Improving roundabouts for cyclists and visually impaired

Sakshaug, Lisa

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Lisa Sakshaug

Department of Technology and Society
Lund University
Traffic and Roads
Box 118, SE-221 00 Lund, Sweden

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Lisa Sakshaug

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Abstract: Roundabouts are continuing to increase due to their high traffic safety, low delay times and their winning design. However, there are also problems related to roundabouts; the traffic safety for cyclists is unclear or even negative and there are reports of accessibility problems for people with visual impairment. The overall objective of this project is to identify designs that improve the situation for these two groups of road users in roundabouts. This implies that acquiring a profound understanding of the current problems and state of knowledge is a prerequisite. Cyclist behaviour, interactions with motorists and the resulting safety were studied in two roundabouts, one with separated cycle crossings and one without cycle facilities. Low-vision and blind people were interviewed in focus group interviews and a questionnaire survey to find out in what way roundabouts differ from other intersection types and to investigate whether there are design solutions to make roundabouts more accessible. The results show that signalised intersections are more accessible than roundabouts. Despite this, they are not perceived as safer. Moreover, no difference in accessibility is found between roundabouts and four-way intersections without signalisation. Roundabouts with separate cycle crossings seem to be safer than those without cycle facility. Roundabouts without a cycle facility are more complex in that they have more conflict points and more interaction types between cyclists and motorists. The implications of the results for the other road user group (cyclists/visually impaired) are also discussed.

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Institutionen för Teknik och samhälle
Lunds Tekniska Högskola
Trafik och väg
Box 118, 221 00 LUND, Sverige

Department of Technology and Society
Lund University
Traffic and Roads
Box 118, SE-221 00 Lund, Sweden

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List of papers

Paper 1: Sakshaug, L., Svensson, Å., Hydén, C. (2009) Accessibility for the whole group of visually impaired at roundabouts compared to other intersections – a questionnaire study. Submitted to Transportation Research Part F

My contribution: Elaboration of questionnaire, analysis of the data and writing of the paper.

Paper 2: Sakshaug, L., Laureshyn, A., Svensson, Å., Hydén, C. (2009) Cyclists in roundabouts – different design solutions. Submitted to Accident Analysis and Prevention

My contribution: Design of the study, performance of field studies, analysis of the data, writing larger parts of the paper

Definitions and abbreviations

Accessibility	The possibility of people with disabilities to independently access different activities and destinations
Blind	Visual acuity of less than 3/60 or corresponding visual field loss to less than 10 degrees in the better eye
Int1	Interaction in integrated roundabout where the motorist enters while the cyclist is circulating
Int2	Interaction in integrated roundabout where the cyclist enters while the motorist is circulating
Int3	Interaction in integrated roundabout where the cyclist and motorist are circulating in parallel and the motorist exits
Int4	Interaction in integrated roundabout where the cyclist and motorist enter in parallel
Int5	Interaction in integrated roundabout where the cyclist and motorist exit in parallel
Int6	Interaction in integrated roundabout where the cyclist and motorist are circulating in parallel
Interaction	Situations between two road users where at least one of the road users changes speed or direction because of the other
Integrated intersections	Intersections without special cycle facilities – the cyclists share the carriageway with the motorists
Integrated roundabout	Roundabout without special cycle facilities – the cyclists share the carriageway with the motorists
Low-vision	Visual acuity of less than 6/18, but equal to or better than 3/60 or corresponding visual field loss to less than 20 degrees in the better eye
Mobility	Delay caused by interactions and design
O&M-specialists	Orientation and Mobility specialists
P1	To find the crossing point.
P2	To decide when it is clear to start crossing.
P3	To walk straight when crossing.
P4	To know where the pavement stops and the carriageway starts and to detect the pavement/traffic island on the other side of the street.

Sep1	Interaction in separated roundabout where the motorist enters while the cyclist is moving in the circulating direction
Sep2	Interaction in separated roundabout where the motorist enters while the cyclist is moving against the circulating direction
Sep3	Interaction in separated roundabout where the motorist exits while the cyclist is moving in the circulating direction
Sep4	Interaction in separated roundabout where the motorist exits while the cyclist is moving against the circulating direction
Separated intersections	Intersections with separated cycle path and cycle crossings next to zebra crossings
Separated roundabout	Roundabout with separated cycle path and cycle crossings next to zebra crossings
SRF	National association for visually impaired
Traffic safety	Objective measure, the number of injury accidents

1.Introduction

1.1. Roundabouts

A roundabout is an intersection where traffic moves in an anticlockwise direction (for countries with right-hand traffic) around a central island. Oncoming traffic has to yield to traffic within the circulating area. There are many advantages with roundabouts; they are relatively safe, reduce vehicle speeds, have good capacity, reduce delay, stopping and queuing (especially compared with traffic signals) and have a winning design. Therefore, roundabouts are becoming more and more common. In 1980 there were 150 roundabouts in Sweden, whereas in 2008 there were more than 1500 roundabouts within its municipalities alone. (Brüde and Larsson 2000; SKL 2008)

There are several reasons why roundabouts present a safe intersection solution:

- low, homogenous speeds because of lateral displacement
- increased awareness because of the need to deflect from the path ahead
- low number of conflict points
- low conflicting angle
- simple decision making because of one-way operation of circulating carriageway

Several studies from all over the world show that roundabouts have a favourable effect on motor vehicle safety. A meta-analysis of 28 studies revealed a best estimate reduction of 30-50% of injury accidents (Elvik 2003). Existing studies indicate safety-improvements for pedestrians as well. A before-and-after study of the construction of 201 roundabouts in Holland shows a significant drop of 47% in the number of pedestrian accidents and a drop of 89% of casualties (Schoon and Van Minnen 1994). A Swedish study found a predicted decrease of pedestrian accidents of 80% (Hydén and Várhelyi 2000). However, the effect on traffic safety for cyclists is unclear or even negative. For this group a Belgian study showed an over 40% increase in fatal accidents whereas a Dutch study showed a 30% reduction in casualties (Schoon and Van Minnen 1994; Daniels, Nuyts et al. 2008). A Swedish study where roundabouts were built at 21 intersections showed a predicted decrease of cyclist accidents by 60% (Hydén and Várhelyi 2000).

However, all roundabouts should not be assessed on a general basis since the qualities of roundabouts can differ extensively depending on the design. Low speed is one of the most important qualities for safe roundabouts (Brüde and Larsson 1999; Herland and Helmers 2002; Hels and Orozova-Bekkevold 2007). The size of the roundabout and the entry and exit path curvatures determine the vehicle speed through the roundabout. The speed is generally lower in one-lane roundabouts than in multiple-lane roundabouts and decision making is a lot more complicated in multiple-lane roundabouts. Moreover, the speed is lower if the radius of the central island is 10-20 meters than if it is smaller or larger. The number of accidents rises with higher speeds in these cases (Brüde and Larsson 2000). Traffic islands at roundabouts have a speed-reducing effect which makes it easier and safer for vulnerable road users to cross the street. (Herland and Helmers 2002)

Research results showing accident risk in one country do not necessarily apply to another country. Driving culture, volumes of different kinds of road users, formal and informal rules vary and roundabout design differs considerably between countries. Therefore, knowledge about behaviour and details of accident types in relation to the roundabout design is needed to draw general conclusions. The roundabouts in Denmark, Germany and the Netherlands are usually smaller than the Swedish ones, presumably because longer trucks are allowed in Sweden. However, in Great Britain and Norway the roundabouts are often wider and two entry and exit lanes are common. (Herland and Helmers 2002)

1.2. Design for different road user groups

Several groups of road users with different needs are to be accommodated in roundabouts; cars, busses, long trucks, emergency service vehicles, and different types of cyclists and pedestrians. Since walking and cycling do not require a driving licence or other qualification, pedestrians and cyclists are more heterogenic groups than vehicle drivers. Seniors, children and people with different kinds of impairments also have the right to walk or cycle to their activities or destinations. Among cyclists there is also a large difference between “leisure cyclists” and “transport cyclists”. Leisure cyclists usually have more time and choose nice routes whereas transport cyclists, for example those commuting to work, usually choose the quickest route. The task of traffic planners is not only to enable passage for all the groups, but to provide a safe and well-functioning passage for each group, but without doing so at the expense of the others.

Design solutions chosen to improve matters for one of the road user groups also affect the others. My research interest is in the specific needs of two different groups, cyclists and the visually impaired. It is complicated to try to optimise roundabout design for all groups simultaneously; there are trade-offs to be done but there are also examples where design allows good solutions for conflicting needs. One example is that a roundabout tight enough to force cars to slow down may be difficult for busses and long trucks. Therefore, many Swedish roundabouts are designed with a large outer ring of the central island, typically elevated 5 cm and covered with cut stones. Such an outer ring is uncomfortable for cars to drive on whereas larger vehicles can easily drive on it. Hence, cars are forced to a large lateral displacement and long vehicles can still pass without major inconvenience. Another example where trade-offs are needed is within different groups of pedestrians. For senior pedestrians and people in a wheelchair a smooth passage with no raised edges is important, whereas no raised edge before the zebra crossing can be fatal for the visually impaired who then cannot detect where the carriageway starts. In order to find solutions that can combine conflicting needs, profound knowledge of the causes and possible solutions of problems is needed. There is not enough knowledge on how to design a roundabout for cyclist safety and accessibility for the visually impaired. Therefore, rebuilding an intersection into a roundabout represents a deterioration for those road user groups. It is beneficial to approach these problems in parallel since behaviour and route choices of cyclists affect the accessibility for the visually impaired. Pedestrians can also reduce mobility for cyclists. Careful design is needed to solve these kinds of problems.

1.3. Accessibility for the visually impaired

The National Association for the Visually Impaired, SRF, has reported accessibility problems in roundabouts and demands traffic signals at all roundabouts (SRF 2005). Due to the above mentioned advantages of roundabouts, it can be assumed that the number of roundabouts will continue to increase and focusing on the problems of the visually impaired will become more and more imminent. However, there is very limited research on accessibility for the visually impaired in roundabouts. In order to solve the accessibility problems for them, more knowledge of the causes and prevalence of the problems is needed.

Accessibility in this context is defined as *the possibility of people with disabilities to independently access different activities and destinations*. Accessibility is a relationship between the individual's capacity and the physical environment (Lewin 1951). Whether an individual can manage a task, for example cross a street, depends on both that individual's capabilities and the demands of the environment. Hence, accessibility at an intersection can be enhanced by either improving the individual's capabilities, for example with a long white cane or other assistive technology, or improving the design of the intersection. Sometimes small changes in design may be enough to reduce the demands of the environment at the intersection so that a larger group of users may manage the task of crossing.

However, accessibility is not the only important quality for the visually impaired. Another important quality is the subjective, perceived safety. A certain level of perceived safety is needed for an individual to dare cross the street; hence that level of perceived safety is a prerequisite for accessibility. Perceived safety is desirable, but not at the expense of objective safety. There are strong indications that a certain extent of perceived unsafety has a positive influence on traffic safety (Hydén 2008). For example, if a motorist runs a red light in a signalised intersection it is likely that the pedestrians will still feel safe and therefore pay no attention to the motorist. However, in unsignalised intersections, especially if the pedestrians feel a bit unsafe, they tend to be attentive to motorists' behaviour in case the latter do not yield as required.

There is also little knowledge about how the difficulties differ within the group of visually impaired, a group that is very broad and heterogenic, including everyone with a vision loss that cannot be corrected. WHO divides people with visual impairment into two subgroups, low-vision and blind. *Low-vision* is defined as visual acuity of less than 6/18, but equal to or better than 3/60, or corresponding visual field loss to less than 20 degrees in the better eye. *Blind* is defined as visual acuity of less than 3/60 or corresponding visual field loss to less than 10 degrees in the better eye (WHO 2004). These subgroups are also used in this project to identify differences within the group of visually impaired.

Globally there were 161 million people with visual impairment in 2002, of which 124 million people had low-vision and 37 million were blind (WHO 2004). The prevalence of people with visual impairment in Sweden is not known. Orientation and mobility specialists interviewed for this project estimate that the large majority of visually impaired are low-vision, fewer are blind and less than 5% of the visually impaired have no vision. The other 95% have different degrees of vision sharpness, field of vision, sensibility to light etc. Not only do people with a vision loss have different sorts and different degrees of problems, they also use different strategies to solve the problems. People who have partial vision use this vision when possible, but darkness or bright light can make if difficult for them. A lot of people with visual impairment use their hearing extensively but not all of them have intact hearing. Moreover, traditional tools like dogs and white canes are used differently – there are different sorts of white canes and different schools in the area of orientation and mobility. To our knowledge, most accessibility research and all roundabout accessibility research regarding the visually impaired focus solely on blind people. My studies attempt to cover the whole group of visually impaired. The objective is to determine their problems when crossing streets in general and at roundabouts in particular and to suggest strategies to solve them.

1.4. Safety for cyclists

The safety situation for cyclists in roundabouts is not satisfactory. As mentioned in Chapter 1.1 the research on the effects of roundabouts on cyclist safety gives diverging results, but there is agreement that the safety has not improved as much for cyclists as for motorists and pedestrians (Schoon and Van Minnen 1994; Brüde and Larsson 1999; Daniels, Nuyts et al. 2008). Why the results differ is not clear. More detailed research on roundabout design, cyclist and motorist behaviour and accident situations is needed to answer that question.

Safety is an objective measure of the prevalence of injury accidents. During 2008, 30 cyclists were killed and 337 were severely injured in traffic accidents in Sweden (SIKA 2009). The political goal in Sweden, the vision zero, aims at no seriously injured or killed people in traffic. In order to reach that goal more knowledge of the underlying causes and the influences of different design solutions is needed. There are also other important factors for cyclists such as mobility and perceived safety. My research does not focus on those factors but they are considered when the results have an effect on them. Mobility is used here as an objective measure of delay caused by interactions and design. Since cyclists use muscle force to go forward the effort of braking, accelerating or making a detour is more pronounced for them than for motorists. Thus mobility is an important factor for cyclists. Nevertheless, the main problem for cyclists in roundabouts is safety; hence that is the focus of this project.

There are three main cycle facilities in roundabouts; a painted cycle lane in the circulation, separated cycle crossings or no cycle facility. Studies have shown that a cycle lane is the least safe measure (Schoon and Van Minnen 1994). Separated cycle crossings seem to be safer than no cycle facility for high motor vehicle volumes (Schoon and Van Minnen 1994; Brüde and Larsson 1999). For roundabouts with fewer than 8000 incoming vehicles per day, the difference is less clear (Schoon and Van Minnen 1994). However, studies of cycle measures in general show that on-road cycling is just as safe or safer than cycling on separated cycle crossings (Aultman-Hall and Hall 1998b; Elvik and Vaa 2004). Why this differs between roundabouts and other types of intersections has not been satisfactorily explained.

While an important aim of integrating cyclists with motorists is to make them more visible, the above-mentioned research shows that it may not be a safer solution in roundabouts. The cyclist's visibility depends not only on how visible the cyclist is but also on the workload for the motorist. It is well known that drivers develop visual scanning strategies that enable them to scan the most important directions to avoid collisions with other motor vehicles (Hills 1980; Moray 1990). However, the development of scanning strategies also includes masking less important information such as cyclists. A motorist that is used to the presence of cyclists not demanding any action, concentrates attention towards other motorists or objects more likely to be important.

More knowledge is needed to find out what really happens in cycle-motor vehicle interactions for different roundabout designs in order to understand the differences in safety. Thus, we examine the behaviour of cyclists and motorists in two types of roundabouts; one with a cycle path ("separated roundabout" hereafter) and one without a cycle facility ("integrated roundabout" hereafter).

2.Objective

The overall objective of this project is to identify designs that improve the situation in roundabouts for two groups of road users – cyclists and visually impaired – without deteriorating the situation for other groups. This implies first getting a profound understanding of the problems and knowledge of today.

A literature review has been performed to find out how to approach the problems for the two groups of road users. It has been found that there are differences not only in the problems of the two groups but also the level of research and knowledge of their problems. In order to take the knowledge a step forward, the aim is to start where the current knowledge ends. Hence, the parallel studies are on different levels of detail. The one on the accessibility for visually impaired starts "from the beginning" in an attempt to capture the perspectives and an overview of the situation. There is a lot more research done on the topic of cyclist safety but the results diverge. Still, the existing knowledge enables this study on cyclist safety in roundabouts to have a more detailed, explanatory aim.

The objective of the study on accessibility for the visually impaired is to determine how the difficulties differ between roundabouts and other intersections for the whole group of visually impaired. The objective was also to find out if there are design solutions that make roundabouts accessible for the visually impaired.

Regarding cyclist safety in roundabouts, the objective was to explore how cyclist and motorist behaviours and interactions are affected by different designs, specifically separated and integrated roundabouts. The objective was also to explore how the behaviours and interactions relate to safety for cyclists.

3.Methods

3.1. Choice of methods

A literature review has helped to obtain knowledge of the advantages, problems and characteristics of roundabouts. The literature also gives an insight into the situation for cyclists and the visually impaired in general and in roundabouts in particular. With this knowledge as a base, the aims and methods of the project have been formulated.

Table 3-1 Overview of methods used.

	Accessibility for the visually impaired		**Cyclist safety**		
Method	*Literature review*				
	Focus group interviews	*Questionnaire study*	*Field studies*	*Accident statistics*	*Video analysis*
Aim	Get an overview of problems and possibilities in roundabouts compared to other intersections for the whole group of visually impaired.	Quantify and validate the results from the focus group interviews.	Get an overview of interaction types, conflict types and behaviour leading to conflicts/accidents in the two roundabout designs.	Get information on which interactions result in most accidents in the two roundabout designs.	Quantify the different interaction types and behaviours and relate them to traffic safety for cyclists.

In order to get an overview of problems in roundabouts for the whole group of visually impaired and to find out how widely spread and severe the different problems are, a combination of qualitative and quantitative methods has been used. In the first stage, focus-group interviews with low-vision and blind people as well as orientation and mobility (O&M) specialists were conducted and later followed up with an extensive questionnaire targeting low-vision and blind people.

The purpose of the focus group interviews was to get an overview of the problems and possibilities in roundabouts compared to other intersections for the whole group of visually impaired. The focus group interviews raised many questions. Therefore, it was decided to further investigate whether the results were generally applicable to visually impaired and test the hypothesis that the problems for low-vision differed from those for the blind. A questionnaire study was conducted to quantify and validate the statements made in the focus-group interviews and to examine whether the results also represent a general opinion of the visually impaired.

The impact on cyclist safety of roundabout design was investigated through in-depth studies of two roundabouts with different cycle solutions, one separated and one integrated. The initial aim was to find out which of the separated and the integrated roundabouts was the safer and why this was so. This was to be done by in-depth studies of traffic conflicts, interactions and behaviours in two roundabouts with similar traffic volumes and speeds but different designs of the cycle facilities. In order to get a large amount of traffic conflicts, field studies of conflicts and behaviours were complemented with five days of video recording of the two roundabouts. This was supposed to give enough serious conflicts as well as behavioural information to obtain better explanations of how and when accidents happen in the two roundabout designs. Automated video analysis was supposed to be used to capture all the serious conflicts for five days per roundabout. However, the automated video analysis is under development, and it was impossible to identify the conflicts. Instead of the conflict study, accident statistics from roundabouts in nine Swedish towns were collected and used to categorize the typical collision situations for the different designs. The accident statistics gave similar information to what the conflicts would have given regarding which type of interactions lead to accidents. However, exposure and risk could not be assessed, nor could details of the behaviour preceding the accidents.

3.2. Methods used

3.2.1. Focus group interviews

A focus group interview is a qualitative group interview that is suitable for finding out what people think about a question. The purpose of focus-group interviews is to get an overview of the different components of an issue. (Wibeck 2000)

Focus group interviews were carried out with two categories of participants, people with visual impairment and orientation and mobility (O&M) specialists. The criterion for the selection of the visually impaired participants was that they should be used to walking in traffic areas without an attendant. To make sure that most participants had experience of crossing streets at roundabouts, the interviews took place in a town with a particularly high number of roundabouts. The visually impaired participants were recruited from the local group of the National association for visually impaired (SRF). O&M specialists are the professionals at the eye clinic that teaches visually impaired how to use their assistive technology, orientate in new environments and find accessible paths to their activities and destinations. It is mostly blind people that get help from O&M specialists. The interviewed O&M specialists were from the local eye clinic.

All the blind interviewees used a long white cane when walking outdoors. One of them had a guide dog in addition. Two of the low-vision interviewees did not use any assistive technology, one had a white crutch and a walker and one had a long white cane.

Since roundabouts have a bad reputation in SRF (SRF 2004; SRF 2005), the interviewees were not told at the beginning of the interview that focus of the research was on roundabouts, but that we were going to talk about crossing streets at different intersection types, but not signalised ones. First all participants were asked to describe in detail how they cross/instruct visually impaired people to cross the street at an intersection that they pass regularly. Then there followed more general questions about what they avoid, what is difficult and what makes it easy to cross the street and the participants were asked to give examples from particular intersections. They were asked if they had experience of crossing streets at roundabouts and if so to describe how they did so. In the end they were told that focus was on roundabouts and were asked if they had something to add to the discussion.

The focus group interviews were recorded and later transcribed and analysed qualitatively using content analysis, which means that the interviews were coded phrase by phrase and the codes were later arranged into categories. The following categories emerged when analyzing the transcribed interviews: choosing crossing point, finding the crossing point, to cross the street, interaction with motorized traffic, cyclists, roundabouts and other intersection types. Since I noticed a difference between visually impaired with more vision and the more severely visually impaired, the phrases were further organized into two sub groups depending on whether it was said by a low-vision or a blind person in order to identify potential differences in their answers.

The results from the focus group interviews, together with the literature study became the basis for the questionnaire. Table 3-2 shows how they relate to each other.

Table 3-2 How the results from the focus group interviews relate to the questionnaire.

Categories from the focus group interviews	Issue in the questionnaire	Approach in questionnaire
Choosing crossing point	Avoidance	Questions on what is avoided
Finding the crossing point	P1. Find the crossing point	Questions about how difficult the four problems are and what strategies are used to solve them.
Interactions with motorised traffic Cyclists	P2. Decide when to start crossing	
Crossing the street	P3. Walk straight P4. Know where the pavement stops/starts	
Roundabouts Other intersection types	Different intersection types	Questions about a round-about, a signalised intersection and an unsignalised four-way intersection that are passed regularly.

3.2.2. Questionnaire

The data was collected by telephone questionnaires during spring 2008. Eye clinics in five Swedish towns with many roundabouts (Trollhätan, Gävle, Halmstad, Växjö and Gislaved), sent out a request to people above the age of 15 registered at their clinics. This limit was chosen because it is not very likely that children below 15 with visual impairment walk alone in a traffic area. The five eye clinics used different procedures to choose those to whom the questionnaires were to be sent. In Trollhättan there were totally 391 individuals above the age of 15 registered at the eye clinic. 280 of these were over 80 years old. The requests were sent to all between 15 and 80 and to 20 (randomly chosen) over 80s. In Gislaved, with only 30000 inhabitants, every one of the 30 people who had received assistive technology during 2007 was sent a request. Due to the lower number of blind people, the eye clinics in Gävle, Halmstad and Växjö were asked to send the request to as many blind as possible and then randomly choose the same number of people with low-vision.

The request was distributed together with a postage-paid return-envelope. The respondents had to tick whether they were used to walking outside on their own and wanted to participate in a telephone-based questionnaire, whether they did not walk outside on their own or whether they did not want to participate for other reasons. They also had to state their name, telephone number and times when it suited them to be called. The interviewees themselves had to decide which group of visually impaired (low-vision or blind) they belonged to. Totally, 232 requests were sent out, of which 72 (31%) did not respond at all. Of the 160 who responded, 87 (54.5%) participated, 37 (23%) answered that they did not walk outside alone, 31 (19.5%) that they did not want to participate for other reasons and 5 (3%) forgot to write their telephone number. Due to professional secrecy we know nothing about those who did not return the request. However, the low participation rate is presumably due to the fact that people with eye diseases, but not very affected vision, are also registered at the eye clinics and probably did not feel targeted by the request. In addition, a considerable number of the respondents with a visual impairment do not walk alone outside.

The questionnaire consisted of five parts; first a general part about the respondent, her/his impairment and frequency of crossing streets, then a part about her/his experience of crossing streets in general. Next, there were three parts where the respondents were asked to answer the questions with regard to a particular roundabout, signalised intersection and four-way intersection that they cross regularly. One important advantage of asking about specific intersections is that the respondents answer with regard to their actual experiences and not to general opinions about the three intersection types.

3.2.3. Field studies

In the study on traffic safety for cyclists field studies were performed in order to get an understanding of how traffic conflicts, interactions and behaviours vary between the two roundabout designs.

The traffic conflicts technique is used to study safety based on the relation between serious conflicts and actual accidents. A traffic conflict is defined as "…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." If enough conflicts are received they do not only predict the number of accidents at a specific spot but also the types of accidents (Hydén 1987).

Interactions are defined as situations between two road users "where at least one of the road users changes speed or direction because of the other". For the integrated roundabout this includes situations where a cyclist and car end up parallel in the carriageway, where there is also an interaction in most cases, but more subtle. Interactions are not directly related to safety but give us information on how and where the road users meet in the different roundabouts. Behaviour such as yielding, adjustment of speed and direction etc is also used for in-depth studies and explanations of the dangerous situations.

Two specially trained field observers studied each roundabout for three days, six hours a day (07:30-9:30, 10:00-12:00, 14:30-16:30) during spring 2008. The conflict observation forms used were modified to suit the specific intersections and included more behaviour information than is usual in traffic conflict studies. Two observers were involved, one focusing mainly on the cyclists and the other one mainly on the motorists. In addition to estimating the speed and the distance to a collision point notes were made on who should yield, which road user passed first, the cyclist's behaviour (*stop, adjust speed, no speed change, get off the cycle*), the motorist's behaviour (*stop, adjust speed, no speed change*) and, in the integrated roundabout, the behaviour when catching up with another vehicle (*proceeding parallel with the other or staying behind*).

The speeds were measured with a radar gun at one of the approaches for free vehicles entering and exiting the roundabouts and for free cyclists in the middle of the crossing at the separated roundabout and when entering and exiting the integrated roundabout. The "free" was defined as not affected by other road users, which in practice meant that there were no other road users closer ahead than 5 seconds. 100 measurements were taken for each vehicle flow and 50 for each cycle flow (cycles going both ways on the crossing at the separated roundabout were considered as the same flow).

3.2.4. Accident statistics

Since accident data from the two sites in Lund is very limited, accident data has been complemented with data from nine other cities in Sweden in order to make a better prediction of what generally occurs in the two types of roundabouts. The accident data and information on the cycle facilities in the roundabouts were received from the traffic departments of the municipalities.

3.2.5. Video analysis

Video recordings of the two roundabouts were used to quantify the different interaction types and behaviours and compare them to cyclist accident statistics. Traffic flows were also received from the video recordings.

Video recordings were performed for five days at each roundabout. The separated roundabout was recorded in the middle of April 2008 and the integrated roundabout in the middle of November 2006. The cameras were mounted on nearby buildings. At the integrated roundabout it was not possible to get a view over the entire area and one of the approaches is not seen at all and two others are only partly seen. To be able to compare the sites, the corresponding limitations are presumed for the separated roundabout as well (Figure 3-3.21).

Roundabout I: field studies | **Roundabout I** video analysis | **Roundabout II:** field studies and video analysis

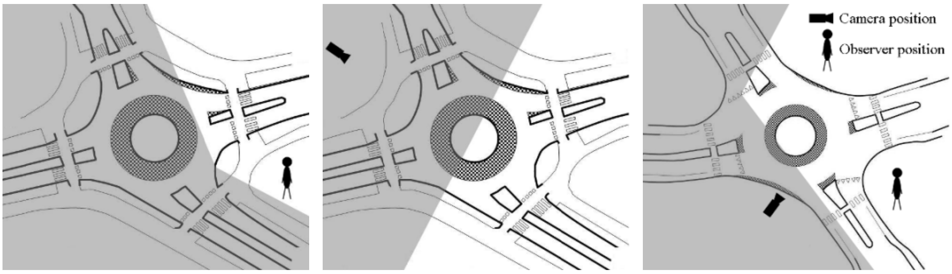


Figure 3-3.21 Parts of roundabouts studied with the different data collecting methods.

For a period of 24 hours (a full weekday) three observers manually registered the interactions, behaviours and route choices of all passing cyclists. Motorists interacting with the cyclists were registered in a similar way. In order to obtain estimates of the traffic flows all motor vehicles passing during the first five minutes of every hour were also noted. As in the field studies, the road user who passed first in an interaction was noted as "yielded for". It is hence possible that both road users adjusted their speeds or stopped, but the yielding one always acted to let the other pass.

4. Results – accessibility for the visually impaired

4.1. Focus group interviews

4.1.1. To choose the crossing point

Zebra crossings and yielding behaviour

Several blind people talked about not being sure of standing at the right spot while waiting to cross. The people with low-vision discussed instead whether the cars stop for them or not. Both blind and low-vision people said that they avoid crossing streets when there is no zebra crossing. However, they mentioned some places where crossing streets is not a problem even though there is no zebra crossing and concluded that it is because the cars go slowly and stop for them anyway. Furthermore, one of the O&M specialists mentioned zebra crossings where hardly any vehicles stop and suggested that no such zebra crossings should exist.

Detours

Taking detours in order to find a crossing point that is perceived to be safer was an issue that was mentioned several times and seemed to be emotional for the interviewees. Some of them took detours and had no problems with that. One said that she would prefer taking detours all the time if there were some crossing points designed with special consideration to the visually impaired where she could feel safe. Several protested, claiming that no detours should be accepted. "But as we risk life when taking a walk it is not possible to be categorical". Several of them avoid crossing streets during peak hours.

4.1.2. To find the crossing point

Reference points

After having chosen the intended crossing point, one has to find it. Crossing points with no reference points are difficult according to several of the blind people. The O&M specialists also mentioned that lack of reference points can be a reason for avoiding a crossing point. Reference points should be located so that they give information on when to turn from the walking direction into the zebra crossing. Examples of reference points mentioned by blind people are:

poles, tactile slabs, larger stones, slopes on the walking path, fountains and sounds from the vehicles in the intersection. A few comments on contrasting colours as reference points came from people with low-vision who mentioned the importance of well maintained painting of the zebra crossings. However, the zebra crossings were harder to find when the cycle path was between the walking path and the zebra crossing. A painted zebra crossing continuing over the cycle path was suggested.

4.1.3. To cross the street

At elevated crossings it is difficult to know where the pavement stops and carriageway starts. It happens that the visually impaired may already be standing on the carriageway when they stop to listen for the traffic. It is also difficult to know when they have come to the pavement on the other side of the street. One interviewee says that she usually continues to walk straight until she reaches the houses on the other side of the pavement in order not to risk turning too early and walking on the carriageway.

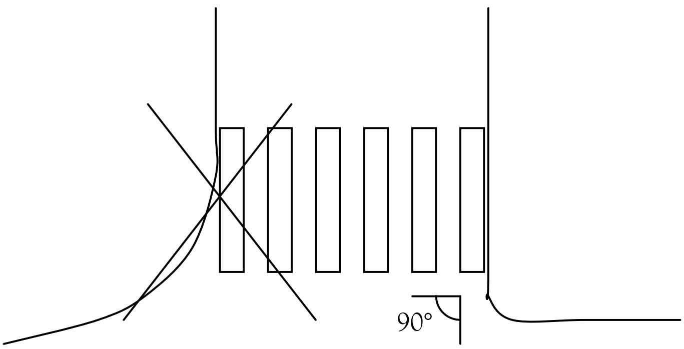


Figure 4-2 Example of curb stone non-perpendicular and perpendicular to crossing direction.

Elevated crossings and places where it is not possible to feel the curb stone or it is not perpendicular to the crossing direction also lead to problems walking straight when crossing the street. Crossing the street a few meters before the zebra crossing, where the curb stone is still full size and perpendicular to the crossing direction, can be a way to solve that problem. The visually impaired then stand with their heels, toes or the white cane against the edge to get the right direction over the street.

Middle islands make crossing easier since they lead to shorter sections and concentration on traffic from one direction at a time is sufficient. However, if middle islands are not elevated it is easy to miss them and the visually impaired risk crossing the whole street while only listening for traffic from the left.

The O&M specialists also stress the importance of well functioning curb stones. They say that the compromise used in Sweden to make the curb stones 4 cm high in order for visually impaired to feel the edge and wheel chair users to be able to pass can be a problem since sometimes neither visually impaired nor wheel chair users manage. For the visually impaired a little snow or gravel is enough to make it impossible for them to feel the edge. The O&M specialists suggest that there should be poles at the crossing points with audible signals that can be activated by the visually impaired to help them to locate both ends of the crossing. Such audible poles exist at the entrance to many schools. Assistive technology could be very helpful but it is important that they are very easy to use so that it does not disturb concentration on the traffic.

4.1.4. Interaction with motorized traffic

Those with low-vision talked a lot about interactions with the traffic, which seemed to be their main problem. Several of the blind people on the other hand claimed that the traffic was not a large problem for them. They explain that if they can be sure of standing at the right spot – next to the zebra crossing – they will know that they have the right to cross and the traffic itself is not a problem. Others say that the long white cane is very useful since most vehicles stop for them when they see the cane. The strategy of raising the cane in order to show the intention to cross was also common. The focus group interviews left the impression that blind people had less trouble with traffic than low-vision.

One of the most important issues in the interaction with motorized traffic seems to be whether the vehicles stop for pedestrians or not. As long as the speeds are low enough, almost all vehicles stop, say some interviewees. Still, one of them comments that it is harder to hear whether the vehicle intends to stop or not when the speeds are too low. However, it is not as dangerous to not hear a car if they drive slowly because then they will almost always manage to stop, says another. Most of them agree that the cars stop for them is a prerequisite to make a crossing point accessible, whereas one of them feels stressed when a vehicle has stopped and prefers waiting until it is totally silent and no vehicles are around.

A few state that they use their long white cane pro-actively to show that they intend to cross; they lift it in order to stop the vehicles. The cane and dog make the visually impaired visible, which is an important issue. Both visually impaired and O&M specialists state the importance of not having vehicles parked along the road next to the crossing. That leads to vehicles not seeing the pedestrians and low-vision pedestrians have to walk out onto the carriageway in order to see the headlights.

There are several statements about following other pedestrians when crossing the street, and most of the interviewees seem to do that regularly, but one of them does not trust other people to cross safely.

Most of the interviewees agree that they always feel a bit unsafe when crossing streets.

Streets with two lanes are more problematic since it is difficult to hear what is happening in two lanes at the same time. High traffic volumes are also a problem. Differences in traffic volumes over the day can make it harder to recognize where you are and high volumes can make it impossible to cross the street.

The visually impaired seem to be very exposed when it comes to crossing streets. The O&M specialists say that they have no tools to give them as they are better at hearing where the vehicles go than the O&M specialists are. "It is very individual how they handle the task, some are very tough, lift the cane and walk while others wait until it is totally silent before they walk."

4.1.5. Cyclists

Cyclists are a large problem for the visually impaired. They are small and silent and are therefore difficult for the visually impaired to detect. In addition they do not follow the traffic rules very well, which means that they can appear on the pavement or walking path, seldom yield to pedestrians etc. Cyclists on the pavement make it impossible for the visually impaired to relax while walking where there should only be pedestrians.

The interviewees find it difficult when they have to cross a cycle path before they come to the zebra crossing. They also state that the separation between cycle path and walking path should be easier to find with good contrasts and tactility. Several complain that cyclists more and more commonly cycle on the pavement and one thinks that they do so because they are scared to be integrated with the traffic, for example at roundabouts.

4.1.6. Roundabouts and other intersection types

Roundabouts were mentioned a lot when talking about intersections in general, before the interviewees knew that the study was on roundabouts specifically. The comments from blind people were generally about three topics: to know when to start crossing the street, to walk straight over the street and lower vehicle speeds in roundabouts than in other intersection types. All the comments on roundabouts from low-vision people, when talking about intersections in general, were about the traffic.

Several participants avoid roundabouts without having tried to cross the street near them. One participant said that she was more negative before trying to walk at a roundabout. A couple of participants became more positive to roundabouts during the discussions and said that they had avoided them because they thought they were impossible for visually impaired, but that they would try one on the next occasion.

Other participants said that it is more difficult to get information from the traffic sounds in roundabouts. It is also more difficult than in other intersections to know where the vehicles are going because you cannot tell from the speeds. Roundabouts with high traffic volumes are therefore very difficult since you never know if the vehicles are going to leave the roundabout.

Several interviewees say that the speeds are generally lower in roundabouts and therefore they feel safer since the vehicles have the possibility of stopping if the interviewee judges the situation wrongly and walks out in front of a vehicle. If the roundabouts are wide the vehicles drive too fast, stated one interviewee.

The O&M specialists say that roundabouts are good because the vehicles do not drive so fast and because they only arrive from one direction. They also mention problems with roundabouts with high traffic volumes. Another problem is that the curb stone in roundabouts is often not perpendicular to the crossing direction which makes it harder to walk straight. There were occasions when a visually impaired failed to walk straight and ended up in the circulation. Some O&M specialists think that roundabouts are not a problem as long as people have no hearing problems, but a lot of visually impaired do.

When starting up the focus group interviews I explained that we were going to talk about all kinds of intersections except signalized intersections. Nevertheless there were many comments on signalized intersections. Traffic signals are a very popular intersection solution among visually impaired which was reflected in comments like: “Signalization is what works best for us” and “that is what we want everywhere”.

However signalized intersections seem not to be without problems. The signals can be hard to see and hard to hear and turning vehicles during the walking interval leads to feelings of unsafety for the visually impaired. The interviewees were also very aware that there are people running red lights and one thought that roundabouts were just as good because the vehicles drove more slowly there.

4.1.7. An accessible intersection – four problems to overcome

The results from the focus group interviews can be summarized into three questions. The two first are the ones that the study aimed at; Q1: What is it that makes a crossing point accessible? and Q2: In what way do roundabouts differ from other intersection types? The third question; Q3: In what way do blind and low-vision differ from each other? emerged during the study.

The analysis of the focus group interviews resulted in four problems that the visually impaired need to solve in order cross a street.

Problem 1. To find the crossing point. This includes detecting the intersection and locating the zebra crossing.

Problem 2. To decide when it is clear to start crossing. Analyze the traffic pattern and decide when there is a large enough gap or when a car has stopped (at signalised intersections, determining when the walk interval starts).

Problem 3. To walk straight when crossing. There is no curb stone or other tactile line to follow over the street. In order not to end up in the circulation area/ the middle of the intersection, the visually impaired has to find a strategy to walk straight.

Problem 4. To know where the pavement stops and the carriageway starts and to detect the pavement/traffic island on the other side of the street.

In the results of the focus group interviews there was also a part about what makes the visually impaired choose one crossing point and avoid another. In the questionnaire study that was handled as questions about what makes the person avoid a crossing point, in order to find out if roundabouts or specific designs that are common in roundabouts are avoided.

During the focus group interviews different intersection types were discussed based on experiences of specific intersections. In the questionnaire interview the comparison of different intersection types was made as three similar parts of the questionnaire where the respondents were asked to talk about a roundabout, a four-way intersection and a signalized intersection that they pass regularly.

4.2. Questionnaire interviews

4.2.1. Difference between low-vision and blind as well as within the groups

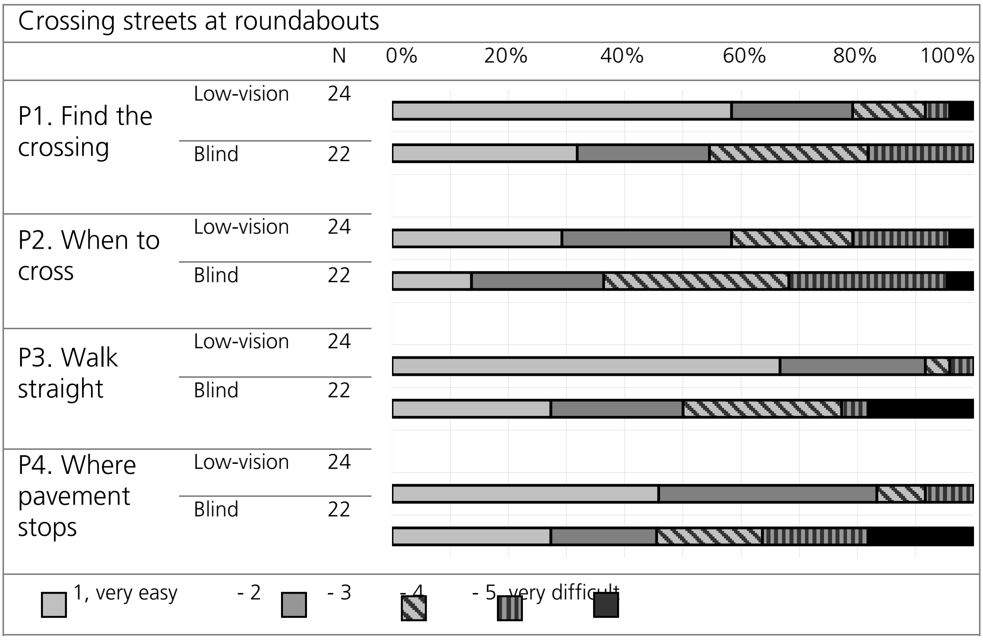


Figure 4-3 Low-vision and blind people's rating of the four problems when crossing streets at roundabouts. (From Paper 1)

The focus group interviews suggested that there is a difference between low-vision and blind, both in which problems they find troubling and how severe they rate the problems. The quantitative analysis of the questionnaire interviews in paper 1 shows that blind people find all the problems more difficult than low-vision (Figure 4-3). The tendency is that blind people find all problems more difficult than low-vision in roundabouts and four-way intersections whereas there is no statistically significant difference between blind and low-vision at signalised intersections.

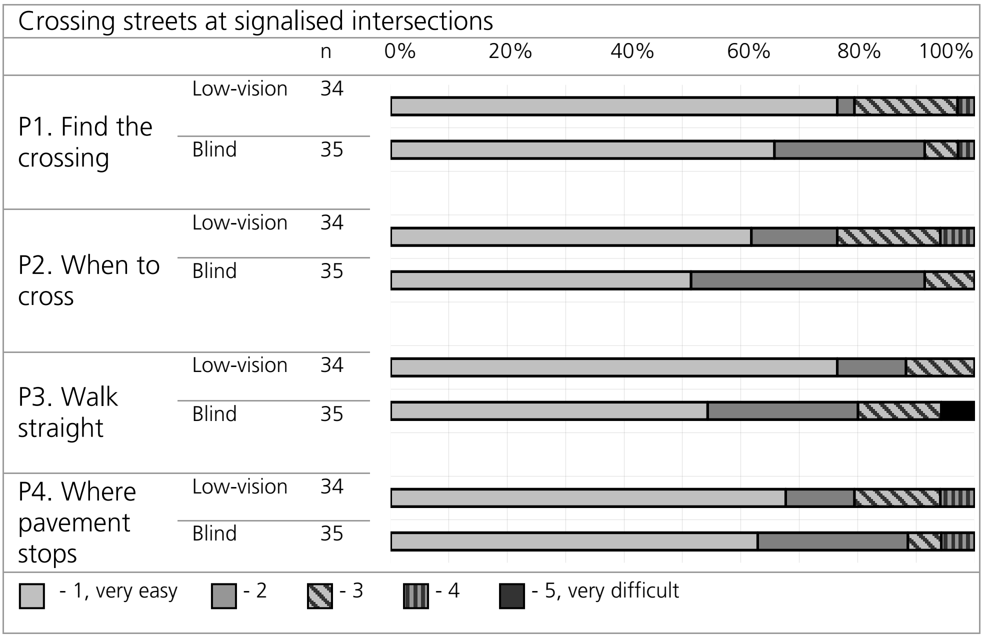


Figure 4-4 Low-vision and blind people's rating of the four problems when crossing streets at signalised intersections. (From Paper 1)

The four problems were also compared within the groups of low-vision and blind and showed that people with low-vision find it less difficult to walk straight over the street and more difficult to know when to start crossing the street than to solve the other problems. For blind people on the other hand there is little difference in how difficult they rate the four problems (in general as well as in roundabouts and signalized intersections).

4.2.2. Strategies used to overcome the problems in intersections in general

P1: The painted zebra crossing is used by more than twice as many low-vision than by blind when trying to find the crossing point. Poles, slopes and curb stones are more important for blind people than for those with low-vision. Traffic signals and traffic sounds are used extensively by both groups.

P2: There are no significant differences between what low-vision and blind pedestrians find important in deciding when to start crossing the street. All the strategies are important for both groups (clear audible picture, cars drive slowly, little traffic, other pedestrians crossing, signal, you feel visible and the cars stop for you).

P3: A straight curb stone and the traffic signal are statistically significantly more used by the blind than by low-vision pedestrians to be able to walk straight. The tendency is that the painted zebra is more used by the low-vision pedestrians and 70% of those with low-vision rate it as most important.

P4: The painted zebra crossing is more used by low-vision than blind pedestrians to know where the carriageway begins/ends. The curb stone and poles are more used by blind than by low-vision pedestrians. However, the curb stone is extensively used by low-vision pedestrians as well.

4.2.3. Comparison between intersections

One of the surprises from the focus group interviews was that signalised intersections were not unambiguously easier than other intersections. Some of the interviewees thought so but others did not agree. To find out the general opinion, the questionnaire respondents were asked to rate the problems at three intersections that they use regularly; one roundabout, one signalised and one four-way intersection.

For low-vision pedestrians, significant differences of the intersections types are only found for P2 (to decide when to cross). P2 turned out to be more difficult at roundabouts than at signalised intersections but there are no significant differences between roundabouts and four-way intersections. (Figure 4-5)

For the blind, significant differences of the intersection types were revealed for all the problems. All the problems were easier at signalised intersections compared to roundabouts. However, there are no significant differences between roundabouts and four-way intersections. (Figure 4-6)

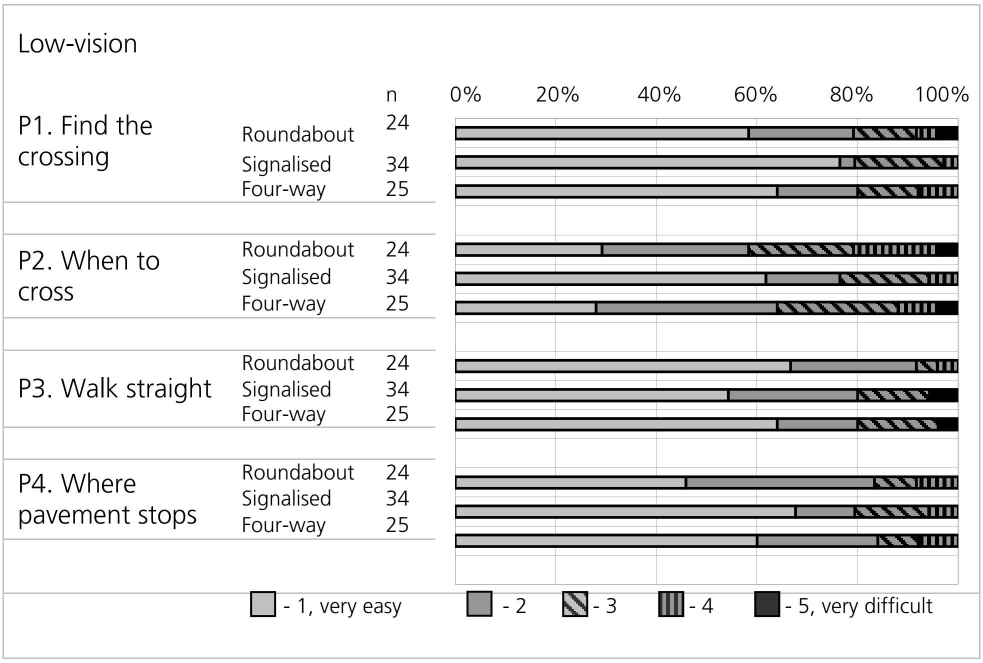


Figure 4-5 Comparison of three intersection types for low-vision. (Paper 1)

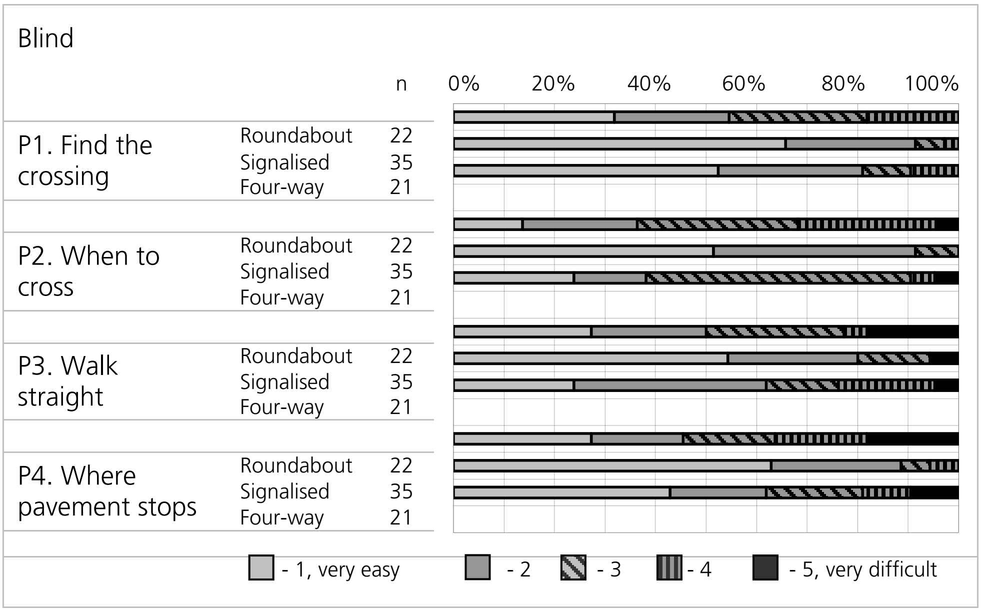


Figure 4-6 Comparison of three intersection types for blind. (Paper 1)

4.2.4. Perceived unsafety at all the three intersection types

No statistically significant differences are found in how low-vision and blind pedestrians rate "their certainty of not being hit by a car" when crossing the street at the three intersection types. However, the tendency is that blind pedestrians rate most certainty at signalised intersections and least certainty at roundabouts.

4.2.5. Different strategies to solve the problems at the three intersection types.

The respondents were given open questions to describe what they used to solve P1, P3 and P4. For P2 they had different alternatives and had to tick whether they use them or not; they also had the opportunity to add other strategies.

Roundabouts compared to signalised intersections

The only difference between what low-vision and blind pedestrians use at signalised intersections compared to roundabouts for P1, P3 and P4 is the signal. Several things are used in both intersection types (similar to 0). There are no differences between roundabouts and four-way intersections in what either group uses to manage P1, P3 and P4.

P2 – Roundabouts compared to signalised intersections

The signal is used by all pedestrians with low-vision at signalised intersections. Pedestrians with low-vision have two strategies that they use at roundabouts to a greater extent than at signalised intersections; they wait until a vehicle has stopped for them and they walk if the gap between two vehicles is big enough. Strategies that those with low-vision use at both roundabouts and signalised intersections are to walk when other pedestrians walk, to wait until they hear no vehicles, start to walk slowly or show the white cane to make the vehicles stop.

The signal is used by all blind pedestrians at signalised intersections. They wait until they hear no cars at all to a larger extent at roundabouts, whereas they show the white cane to a larger extent at signalised intersections. For blind pedestrians as well there are a few strategies they use both at roundabouts and signalised intersections: they wait until a vehicle has stopped, walk in a gap between vehicles (not so common), and start to walk slowly to make the vehicles stop and walk when other pedestrians start to walk.

P2 – Roundabouts compared to four-way intersections

There are no statistically significant differences between what strategies people with low-vision or the blind use at roundabouts compared to four-way intersections.

5.Results – cyclists in roundabouts

5.1. Interaction types and accidents

The integrated roundabout turned out to be more complex than the separated in that there were more interactions types and more conflict types. In addition the interaction types in the integrated roundabout differ from those in other intersection types.

There are four interaction types in the separated roundabout:
Sep1. – entering motorist and cyclist in the circulating direction,
Sep2. – entering motorist and cyclist against the circulating direction,
Sep3. – exiting motorist and cyclist in the circulating direction,
Sep4. – exiting motorist and cyclist against the circulating direction.

However, in the integrated roundabout there are six interaction types:
Int1. – entering motorist and circulating cyclist,
Int2. – entering cyclist and circulating motorist,
Int3. – exiting motorist and circulating cyclist,
Int4. – cyclist and motorist moving in parallel when entering,
Int5. – cyclist and motorist moving in parallel when exiting,
Int 6. – cyclist and motorist moving in parallel when circulating.

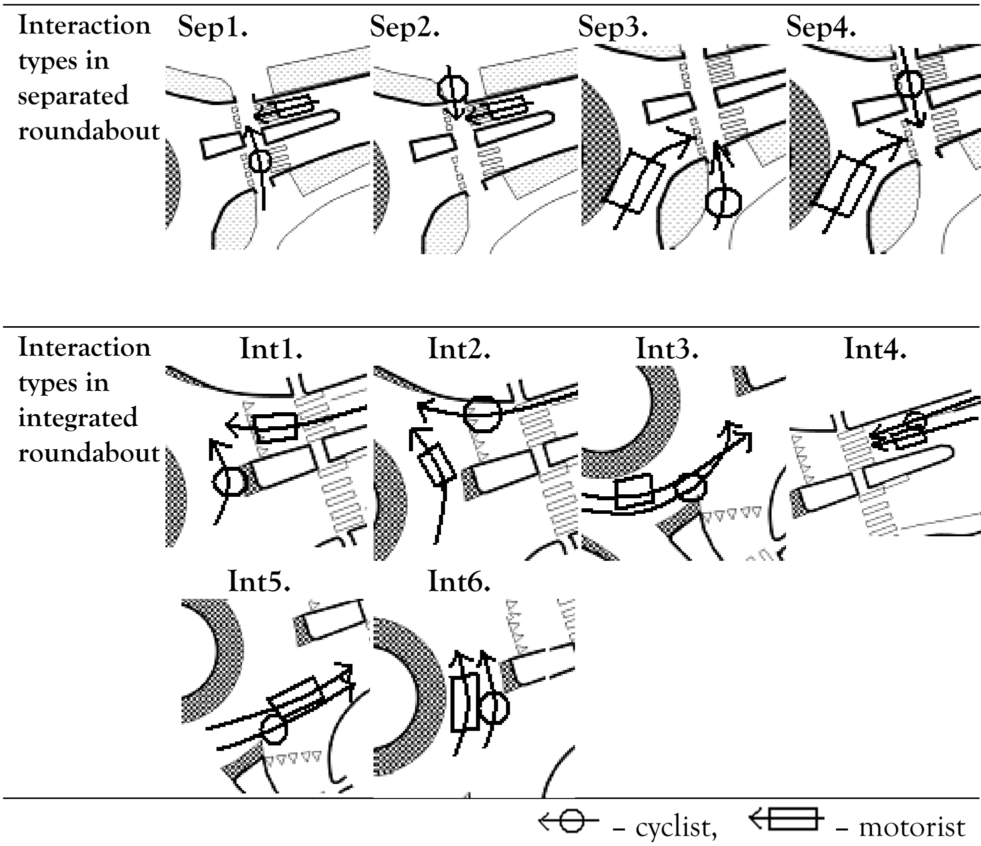


Figure 5-7 Interaction types in separated and integrated roundabouts.

5.1.1. The interaction types with most frequent accidents

Accident statistics from separated and integrated roundabouts in nine Swedish towns have given a good picture of which interaction types are the most dangerous (Table 5-3, Table 5-4). In the separated roundabout it seems as if accidents are split in a fairly equal manner between vehicles entering and vehicles exiting. Cyclists riding against the circulating direction represent around two thirds of all accidents. Sep2, entering vehicles and cyclists from the right, (against the circulating direction) is the largest individual type, 34% of all accidents.

Table 5-3 Separated roundabouts. Cycle accidents in nine different cities in Sweden for 5 years (2004-2008) presented with regard to type.

	Sep 1	Sep 2	Sep 3	Sep 4	Unknown /irrelevant	Total (exkl unknown)
TOTAL, n	16	27	15	22	11	80
TOTAL, %	20%	34%	19%	27%	-	100%

In integrated roundabouts by far the most common accident type is Int 1 – motorists entering the roundabout with cyclists circulating, while Int 2, cyclists entering the roundabout with motorists circulating has only happened in 2 out of 34 accidents. All other accidents in different ways represent cyclists and motorists moving in parallel where the largest problem seems to be linked to Int 3, cyclists circulating and motorists exiting the roundabout.

Table 5-4 Integrated roundabouts. Cycle accidents in six different cities in Sweden for 5 years (2004-2008) presented with regard to type.

	Int 1	Int 2	Int 3	Int 4	Int 5	Unknown /irrelevant	Total (exkl unknown)
TOTAL, n	25	2	5	1	1	1	35
TOTAL, %	73%	6%	15%	3%	3%		100%

5.2. Yielding behaviour

5.2.1. Separated roundabout

The motorists yield in 68% (n=354) and the cyclist in 32% (n=164) of the interactions at the cycle crossing in the separated roundabout. The motorists yield for cyclists to a larger extent when entering the roundabout (75%) than when exiting (61%). However, this difference is smaller when only including no-queue situations. The motorists entering the roundabout yield to a larger extent to cyclists coming from their left (in the direction of the circulation) (87% compared to 64%). The exiting motorists yield also to a larger extent to cyclists coming from their left (against the direction of the circulation) (75% compared to 55%). The queuing motorists yield to a larger extent than free vehicles.

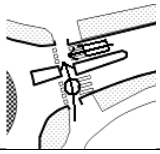
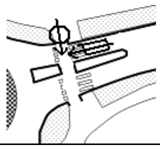
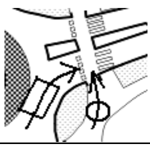
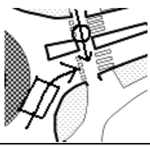
Interaction type		Total	Motorist yields		Chi2, p-level
			n	%	
Sep1		*132*	*115*	*87%*	*P*=0.000
Sep2		*143*	*91*	*64%*	
Sep3		*169*	*93*	*55%*	*P*=0.003
Sep4		*73*	*55*	*75%*	

Figure 5-8 Yielding motorists when cyclists moved in and against the circulating direction in separated roundabout. (From Paper 2)

5.2.2. Integrated roundabout

There were 138 Int1-interactions (where the motorist entered the roundabout and the cyclist circulated) during 24 hours. The motorist did not yield in 4% (n=6) of those situations. In four of the six interactions where the motorists did not yield they did not adjust at all to circulating cyclists.

There were 171 Int2-interactions (where the cyclist entered and the motorist circulated). The cyclists did not yield in 14% (n=24) of those. In 18 of the 24 interactions where the cyclists did not yield they did not adjust at all to the circulating motorist. In 7 of these 18 interactions the motorists also continued and they circulated in parallel; in the other cases the circulating motorist yielded. Even when the cyclist yielded, the motorist adjusted his speed or direction in 8 % of the interactions. There were 23 Int3-interactions (where they circulated in parallel and the motorists exited). The motorist did not yield, but continued unchanged, in 6 of these interactions. In 2 of the 17 interactions where the motorist did yield, the cyclist also adjusted speed or direction.

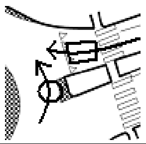
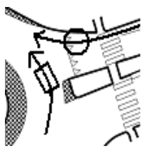
Interaction type	Who should yield?	Who yields?	n	%	Behaviour: Cyclist adjusts	Cyclist unchanged	Motorist adjusts	Motorist unchanged
Int1 	Mo	Mo	*132*	*96%*	*11 (8%)*	*121 (92%)*		
		Cy	6	*4%*			*2*	*4*
Int2 	Cy	Mo	*17*	*10%*	*3*	*14*		
		Cy	*147*	*86%*			*12 (8%)*	*135 (92%)*
		Parallel	*7*	*4%*	*3*	*4*		*7*
Int3 	Mo	Mo	*17*	*74%*	*2*	*15*		
		Cy	6	*26%*				6
		Not known	*4*					

Figure 5-9 Behaviour in different interaction situations in the integrated roundabout. (From Paper 2)

When a cyclist and a motorist catch up with each other they have a choice to make. Either they stay behind each other or the vehicle catching up moves up in parallel with the vehicle in front. Moving in parallel could lead to squeezing or Int3-situations. Half of the motorists catching up with cyclists moved up in parallel with them, whereas only one third of cyclists catching up with a motorist moved up in parallel. When catching up with heavy vehicles cyclists stayed behind in all situations (n=8) whereas the heavy vehicles moved up in parallel in 6 out of 15 situations.

6. Discussion

6.1. Separated and integrated design solutions – impact on visually impaired and cyclists

6.1.1. Separated solution

The interactions between cyclists and motorists in the separated roundabout are similar to those at other types of intersections in that the cyclist crosses the road on a cycle crossing at connecting roads (but roundabouts generally generate lower motor vehicle speeds). In addition, similar yielding rules to other separated intersections (where cyclists are on cycle paths and cycle crossings) are valid. Like other types of intersections, Paper 2 shows that the most common feature of cyclist accidents in separated roundabouts is the cycling direction; most accidents happen when the cyclist moves against the circulating direction. Several studies of different four-way intersections have also shown that cycling on the left side of the road on bi-directional cycle paths runs a higher risk of being involved in accidents (Linderholm 1992; Summala, Pasanen et al. 1996b). In the case of roundabouts only entering motorists' behaviour has been studied before, showing that entering motorists yield more to cyclists riding in the circulating direction and interpreting that as higher attention towards these cyclists and lower risks for them (Räsänen 2000). Our results from the field studies confirm those of Räsänen in that entering motorists yield more to cyclists coming from the left (circulating direction). Nevertheless, our results show that motorists exiting the roundabout also yield more to cyclists from the left, i.e., cyclists riding *against* the circulating direction. Still, as mentioned before, cyclists riding against the circulating direction are more involved in accidents. Hence, the relation between yielding and accidents is complicated, involving many factors where attention to the cyclist is only one of them. Additional studies focusing more thoroughly on motorists' attention and cyclists' risk should therefore be performed to expand and explain these results.

One way of avoiding accidents with bicyclists moving against the circulation direction could be to use one-way cycle paths. However, there are cyclists that ride illegally against the direction on one-way cycle paths. Moreover, cyclists on the right side of the road may have to cross the road more times and since many accidents happen at the crossing points, the safety benefits are not obvious.

The yielding rules at cycle crossings in Sweden are perceived to be ambiguous (Jonsson and Hydén 2005b), in reality both road users should yield but the motorists do not have a "strict" yielding obligation as they have towards pedestrians. Still, the field studies show that 68% of the motorists yielded to cyclists in the separated roundabout. However, in 30 % of the interactions both cyclist and motorist adjusted their speed and direction indicating that they were not sure of the following behaviour of the other road user. The yielding rules for pedestrians at zebra crossings were similar to those for cyclists at cycle crossings before the rules were changed to a strict yielding towards pedestrians in May 2000. Evaluation of the changed yielding rule shows that injury accidents for pedestrians at zebra crossings increased by 15-20 % and fatal accidents by 5-10 % (Thulin 2007). There is also evidence that a strict yielding obligation towards cyclists results in expectations that the motorist should yield and therefore results in less attention towards the motorist (Räsänen and Summala 1998). Generally, one can say that the ambiguous yielding rules in the separated roundabout not only lead to higher attentiveness and lower mobility for cyclists, but presumably also to lower risk.

In the separated solution the cyclists ride along a path parallel to the pedestrian path. During the focus group interviews, the visually impaired expressed a preference for separated walking and cycling areas as long as the separation between them is well enough defined and easy to perceive. The separation should be tactile and thereby possible to perceive with the long white cane and have enough contrast to the surrounding materials for people with low vision. For the visually impaired it should preferably also prevent cyclists from crossing it. The separation that best keeps the pedestrians and cyclists to their respective sides of the path is one with 3-4 cut stones or a curb stone. Moreover, if the pedestrian and cycle paths have different paving – asphalt/tiles – the separation functions even better (Jonsson and Hydén 2005a).

There are also other problems in having the cycle path parallel to the pedestrian path; the pedestrian path gets further away from the zebra crossing and the painted zebra can be difficult to discover. The visually impaired have to cross the cycle paths first, which is difficult since the cyclists are so difficult to perceive. Having crossed the cycle path, the pedestrians should not have to stand in the cycle path to prepare to cross the street, but have a "safe" spot to stand on while listening for the traffic. Parallel cycle and pedestrian paths are not optimal for cyclists either. Pedestrians walking on the cycle path are known to be irritating and can be a mobility problem for cyclists. This problem could be reduced by careful design of the separation. In addition, the volumes of cyclists and pedestrians have been shown to have a great impact on whether they keep to the right path or not, i.e. the more cyclists and pedestrians the more they keep to their respective path. (Jonsson and Hydén 2005a)

In addition it can be difficult for the visually impaired to know whether there is a cycle path or not and they might therefore not be aware that they are walking on or crossing a cycle path. Some of the interviewees in the focus group interviews wanted the zebra crossing to be painted on the cycle path as well, to make it more visible and to make the cycles stop. This may seem like a simple solution, but in reality it is probably difficult to force cyclists to stop for pedestrians. During the field studies we noted that cyclists do not yield to pedestrians but only swerve and pass right in front or behind the pedestrian. The focus group interviews also show that this is a known phenomenon. To paint the zebra crossing over the cycle path could be of help to show that there is a cycle path and lead the visually impaired to the crossing point. Nevertheless, it could also lead to false safety, i.e., that pedestrians feel safe and are aware of the cyclists' obligation to yield and therefore walk without looking for cyclists. However, false safety is probably less pronounced for the visually impaired since paper 1 shows that they generally feel unsafe when crossing streets. However, the painted zebra crossing on cycle paths might not fulfil the intended goals. Other ways to visualise the cycle path should be investigated. If assistive technology to detect motorists is to be tested, its ability to detect cyclists should be tested as well.

6.1.2. Integrated solution

The interactions between cyclists and motorists in the integrated roundabout are supposed to work like interactions between two motorists in a roundabout, i.e., the entering vehicle yields for the circulating. Nevertheless, the situation turns out to be substantially different, primarily because the cyclist can enter in parallel with the motorist, the motorist can catch up with and drive up parallel to the cyclist in the roundabout and vice versa. In addition, the yielding rules often seem to be ignored.

In the integrated roundabout 1/3 of the interactions are Int1 (circulating cyclist, entering motorist) or Int2 (circulating motorist, entering cyclist). Int 1 is the situation resulting in most cyclist accidents according to the accident statistics and conflict data. “The opposite situation”, Int2, is not at all as common in the accident statistics. The conflict data suggests that this might be because these conflict situations more often can end up in parallel driving if the drivers (specifically the cyclists) adjust direction slightly. The consequence might be that Int 2 accidents are avoided but instead the cyclists end up in parallel with motorists in the roundabout, which then can lead to “parallel conflicts and accidents”.

The majority of the interactions (2/3) in the integrated roundabout are parallel situations. When motorists come up parallel with the cyclist, the latter has problems finding a position where he can still be in control of the event. When the cyclist appears from behind the motorist has great difficulties in observing the cyclist at the side of the vehicle. Of the parallel situations, Int3 (exiting motorist and circulating cyclist) seems to be the most risky situation in our studies, which is in accordance with earlier notions that Int 3 is the second most common accident situation in roundabouts (Jørgensen and Jørgensen 2002; Hels and Orozova-Bekkevold 2007). The risk with parallel driving, apart from ending up in Int3-situations, is that the cyclist will be squeezed by the motorist. One of the reasons for roundabouts being safer than other intersections for motorists is the small conflicting angle. However, cyclists, as vulnerable road users, can be just as badly hurt when the collision angle is small.

In the integrated roundabout only one of the interacting road users is obliged to yield; e.g., the entering vehicle has to yield to the circulating vehicle. In Int1 situations (entering motorist, circulating cyclist) 96% of the motorists yielded and in Int2 situations (entering cyclist and circulating motorist) 86% of the cyclists yielded. Only in 8% of the interactions did both the cyclist and the motorist adjust their speeds or directions in the integrated roundabout. This indicates that most motorists and cyclists rely on each other to yield as required, which causes safety problems once somebody violates the yielding rules as the other part in such a case is not prepared to deal with this situation (Räsänen and Summala 1998; Svensson 1998a; Thulin 2007).

How are the visually impaired affected by cyclists moving together with the motorists on the carriageway in the integrated solution? Some visually impaired stated that cyclists do not respect the long white cane and never stop for them at the zebra crossing. As mentioned before, they pass a very short time before or after the pedestrian and this is perceived as very frightening for the visually impaired, who are seldom aware that a cyclist is approaching.

Moreover, paper 2 shows that 5% of the cyclists in the integrated roundabout chose to ride on the pavement instead of on the carriageway. During the focus group interviews the visually impaired stated that cyclists riding on the pavement was a big problem since it resulted in the visually impaired never being able to relax but always being afraid of being hit during a walk. Cyclists are a heterogenic group and it is just as difficult to make transport cyclists use a bicycle path with bad mobility as it is to make all seniors and children ride on the carriageway through a roundabout.

6.2. Design solutions suggested for accessibility of the visually impaired – impact on cyclists and visually impaired

Although the number of blind pedestrians is relatively small, they have the same rights to an accessible environment as anybody else and most research has focused on them. Nonetheless it is also important not to forget the larger group of visually impaired with low-vision. This project has shown that low-vision and blind groups differ in the experienced severity of the four problems and in the strategies used to solve the problems. Generally, for problems 1, 3 and 4 (find crossing point, walk straight and know where the carriageway begins/ends) the painted zebra crossing is the most important strategy for the low-vision group. The corresponding strategies for blind pedestrians are the traffic signal and curb stone. For P2 (decide when to start crossing) no significant differences are found. All the mentioned strategies to solve P2 are used extensively by both groups. The fact that one strategy is not enough, but all available strategies are combined, serves to indicate the complexity of that task.

The most useful strategy for the group of low-vision, the painted zebra crossing, has been removed from many places due to the higher accident risks for pedestrians at zebra crossings (Ekman 1997). Where the pedestrian flows are small the zebra crossings are simply removed, where they are larger the zebra crossings are often rebuilt into "safe passages" –elevated crossings that force motorists to slow down and hence increase traffic safety for pedestrians. This solution is disapproved of by the blind since they find it more difficult to solve P3 and P4 (to know where carriageway begins/ends, and to walk straight over the street). For low-vision the disadvantages of elevated crossings are small if the painted zebra crossing is kept. The lack of painted zebra crossings is sometimes compensated for by other contrast marking such as rows of white cement tiles before and after the pedestrian crossing. It is not clear, though, whether this compensation is sufficient to maintain the accessibility for pedestrians with low-vision regarding P1, P3 and P4. Regarding P2 the elevated crossing is helpful for both the blind and low-vision. Therefore, if measures are taken to help the blind with P3 and P4, the elevated crossing could be positive for all. A suggested such measure is audible poles located at both ends of the crossing.

The design solutions suggested for the visually impaired are not as critical for cyclists as the other way around. Reference points like painted zebra crossings, slopes and the angle of the curb stone are not of crucial importance for cyclists. However, several things that are positive for the visually impaired are also beneficial for cyclists. Designs that force vehicles to slow down are asked for by the visually impaired and result in safety advantages for cyclists. Middle islands simplify crossing considerably for the visually impaired and for cyclists in the separated solution. Roundabouts with two lanes are problematic for the visually impaired and also disadvantageous for pedestrians in general and cyclist safety (Brüde and Larsson 1999).

Our results show that the only difference in what the visually impaired use to solve *all* the problems at signalised intersections compared to roundabouts is the signal. This means that when a signalised intersection is transformed into a roundabout, the most important strategy for orientation and mobility of the visually impaired is taken away and they get nothing to compensate for the loss. It is important to note that the signal is not only used to decide when to cross the street, but also to solve the other three problems. One way to improve the accessibility in terms of P1, P3 and P4 at roundabouts could hence be to put up audible poles at the crossing points. The ticking sound and the poles on which the audible signal is mounted would lead the visually impaired to the crossing point, help them walk straight over the street and, if carefully placed, be of help to know where the carriageway starts and ends.

The suggested audible poles that would stand next to the zebra crossing to help visually impaired with P1, P3 and P4 have to be carefully located in order not to be a safety risk for cyclists. Single accidents are one of the most common accident types (2/3 of the hospital-reported accidents in Sweden) and obstacles in the street are a risk (Hydén 2008). Especially poles that are low and therefore easy to miss for the cyclist who is just about to cross and therefore concentrates on the traffic.

P2 (to know when to start crossing) seems radically more difficult to solve, especially in cases of large traffic volumes. It is obvious that an important strategy for both blind and low-vision pedestrians is to try and understand what motorised traffic is doing (wait until it is totally silent, wait until a car has stopped, wait for a gap). All these aspects are related to yielding, traffic volumes and speeds.

6.3. Yielding, communication and speed

There are yielding rules that regulate our traffic system. If everyone followed the yielding rules without ever failing to do so the number of accidents would probably diminish. However, the rules can be ambiguous, road users fail to see each other, misunderstand the situation etc. As shown in paper 2, in integrated roundabouts motorists failed to yield to cyclists in 4% of the interactions when they entered the roundabout and cyclists in 14% of the interactions when they entered. Studies show that on average only 70% yielded for pedestrians at zebra crossings in Sweden even though we have a strict yielding rule regarding pedestrians. The corresponding number for motorists yielding to cyclists on cycle crossings is 40%. (Jonsson and Hydén 2005b) As mentioned before there is also evidence that stricter yielding rules towards pedestrians and cyclists result in more accidents. Where following the yielding rules fail, communication has to take over.

Since the yielding rules at separated roundabouts are perceived to be very ambiguous and both cyclist and motorist should yield, there is reason to believe that the yielding behaviour there is decided primarily through communication. This includes the fact that neither of the road users counts on the other to yield and both try to find out what the other is intending to do. As long as it seems impossible to make everyone yield strictly according to the rules, and this seems even harder when one of the road users is a pedestrian or cyclist, then ambiguous situations that force the road users to communicate might be the best solution from the safety perspective. In order to promote communication, low vehicle speed is essential. Low speed also leads to a higher yielding rate towards pedestrians and cyclists regardless of the rules. (Räsänen and Summala 1998; Jonsson and Hydén 2005b)

Yielding that depends on communication is, for obvious reasons, a problem for the visually impaired. Nevertheless, despite the problems in seeing the driver's gestures or establishing eye contact, there is definitely communication. The motor vehicle signals when braking or other pedestrian signals are interpreted and many visually impaired raise their white cane or hand as a stop signal when they intend to cross the street. Low speed has been mentioned as one of the factors important for the visually impaired to decide when to start crossing the street. It is also one of the most important prerequisites for communication among road users since lower speeds give the road users more time to discover and interpret each other’s signals. Furthermore, low speed is one of the most important safety prerequisites and lead to less injury if there is an accident. There are reasons to believe that the factors promoting communication could also be positive for the visually impaired. Nevertheless, even though low speed is helpful, it does not seem to be enough to make an intersection with high vehicle volumes accessible.

It is therefore hard to imagine design solutions, suitable for roundabouts, that help the visually impaired solve P2 in high vehicle volumes. If the environment cannot be changed in order to make the intersection accessible, it has to be done by improving the individuals’ capacity. This could be done by modern assistive technologies that discover approaching vehicles. Such equipment would be particularly suitable at roundabouts, since the vehicles only approach from one direction and are therefore easy to aim at. The automobile industries are developing very accurate systems to inform and warn of obstacles or approaching vehicles. Further studies should be undertaken to adapt such assistive technology to the special needs of the different groups of visually impaired. Such a tool could improve the accessibility of all the visually impaired not only at roundabouts but also at four-way intersections and signalised intersections without separate phases for pedestrians.

6.4. Roundabouts compared to other intersections

Unlike other intersection types, the separated solution seems to be safer than the integrated one for cyclists in roundabouts (Schoon and Van Minnen 1994; Aultman-Hall and Hall 1998b; Elvik and Vaa 2004). The theory that tries to explain why integrated solutions are safer in most intersections is that the cyclists are more visible and the motorists and cyclists are more aware of each other in integrated intersections. Why this should be different in roundabouts compared to other intersections is not evident.

The results in paper 2 show that the most dangerous situations in separated roundabouts are when the cyclist moves against the circulating direction. This is in accordance with results from other intersections where the risks are higher for cyclists on the left side of the road on a bi-directional cycle path (Linderholm 1992; Summala, Pasanen et al. 1996b). Hence, those mechanisms do not seem to differ between the intersection types. The motorists are also aware of and adjust to cyclists to a larger extent in separated roundabouts than in other intersection types, presumably because the speeds are lower in roundabouts (Jonsson and Hydén 2005b). The reason why integrated solutions are safer in most intersection types but not in roundabouts might not be found in a comparison of the separated solutions but in a comparison of the integrated ones.

In most of the interactions between cyclists and motorists in the integrated roundabout none of the road users have to stop, but can just swerve a little and continue in parallel. The two interactions where they actually cross each other's paths are also the ones with most accidents, Int1 – circulating cyclist, entering motorist, and Int3 – circulating in parallel and motorist exits. One hypothesis is that extensive parallel driving in roundabouts affects attentiveness since in most interactions none of the drivers have to yield. Hence, cyclists become less important to note and this could lead to the fact that they get a lower priority when it comes to the driver's scanning strategies and are more often not noticed. Further studies of this hypothesis are warranted. One way to study the phenomenon would be to design a roundabout where it is impossible for motorists and cyclists to move in parallel. Such a design would prevent parallel driving and probably force the motorists to drive even slower. If that could be done, cyclists would have to behave more like motorists and motorists would have to treat them accordingly. The most challenging point in such a design is probably the one where the cyclists and motorists are merged. Further studies are needed to test the hypothesis and find a solution for merging that does not result in new accident types.

Another hypothesis is that the circulating cyclist misinterprets the intentions of the motorist to a larger extent in a roundabout than in a four-way intersection. In a four-way intersection drivers who do not intend to stop do not slow down as much as in a roundabout (presuming fair sight-conditions). This need to slow down is one of the main advantages of roundabouts, but a circulating cyclist could misinterpret the situation and believe that the deceleration is a sign that the motorist will yield even when the motorist has not noticed the cyclist. Further research is warranted to test these hypotheses.

There is a widespread perception that roundabouts are particularly difficult for pedestrians with visual impairment, but the results in paper 1 show that roundabouts do not differ from unsignalised four-way intersections in how difficult they are or in how the four problems are solved. A probable reason for the bad reputation of roundabouts is that signalised intersections are often rebuilt into roundabouts and, since signalised intersections are perceived to be better for both low-vision and blind pedestrians, the rebuilding leads to accessibility deterioration.

Signalised intersections are more accessible than roundabouts. The blind find all the problems easier to solve at signalised intersections whereas the low-vision pedestrians only find their main problem, deciding when to start crossing, easier. As mentioned before, the only strategy that makes signalised intersections different from roundabouts for all four problems is the signal. At the same time it is important to note that there are no significant differences in how safe the blind or low-vision pedestrians feel at signalised intersections compared to roundabouts and four-way intersections. It is remarkable that they find it easier to decide when to start crossing but still do not feel more certain of not being hit by a car. The possibility that turning drivers may continue driving in the walk interval is one probable factor contributing to the perceived unsafety. The higher speeds at signalised intersections seem to be another. Several studies show that roundabouts significantly increase pedestrian safety (Schoon and Van Minnen 1994; Brüde and Larsson 1999; Hydén and Várhelyi 2000). At the same time meta analysis of the safety effect of signalised intersections for pedestrians shows that when a four-way intersection is signalised with separate phases for pedestrians the best estimate of the effects is a 30% reduction of injury accidents. When the same type of intersection is signalised without separate phases for pedestrians, however, the estimate is an **increase** by 8% (Elvik 2006). Most signalised intersections in Sweden have non-separated pedestrian phases. This, together with the higher accident risk in this kind of signalised intersection compared with roundabouts, makes it quite likely that pedestrians, with or without visual impairments, may feel less safe with this kind of traffic signal.

The focus group interviews show the great stress that the visually impaired are exposed to when walking in traffic areas. They can seldom be confident that crossing the street will be safe and they are very aware that they risk their lives when going for a walk. In addition to the level of visual impairment, personality also seems to be important for how they perceive the risks of crossing streets and for which intersection solution they prefer. It is remarkable that roundabouts seem to have a worse reputation than they deserve. During the focus group interviews there were comments from a person who was more negative to roundabouts without having tried cross one and others who had not dared to but wanted to try after hearing the other descriptions. Some of the focus group interviewees prefer the signal, since at least they know that they have the right to cross when they start crossing. The responsibility is hence not solely on themselves. Others are very aware of the importance of speed for the severity of an accident. They are also aware that if they make a mistake, lower speed will raise the vehicle's chance of stopping. Humps and places where traffic is slow are mentioned as reasons why some intersections are accessible and the low speeds are perceived advantages in roundabouts compared to signalised intersections.

7.Conclusions

Based on the experience from my research and studies I am attempting to suggest a roundabout design that will improve the situation for cyclists and the visually impaired. Further field studies should be performed in order to evaluate the implications of the proposed design.

The roundabout should have only one lane. There should be a combination of separated and integrated cycle solutions in order meet the demands of different kinds of cyclists. The cycle facilities should be one-directional. The separated part should be designed so that it is the natural choice and leisure cyclists not accidentally end up on the carriageway – transport cyclists usually find the quickest route anyway. To ensure the safety of the cyclists in the integrated solution the circulation should be tight enough to prevent parallel driving. The merging point should be designed with extra caution and its safety effect evaluated.

The separation between cyclists and pedestrians should be clear in order to prevent road users from using the other path. The recommended separation is 3-4 cut stones or a curb stone and contrast marking. The entry and exit to the roundabout should be tight to ensure low entering and exiting speeds. There should be audible poles at each side of the zebra crossing to help the visually impaired find the crossing point, know where the zebra crossing starts and walk straight over the street. There should be a middle island, elevated on the walking path. The ambiguous yielding rules, together with the lower speeds, will ensure safety for both cyclists and pedestrians. As long as the speed is forced to be low, the safety problem with painted zebra crossings will be small and they can therefore be used. Assistive technology to help the visually impaired detect vehicles should be developed and tested in high traffic volumes.

A summary of the results of this licentiate thesis is as follows:

- Roundabouts can be accessible for the visually impaired – at least as long as the motor vehicle volumes are not too high. However, the design details are very important.

- There are differences between low-vision and blind pedestrians both in what they find difficult and in their strategies to solve the problems. Therefore, both groups must be considered when building an accessible environment.
- In order to make an intersection accessible for the visually impaired, there are four problems they must be able to solve:
  - P1. To find the crossing point.
  - P2. To decide when it is clear to start crossing.
  - P3. To walk straight when crossing.
  - P4. To know where the pavement stops/starts and the carriageway stops/starts.

  For low-vision, the painted zebra crossing is the most important strategy to solve P1, P3 and P4, whereas the traffic signal and the curb stone are most important for the blind. P2 is the most complex problem and all available strategies are used to solve it.
- Roundabouts are less accessible for the visually impaired than signalised intersections. However, the traffic signal is the only strategy that differentiates roundabouts from signalised intersections. Therefore, further studies are warranted to find out whether audible poles at both ends of the crossing could be used to solve P1, P3 and P4 in roundabouts.
- In order to solve P2 in roundabouts with high motor vehicle volumes, the development of assistive technology to discover vehicles and gaps between vehicles is warranted. Such technology should also be able to discover cyclists. Roundabouts seem to be particularly suitable for this technology since all vehicles come from one direction.
- No difference in accessibility is found between roundabouts and unsignalised four-way intersections.
- No difference in perceived safety is found between roundabouts, signalised intersections and unsignalised four-way intersections.
- Roundabouts (at least those with small traffic flows) seem to have a worse reputation than they deserve.
- In separated roundabouts cyclists riding against the circulating direction are most frequently in the accident statistics. However, exiting motorists yield more to cyclists riding against the circulating direction. The relation between yielding and accidents is hence hard to determine, at least for smaller differences.

- In the integrated roundabout a motorist entering while a cyclist is circulating leads to the most frequent accidents. Circulating in parallel when the motorist is about to exit is also common in accident statistics, and since this is a much less frequent interaction type, it is probably as risky a situation as the first.
- The yielding situation differed substantially between the separated and integrated roundabouts. In the separated roundabout the yielding rules were ambiguous and motorists yielded in 50-90 % of the interactions depending on the situation. Moreover, in 30% of the interactions both motorist and cyclist adjusted speed or direction because of the other, indicating uncertainty of the other's behaviour. In the integrated roundabout 96% of the motorists yielded to a circulating cyclist and 86% of the cyclists yielded to a circulating motorist. Only in 8% of the interactions did both adjust speed or direction. Hence most motorists and cyclists rely on the other to yield as required, which causes safety problems once either of them violates the yielding rules since the other part in such a case is not prepared to deal with this situation. The safety consequences of the difference in yielding behaviour between the two types are difficult to predict. Generally one can say that the more ambiguous yielding rules in the separated roundabout lead to higher attentiveness and presumably also to lower risk.
- The possibility for cyclists and motorists to move in parallel in integrated roundabouts leads to the fact that no action (except for a slight swerving) is needed in most of the interactions. This could lead to a reduction of motorists' attention towards cyclists and thus to more accidents in this kind of roundabout. Further studies of the phenomenon are warranted.
- Earlier notions, that the separated solution is the safest for cyclists, are supported by the results of this project. Moreover, our results also indicate that a certain number of cyclists choose to ride on the pavement in integrated roundabouts which leads to that the visually impaired never being able to relax during a walk. Therefore my interpretation is that a well designed separated solution is better for both cyclists and the visually impaired than the integrated solution.
- Designing roundabouts that enforce low speeds is crucial for both cyclists and the visually impaired.

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