 837 $m^2$ of the surrounding area. This calculation does not include the additional area for the approaches. A Dutch design manual features a similar solution for bicycle traffic (Crow, 2007). The details provided there could be used as guidelines for the current study:

- the width of the cycle path – should be based on the number of cyclists passing through the roundabout
- the distance between the cycle path and the carriageway - should be between 5 and 7 metres – sufficient for a car exiting the roundabout to stop and give way to cyclists on the cycle path, without impeding vehicles circulating in the rountbabout
- the median – should be around 2.5 meters

Accoding to the same manual, the pavement of the cycle path should be continued where the carriageway is crossed.

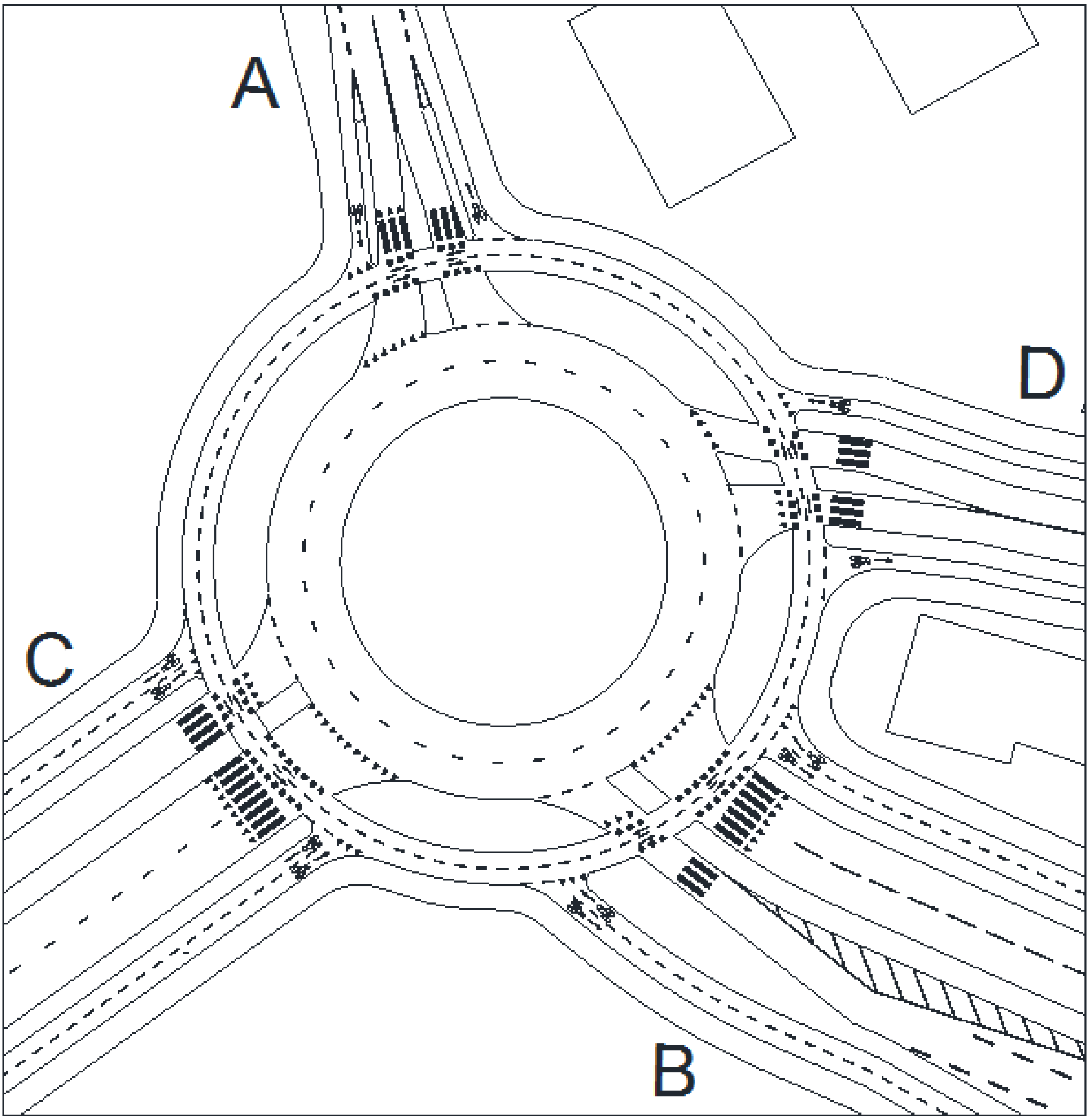


Fig. 76. A separate Cycle path

Generally there could be two types of priority rules on such crossings. For the studied roundabout, it was decided that cyclists coming along the cycle path would have priority over vehicles approaching or exiting the roundabout. Thus, the traffic users approaching the roundabout would have to yield to cyclists on the cycle path and this is exactly what they have to do to pedestrians and vehicles circulating inside the roundabout.

A detailed drawing of the proposed solution for approach C is shown on Figure 77.

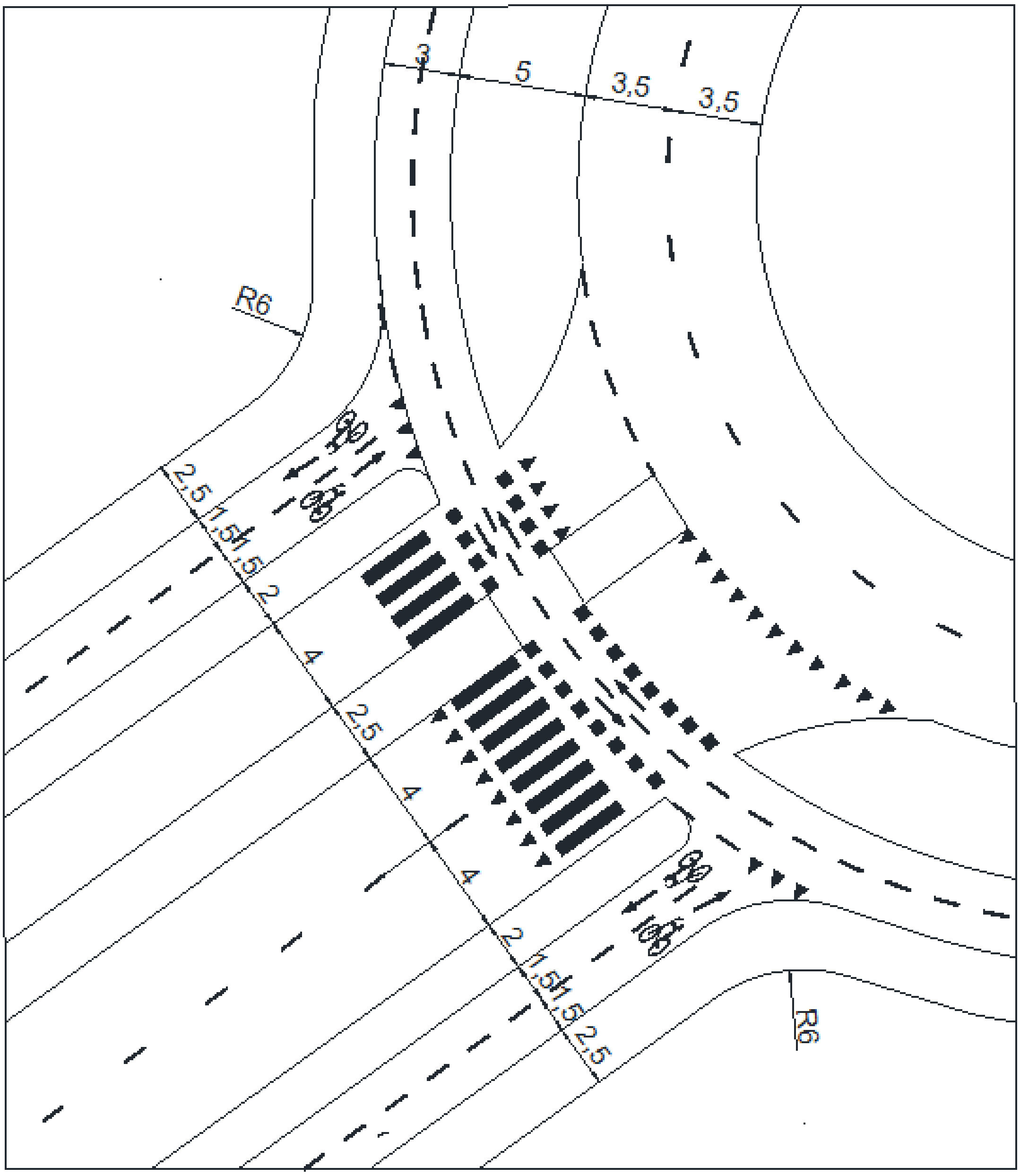


Fig. 77. – Detail of approach C

This solution would require major redesign operations affecting the entire roundabout. Those would be time consuming, highly expensive and would also require the use of much more of the area surrounding the roundabout.

# 5.2.Proposed solutions for improvement of the regular intersection

The study of the particular intersection revealed a considerable potential for conflict and near accident situations. Additionally, three accidents involving cyclists were registered there by the Norwegian Public Roads administration since November, 2004. To improve the safety and ease of movement through the intersection, a careful analysis of the traffic flows was conducted. It was established that three of the routes through the intersection were used by cyclists far more often than all other routes. Those are marked as A1, B1 and D1 on Figure 78. These routes will be main target points of the improvement measures reviewed below.

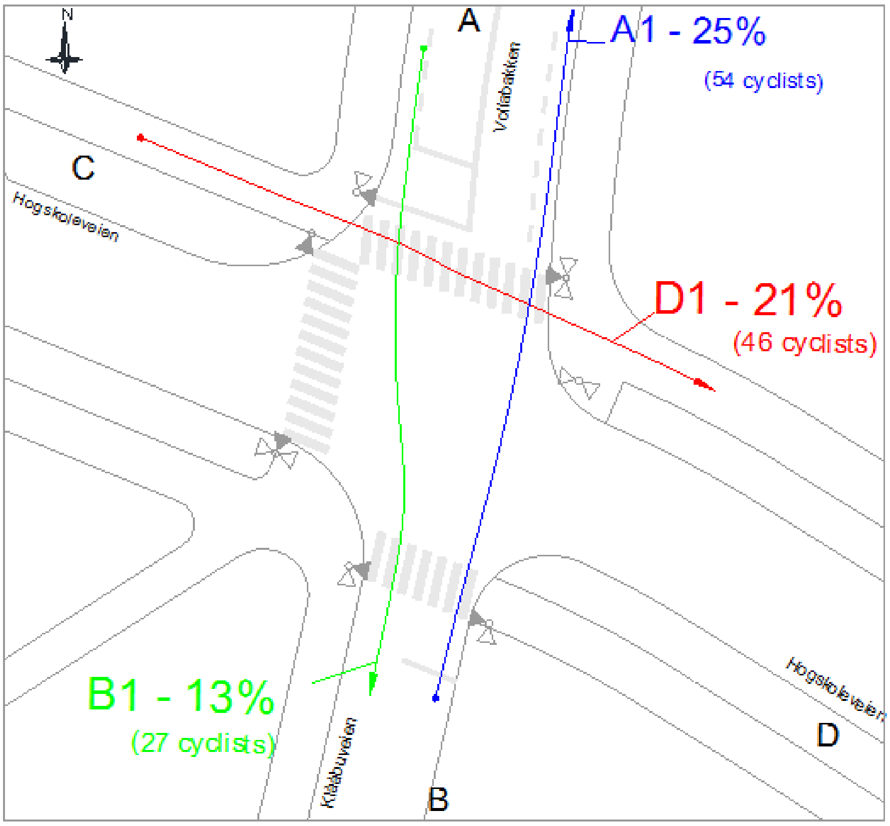



Fig. 78. - Major routes on the regular intersection

Most of the cyclists who moved from approach B to approach A (Main stream 1) followed route A1. However there were nine percent who used alternative routes, where car drivers don’t usually expect to see them. One of the cyclists used the pedestrian crosswalk without getting off the bike, probably erroneously assuming that he has priority over motorists there and thus increasing the potential for conflict situations. Moreover, cyclists who followed route A1 needed half of the time in average than these following the alternative routes.

Cyclists who followed Main stream 2 (approach A to approach B) used mainly route B1 (77 percent). Nevertheless 23 percent of the cyclists on this stream used other routes to negotiate their way through the intersection. One of the cyclists followed an alternative route which involved the usage of the pedestrian crossings on approach A and approach C. He did this without getting off his bike which increases the potential for conflict situations. Based on the above observations, it is assumed that more cyclists should be encouraged to follow the A1 and B1 major routes in order to enhance their safety and increase the throughput of the intersection.

# I. Implementation of Cycle lanes through the intersection

The on-street dashed cycle lanes through the intersection are planned as a continuation of the lanes provided on approach A (Fig. 79). The lanes have the same width as the lanes on approach A (1,5 meters) but are denoted with square markings 0.5 meters of size. It is expected that the marked lanes would increase the awareness of the motorized drivers and reduce the risk of accidents. This is especially important for the increased traffic flow of vehicles entering along approach A and turning right via approach C. Having a marked cycle lane trough the intersection would reduce the risk of 'right hook' collisions between straight travelling cyclists on route B1 and the vehicles that turn right.

According to the Norwegian regulations, if traffic lights signalization is not deployed or is out of service, marked cycle lanes should only be present following the priority approaches of the intersection. So even though the motorized traffic is heavier on Hogskoleveien, it was decided that the cycle traffic moving from approach A to approach B should be prioritized if the light signal regulation is out of order. This should be done by providing give-way signs on approaches C and D, as it is shown in Figure 79. This corresponds to the idea of The Norwegian National Transportation Plan to enhance bicycle transport.

Another design measure that would enhance the safety of cyclists is increasing the visibility of cycle lanes inside the intersection by applying colored pavement markings. This would make drivers aware that that they are crossing a cycle lane and make them more cautious of approaching cyclists. Additionally, cyclists feel more confident when following a distinctively marked cycle lane. Studies in various countries have proven that a higher number of cyclists follow blue cycle lanes as compared to other colors. Strangely enough, studies have also revealed that the efficiency of colored pavement lanes is greatest when only one is used. The increase of the number of marked blue cycle lanes in an intersection is decreasing the safety effect of the implementation (Jensen, 2008). That is why a single blue-colored cycle lane would be implemented along the busiest route A1.

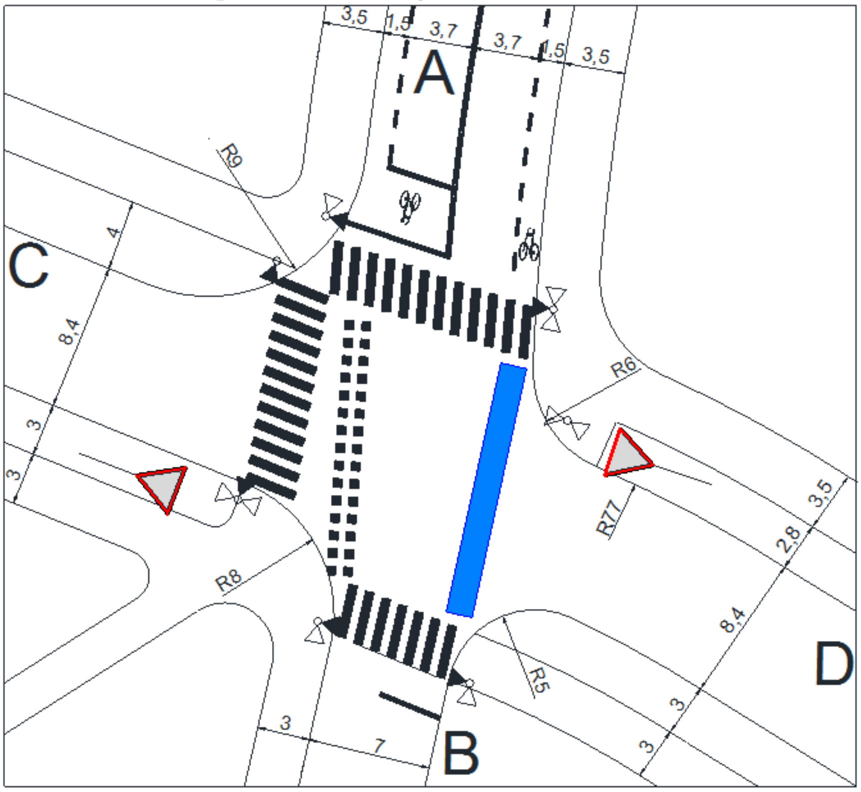



Fig. 79. - On-street cycle lanes

## II. *Implementation of Advanced stop line*

Further improvement of the design aimed at assisting cyclists who follow routes A1 and B1 is to provide cycle lanes and an Advanced stop line (Bike box) for cyclists along approach B (Fig. 80). These facilities would provide cyclists with a safer and quicker way through the intersection. The advanced stop line would ensure a head start for cyclists when the traffic light signal changes to green. The new cycle lane on approach B would eliminate the current cycling facility discontinuity at this intersection. Due to the insufficient width of the road along approach B, it would need to be extended with at least 1.5 meters in order to accommodate the proposed cycle lanes.

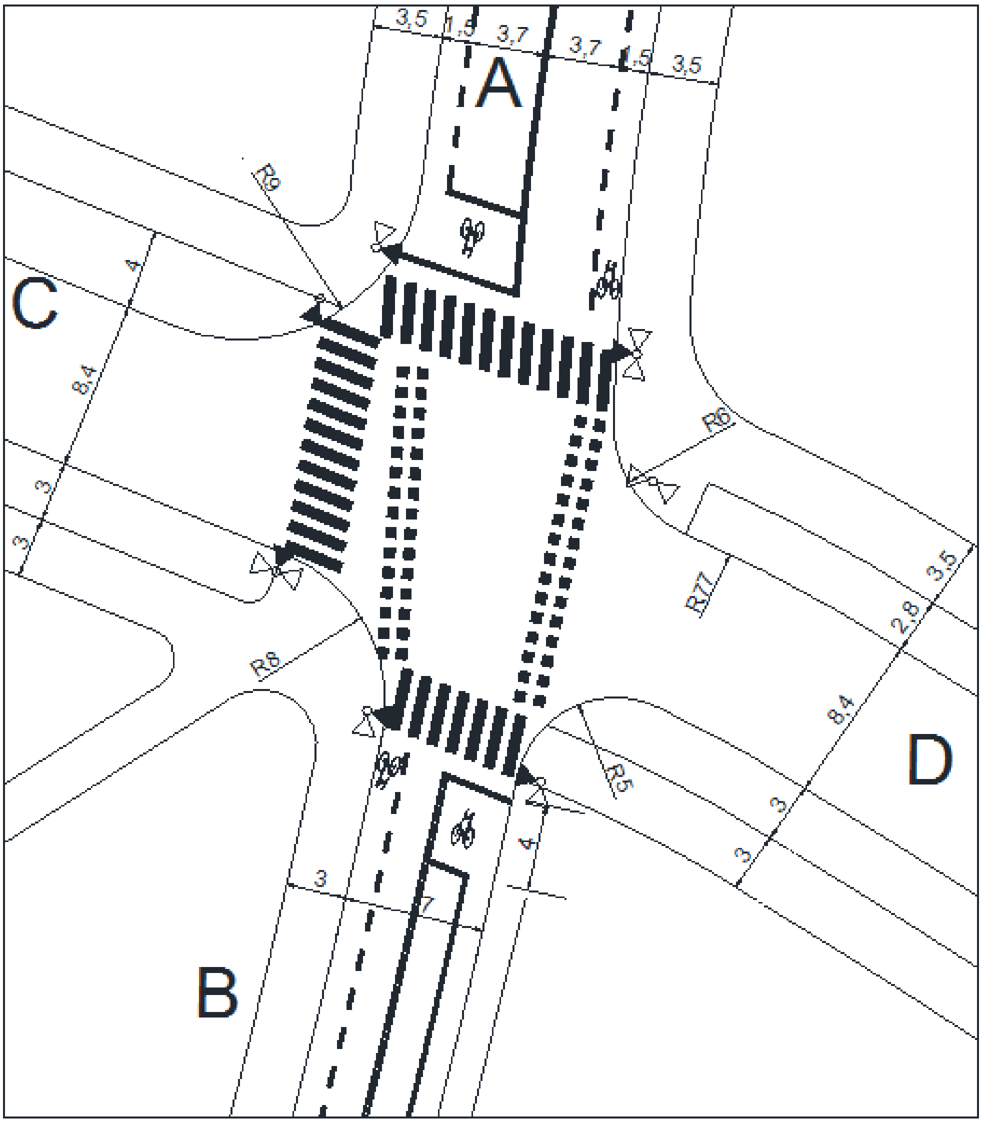


Fig. 80. - Advanced stop line on approach B

## *III. Implementation of Cycle path with sidewalk*

To accommodate the considerable cycle traffic on route D1 it was decided that a 'Cycle path with sidewalk' should be implemented (Fig. 81.). This solution is intended to regulate the use of the area on the northern sidewalk of approaches C and D. If both cyclists and pedestrians are provided with a separate area the interactions between them would be significantly reduced. The cyclists would have to use the pedestrian crossing on approach A again. Due to the limited space and the bike box situated on approach A, serious reconstructions of the crossing are not possible. The pedestrian crosswalk should be expanded from 3 to 4 meters in width to ease the movement of both cyclists and pedestrians. A slight elevation of the crossing is also recommended to help cyclists negotiate their way without changing grade and to increase the attentiveness of motorized drivers.

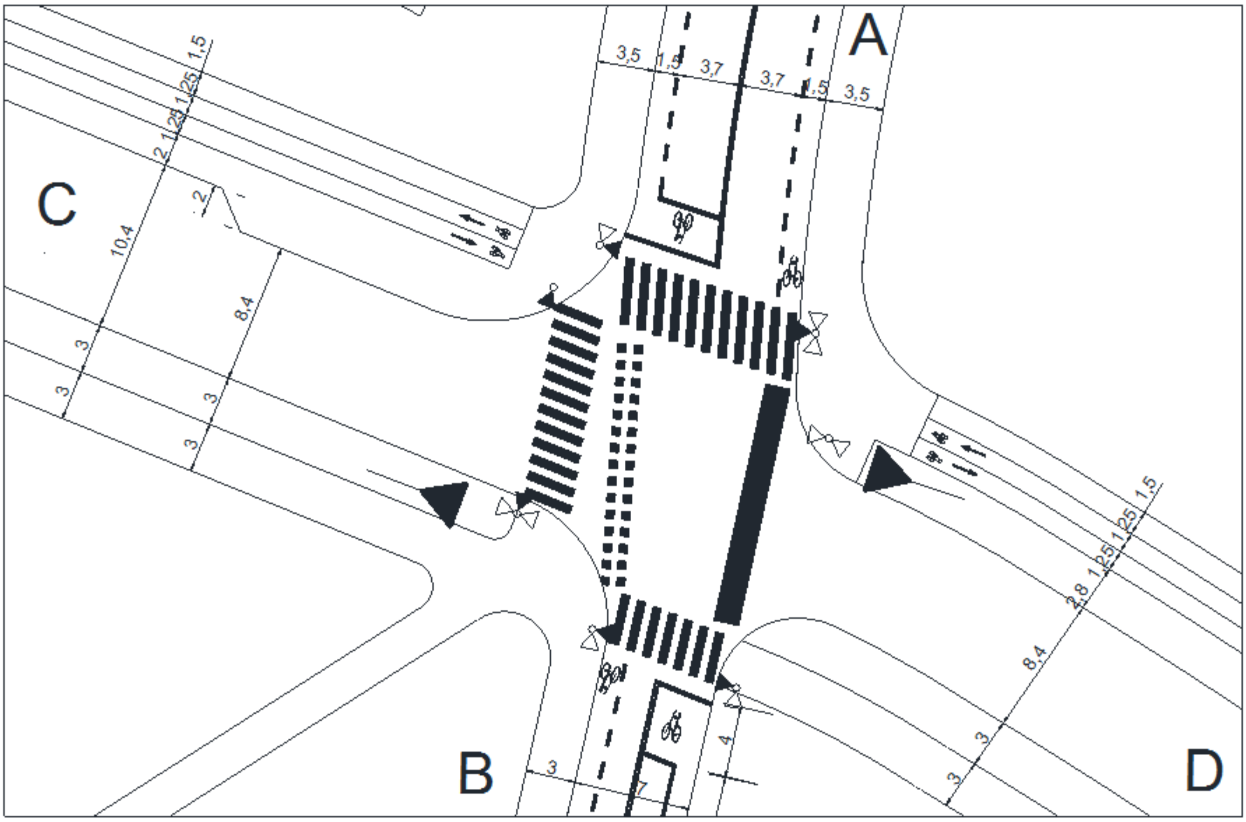


Fig. 81. 'Cycle path with sidewalk' on approaches C and D

The main drawbacks of the solutions for improvement proposed above are their high cost and complexity having in mind that this is a relatively small roundabout. Nevertheless, the expected positive results could be viewed as future investment which is in conjunction with the general Norwegian country strategy of encouraging cycling bicycle transportation.

## 5.3.Recommendations

Based on the research of best practices from all over the world and the development of suggested layout improvements aimed at facilitation of the cycle commuters through the study intersections, general design recommendations for bicycle infrastructure at intersections in Norway could be proposed.

Regarding cycle facilities at roundabouts recommendations should be given depending on the traffic volume, specific traffic patterns and the geometric characteristics of every roundabout. In accordance with the Norwegian regulations where the traffic volume is below 8000 pcu/day, the most reasonable solution would be to mix cyclists with the rest of the traffic users inside the circulatory area of the roundabout. For roundabouts where the traffic volume exceeds 8000 pcu/day the best solution would be to provide cyclists with a dedicated cycle path outside the perimeter of the roundabout. This design solution would not only reduce accidents but would also improve cyclists' comfort level which would lead to increased number of commuters who choose cycling as a way of transport. Separate cycle paths would have the capacity to accommodate the anticipated growing number of cyclists in Norway.

The provision of cycle lanes inside the circulatory area of the roundabout is not a recommended solution as it is commonly regarded as having a controversial and in most cases negative impact on the safety of cyclists. Especially in Norway, this solution could prove quite unpractical due to the fact that transport users are not accustomed to similar designs.

Raised crossings are the recommended solution where cycle tracks intersect with the carriageway as they improve cyclists' safety and are not too expensive or time consuming to implement.

For regular intersections a proposed facility design improvement is to provide blue-colored cycle lanes to lead cyclists through the intersection. As it was pointed out earlier these facilities have proven positive effect on the behavior of both cyclists and motorized vehicle drivers.

For busy, signalized intersections Advanced Stop Lines should be implemented. These cycling facilities are applied successfully all over the world Norway included and should continue to be used as a way of promoting bicycle commuting.

# 6.CONCLUSIONS

The examination of possible improvements of cycle facility designs at intersections and discontinuities in Norway was the main purpose of this study. Discontinuities are places where cycle facilities terminate and cyclists have to merge with motorized vehicles. The provision of infrastructure that guides cyclists through intersections would create a safe environment for them and would encourage more people to cycle.

The study focused on the provision of design improvements of two intersections in Trondheim. Observations of the traffic were carried out on the sites followed by a thorough analysis of the results.

Researches from Denmark, Germany, The UK, Finland, Sweden, The Netherlands, Australia, New Zealand, The USA and other countries were investigated to find innovative design solutions that have been proven to work successfully. Based on the results of the analysis of the collected data the most appropriate layout improvements were suggested. The design solutions proposed for implementation at the study intersections in accordance with the Norwegian regulations were:

- Raised crossings (both intersections);
- Separate cycle paths (the roundabout);
- Cycle lanes through the regular intersection;
- Advanced stop line (the regular intersection)
- Cycle path with sidewalk (the regular intersection).

However there is no guarantee that the implementation of a certain solution in one country would give the same results in a different country or even at a different intersection. The correct way to measure the actual efficiency of an implemented solution would be to conduct an in-depth before-and-after study. The results of these studies would help with the improvement of future projects.

There are excellent examples of layout enhancements aimed at facilitating cyclists at intersections from around the world and Norway is on the right track examining and implementing them.

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