Traffic safety analysis for cyclists at roundabouts, a case study in Norrköping

Shengjie Tang

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Shengjie Tang

Handledare Ghazwan Al-Haji
Examinator Ghazwan Al-Haji

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Upphovsrätt

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Abstract

Cyclists as vulnerable road users are oftentimes unprotected with exposed human body, can fall easily and sustain serious injuries when encountered collisions, especially with motorists. At roundabouts, accident reduction rate for cyclists is rather uncertain or sometimes less favorable compared to other road users (e.g. motorists, pedestrians). This thesis focuses on advancing the understanding of traffic safety issues for cyclists at roundabouts by identifying concerns faced by cyclists and evaluating their designs to find out which configuration has high or higher safety level towards cyclists. The research approach adopted in this work includes a wide review of relevant literature on cyclist safety and roundabouts and the implementation of empirical research, the latter was carried out through a Case Study in Norrköping city by obtaining cyclist related accident data from Swedish Traffic Accident Data Acquisition database to identify roundabouts with high cyclist-related accidents in the city assisted with PTV Visum Safety tool and fetching traffic volume from city network model operated by Norrköping Municipality for each identified roundabout. The main findings from this research conclude that single-lane roundabouts with separated cycle paths in high traffic volume setting provide better or higher safety performance for cyclists compared to other roundabout configurations.

Keywords: Cyclist Safety, Roundabout Designs, Geometric Elements, Safety Assessment, Safety Performance, Traffic Safety
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1. Introduction

Even though cycling has potential health benefits as an active transport mode (Harris et al. 2013), cyclists are considered as vulnerable road users (VRUs). Because cyclists with exposed human body are oftentimes unprotected (sometimes with bicycle helmet) and fragile most of the time, and they can fall easily and sustain severe injuries (Wegman et al. 2012; Cripton et al. 2014; Evgenikos et al. 2016). Wegman et al. (2012, p.19) also asserted that “Often cyclists fail to obey the traffic rules and show unexpected behavior in the eyes of other road users. The consequence is that cyclists have a relatively high crash rate compared to that of pedestrians and particularly that of drivers”. It shows that cyclists perceive higher risk in terms of collisions when compare to other road users under certain conditions (Sanders 2015).

According to Harris et al. (2013), there is observed difference in cycling safety which depends on the road infrastructure integrated with bicycle specific infrastructure or not, with bicycle specific infrastructure, such as bike paths, bike routes, painted bike lanes, injury risks were mitigated to the minimum. And higher risks were involved on the sidewalks and multi-use trails. From the conclusions of Harris et al.(2013), injury risks of cyclists at intersections or roundabouts were influenced by several variables, the significant one is route types (major streets, minor streets, etc.) meeting at the intersection or roundabouts, the rest are cyclist travel direction, motorized vehicle speed, intersection type, cyclist traffic count, etc.

1.1. Background

Intersections are normally 4-way intersections (4-arm junctions) or 3-way intersections (T junctions or Y junctions). And roundabouts are deviation from the traditional intersections, which have circular junctions with an island in the center, where traffic moves in an anti-clockwise direction (in countries with a drive right policy)(Sakshaug 2009). As stated by several studies (Brüde & Larsson 1996; Daniels et al. 2008; Hels & Orozova-Bekkevold 2007; Daniels et al. 2011; Daniels et al. 2010), conversion of intersections into roundabouts have been increasing in the past decades, both in Europe and in the US, also gaining popularity in some other countries and regions that were not converted in the past. Due to roundabouts have resulted in fewer traffic accidents causing injuries and fatalities, and have positive effects in traffic safety, and been shown that significant reduction of the number of crashes with fatalities and injuries (Daniels et al. 2008; Hels & Orozova-Bekkevold 2007), especially for motorized vehicle traffic. Brüde and Larsson (1996) described, a Danish study shown that there were 85% reduction in injury accidents for cars, but the safety effects for other types of road users related to roundabouts are less favorable or uncertain, in particular for cyclists (Hels & Orozova-Bekkevold 2007). Daniels, et al. (2008) acknowledged that, in the Netherlands, there were only 30% reduction of cyclists accidents at a roundabout, while other types of road users had substantial reductions, 95% for motorists; 63% for pedestrians; 64% for motorcyclists, etc. However, this is the data from only one specific country, but it may bring up and reflect the issues with cyclists who are experiencing at roundabouts on an international level.
In a roundabout, cyclists will mostly involve with motorists for interactions, and Sakshaug et al. (2010) consider one crucial issue for cyclist safety is that motorists sometimes neglect to see cyclists, when they primarily look for other motorized vehicles, especially when a car driver enters or exits the roundabout, while a cyclist is circulating in it. Therefore, it would not be a safe solution to integrate cyclists with motorized vehicles under certain settings, so geometric designs/features of roundabouts will be one of the key factors to correlate and affect the safety for cyclists, as shown in Fig 1.1.

The purpose of this study is to advance the understanding of traffic safety issues for cyclists especially at roundabouts, in this work, the main objective for the author is to identify the issues/concerns encountered by cyclists at roundabouts and evaluate geometric designs/features of roundabouts, and it is interesting to find out which configuration has high or higher safety level towards cyclists under certain circumstances, and use certain roundabouts in Norrköping city as a case study to complement the project.

Figure 1.1. Roundabouts and traffic safety: Chain of events (Daniels & Wets 2005)

1.2. Aim

The overall aim of this research is to advance an understanding of traffic safety issues for cyclists at roundabouts, using certain roundabouts in Norrköping as a case study.

Specifically, within the context of traffic safety, the following research questions would like to be answered in helping to achieve aforementioned aim:

- What are the traffic safety issues/concerns encountered by cyclists at roundabouts?
- What are the common traffic safety issues faced by cyclists in general?
- What are the differences between roundabouts and traffic circles?
- What are the traffic safety effects at roundabouts in comparison to conventional intersections?
- Which design of roundabouts integrated with cyclists in general can have higher safety performance towards cyclists?
- What are the overall safety performance of the identified roundabouts for cyclists in Norrköping? And which roundabout is the most hazardous towards cyclists?
1.3. Limitations

- The daily volumes (AADT) of cyclists and motorized vehicles are presented at the identified locations, which were fetched from Norrköping city network model. The data were collected by Norrköping Municipality during a full year in 2014.

- The case study of this work only focused on urban roundabouts (for right side driving countries) and their relations with cyclists, rural roundabouts were not included. Since the collected dataset of the 4 selected roundabouts is rather small, therefore, only the safety performance assessment of the most hazardous location for cyclists will take place based on certain geometric features of the location instead of using the Safety Performance Functions (SPFs).

- Since the identified roundabouts in the case study are only 4-arm roundabouts with separated cycle paths, so analysis and discussion of other design types of roundabouts which are integrated with cyclists are not considered.

1.4. Methodology

For the methodology, the author first starts with literature review of common issues for cyclists to identify problems and concerns of bicyclists in terms of traffic safety in general. Followed by reviewing traffic safety effects at roundabouts in order to have a deeper understanding on the characteristics of roundabouts compared to traffic circles and discuss the differences in terms of speeds and conflicts compared to conventional intersections. Subsequently, designs of roundabouts which integrate with cyclists are discussed to find out which design has better safety performance towards bicyclists, and also safety issues for cyclists at roundabouts are reviewed with respect to clarify the correlation between safety level of cyclists and roundabouts. Cyclist safety at roundabouts in certain countries will be discussed is to share some insights regarding the relation between cyclist safety and roundabouts in those countries. Based on the review of Accident Prediction and Assessment Models for intersections/roundabouts, the assessment of safety performance level with respect to certain geometric features of the most hazardous roundabout for cyclists in the city will take place, and through comparison of the results of the acknowledged roundabouts that based on the collected variables from the case study in order to identify which location will be the most hazardous for cyclists.

For the data collection, recent historic accident data of the city (cyclist related accidents at roundabouts) were collected from STRADA (Swedish TRaffic Accident Data Acquisition) database at Transportstyrelsen (Swedish Transport Agency) from January 2010 to September 2017. Accident data (locations of accidents were geo-referenced) will be imported into Visum Safety application and incorporated with the network model of Norrköping (received from Norrköping Municipality) on the Open Street Map to pinpoint roundabouts with high cyclist related accidents using heat map visualization within the software for the case study. The daily volume (Annual Average Daily Traffic, also known as AADT) of motorized vehicles and cyclists at the selected locations were obtained from Norrköping municipality, which will be applied as a major part of the variables to the accident assessment for the case study.
1.5. Thesis Outline

Chapter 1 introduces the background of information on relation between cyclist safety and roundabouts in general, shows that reduction of accidents for cyclists is uncertain at roundabouts compared to other road users and led to the aim of this work. It also lists out the research objectives to achieve the aim. In addition, limitations and methodology are presented.

Chapter 2 presents literature review according to the research objectives and the aim of the work. It starts out with common traffic safety issues related to cyclists, traffic safety effects at roundabout, and then to cyclist safety concerns at roundabouts, roundabout designs integrated with cyclists, cyclist safety at roundabouts from several European countries (includes Sweden). Afterwards, accident prediction and assessment models for intersections/roundabouts is discussed.

Chapter 3 illustrates the case study. It first gives details and statistics of cyclist safety in Norrköping city, and followed by the discussion of cyclist safety at roundabouts in the city to identify which roundabouts have higher cyclist related accidents based on the STRADA data. Information of each of the identified roundabouts was provided and discussed in detail.

Chapter 4 reveals the results that collected from the case study, and finds out which identified roundabout is most hazardous towards cyclists in the city. Followed by the discussion of safety performance assessment of the most hazardous roundabout based on evaluation of certain geometric elements of the roundabout.

Chapter 5 gives the summary of findings from the research objectives of the work and conclusions based on the findings and the case study of the work.
2. Literature Review

2.1. Common Traffic Safety Issues Related to Cyclists

Before the author gets into traffic safety issues/concerns encountered by cyclists at roundabouts, would like to firstly discuss certain common issues which cyclists are experiencing in relation to traffic safety in this chapter. These issues will be reviewed over into the following subsections, such as under reporting of casualties for cyclists, cyclists’ casualties in relation to different age range and gender, and causes of risks and injuries for cyclists (Wegman et al. 2012).

2.1.1. Under Reporting of Casualties for Cyclists

One well known phenomenon for vulnerable road users, especially for cyclists, is the reporting rate of crashes inclines toward lower part of the scale when compared to other transport modes (Wegman et al. 2012). Even those crashes involve cyclists with severe injuries are not reported to the police constantly. Motorists are more likely to be reported and recorded when hospitalized than vulnerable road users (Derriks & Mak 2007; Wegman et al. 2012). Wegman et al (2012) illustrated a study from the Netherlands in 2009, showed the police records included 59% of severe injuries in motorist collisions, and only approximately 4% of the injuries were recorded without participation from motorized vehicles (e.g. bicycle and bicycle collisions), when comparing severe traffic casualties in the hospital database with police data. Therefore, the factual number of cyclists’ casualties are overly underrated by the police.

Derriks and Mak (2007) acknowledged that under reporting is biased and selective towards vulnerable road users, and under reporting rate for cyclists is higher than the average under reporting rate. According to Kaplan et al. (2017), under reporting is not allocated stochastically, but depends on the bias selection towards police control area, crash location, involved road users, and crash severity. Estimation of under reporting rates of bicycle crashes differs from countries to countries, it can range from 3% in Nicaragua to 26% in New Zealand and 80% in France. And Denmark surprisingly has one of the highest under reporting rates in the world, considers the country is one of the top 5 countries within the context of high bicycle shares per trip or modal split in the world. Only 10% of the bicycle crashes in Denmark have been put into the official recording systems collected by the police (Kaplan et al. 2017). Sweden also has considerably high under reporting rate compared to other transport modes in recent decades, as shown in Table 2. 1. Wegman et al (2012) and Kaplan et al. (2017) agree on under reporting rate is significantly lower, especially there are only bicycle crashes without motorized vehicle involved in which having lighter injuries. (bicyclists fell, tripped, or bumped with an obstacle)(Räsänen & Summala 1998; Evgenikos et al. 2016). Consequently, it would obfuscate comparisons on the international level, and have biased judgments against safety analysis among countries, injury and crash data of cyclists should be used with cautiousness. So, there is a need to create one standardized international reporting systems for accident data in order to unify and access the data across different countries in the world. Good data can give nonbiased
analysis towards traffic safety problems for road users, in this case, proper measures can be applied to specific traffic safety problems for cyclists at roundabouts.

Table 2. 1. Ratio between casualties recorded in the hospital database and casualties collected by the police in Sweden from 1998-2002

(the higher the number, the higher the underreporting rate)
(Derriks & Mak 2007)

<table>
<thead>
<tr>
<th>Transport Modes</th>
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<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
</tr>
</thead>
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<td>1.7</td>
<td>1.86</td>
<td>1.88</td>
<td>2.03</td>
<td>1.81</td>
</tr>
<tr>
<td>Motorcyclists</td>
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<td>3.74</td>
<td>3.75</td>
<td>3.65</td>
<td>3.29</td>
</tr>
<tr>
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<td>7.47</td>
<td>7.83</td>
<td>8.23</td>
<td>8.47</td>
</tr>
<tr>
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<td>2.39</td>
<td>2.71</td>
<td>2.27</td>
</tr>
<tr>
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<td>3.17</td>
<td>3.18</td>
<td>3.29</td>
<td>2.98</td>
</tr>
</tbody>
</table>

2.1.2. Cyclists Casualties in Relation to Different Age Range And Gender

According to the statistics from European Road Safety Observatory (2016) in 2014, 2112 bicyclists were killed in road traffic accidents in the 32 EU countries, accounting for 8.1% of total road traffic fatalities. From the results of a more specified analysis by age groups and gender, cyclists who were equal to or older than 65 years old taking up high percentage of fatalities across Europe approx. 44%, as the cause of a traffic accident, as shown in Fig 2. 1. And 79% of all bicycle fatalities are male riders, though, with a significant difference between countries, for instance, 62% in the Netherlands and over 90% in Estonia and Romania. Evgenikos et al (2016) summarized that substantial regional differences in relation to the share of cyclists fatalities differing widely between countries, can be determined by the combination of two factors: the cycling infrastructures of a country and the use of bicycles (cycling culture and exposure). However, comparison of these graphs and figures with the ones from other continents or parts of the world, which will possibly lead to whole different conclusion (Wegman et al. 2012).
Fig 2. 1. Different age groups in relation to cyclist fatalities across the EU countries  
(European Road Safety Observatory 2016)
validated the results which have shown that senior/elderly bicyclists who are aged between 70-80 years old, are having almost three times more at stake/danger than the average cyclists for involving with a road traffic accident. The most visible reduction can be observed in the elderly age group between 65-70 and the teenager age group between 12-17. Conversely, the peak of bicycle fatalities has disappeared within the same period for the age group between 12-17, whereas during that age period, kids or children are most likely to gradually be going for solo travel and undertaking independence (Evgenikos et al. 2016). However, it may implicate that traffic departments in the governments, schools, and parents across the EU countries did a good job putting high focus and priorities on traffic safety education for youth cyclists.

2.1.3. Causes of Risks and Injuries for Cyclists

Cyclists are usually vulnerable in crashes with other types of road users (e.g. motorized vehicles, heavy goods vehicles), because of the nature of cyclists’ fragility and lacking of protection (Wegman et al. 2008), as the author stated in Chapter 1.

Speeds can be one of the causes for cyclists to experience risks and injuries, even fatalities, in which they are interacting with other types of road users, especially when these road users are moving at higher speeds. In order for cyclists to survive under the crash, motorized vehicle crash speeds are necessary to stay under 30km/h. A straight forward solution should be given by isolating or separating cyclists from high speed traffic with motorized vehicles (Wegman et al. 2008; Siman-Tov et al. 2012; McNally & Rosenberg 2013). A study in California had shown that separation of bicycles and motorized vehicles reduced the crash rate between bicycle and car by 31% (Rowe et al. 1995).

Rivara et al (2015) mentioned, improperly use, misuse or lack of use of bicycle helmets were associated with substantial increase in fatality rate, thus, misuse or without wearing bicycle helmets can be one of the reasons for cyclists resulted in risks and casualties. And Siman-Tov et al.(2012) address that misuse or different use of helmets may result in higher rates of head injury, especially for children, because they are most commonly involved with off road accidents, that’s what helmets are really designed for (McNally & Rosenberg 2013). A case study in Seattle, U.S (Rivara et al. 2015) has shown that with the use of helmet for cyclists was associated with a 93% decrease in risk of fatality. These authors (Rowe et al. 1995; Bil et al. 2016; Rivara et al. 2015; McNally & Rosenberg 2013) agree that wearing a helmet significantly reduces the risk of death for cyclists, and bicycle helmets are more effective particularly when a cyclist falls from a bicycle or crashes into an obstacle (non-vehicle collision accidents). For low speed vehicle collisions, helmet can reduce or even eliminate the probability of a fatal head injury (McNally & Rosenberg 2013).

Misbehavior of cyclists is also a source to cause risks and injuries for themselves, because they often fail to follow traffic rules and show unexpected behavior to other road users, if they behave predictably (e.g. cross roads only when the lights are green, use their bicycle lights at night), then this will eradicate a cause of crashes to prevent risks and injuries for cyclists (Wegman et al. 2008).
2.2. Traffic Safety Effects at Roundabouts

In the past 20-40 years, roundabouts as a non-conventional type of intersection have gained more and more recognition and popularity as a solution on increasing traffic safety level on roads to reduce the number and severity of intersection crashes for pedestrians, bicyclists, especially vehicle occupants (Jensen 2017). In fact, roundabouts nearly exist as long as the period when cars were invented. The actual design of roundabouts originates from the large traffic circles or rotaries which were constructed in France in the early 19th century, and this kind of circular intersections was first introduced in the U.S. in 1905. But these prevalent designs at the time allowed high-speeding merging and weaving of vehicles, and no priority was given to circulating traffic, facilitating high-speed entries, thus, caused traffic congestion and high crash rate in the circles. Consequently, the experience with rotaries or traffic circles was negative not only in the U.S. and also on an international level. However, in 1960’s, the modern roundabout was developed in the United Kingdom to resolve problems correlated with these traffic circles which adopted an obligatory yielding rule at all circular intersections (i.e. the traffic in the roundabout has right of way), which required entering traffic to give way to circulatory traffic. And this rule prevented circulatory carriageway getting congested and locked up by not allowing vehicles to enter the carriageway until there were sufficient gaps in circulating traffic (Daniels & Wets 2005; Robinson et al. 2000). Therefore, it is critical to know traffic safety effects at roundabouts compared to conventional intersections or other circular intersections, why roundabouts are the preferred solutions at crossroads on increasing traffic safety level.

Under the sub-sections, the author will firstly discuss characteristics of roundabouts and differences with traffic circles or rotaries, afterwards, safety effects of speeds and conflicts at roundabouts in comparison to conventional intersections will be discussed. Most of the discussions and reviews are based on the work issued by these authors or organizations (Robinson et al. 2000; Daniels & Wets 2005; National Research Council Transportation Research Board 2000). More details are in their work.
2.2.1. Characteristics of Roundabouts

Roundabouts were briefly introduced in Chapter 1, and three main features of roundabouts are the central island (raised), the splitter island (raised or painted, mostly raised), and the circulating roadway (Robinson et al. 2000), as shown in Fig 2.3. The author would like to discuss about the characteristics of roundabouts in order to clear some confusion between roundabouts and traffic circles or rotaries. Since these distinctions may not always be obvious, therefore, it is critical to have the ability or knowledge to distinguish roundabouts from traffic circles for public understanding. A roundabout can be distinguished from a traffic circle in general by the following characteristics, listed by Highway Capacity Manual (2000, pp.10–31):

- Circulating vehicles have the right of way at a roundabout. Some small traffic circles are unable to deflect vehicle paths properly to achieve the desired speed reduction, because of right-of-way constraints.

- Vehicles speed into and through roundabouts is controlled by the physical features of a roundabout and not by signs or pavement markings.

- All vehicles circulate counterclockwise (in countries with a drive right policy), passing to the right of the central island. In some small traffic circles (sometimes called mini–traffic circles), left-turning vehicles are expected to pass to the left of the central island.

- Roundabouts are designed to properly accommodate specified design vehicles (e.g. heavy goods vehicles). Some smaller traffic circles are unable to accommodate large vehicles, usually because of right-of-way constraints.
Roundabouts have raised splitter islands on all approaches. Splitter islands are an essential safety feature, required to separate traffic moving in opposite directions and to provide refuge for pedestrians (and cyclists, depends on design of the roundabout). Some smaller traffic circles do not provide raised splitter islands.

Some small circles do not control speed, because the central island diameter is rather small and the radius of the vehicle path is large.

No parking is allowed on the circulating roadway. Parking maneuvers, if allowed, would prevent the roundabout from operating in a manner consistent with its design. Some larger traffic circles permit parking within the circulating roadway.

No pedestrian or cyclist activities take place on the central island. Pedestrians are not expected to cross the circulating roadway. Certain larger traffic circles provide for pedestrians and cyclists crossing to, and activities on the central island.

When pedestrian and bicycle crossings are provided for on the approach roads, they are placed approximately one car length back from the entry point. Some traffic circles accommodate pedestrians in other places, such as the yield point.

According to the aforementioned characteristic of roundabouts, general reasons of modern roundabouts on improving traffic safety can be summarized into the following points (Hydén & Várhelyi 2000):

- Road users approaching the roundabout must yield to the traffic inside the circulatory roadway;
- All traffic inside the circular carriageway comes from one direction;
- Roundabouts eliminate left turning movements in front of approaching traffic;
- Roundabouts reduce the number of conflict points among traffic flows; and
- Lateral displacement or deflection (depends on curvature of entries and exits, and inscribed diameters of central island) reduces speed.

Fig 1.1 shows safety effect of roundabouts can be classified into or based on speeds, conflicts, and other effects such as traffic operations, emissions, etc. Moreover, effects on speeds and conflicts are the two dominant factors for roundabouts at which significantly reduce accident rate and crash severity for majority of the road users (for bicyclists, the reduction is less substantial or unclear, according to the studies mentioned in Background section) compared to conventional intersections or other types of intersections.
2.2.2. Effects on Speeds at Roundabouts Compared to Conventional Intersections

Compared to nature of the design for conventional intersections, which often large differences in speeds among different road users are recorded (Daniels & Wets 2005). Roundabouts, on the other hand, provide low and consistent speeds (i.e. low relative speeds for different road users in comparison to each other) for different types of vehicles and vulnerable road users, such as cyclists, required by its physical design, as stated earlier. Moreover, based on the information given by Federal Highway Administration from the U.S. (2000), good design of roundabouts puts a high priority on speed consistency and speed reduction. Geometric features of roundabouts predominantly determine speed control with the integration of traffic control devices (e.g. yield sign) and/or the impedance of other traffic. To be more specific, the speed of approaching traffic is largely influenced by the deflection forced by the roundabout. And the deflection or lateral displacement is done by the curvature or the angle of the entry (approaching lane) and the inscribed diameter of the central island (Hydén & Várhelyi 2000).

Theoretically, a roundabout with good design for low vehicle speeds (generally less than 30km/h) should deliver the following safety effects or benefits which conventional intersections hardly provide (Robinson et al. 2000, p.24):

- Collisions severity can be reduced for cyclists and pedestrians, also including handicapped persons, children, elderly pedestrians;
- Provide enough reaction time for entering motorists to consider, adjust speed for, and enter a gap in circulating roadway;
- Permit secure merges into circulatory traffic;
- Give more time for all road users to detect and correct for their errors or errors of others;
- Present crashes in a less frequent and less severe manner; and
- Let the intersection safer for novice users.

Thus, it is essential for road users who are not under the protection of a motorized vehicle experience less crash severities when involved in an accident by minimizing the difference in design speed of roundabouts and speed of road users. Because Robinson et al. (2000) concluded that the severity of a crash is influenced mainly by the speed of impact (and the angle of impact.), the higher the speed, the more severe the collision. For instance, typical commuter cyclist speed is approx. 25km/h (Robinson et al. 2000), if good design is achieved at the roundabout, then vehicle speeds are less than 30 km/h, the difference of the speed is around 5 km/h, when there is an accident involved between these two road users, the cyclist is more likely to survive and has lower level of crash severity than at a roundabout with higher speed design (or i.e. large speed differences between the bicyclist and the motorist). As mentioned in Chapter 2.1, speeds can be one of the causes for cyclists getting involved with risks and casualties. Therefore, to constrain the speed difference of different road users at roundabouts may potentially improve the safety level for bicyclists.
The number of conflict points has the direct influence on the frequency of crashes at an intersection. The definition of a conflict point is “a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other.” (Robinson et al. 2000, p.104). For conventional intersections, traffic control devices and segregated turn lanes cannot eliminate the number of crossing conflicts but reduce them by separating conflicts in time and/or space. Compared to traditional intersections, the reason for which roundabouts can reduce severity or eliminate many severe conflicts, is due to crossings of road users are eliminated as potential conflicts (i.e., eliminate crossing conflicts by converting all movements to right turns), especially for single-lane roundabouts. As you can see in Fig 2. 4., the number of conflict points at a roundabout with four single lane approaches where traffic flows merge or diverge is decreased to half of the number of conflict points at a traditional four-leg intersection. The total number of conflict points at a single lane roundabout is four times lesser than the ones at a conventional four leg intersection, at which leads to a 75 percent decrease. Subsequently, less conflict points may present fewer chances or possibilities for crashes (Daniels & Wets 2005; Robinson et al. 2000).

![Diagram of intersections](image)

**Figure 2. 4.** Comparison of vehicle conflict points between an intersection and a single-lane roundabout  
(Robinson et al. 2000)

Besides conflicts with other road users, one particular hazard emerges that the central island of a roundabout can appear to be an obstacle which may result in a raised level of single vehicle collisions, where incline to happen during low traffic volume (Robinson et al. 2000; Daniels & Wets 2005).
Basically, as illustrated in Fig 2. 4, vehicle conflicts can be categorized into three types, from which the degree of severity differs, as follows (Robinson et al. 2000):

**Queuing conflicts.** These conflicts are caused by a vehicle driving into the back of a vehicle queue on an approach lane. These types of conflicts can occur at the back of a through-movement queue or where left-turning vehicles are queued waiting for gaps (commonly happens at a conventional intersection). These conflicts are typically the least severe of all conflicts.

**Merge and diverge conflicts.** These conflicts are caused by the connecting or separating of two traffic streams (present at both conventional intersections and roundabouts). Merge conflicts cause the most common types of collisions which are sideswipes and rear-end collisions. Merge conflicts can be more severe than diverge conflicts due to having the inclination on the likelihood of collisions to the side of the vehicle, which is characteristically less protected than the front and rear of the vehicle.

**Crossing conflicts.** These conflicts are caused by the intersection of two traffic streams. These are the most severe of all conflicts and the most likely to involve injuries or fatalities. Typical crash types are right-angle crashes and head-on crashes (the most severe vehicular crossing conflicts at single lane roundabouts usually are eliminated, and substituted by less severe merging conflicts, for double lane roundabouts, the situation is somewhat different and the safety performance is poorer).

In addition, when the traffic control device at signalized intersections is configured to separate conflicts by time (e.g. traffic signals) got violated, the most severe crashes will occur, for instance, vehicle-pedestrian crashes, right angle crashes (e.g. continue driving when the signal is red)(Robinson et al. 2000). Thus, in comparison to conventional intersections, the ability of single-lane roundabouts to reduce conflicts through the perspective of geometrical features and physical designs has been demonstrated to be more effective than the dependence on motorists’ compliance of traffic control devices (Elvik 2017; Retting et al. 2001; Persaud et al. 2001; Robinson et al. 2000). More details are discussed in *Roundabouts: An Informational Guide* issued by Federal Highway Administration (FHWA), U.S. Department of Transportation (Robinson et al. 2000).
2.3. Bicyclist Safety Concerns at Roundabouts

In Chapter 2.2, traffic safety effects at roundabouts have been discussed, although safety effects in general are positive towards all road users, the safety effect especially for cyclists is still unclear, and in some studies even presented in a negative way (Daniels et al. 2008; Jensen 2017).

In the study which carried out by Daniels et al. (2008) in Belgium, after studying 91 roundabouts in total, they found that roundabouts increase the number of injury accidents for cyclists by 27%, and of fatal and severe injuries by 41-46% due to having conflicts mostly with motorists. Thus, interactions between cyclists and motorists at roundabouts will be discussed in this section in order to identify why the safety level is uncertain for bicyclists at roundabouts.

![Figure 2.5. Bicycle conflicts at roundabouts (Robinson et al. 2000)](image)

Depending on the design and configuration of a roundabout (which will be discussed further in Chapter 2.4), bicyclists should be offered with the option of traveling as either a pedestrian or a vehicle through the roundabout (Robinson et al. 2000). Subsequently, in terms of experiencing the conflicts, cyclists are determined on how they select to interact with the roundabout based on the design. When a cyclist traveling as a vehicle at a single-lane roundabout, which means the road user is integrated into motorized traffic and riding on the entry lane, circulating roadway and exit lane with other vehicular occupants, so an additional conflict may occur at the location or point where the bicyclist merges into the traffic stream; the rest of the conflicts are similar to those for motorized vehicles (Robinson et al. 2000), as illustrated in Fig 2.5.
this kind of conflicts for treating cyclists as vehicles will normally happen at mixed traffic roundabouts and roundabouts with adjacent cycle lanes. Compared to mixed traffic roundabouts and two other design types (roundabouts with separated cycling paths; roundabouts with grade-separated configuration), mentioned by the Belgian study from Daniels et al (2009), roundabouts with adjacent cycling lanes had worse performance in terms of the safety effect on all injury crashes for bicyclists. (see also (Daniels & Wets 2005; Brüde & Larsson 1996; Dijkstra 2005)). Also, a Swedish study (Sakshaug et al. 2010) showed that the biggest concern for cyclists at integrated roundabouts (i.e., mixed traffic) is entering motorists are not yielding to circulating cyclists, 4 out of 10 conflicts occurred under this kind of interaction in this study. Since the cyclist can enter in parallel with motorists on the circulatory roadway, regarding the parallel situation in relation to accidents, the main concern for cyclists will be a driver exits the roundabout, whilst the bicyclist is still circulating on the carriageway. Moreover, according to their study, another issue is that motorized vehicles do not perceive driving in parallel as a hazardous behavior, when motorists exit the roundabout, only 32% of the motorists stayed behind a cyclist compared to 50% of the drivers did not stay behind the bicyclist when entering and circulating the roundabout.

When travels as a pedestrian at a roundabout, which means conflicts with motorized traffic emerge at the points where the cyclist rides onto the bicycle crossings (adjacent to the pedestrian crossing) at the entry lanes and the exit lanes (i.e. the motorist and the cyclist meet perpendicularly). This kind of conflicts for cyclists usually applies to roundabouts with separated cycling paths. Based on the arrangement of priority in regard to cyclists (given or not given) at the roundabout, the safety effects for cyclists tend to differ, according to the traffic statistics from several studies (Dijkstra 2005; Daniels & Wets 2005).

In the Dutch study from Dijkstra (2005), showed that when cyclists are without priority at the separated roundabout, there is 87% reduction of crash injuries compared to conventional intersections, and when priority is given to cyclists at the roundabout, the reduction rate is 11% in comparison to ordinary crossroads. One study cited in the research from Daniels and Wets (2005) validates the aforementioned result from Dijkstra, shows that the cyclists without priority (0.04 victims per million passages) had lower accident rates compared to the cyclists with priority (0.16 victims per million passages). Regarding the conflicts, there is also an interesting finding in that research from the authors, they mentioned that in one Dutch research project, observations were made on the yielding behavior between cyclists and motorists at roundabouts with separated cycling paths. When bicyclists have the priority status, regardless of their priority arrangement, there still were approximately 20% of the cyclists seemed to halt and yield to motorists. When the priority is not given to cyclists, cyclists were given way by the motorists around 33% of the cases instead. And the yielding rates of approaching traffic (46% of the cases) was much higher than with exiting traffic (14% of the cases). The result of that study indirectly agrees to the opinion from Sakshaug et al. (2010), which is in the separated roundabout, it is conspicuous for these two road users that one of them is obliged to yield, but that does not mean the yielding rules are clearly aware or acknowledged by either motorists or cyclists, even though both parties are obligated to yield based on priority rule arranged at the roundabout. Thus, there is a possibility to say that when the yielding rules at the separated
roundabout are getting more unclear, in this case, cyclists are paying more attention at the crossing and slowing down their movements, which will putatively lead to lower crash rates or risks for cyclists. For separated roundabouts, Sakshaug et al. (2010) concluded that cyclists will have lowest yielding rate from motorists when motorized vehicles exit the roundabout while cyclists are moving in a counterclockwise or circulating direction (for right side driving countries), i.e. cyclists coming from the right side in exiting motorists’ point of view. However, majority of accidents happen at separated roundabouts when drivers enter or exit the roundabouts at the same time as cyclists are riding in the clockwise (against circulation) direction. In addition, Rasanen & Summala (2000) acknowledged in their study that entering drivers gave priority more to cyclists moving in a circulating direction at roundabouts.

2.4. Roundabout Designs Integrated with Bicyclists

Different countries have various designs for roundabouts, and there are some standard types of designs for cyclists can be recognized. In general, the designs of roundabouts can be fallen into four categories with the considerations of cyclists, listed as below (Daniels et al. 2009):

- Mixed traffic roundabout
- Cycle lanes within the roundabout (also known as adjacent cycle lane roundabout)
- Separated cycle paths (with or without priority for cyclists)
- Grade separated (multi-level) cycle paths

The author will discuss further these four basic types of roundabout designs for cyclists in the subsections respectively, and start with description of roundabout designs, follow up with findings review from journals, conference proceedings, etc., on effects of roundabout designs correlated to safety of cyclists.

2.4.1. Mixed Traffic

Mixed traffic can be described as treating cyclists the same manner as motorists, and share the same entry lane, exit lane, and carriageway as other types of road users before and after the roundabout (Sakshaug et al. 2010), let cyclists traffic and motorists traffic form one mixed flow, and integrate into the roundabout, see Fig 2. 6.
As stated in previous studies (Andersen et al. 2000; Daniels et al. 2009), this kind of roundabout design, which excludes specific facilities for cyclists, is a common solution for some countries. But the disadvantages of the design regarding cyclists are emerged, especially when cyclists are facing high volume traffic at high speeds at the roundabout. Physically and psychologically, cyclists will feel unsafe and insecure towards them. So, the roundabout should be designed with low traffic volume and suitably slow speeds to ensure cyclists’ safety. According to Brüde and Larsson (1996), a Dutch study has shown, if the average daily traffic (ADT) flow is over 8000 motorized vehicles, then the safety level of cyclists is perceived as less favorable in the mixed traffic design.

2.4.2. Adjacent Cycle Lanes

Adjacent cycle lanes roundabout is similar to mixed traffic roundabout, the only difference is there is a lane marking (may use a different pavement or painted in different colors, e.g. red, green, blue) or a slight elevation are constructed on the outer side of the roundabout, adjacent to the carriageway, it may seem motorists and cyclists have their own road facilities (Daniels & Wets 2005; Daniels et al. 2009; Sakshaug et al. 2010). And normally, there is no actual
physical barrier between cyclists and motorists at the roundabout. Therefore, the roundabout can be interpreted as a slight variation of the mixed traffic roundabout, as shown in Fig 2.7.

For adjacent cycle lanes, there should be a huge potential risk of serious conflicts, when motorists are about to enter or exit the roundabout, cyclists circulating around in it, and vice versa. Second case will be these two road users circulating in parallel, when the motorist exits, but does not yield to the cyclist. Other scenario will be heavy good vehicles (trucks, buses, lorries, etc) riding parallel with cyclists, they enter or exit the roundabout without noticing cyclists, because of limited sight of large sized vehicles, and may cause severe conflicts (Daniels & Wets 2005; Sakshaug et al. 2010).

Sakshaug et al.(2010) examined in their conflict studies in Sweden, shown that 10 serious conflicts happened during a 3-day period in the integrated roundabout, is equal to 4.6 conflicts per 1000 cyclists and 0.2 conflict per 1000 motorists. And Daniel et al.(2009) concluded that roundabouts with cycle lanes have higher injury crashes rate compared to other designs from their Belgian field study. Similar to mixed traffic design, we would suggest the adjacent cycle lanes design applied for low, medium traffic flow and low speeds conditions. Therefore, Sakshaug et al.(2010) mentioned that if average daily traffic volume for motorized vehicles is under 8000 veh/day, the safety difference is less clear, and on-road cycling design might be just safe or safer than separated cycle paths, as previously stated.

2.4.3. Separated Cycle Paths

![Figure 2.8](image)

Figure 2.8. Roundabout with separated cycle paths

(Left: Priority Given to cyclists; Right: No Priority Given to cyclists)

(Daniels et al. 2009)
Roundabout with separated cycle paths is to construct cycle facilities alongside with pedestrian paths outside the carriageway of roundabout, use different pavements to characterize between pedestrian paths and cycle lanes (Sakshaug et al. 2010; Daniels & Wets 2005; Daniels et al. 2009), but one or more lanes need to be crossed for cyclists to get around the roundabout, in this case, cyclists and motorists can have better sight and awareness of the presence of each other. One alternative will be given priority to cyclists over motorists’ traffic, the other will be no priority to the cyclists, as shown in Fig 2. 8.

With the priority given to cyclists at the roundabouts, according to the study from Dijkstra (2005), the author summarized that only 11% less injuries or casualties than on the regular types of intersections. But the Dutch study was found that if there is no given priority for cyclists on the separated cycle lanes, the reduction was improved significantly, it resulted in 87% less injuries or casualties than on the conventional intersections. The results show the substantial differences of the safety effects between the priority given to cyclists and without priority to the cyclists on separated cycle paths at roundabouts, therefore, it indicates that when go for separated cycle lanes design for roundabouts, the preferred solution should be given no priority to the cyclists, in order to prevent high percentage injuries and fatalities occur at roundabouts. Also several authors (Jensen 2017; Daniels & Wets 2005; Rasanen & Summala 2000; Sakshaug et al. 2010) suggest to use the separated cycle paths design in order to mitigate injuries or casualties to the minimum for cyclists at roundabouts, especially with high traffic volume.

2.4.4. Grade Separated Cycle Paths

Grade separated cycle paths also known as multi-level cycle facilities, where cycle paths (also pedestrian paths) are integrated into the bridges above/as the roundabout or underpass the roundabout as tunnels, for the purpose of isolating vulnerable road users traffic (e.g. cyclists, pedestrians, etc) from motorized traffic, whether priority is given to cyclists or not (Mulvaney et al. 2015), as shown in Fig 2. 9.
According to Schepers et al. (2017), they mentioned grade separated cycle paths solution has positive impacts on reducing the fatality crash rate at intersections, and measured that 24% possible reduction of fatal bicycle crashes after Dutch municipalities were applied to the solution. Therefore, it implies that when the design is applied to roundabouts, will also show greater positive influence in terms of the safety level of cyclists. But the drawbacks of grade separated solution are high costs on the construction, and are complex on building the infrastructure, consuming huge amount of space, in order to suit the safety needs of cyclists or pedestrians alone, it would not be a wise option to just consider one aspect and neglect other aspects, such as, cost benefit analysis, time consumption on construction, etc. Even though, cyclists’ safety is important, needed to be taken into account (Dufour 2011). Moreover, these researchers (Brüde & Larsson 2000; Schramm et al. 2014; Daniels et al. 2009; Brilon 2011; Hydén & Várhelyi 2000; Daniels & Wets 2005; Sakshaug 2009; Sakshaug et al. 2010; Hels & Orozoa-Bekkevold 2007) did not give opinions on the grade separated cycle lanes solution should be the first choice to ensure cyclists’ safety at roundabouts. Therefore, this design might not be recommended for majority of the cases.

2.5. Cyclist Safety at Roundabouts from Certain European Countries

In this chapter, the author will discuss roundabout designs and configurations from the countries (designs of roundabouts vary among countries) where cycling are really popular and take up high percentage from their local trips, especially in European countries, for instance, 27% in the Netherlands, 18% in Denmark, and 10% in Sweden, etc, as displayed in Fig 2. 10. Furthermore, what is the relation between roundabouts and cyclists’ safety in these countries.
2.5.1. Cyclist Safety at Roundabouts in the Netherlands

According to Ministry of Transport/Public Works and Water Management in the Netherlands (2009), cycling is really prevalent activity in the country, when the distance is up to 7.5km, the first choice of transport will be bicycle, and it took up 34% of all trips back in 2007. In urban area, the bicycle share is even higher, about 50% above the average in the Netherlands (26%, the average of cycle share), in cities like Groningen and Zwolle.

The general design of entries at roundabouts is recommended to be radial in the Netherlands (Schramm et al. 2014), as mentioned above, the perks for this design are to have better sight conditions, and create lateral displacement in the roundabout which reduces vehicle speeds. Brüde and Larsson(1996) summarized that, roundabouts in the Netherlands have single lanes and are reasonably small, yielding rule is similar or the same as in Sweden, entering vehicles should have yielded to circulating vehicles at the roundabout. Cyclists have their own bicycle facilities outside of the roundabout should yield to motorized vehicles. A Dutch study shown that roundabouts with separated cycle lanes can cater more than 8000 vehicles of daily traffic, while maintaining to reduce cyclists’ injuries or casualties at the roundabout(Brüde & Larsson 1996).
Regarding the priority regulation, for separated cycle paths at Dutch roundabouts which there is no given priority to cyclists, means cyclists must yield to motorized traffic (Räsänen & Summala 2000). Furthermore, Dijkstra (2005) confirms that cyclists with no given priority have resulted in significant reductions on casualties compared to the one with given priority to cyclists. Therefore, the author would recommend use separated cycle paths design at roundabouts (especially, when traffic volume is higher than 15,000 veh/day (Brilon 2011)), in which have no given priority to cyclists, to lessen injuries for cyclists.

2.5.2. Cyclist Safety at Roundabouts in Denmark

In Denmark, the culture of cycling is robust, developed over more than a century, especially in urban area (Andersen et al. 2000), cycling is taking up high percentage from people’s local trips, as indicated in Fig.. Cycling embassy of Denmark actively promotes and encourages more people to cycle, to increase bicycle traffic and improve safety on the road collectively, and also should put cyclists attentiveness into perspective when concerning their safety on road (Andersen et al. 2000). There are more than 1000 roundabouts in Denmark, which are popularly used to improve safety on road in the countryside and in cities (Andersen et al. 2000; Räsänen & Summala 2000; Jensen 2017), but roundabouts in Denmark do not constantly decrease injury rates of cyclists.

The general design of entries at roundabouts is recommended to be radial in Denmark (Schramm et al. 2014), the main advantage of this design is to create greater deflections in order to reduce vehicle speeds and improve visibility.

From the publication issued by cycling embassy of Denmark (Andersen et al. 2000), design standards on the width of entry lane should be smaller than or equal to 3.5 meters, for exit lanes, these shoud not be wider than 4 meters, and the authors recommend not to integrate bicycle traffic into the roundabouts with more than one lane in the circulating area or carriageway. Set 30-50 km/h speed limit for small roundabouts, suggest to mix cyclists with motorists into the one lane carriageway at the roundabouts. It indicates mixd traffic solution can be applied at small sized roundabouts with relatively slower speeds.

Several researchers have done a few swedish roundabouts’ studies (Brüde & Larsson 1996; Hydén & Várhelyi 2000) acknowledge that roundabouts with adjacent cycle lanes are indeed common in Denmark, even at larger roundabouts. However, there is barely any reliable information can be found regarding safety effects of cyclists at Danish roundabouts with adjacent lanes solution. Only one recent Danish study (Hels & Orozova-Bekkevold 2007) concluded roundabouts with high traffic flows, roundabouts followed by old design standards have higher accident risks.

The adjacent lane solution is not recommended from majority of the findings (Daniels et al. 2009; Sakshaug et al. 2010; Daniels & Wets 2005; Brüde & Larsson 1996; Räsänen & Summala 2000), considered as a doubtful solution to ensure cyclists’ safety at roundabouts.
2.5.3. Cyclist Safety at Roundabouts in Sweden

Sweden is a country where always prioritizes and emphasizes traffic safety first on the road. Swedish transport administration promotes the widely known road safety program called “Vision Zero”, which aims at reducing fatalities or severe injuries to zero on the road, and roundabouts can play a role in the road safety program to show significant results, if the key objective is to avoid severe injuries (Trafikverket 2015). Based on the historical data from Rasanen and Summala (2000), Sweden has now more than 750 roundabouts and counting. Therefore, it reflects that roundabouts have overall positive effects in relation to road safety measure in Sweden.

According to Schramm et al. (2014), the general design of entries at roundabouts is recommended to be tangential in Sweden, the advantage of this design is to maintain higher travel speeds for motor vehicles, and increase capacity. The design can be confirmed from the several field studies were conducted in Sweden (Sakshaug et al. 2010; Hydén & Várhelyi 2000). However, in author’s opinion, this design may not be favorable to cyclists’ safety depends on different features of roundabouts (e.g. mixed traffic roundabouts or roundabouts with cycle lanes), as previously stated, if the design supports higher speeds and capacity for motor vehicles, cyclists may not feel secure around the roundabouts.

The review from Schramm et al. (2014) on the study conducted by Sakshaug et al. (2010), conclude that yielding rules at roundabouts are crucial for both cyclists and motorists, should be clear as road users in Sweden. Motorists and cyclists should yield at crossing points at roundabouts with separated cycle paths, motorists should have more obligation to yield when exit a roundabout, cyclists should be aware of motorized vehicles at all time at a roundabout, should only cross when it is safe for them. At integrated roundabouts, entering vehicles should yield to circulating vehicles, whether vehicles are bicycles or motorized vehicles (Schramm et al. 2014). The study of Hydén and Várhelyi (2000) has shown that, car drivers were tended to have willingness to yield to entering cyclists with the installment of small roundabouts, and there was 60% reduction between bicycle and car accidents. Single-lane roundabouts, which radius of central island is equal to or larger than 10 meters, had resulted in less bicycle accidents per year compared to two-lane roundabouts (Brüde & Larsson 2000).

Overall, researchers from Sweden (Brüde & Larsson 1996; Sakshaug et al. 2010; Brüde & Larsson 2000) mostly recommend the roundabout design with separated cycle paths, and also it is the most common solution in Sweden. The solution has shown the most positive impacts on reducing cyclists’ accidents at roundabouts from their studies, however, assign priority (priority regulation) to road users (motorists or cyclists) on the design may differ from countries to countries, and with no given priority to cyclists within the solution tend to show better results on mitigating cyclists casualties at roundabouts (Dijkstra 2005).
2.6. Accident Prediction and Assessment Models for Intersections/Roundabouts

In terms of assessing the expected accident frequencies on entities such as roadways and intersections (e.g. unsignalized intersections; roundabouts, etc), it’s practical to set up accident prediction models. The estimations of accidents at the locations can usually be used during the ongoing process of identification of sites for potential treatments of traffic safety and in the evaluation of such treatments (Lord & Persaud 2000). In other words, this knowledge should be used to decide and judge whether a junction needs to be improved from the perspective of traffic safety. Essentially, an accident prediction model is a mathematical formula, which expresses the average accident frequency of a location as a function of traffic volume and other features for the location. Furthermore, it describes the relationship between explanatory variables that can explain the safety level (e.g. traffic volume, speed, road length etc.) and the safety level of the locations (i.e. injuries, severe injuries, fatalities, etc) (Lord & Persaud 2000; Eenink et al. 2005).

In terms of assessing safety performance level at junctions, traffic volume and potential geometric features can be two of the main associated factors for accident occurrences at a location. In addition, the relationship between possible geometric elements and accident rates that lead to the accidents at a location can be determined by the safety performance functions (SPFs) models, which are statistical regression models that calculate crash frequencies (Chiu 2014), therefore, the models can be applied for assessing safety level at the roundabouts with sufficient amount of sampling data.

In the following sub-sections, the author discussed over the topic of accident prediction models and safety performance assessments for intersections/roundabouts are based on several previous research studies, started with the review of model forms for APMs at intersections/roundabouts (Eenink et al. 2005; Adedokun 2016; Lord & Persaud 2000; Greibe 2003; Sayed & Rodriguez 1999; Brüde et al. 1998), followed by assessment of safety performance level at roundabouts associated with their geometric elements that potentially lead to traffic accidents (Aumann et al. 2017; Chiu 2014; Robinson et al. 2000).

2.6.1. Model Forms for APMs at Intersections/Roundabouts

The basic formula of almost all modern accident prediction models is as follows (Eenink et al. 2005; Adedokun 2016; Lord & Persaud 2000; Greibe 2003):

\[ E(\lambda) = \alpha \times Q^\beta \times e^{\sum y_i x_i} \quad [2.1] \]

where \( E(\lambda) \) is the expected number of predicted accidents, and is correlated to traffic volume, \( Q \), and a set of risk factors, \( x_i \) (\( i = 1, 2, 3, \ldots, n \)). And traffic volume \( Q \) up to the power of \( \beta \) is to show the influence of traffic volume linked to accidents with respect to an elasticity (Eenink et al. 2005). Based on the summary of Nambuusi et al. (2008), in terms of the elasticity, it shows the certain change in percentage in the expected number of accidents associated with a 1% change in traffic volume. Also, both Ivan(2004) and Adedokun (2016) mentioned that if \( \beta \) is
less than 1, the number of accidents increases by a greater percentage than traffic volume. If $\beta$ is 1, then the relation between the number of accidents and traffic volume is in proportion (higher traffic volume, higher crash frequency), and it is conventional assumption when in use of accident frequencies/rates in traffic safety analysis.

And for intersections, the rather common equation for accident prediction models can be formed as follows (Eenink et al. 2005; Nambuusi et al. 2008; Greibe 2003):

$$E(\lambda) = \alpha \times Q_{MA}^\beta \times Q_{MI}^\beta \times e^{\sum y_i x_i}$$  \hfill [2.2]

Based on the model, $Q_{MA}$ represents the number of vehicles entering an intersection from the major road, $Q_{MI}$ represents the number of vehicles entering an intersection from the minor road. For the fourth variable in the equation, Eenink et al. (2005, p.18) concluded that “the effects of various risk factors that influence the probability of accidents, given exposure, is generally modelled as an exponential function, that is as $e$ (the base of natural logarithms) raised to a sum of the product of coefficients, $y_i$, and values of the variables, $x_i$, denoting risk factors.”

Some variations established from this basic model form have been developed in several studies (Greibe 2003; Sayed & Rodriguez 1999; Lord & Persaud 2000; Turner et al. 2009; Brüde et al. 1998). Moreover, certain developed models from those studies for different intersection types (e.g. unsignalized intersections, roundabouts) are discussed below.

A research done by Sayed & Rodriguez (1999), they conducted a study which was designed to develop accident prediction models for urban unsignalized intersections, to estimate the safety performance at the locations as a function of traffic flows on major and minor roadways based on the type of intersections. In this study (Sayed & Rodriguez 1999), the authors mainly focused on 3-arm and 4-arm unsignalized intersections in Vancouver, British Columbia, Canada. Generalized linear modelling (GLIM) approach was used in this model, and is based on the work of Kulmala (1995) and Hauer et al. (1988). Furthermore, the model structure associates accident frequency to the product of traffic volumes entering the intersection and raised to a particular power, as shown below:

$$E(\Lambda) = a_0 \times V_1^{a_1} \times V_2^{a_2}$$  \hfill [2.3]

Where:

- $E(\Lambda)$ = the number of expected accidents;
- $V_1$ = major road traffic flow (AADT);
- $V_2$ = minor road traffic flow (AADT);
- $a_0; a_1; a_2$ = model parameters.

A Swedish research conducted by Brüde et al. (1998), they’ve developed separate accident prediction models for different road users (with motorized vehicles alone or with cyclists and pedestrians), and can be applied to all junction types (e.g. roundabouts). Within the focus of
this thesis with respect to cyclist safety, the prediction model for accidents involving cyclists from the study is listed as follows:

\[
\text{Cyclist accident rate} = a \times \text{Vehs}^b \times \text{Cycs}^c \quad [2.4]
\]

\[
\text{Annual}_{\text{cyc.acc.rate}} = \text{Cyclist accident rate} \times \text{Cycs} \times 365 \times 10^{-6} \quad [2.5]
\]

Where:

\[
\text{Vehs} = \text{Annual average number of incoming motorized vehicle per day}
\]

\[
\text{Cycs} = \text{Annual average number of passing cyclist per day}
\]

\[
\text{Cycs.acc.rate} = \text{Accident frequencies per million cyclists}
\]

\[
\text{Annual}_{\text{cyc.acc.rate}} = \text{Predictive number of cyclist accident per million passing cyclists per year}
\]

\[
a, b, c = \text{regression coefficients}
\]

Even though the aforementioned equations are presented in various forms and developed for different types of intersections, and in each formula, distinctive variables are carried out due to dissimilar characteristics of locations, but all of which refer to the same definition for variables overall. For instance, \( Q \) was used to denote traffic flow in equation 2.1 and 2.2, but \( V \) was chosen to represent traffic volume in equation 2.3.

### 2.6.2. Assessment of Safety Performance Level at Roundabouts

Done by Chiu (2014), a research was designed to develop two types of safety performance functions of roundabouts in Wisconsin, United States by using the negative binomial regression models. The author also mentioned that accident rates of roundabouts can be influenced not only by AADT, but also affected by certain geometric elements at the locations. One type is the intersection level Safety Performance Functions (SPFs) which are based on traffic flow, accident rates and geometric attributes/features of entire roundabouts. The other type is called single approach-level SPFs which are taken consideration into roundabouts with their accident rates and geometrical elements at the entering-circulating locations of theirs. More detailed information can be found in the report (Chiu 2014).

Both of the safety performance functions in the aforementioned study are involving geometric features of roundabouts, therefore, the author reviewed some geometric features of roundabouts that are possibly related to traffic accidents, such as inscribed circle diameter, entry width, entry angle, sight distances, entry curves, exit curves, central island, etc. These geometric elements are discussed as follows:

**Inscribed circle diameter**, which defines as the size of a roundabout. It’s a measurement of the circle related to the outer edge of the circulatory roadway, and also it consists of central island diameter and each side of the circulatory roadway (Chiu 2014; Robinson et al. 2000). For a double-lane roundabout, the minimum value of inscribed circle diameter is recommended to be 45 meters. However, the overall safety for roundabouts is better in general when they have smaller inscribed circle diameters due to maintaining lower speeds for the drivers. Thus, when the inscribed diameter is relatively large (larger than 60 meters), in which should not
recommend to be used. The reason being, the motorized vehicles will have high circulating speeds which can potentially lead to more accidents with greater level of severity. For urban single lane roundabouts, the typical inscribed circle diameter range from 30 meters to 40 meters. For urban double lane roundabouts, the typical inscribed circle diameter ranges from 45 meters to 55 meters (Robinson et al. 2000).

*Entry width*, the definition is the width of the entry where it reaches the inscribed circle. It’s the measurement of the perpendicular distance between the right edge of the entering lane and the crosspoint of the left edge line and the inscribed circle (Chiu 2014; Robinson et al. 2000). The entry width is crucial in terms of the design of roundabouts due to the capacity for approaching vehicles is determined by the width, is the largest determinant of a roundabout’s capacity. Even though wider widths can allow higher capacity for vehicles, but the downside is the entering vehicles will maintain higher speeds and it therefore will increase accident rates (Chiu 2014). Thus, it will also lead to higher severity level for cyclists when there are conflicts between motorists and cyclists. For single lane entrances, the entry widths are normally ranged from 4.2 meters to 5.5 meters. And typically entry widths for two lane entrances range from 7.3 meters to 9.1 meters (Aumann et al. 2017).

*Entry angle*, can be denoted as Phi (Symbol: $\Phi$) in geometry of roundabout. Generally, an appropriate design for entry angle is between 20 and 30 degrees for roundabouts. Visibility issues may arise if entry angles are narrow (Chiu 2014). It can be one of the influencing factors for conflicts between cyclists and motorists. According to Chiu (2014), there are two conditions for measuring the entry angle. The measurement of these two conditions are different, condition No.1 can be suitable for a larger roundabout where the distance between the left side of the roundabout entry to the next exit is within approx. 30 meters. Condition No.2, on the other hand, can be suitable for a smaller roundabout where the distance compared to condition no.1 is more than 30 meters or non existence of adjacent exit (Chiu 2014). Methods of entry angle measurement are illustrated in Fig 2.11.
Figure 2.11. Measurement of entry angle (Chiu 2014)

(Top: Condition No.1; Bottom: Condition No.2)

*Sight distance*, includes Stopping Sight Distance (SSD) and Intersection Sight Distance (ISD) at roundabouts. And adequate sight distance is necessary to ensure a roundabout to function safely for road users, also allow motorists to identify the presence of a roundabout. Stopping sight distance, which is the distance obligatory for a motorist to notice and react to an entity in a roadway and to reduce speed to zero before getting close to the entity, and the distance is adjacent to the roadway. It should be provided at every point within a roundabout and on each entering and exiting approach. At roundabouts, there are at least three essential types of locations should be examined for stopping sight distance, such as approach sight distance, sight distance on circulating carriageway and sight distance to bicycle/pedestrian crossing on exit, as shown in Fig 2.12 (Robinson et al. 2000; Aumann et al. 2017). Furthermore, according to *Roundabouts: An Informational Guide* (2000), the recommended design values for stopping sight distance at the approaching speed of 40km/h and 50km/h are 46.2 meters and 63.4 meters respectively.
On the other hand, intersection sight distance which is the distance obligatory for a motorist that without the right of way to notice and react to the presence of conflicting vehicles at a roundabout. A motorist can observe and react safely to potentially conflicting vehicles if sight lines are adequate for intersection sight distance. It should be evaluated particularly at the entries of roundabouts, and is measured through the determination of a sight triangle, moreover, “arms” of the roundabouts should be assumed to follow the curvature of the roadway, therefore, the distances should be measured along the vehicular path instead of straight lines. And the length of the approach arm of the sight triangle (sight distance before the yield line) should be limited to 15 meters in order to slow down vehicles before entering the roundabout, if the length is more than 15 meters, addition of landscaping shall be suggested to constrain the sight distance to match the minimum requirements. (Aumann et al. 2017; Robinson et al. 2000), as illustrated in Fig 2. 13.
From the above figure, there are two conflicting approaches of the sight distance triangle should be examined at each entry for intersection sight distance (Robinson et al. 2000),

- **Entering stream**: involved with vehicles from the immediate upstream entry. Using the average of the entering speed and circulating speed for the estimation of the speed for this movement.

- **Circulating stream**: involved with vehicles that entered the roundabout prior to the immediate upstream entry. Using the speed of left turning vehicles for the estimation of this speed.

**Entry curves**, present themselves along the right curb of the entering lanes of a roundabout and lead into the circulatory roadway (i.e. curvilinearly tangential to the outer edge of the circulating roadway), with path/entry radii that designed to reduce/slow down the speed of vehicles prior to entering the roundabout. Therefore, the speed of entering vehicles is influenced by the design of entry curves, so this geometric element is a rather important factor to determine the operation of a roundabout and its’ safety. In addition, larger entry curves/radii (especially at tangential entries) will lead to or permit faster entering speeds, thus accident rates between circulating and entering vehicles will possibly rise. Small entry curves could lead motorized vehicles to crash into curbs. At multi-lane roundabouts, perhaps the application of small entry radii will generate low entering speeds, though frequently leads to path overlap due to its tendency on leading vehicles of the outer circulating lane into inner circulating lane (i.e. may lead to vehicle to vehicle collisions), and larger entry radii can potentially reduce path overlap. For urban single-lane roundabouts, the radii of entry curves should range from 10-30 meters. For double-lane entries in urban environments, the radii can range from 30 to 60 meters (Aumann et al. 2017; Chiu 2014; Robinson et al. 2000).
Exit curves, present themselves along the left curb of the exiting lanes of a roundabout and diverge away from the circulatory roadway. The radii of the exit curves are usually larger than the radii of entry curves in order to reduce the probability of traffic jam at the exit lanes. Though, this aforementioned design setting in urban areas is settled by the requirement to keep speeds relatively low at the bicycle and pedestrian crossings on exit lanes for maximizing safety and comfort for vulnerable road users, especially cyclists and pedestrians. For single-lane roundabouts, in urban settings, the radii of exit curves suppose to be more than 15 meters. Recommendation for double-lane roundabouts is not provided (Robinson et al. 2000).

Central island, which is located at the center of a roundabout and is a raised, non-traversable area encircled by the circulating carriageway (includes truck apron, if applicable), and to increase recognition for motorists in terms of the landscape of a roundabout before entering. The reason behind the raised central island is to attempt to obstruct motorists’ forward visibility in order to eliminate distractions from motorized vehicles entering from the opposite arm of the roundabout. Normally, the central island is recommended to be constructed in circular shape, because it can help to promote constant speeds around the central island. But for non-circular shapes (e.g. oval shapes), they are able to promote higher circulating speeds on the straight sections and reduced circulating speeds on the arcs of the oval, thus will result in higher differential speeds for the driver, and perhaps will lead to loss of control type of accidents. Unless the oval-shape central islands are relatively small and maintaining with low speeds, then it will not be an issue. Furthermore, the central island diameter should be big enough to not allow motorized vehicles to turn left before the central island. For a single lane roundabout, the recommended diameter of a central island range from 15 to 30 meters. For a multi-lane roundabout, the range should fall between 20 meters and 40 meters. Moreover, a central island between 20 meters and 40 meters offers the best safety for cyclists (Silvano & Linder 2017; Aumann et al. 2017; Robinson et al. 2000; Montella et al. 2013; Chiu 2014).

The author from the study has developed two types of safety performance function models for roundabouts, as mentioned earlier. The first one is the roundabout safety performance functions model which was built on intersection level, and evaluated as the whole roundabout. The second one is the single approach safety performance functions model which was built for the single approach of the roundabouts and built for total accidents only (Chiu 2014). The forms of the two SPF models will be summarized below.

The general form of roundabout safety performance functions model at intersection-level for the study is listed by the following equation:

\[
\text{Accidents per year} = \exp(\text{Intercept}) \times \text{AADT}^{b_1} \times \exp(c_1X_1 + c_2X_2 + \cdots + c_nX_n) \tag{2.6}
\]

Where:

- AADT : Annual average daily traffic entering the intersection;
- \(X_1 + \cdots + X_n\) : Other geometric features that affect the accident rate;
- \(b_1, \ldots, b_n, c_1, \ldots, c_n\) : calibration coefficients.
The general form of single approach safety performance functions model for the study is not listed in the report, but it can refer to the following form for single approach SPFs model developed by NCHRP (National Cooperative Highway Research Program)(Chiu 2014):

\[ Accidents \ per \ year = \exp(\text{Intercept}) \times (AADT_E)^a \times (AADT_C)^b \times \exp(c \times E - d \times \theta) \quad [2.7] \]

Where:

- \( AADT_E \): Entering AADT;
- \( AADT_C \): Circulating AADT conflicting with the subject entry
  - \( E \): Entering lane width
  - \( \theta \): Angle to the next arm (degrees)
- \( a, b, c, d \): calibration coefficients
3. Case Study

This chapter starts with the brief description and analysis of cyclist safety in Norrköping, followed by the description and analysis of cyclist safety at roundabouts in the city, and led to why there are 4 identified roundabouts chosen for the case study of this work.

3.1. Cyclist Safety in Norrköping City

Norrköping municipality, which is located in Östergötland County in southeastern Sweden has approx. 139,363 inhabitants (Statistics Sweden 2017). During the period from Jan.1st. 2013 to Dec. 31st. 2015, according to the cyclist related traffic accident data in Norrköping, which was obtained from STRADA database, 625 traffic accidents in total were recorded with 3 fatal accidents, 21 severe accidents, 144 moderate accidents and 457 minor accidents in Norrköping (Loebjer 2016), as shown in Fig. 3.1. Within this 3-year period, there were totally 65 cyclists got killed in road accidents in the entire Sweden (Ågren 2016).

![Figure 3.1. Number of cyclists’ accidents in NKPG categorized by severity level from 2013-2015 (Loebjer 2016)](image.png)

From Fig 3.1, we can clearly spot that the majority of the traffic accidents are experienced by cyclists is minor accidents, and takes up approx. 73% of total road accidents for cyclists in Norrköping city during the period. As you can see, in year 2015, the number of traffic accidents for cyclists decreased significantly. But the drop is uncertain, it may or may not be the actual reduction in the number of accidents due to the loss of registration for medical reports of the accidents in the database. Because during year 2013 and 2014, a new reporting system was introduced, although the new system is no longer in used now. Also, because of the new
reporting system at the time, approximately 25 hospitals in 2015 needed to change their routine and workflow which increased their workload, moreover, lacking of staff to help out, led to not be able to register standard medical reports for accidents in STRADA database (Loebjer 2016).

Table 3. 1. Conflict table between two primary traffic elements in traffic accidents from ‘13-’15 in Norrköping (Loebjer 2016)

<table>
<thead>
<tr>
<th>Type of road user / in conflict with</th>
<th>Single (cyclist)</th>
<th>Animal</th>
<th>Pedestrian</th>
<th>Cyclist</th>
<th>Noped</th>
<th>Motorcyclist</th>
<th>Passenger Car</th>
<th>Heavy Vehicle</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclist</td>
<td>449 (0,16,111,122)</td>
<td>1 (0,0,0,1)</td>
<td>14 (0,0,5,9)</td>
<td>23 (0,1,3,10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moped</td>
<td>4 (0,0,1,3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorcycle</td>
<td>1 (0,0,0,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger car</td>
<td>125 (2,4,18,101)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy Vehicle</td>
<td>4 (1,0,1,2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus</td>
<td>1 (0,0,0,1)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

As shown in Table 3. 1, this is the table which shows the conflict(s) between two main traffic elements involved in the traffic accidents. The numbers listed in the cells, which are outside of the parentheses are total accident counts between two primary traffic elements, within the parentheses, these numbers are the counts for fatal accidents, severe accidents, moderate accidents, and minor accidents respectively. In the table, we can notice that the major type of traffic accidents for cyclists is single casualties (449 accident counts), and the runner up is the accidents involved with passenger cars (125 accident counts). Most of the severe accidents happened in single accidents. A total of three fatal accidents had occurred when cyclists interacted with motorized vehicles, which indicates potential issues in terms of traffic safety behind the interactions between cyclists and motorists.
Figure 3.2. Heatmap visualization in Visum Safety for traffic accident counts in Norrköping city from 2010-2017

(Top: For all road users; Bottom: For cyclists only)

Fig 3.2 shows the function of heatmap visualization in Visum safety in order to identify high accident areas in Norrköping with different color groupings. In these figures, the threshold
value of accident counts was set to 10 and a location radius of 50 meters. The locations with green shadow indicate the accident counts are lower than 5, as for yellow shadow locations where imply the traffic accident counts are below 10 and larger or equal to 5, and red shadow area have more than (or equal to) 10 traffic accidents. Furthermore, before the importation of the accident data in Visum safety, the data is needed to convert into the format which is compatible with the software in order to display properly on Open Street Map in Visum Safety. The accident data for all road users in Norrköping was fetched from STRADA database within the period from Jan. 2010 to Sept. 2017. In the top figure, the heatmap visualizes the road accidents for all road users in the whole region of the city. The bottom figure represents the heatmap for cyclist only traffic accidents filtered out from the fetched accident data in the city, based on the bottom figure, it appears that the majority of accidents involved with bicyclists happened at intersections in Norrköping. Therefore, it is interesting to investigate further and select accident data involved with cyclists at roundabouts from the database, to find out which roundabouts have high road accidents for cyclists in the city.

### 3.2. Cyclist Safety at Roundabouts in Norrköping City

![Heatmap for cyclist related accidents at roundabouts in Norrköping from ’10–’17](image)

The requested traffic accident data for cyclists at roundabout in the city of Norrköping was obtained from STRADA database within the period from January. 2010 – September. 2017. The data was received in Microsoft Excel format, and the excel file is categorized into different attribute sheets such as abstract, map for selected area, accidents, persons, persons for police, persons for hospital, injuries, severely injured, and each sheet has its own detailed report as titled. According to the report, there is 59 accidents in total which consists of 1 severe injury, 9 moderate injuries, and 49 slight injuries during the specific time span.
As the author briefly mentioned in Chapter 3.1, in order to visualize the accident data in Visum Safety, we first need to convert the accident data (‘Olyckor’ sheet) in excel format into the STRADA format text file, which is compatible in Visum Safety after configured with the customized format file received from PTV Group.

As shown in Fig 3.3, the heatmap visualizes the accident data for cyclists at roundabouts in Norrköping, the threshold value of accident counts was set to 4 with a location radius of 50 meters for the visualization due to the total number of accidents for cyclists at roundabouts is only a fraction of the total number of accidents for all road users in the city within the period. Using this setting, the accidents can be more visible in heatmap visualization on the map. In this figure, the accident prone locations are presented visibly. The red shadow locations are the roundabouts where have more than (or equal to) 4 accidents, for yellow shadow locations where the accidents are less than 4, the green shadow locations have less than 2 accidents.

Table 3.2. Conflict table for cyclists at roundabouts in Norrköping from 2010-2017

<table>
<thead>
<tr>
<th>Type of road user / in conflict with</th>
<th>Single (cyclist)</th>
<th>Animal</th>
<th>Pedestrian</th>
<th>Cyclist</th>
<th>Moped</th>
<th>Motorcyclist</th>
<th>Passenger Car</th>
<th>Heavy Vehicle</th>
<th>Bus</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cyclist</td>
<td>12(0,0,0,12)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Moped</td>
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<td></td>
<td></td>
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<tr>
<td>Motorcycle</td>
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<td></td>
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<tr>
<td>Passenger car</td>
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<tr>
<td>Heavy Vehicle</td>
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<td>Bus</td>
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<tr>
<td>Other</td>
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</tr>
</tbody>
</table>

Table 3.2 shows the conflicts between cyclists and other road users, and single causalities for cyclists, etc. According to the statistics above, the most frequent accidents for cyclists at roundabouts are involved with motorized vehicles, especially with passenger cars. And followed by bicyclist single causalities as the second most common accidents at the roundabouts in the city. Therefore, it is necessary to choose certain roundabouts in the city for investigation to analyze and understand the cause behind the accidents involved with cyclists.

Based on the heatmap visualization in Fig 3.3, the author has identified four roundabouts for the case study due to higher traffic accident counts for cyclists at these locations compared to other roundabouts in the city. The selected locations are Packhusrondellen, Fenixrondellen, Finspångsrondellen, and Stockholmsrondellen, as shown in Fig 3.4.
Figure 3. 4. Identified roundabouts in Norrköping for the case study
(a. Packhusrondellen, b. Fenixrondellen, c. Finspångsrondellen, d. Stockholmsrondellen)

Packhusrondellen

Figure 3. 5. Distribution of cyclist related accidents at Packhusrondellen
This location is a major roundabout placed at the north side of Norrköping city. It is an unsignalized 4-arm roundabout with separated cycling paths. Within the period of 2010-2017, there is a total of 8 accidents involved cyclists occurred at the location, which consist of 6 minor accidents, 1 moderate accident, and 1 severe accident. In Fig 3.5, the letter C is one of the abbreviations for the classification of accidents in STRADA database which stands for collision between a motorized vehicle and a cyclist, and G1 stands for accident involving only a cyclist (Red square: Only hospital report registered in the database; Blue square: Only police report registered in the database; Blue/Red square: Both police and hospital report registered in the database).

As shown in the figure, most of the accidents for cyclists happened due to encounter a conflict with a motorized vehicle at bicycle crossings, especially two crossings at Packhusgatan and Ståthögavägen. The north bound of the roundabout is Ståthögavägen which connects all the way to 55 freeway, which translates to the roundabout carries high motorized vehicle volume daily. According to the city network model for year 2014 obtained from Norrköping municipality, the average daily traffic for motorized vehicles on two of the arms (Packhusgatan and Ståthögavägen) are more than 20,000 respectively, and the volume for the other two arms (Norra Promenaden West and Norra Promenaden East) are approx. 10,000 respectively. The author can confirm that Packhusgatan and Ståthögavägen have high vehicle volume, especially at peak hour based on his observation. Thus, the main cause behind the accidents for cyclist at the location can be high motorized vehicle volume, also, placement of bicycle crossings and pedestrian crossing is rather close to the roundabout. Relocation of the crossings should be advised. In addition, the circulatory roadway is double-lane at the roundabout, and three of the arms have double-lane entries, this means the chances of conflicts increase between cyclists and motorized vehicles. Below is the summary table of Packhusrondellen with the variables that the author gathered from various of sources.

Table 3.3. Summary of presented variables at Packhusrondellen

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of the roundabout (Integrated with cyclists)</td>
<td>With separated cycling paths</td>
</tr>
<tr>
<td>Total accidents for cyclist (2010-2017)</td>
<td>8</td>
</tr>
<tr>
<td>Cyclist speed</td>
<td>15km/h-19km/h</td>
</tr>
<tr>
<td>Speed limit for vehicles</td>
<td>40km/h</td>
</tr>
<tr>
<td>Vehicle volume from each arm (Annual Average Daily Traffic)</td>
<td>Packhusgatan South: 23537;</td>
</tr>
<tr>
<td></td>
<td>Ståthögavägen North: 24236;</td>
</tr>
<tr>
<td></td>
<td>Norra Promenaden West: 9624;</td>
</tr>
<tr>
<td></td>
<td>Norra Promenaden East: 12164;</td>
</tr>
<tr>
<td>Cyclist volume from each bicycle crossing (Annual Average Daily Traffic)</td>
<td>Packhusgatan South: 323;</td>
</tr>
<tr>
<td></td>
<td>Ståthögavägen North: 30;</td>
</tr>
<tr>
<td></td>
<td>Norra Promenaden West: 405;</td>
</tr>
<tr>
<td></td>
<td>Norra Promenaden East: 30;</td>
</tr>
<tr>
<td>Geometric design for entries</td>
<td>Tangential entries</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Type of the roundabout</td>
<td>Urban Double-Lane</td>
</tr>
<tr>
<td>inscriCD: approx. 45m</td>
<td></td>
</tr>
<tr>
<td>Max. EL: 2**</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of conflicts points involved with cyclists</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Packhusgatan South:</td>
<td>2 (EL*); 2 (ExL*)</td>
</tr>
<tr>
<td>Ståthögavägen North:</td>
<td>2 (EL); 2 (ExL)</td>
</tr>
<tr>
<td>Norra Promenaden West:</td>
<td>2 (EL); 1 (ExL)</td>
</tr>
<tr>
<td>Norra Promenaden East:</td>
<td>1 (EL); 1 (ExL)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Visibility for cyclists at each bicycle crossing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Packhusgatan South:</td>
<td>Exit: Good; Entry: Poor</td>
</tr>
<tr>
<td>Ståthögavägen North:</td>
<td>Exit: Good; Entry: Normal</td>
</tr>
<tr>
<td>Norra Promenaden West:</td>
<td>Exit: Good; Entry: Good</td>
</tr>
<tr>
<td>Norra Promenaden East:</td>
<td>Exit: Good; Entry: Normal</td>
</tr>
</tbody>
</table>

* EL = Entering Lane; ExL = Exit Lane
** inscriCD = inscribed Circle Diameter; Max.EL = Maximum Entering Lane per Approach

**Fenixrondellen**

This roundabout is located at approx. 1.5km northwest of Linköpingsrondellen, it is an unsignalized 4-arm single-lane roundabout with separated cycling paths. There is a total of 6

![Figure 3. 6. Distribution of cyclist related accidents at Fenixrondellen](image)
accidents involved with cyclists happened at the location over the last 8 years. All of the accidents were minor accidents.

As shown in Fig 3. 6, most of the accidents were taken place at Kungsgatan, conflicts between cyclist and motorist happened at the bicycle crossing. Even though the daily vehicle volume on kungsgatan is less than 8000, and around 250 cyclists ride on the particular bicycle crossing daily. Based on the author’s observation in the field, visibility of the entering lane at Kungsgatan is not good for motorists, the right side of the lane in particular. There are fences alongside with shrubberies and trees at the right side of the approaching lane, it can block the sight of motorists from looking to the right side of the street while approaching the roundabout. Since motorists already tend to primarily look at the left side of the roundabout to observe incoming vehicles on the circulatory roadway than paying attention to the traffic from the right before getting close to the yield line at the location (Räsänen & Summala 2000), with poor visibility, it’s even harder for motorists to notice vulnerable road users. Therefore, it would definitely increase risks for conflicts between bicyclist and motorist. It can be the main cause behind these accidents. Moreover, bicycle and pedestrian crossings at Albrektsvägen, east side of Södra Promenaden and Kungsgatan are too close to the roundabout, the crossings should be placed at least one vehicle length (5 meters) away from the roundabout in order to reduce impact of conflicts between vulnerable road users and motorists (Robinson et al. 2000). Below is the summary table of Fenixrondellen with available variables.

Table 3. 4. Summary of presented variables at Fenixrondellen

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of the roundabout (Integrated with cyclists)</td>
<td>With separated cycling paths</td>
</tr>
<tr>
<td>Total accidents for cyclist (2010-2017)</td>
<td>6</td>
</tr>
<tr>
<td>Cyclist speeds</td>
<td>15km/h-19km/h</td>
</tr>
<tr>
<td>Speed limit for vehicles</td>
<td>40km/h</td>
</tr>
<tr>
<td>Vehicle volume from each arm (Annual Average Daily Traffic)</td>
<td>Albrektsvägen South: 10533; Kungsgatan North: 7386; Södra Promenaden West: 9400; Södra Promenaden East: 10597;</td>
</tr>
<tr>
<td>Cyclist volume from each bicycle crossing (Annual Average Daily Traffic)</td>
<td>Albrektsvägen South: 174; Kungsgatan North: 247; Södra Promenaden West: 204; Södra Promenaden East: 923;</td>
</tr>
<tr>
<td>Geometric design for entries</td>
<td>Tangential entries</td>
</tr>
<tr>
<td>Type of the roundabout inscriCD: approx.33m Max.EL:1</td>
<td>Urban Single-Lane</td>
</tr>
</tbody>
</table>
| **Number of conflicts points involved with cyclists** | Albrektsvägen South:  
1 (EL); 1 (ExL)  
Kungsgatan North:  
1 (EL); 1 (ExL)  
Södra Promenaden West:  
1 (EL); 1 (ExL)  
Södra Promenaden East:  
1 (EL); 1 (ExL) |
|-------------------------------------------------|---------------------------------------------------------------|
| **Visibility for cyclists at each bicycle crossing** | Albrektsvägen South:  
Exit: Good; Entry: Good  
Kungsgatan North:  
Exit: Poor; Entry: Normal  
Södra Promenaden West:  
Exit: Normal; Entry: Normal  
Södra Promenaden East:  
Exit: Good; Entry: Normal |
This roundabout is located at approx. 1.27 km north of Linköpingsrondellen, it is an unsignalized 4-arm grade separated double-lane roundabout with two separated cycling paths on Finspångsvägen and two “adjacent” cycle lanes (elevated by curbs) on Riksvägen. The south bound of Riksvägen carries traffic from E22 expressway which indicates high vehicle volume going through the roundabout daily. The geometric design of entries is tangential, which allows motorized vehicles to maintain higher travel speeds to improve capacity (Schramm et al. 2014). The shape of roundabout is not conventional, it is an oval-shaped circle instead of a standard round-shaped circle. The diameter of the central island is approx. 69 meters, which is rather large for a roundabout. In the last eight years, there is a total of 16 cyclist related accidents occurred at the scene, which consist of 1 fatal accident, 4 moderate accidents, and 11 minor accidents. This location has the most accidents for cyclists compared to the rest of the identified roundabouts.

As shown in Fig 3. 7, most of the accidents for bicyclists happened at this roundabout are also connected to conflicts between cyclist and motorist, and one single causality for cyclist. Majority of the cyclist-motorist accidents occurred at the crossing points between the south bound of Riksvägen and the east and west bound of Finspångsvägen, as well as the west bound of Finspångsvägen and the north bound of Riksvägen. For a double-lane roundabout, there are 24 conflict points compared to 8 conflict points on a single lane roundabout. This increases risks for conflicts between motorist and cyclist. Through the observation at the field, in the vicinity of the entering lanes at the roundabout, not all the lanes are placed with ‘pay attention to cyclists’ signs on the side of the road (since the daily cyclist volume is relatively low
compared to the other identified roundabouts, and different entering speed limit signs (40km/h; 50km/h) are placed on different arms, even though the visibility is good. Due to the nature of the design for entries, motorists can maintain higher travel speeds in favor of keeping high traffic flow, and when encounter conflict with cyclists, the reaction time for them to take evasive action (i.e. press break pedeal) is less, which increases injury level of the conflict for cyclists and other vulnerable road users. In addition, two “adjacent” cycling lanes of the roundabout on Riksvägen would increase the probability of conflicts for bicyclists with circulating vehicles, especially in rainy and snowy conditions. And the design is not recommended for high volume (more than 8000 veh/day) roundabouts, as previously stated in Chapter 2.4.2. All of the factors mentioned above are influential for the accidents taken place at the roundabout. Below is the summary table of Finspångsrondellen with available variables.

Table 3.5. Summary of presented variables at Finspångsrondellen

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design of the roundabout (Integrated with cyclists)</strong></td>
<td>Grade separated roundabout with two separated cycle paths on two arms and two adjacent cycle lanes on the other two arms</td>
</tr>
<tr>
<td><strong>Total accidents for cyclist (2010-2017)</strong></td>
<td>16</td>
</tr>
<tr>
<td><strong>Cyclist speed</strong></td>
<td>15km/h-19km/h</td>
</tr>
<tr>
<td><strong>Speed limit for vehicles</strong></td>
<td>40km/h (50km/h on Riksvägen South)</td>
</tr>
<tr>
<td><strong>Vehicle volume from each arm (Annual Average Daily Traffic)</strong></td>
<td>Riksvägen South: 38555; Riksvägen North: 14316; Finspångsvägen West: 19250; Finspångsvägen East: 16371;</td>
</tr>
<tr>
<td><strong>Cyclist volume from each bicycle crossing (Annual Average Daily Traffic)</strong></td>
<td>Riksvägen South: 220; Riksvägen North: 217; Finspångsvägen West: 60; Finspångsvägen East: 169;</td>
</tr>
<tr>
<td><strong>Geometric design for entries</strong></td>
<td>Tangential entries</td>
</tr>
<tr>
<td><strong>Type of the roundabout inscriCD: approx.89m Max.EL:2</strong></td>
<td>Double-Lane</td>
</tr>
<tr>
<td><strong>Number of conflicts points involved with cyclists</strong></td>
<td>Riksvägen South: 2 (EL); 1 (ExL) Riksvägen North: 1 (EL); 1 (ExL) Finspångsvägen West: 2 (EL); 1 (ExL) Finspångsvägen East: 2 (EL); 2 (ExL)</td>
</tr>
<tr>
<td><strong>Visibility for cyclists at each bicycle crossing</strong></td>
<td>Riksvägen South: Exit: Good; Entry: Good Riksvägen North: Exit: Good; Entry: Good Finspångsvägen West: Exit: Good; Entry: Good Finspångsvägen East: Exit: Good; Entry: Good</td>
</tr>
</tbody>
</table>
This roundabout is located at approx. 900m north of Finspångsrondellen, it is a 4-arm oval-shaped double-lane roundabout with separated cycling paths. It is a similar shape of roundabout compared to Finspångsrondellen. During 2010-2017, there is a total of 9 accidents for cyclist happened at the location, which consist of 2 moderate accidents, and 7 minor accidents.

As shown in Fig 3. 8, most of the cyclist-motorist accidents were taken place at the west bound of Breda vägen along with few single causalities for cyclist at the roundabout. Based on the observation at the field, the author noticed a good practice at the entering and exit lane on the arm of Riksvägen, which is the speed reducers they set up before the cyclist and pedestrian crossings. Because the implementation can enforce motorized vehicles to reduce speed before entering the roundabout without changing the nature of its design (tangential entries), the setup is able to mitigate impact of conflicts between motorists and vulnerable road users. Additionally, we spotted that the bicycle and pedestrian crossing on the arm of Breda vägen is too close to the roundabout, which translates high risk and expose for conflicts between vulnerable road users and motorized vehicles. It can be the one of the main causes behind these accidents. Another cause could be high vehicle volume coming from the north bound of Stockholmsvägen daily, and relatively high cyclist volume from Breda vägen. Below is the summary table of Stockholmsrondellen with the available variables.
Table 3. 6. Summary of presented variables at Stockholmsrondellen

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of the roundabout (Integrated with cyclists)</td>
<td>With separated cycling paths</td>
</tr>
<tr>
<td>Total accidents for cyclist (2010-2017)</td>
<td>9</td>
</tr>
<tr>
<td>Cyclist speed</td>
<td>19km/h</td>
</tr>
<tr>
<td>Speed limit for vehicles</td>
<td>40km/h</td>
</tr>
<tr>
<td>Vehicle volume from each arm (Annual Average Daily Traffic)</td>
<td>Riksvägen South: 14316; Stockholmsvägen North: 21938; Breda vägen West: 8635; Stockholmsvägen South: 10541;</td>
</tr>
<tr>
<td>Cyclist volume from each bicycle crossing (Annual Average Daily Traffic)</td>
<td>Riksvägen South: 656; Stockholmsvägen North:128; Breda vägen West: 436; Stockholmsvägen South: share the volume together with the crossing at Riksvägen South</td>
</tr>
<tr>
<td>Geometric design for entries</td>
<td>Tangential entries</td>
</tr>
<tr>
<td>Type of the roundabout inscriCD:approx.85m Max.EL:2</td>
<td>Double-Lane</td>
</tr>
<tr>
<td>Number of conflicts points involved with cyclists</td>
<td>Riksvägen South: 2 (EL); 2 (ExL) Stockholmsvägen North: 2 (EL); 2 (ExL) Breda vägen West: 2 (EL); 2 (ExL) Stockholmsvägen South: 2 (EL); 1 (ExL)</td>
</tr>
<tr>
<td>Visibility for cyclists at each bicycle crossing</td>
<td>Riksvägen South: Exit: Good; Entry: Good Stockholmsvägen North: Exit: Good Entry: Good Breda vägen West: Exit: Good; Entry: Poor Stockholmsvägen South: Exit: Normal; Entry: Good</td>
</tr>
</tbody>
</table>
4. Results and Discussion

This chapter reveals the summarized results of all relevant variables from the case study (as listed in Table 4.1) such as volumes of motorized vehicles and cyclists (AADT) at identified locations obtained from Norrköping municipality, total number of accidents for cyclists during 2010-2017 at the locations fetched from STRADA, etc. Followed by safety performance assessment of the locations based on certain variables given in Table 4.1 to identify which selected roundabout is the most hazardous towards cyclists, afterwards the assessment of the roundabout based on certain geometric features will take place, and discussion/analysis will be weaved in into the assessment of the selected roundabouts, which is tied with the main objective of the thesis work.

Moreover, based on the identified locations from the case study, the analysis and discussion focused on 4-arm roundabouts with separated cycling paths, other design types of roundabouts integrated with cyclists are not considered and discussed.
Table 4.1: Summary of the four identified roundabouts for the case study

<table>
<thead>
<tr>
<th>Roundabout Type</th>
<th>Location</th>
<th>Type of Conflict</th>
<th>Total No. of Vehicles</th>
<th>Conflicts</th>
<th>Median Speed (km/h)</th>
<th>Speed Limit (km/h)</th>
<th>Number of Vehicles</th>
<th>Combined (Cyclist) Volume (veh/h)</th>
<th>Combined (Cyclist) Volume (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Location 1</td>
<td>Thru</td>
<td>1200</td>
<td>5840</td>
<td>0</td>
<td>0</td>
<td>1.2</td>
<td>0.9</td>
<td>9</td>
</tr>
<tr>
<td>2nd</td>
<td>Location 2</td>
<td>Thru</td>
<td>660</td>
<td>1840</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>0.9</td>
<td>16</td>
</tr>
<tr>
<td>3rd</td>
<td>Location 3</td>
<td>Thru</td>
<td>1390</td>
<td>3140</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>0.9</td>
<td>6</td>
</tr>
<tr>
<td>4th</td>
<td>Location 4</td>
<td>Thru</td>
<td>990</td>
<td>2290</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>0.9</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 4. 1. Correlation between total accidents for cyclists and total volume for different road users at selected roundabouts

(Top: Total volume for cyclists (AADT); Bottom: Total volume for vehicles (AADT))

The relationship between total accident rates for cyclists and total volume for different road users (cyclists and motorists) are presented, as shown in Fig 4. 1. We can notice that Finspångsrondellen has the highest number of aggregated accidents for cyclists from 2010 to 2017 compared to the rest of the identified roundabouts. From the top figure, we can spot that
the total volume for cyclists at Finspångsrondellen is the least among four roundabouts, but the total accident rate for cyclists is the highest. With respect to the top figure above, the correlation between accident rates of cyclists and cyclist flows at the roundabout can be interpreted as the less the cyclist flows at the location, the higher accident rates for cyclists. This interesting relation is confirmed from a study done by Jacobsen (2003), which the conclusion is if more people cycle (or walk), the chance for a motorist to have a collision with a person cycling (or walking) is lower, also known as ‘Safety in Numbers’ effect. That means more cyclists showing the presence on the road at the location can increase more exposure to the drivers, therefore, the drivers become more cautious/aware while driving in the presence of people cycling in order to avoid collisions with cyclists.

The statistics at Fenixrondellen can be the example for the aforementioned interpretation. What we can take away from the bottom figure is, the number of motorized vehicles volume is one of the dominant factors that influencing the accident rates of cyclists at the roundabouts. When the volume of motorized vehicles is higher at the location, the accident rates for cyclists tend to increase, perhaps it is one of the main reasons behind the relatively high accident rates for cyclists at Finspångsrondellen among these four identified roundabouts.
The relationship between total number of serious injuries for cyclists and total volume of different road users (cyclists and motorists) are presented, as illustrated in Fig 4. 2. The data for serious injuries for cyclists at the locations include the number of moderate and severe level injuries, which Injury Severity Score (ISS) for these injuries is 4-8 and 9- separately. Compare
to Fig 4.1, the correlation for total volume of cyclists and motorized vehicles respectively with total accidents for cyclists and total number of serious injuries for cyclists during 2010-2017 is quite similar in Fig 4.2. We can spot that from the figure, the total number of serious injuries for cyclists is also the highest at Finspångsrondellen during the period of 2010-2017. Based on the type of these four roundabouts in Table 4.1, it shows that three double-lane roundabouts incline to attract relatively higher number of accidents with serious injuries for cyclists when compared to a single-lane roundabout (Fenixrondellen) in Fig 4.2. Furthermore, cyclists cross these roundabouts the same way as pedestrians, as previously stated in section 2.3. And the number of conflict points for cyclists at the three double-lane roundabouts (12, 13, 15) are almost double the number of conflict points at Fenixrondellen which is the single-lane roundabout (8), according to the author’s own observation. This indirectly translates to double lane roundabouts in the city perceive higher risks and more hazardous towards cyclists. Linking Fig 4.1 and Fig 4.2 together, we can see a pattern that the quantity of traffic volume, in particular, volume of motorized vehicles at the identified roundabouts is definitely one of the main factors to influence the safety level of cyclists, besides the geometric features of the roundabouts.

According to Fig 4.2, there was only one fatal accident occurred among these four roundabouts during the period of 2010-2017, which is at Finspångsrondellen. In comparison of both Fig 4.1 and Fig 4.2, we acknowledge that Finspångsrondellen is most hazardous roundabout towards the safety of cyclists at the time of this work. Since the collected dataset from the case study is relatively small or limited, the assessment of roundabouts cannot be applied by using the SPFs models in section 2.6.2 due to lack of sufficient sampling data of identified roundabouts (only contains datasets for four locations), which probably will lead to low accuracy of the predicted results from the models. However, based on the discussion on section 2.6.2, other than traffic volume (AADT) being one of major factors affecting safety level of cyclists, certain geometric features of this particular roundabout are also necessary to investigate in terms of assessing safety performance of the location for cyclists and correlation of these features and crash frequencies, i.e. certain geometric features of the roundabout are potentially related to the traffic accidents that were involved with cyclists at the location.

For Finspångsrondellen, the geometric elements/variables which are possibly related to accidents involved with cyclists will be discussed over as follows: inscribed circle diameter, entry width, entry angle, sight distances, entry curves, exit curves, and central island. As listed in Table 9, the observed values and recommended values of each geometric variable are presented, and evaluated below based on three levels of relevance of safety towards cyclists (safe; acceptable; not safe). In addition, majority of the accidents involved with cyclists and motorists were occurred at cross sections between the entrance of Riksvägen South and the exit of Finspångsvägen East, and between the entrance of Finspångsvägen West and the exit of Riksvägen South, as exhibited in Fig. 3.7, therefore certain geometric elements will be specifically examined and discussed on these entries and exits.
Table 4.2. Summary of Geometric Elements that Potentially Lead to Accidents for Cyclists at Finspångsrondellen

<table>
<thead>
<tr>
<th>Geometric Elements</th>
<th>Observed Values</th>
<th>Recommended Values</th>
<th>Relevance by Safety (Potentially lead to accidents for cyclists)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inscribed Circle Diameter (m)</td>
<td>≈ 89</td>
<td>≥ 45 ≤ 55</td>
<td>Not Safe</td>
</tr>
<tr>
<td>Entry Width (m)</td>
<td>≈ 9.0 ≤ 10.4</td>
<td>≥ 7.3 ≤ 9.1</td>
<td>Not Safe</td>
</tr>
<tr>
<td>Entry Angle (degree)</td>
<td>≈ 20 ≤ 35</td>
<td>≥ 20 ≤ 30</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Sight Distance (m)</td>
<td>SSD: Adequate overall ISD: Adequate overall</td>
<td>SSD ≈ 46 (40 km/h) 63 (50 km/h) ISD = 15 (limited to)</td>
<td>Acceptable (But sight distance to crosswalk on exit at Finspångsvägen West and Riksvägen South are relatively short.)</td>
</tr>
<tr>
<td>Entry Curve Radius (m)</td>
<td>≈ 12 ≤ 29</td>
<td>≥ 30 ≤ 60</td>
<td>Not Safe</td>
</tr>
<tr>
<td>Exit Curve Radius (m)</td>
<td>≈ 15 ≤ 18</td>
<td></td>
<td>Not Safe</td>
</tr>
<tr>
<td>Central Island Diameter (m)</td>
<td>≈ 69</td>
<td>≥ 20 ≤ 40</td>
<td>Not Safe</td>
</tr>
</tbody>
</table>

**Inscribed Circle Diameter**

Figure 4.3. Inscribed circle diameter of Finspångsrondellen
As shown in Fig 4.3, the size of the inscribed circle diameter at this specific location is approx. 89 meters, and based on the definition of roundabout categories according to *Roundabouts: An Informational Guide* (Robinson et al. 2000) and also briefly mentioned in section 2.6.2. Even though Finspångsrondellen is a double-lane roundabout, but it does not fit into the standard for urban double-lane roundabout in which the typical inscribed circle diameter only ranges from 45 meters to 55 meters. In the guideline, it is recommended that the inscribed circle diameter of a roundabout should not be larger than 60 meters. Because this will permit drivers/motorists to travel in higher speeds, especially on circulating lanes. And when drivers exit the roundabout with higher circulating speeds may lead to more potential accidents with vulnerable road users (pedestrians and cyclists in particular) at the separated crossings of the roundabout, which will increase level of severity of the crashes due to large speed differentials between motorists and vulnerable road users, as mentioned earlier in section 2.2.2. Therefore, the size of inscribed circle diameter at the roundabout can be evaluated as not safe towards cyclists in terms of relevance that potentially lead to accidents for cyclists.

**Entry Width**

Figure 4. 4. Entry widths at Riksvägen South (Top) and Finspångsvägen West (Bottom)
As shown in Fig 4.4, the widths of the entry at the south bound of Riksvägen and of the entry at the west bound of Finspångsvägen are widest (approx. 9.6 meters and 10.4 meters respectively) compared to rest of the entries at the location. Based on the review in section 2.6.2, the recommended width for entries at a double-lane roundabout is between 7.3 meters and 9.1 meters, and we acknowledge that entry width is the largest determinant for a roundabout’s capacity. The wider the entry width, the higher the capacity for vehicles, thus the higher crash frequency. And the daily vehicle volume is relatively high compared to the rest of the identified roundabout. Although wider entry allows a roundabout to carry more traffic, this also enables entering motorized vehicles to travel through the roundabout with higher speeds, which indicates that large speed differences will be experienced between motorists and bicyclists when there are collisions occurred at certain conflict points of the roundabout (e.g. when drivers exit the roundabout) and it will increase the level of injury severity for cyclists, as mentioned earlier. So it is suggested that entry widths should be held to a minimum in order to maximize safety and achieve objectives for capacity and performance (Robinson et al. 2000).

The widths of the two entries exceed the recommended width for entries at double-lane roundabouts. According to the accident distribution at Finspångsrondellen in Fig. 3.7, most of the cyclist involved accidents took place at these two entries, it therefore implies the design of entry widths at the roundabout are not safe towards cyclists in terms of relevance that potentially lead to accidents for cyclists.

**Entry angle**

![Figure 4.5 Entry angles at Riksvägen South (Left) and Finspångsvägen West (Right)](image)

According to the review of entry angle in section 2.6.2, entry angles at Finspångsrondellen can be measured by using the method in Condition No.1, as illustrated in Fig. 4.5. The angles of entrances of the roundabout at Riksvägen South and Finspångsvägen West are 35 degrees and 20 degrees respectively. As mentioned earlier, visibility of drivers may get affected if entry angles are narrow, and an appropriate entry angle is range from 20 to 30 degrees. In the case of this roundabout, entry angles are acceptable, most of them can fit into or close to the standards. Based on the observation, visibility is good overall at entrances of all 4 approaches of the
roundabout, there is no sign of obstruction of the views at the entries (e.g. shrubberies). Thus, the entry angles of this particular roundabout can be considered as the geometric element that does not potentially lead to accidents for cyclists.

**Sight distance**

![Figure 4. 6. Sight distance to bicycle crossings on exit lanes at Riksvägen South (Top) and Finspångsvägen West (Bottom)](image)

In reference to the review of sight distance in section 2.6.2, we know that sight distance consists of stopping sight distance and intersection sight distance. In terms of examining stopping sight distance at this roundabout, the recommended SSD is 46.2 meters at the speed of 40km/h (63.4 meters, at the speed of 50 km/h), according to the guideline, and three types of locations should be checked for SSD which are approach sight distance, sight distance on circulatory roadway, and sight distance to crosswalk on exit. Through observation, apart from the sight distance to bicycle crossings on exit lanes at the the entries of Riksvägen South and Fingspångsvägen West (before the yield line) are insufficient (as illustrated in Fig 4. 6), rest of the sight distance at each approach of the roundabout are adequate in general. Since the sight distance to crosswalk on exits at those two entries are relatively short compared to the recommened stopping sight distance, when drivers enter the roundabout with high speeds and exit the roundabout with right turn movement, it will be rather difficult for drivers to detect cyclists crossing the exits at those two entries due to the short sight distance. Even if the driver noticed the cyclist, because of
possible high travel speeds from the driver, he or she will take longer reaction time to react and need longer braking distance to stop before getting close to the cyclist (Silvano & Linder 2017), it therefore will increase accident risks and injury severity for cyclists at the roundabout (especially at the above-mentioned entries). In terms of intersection sight distance, the sight distance on each entry of the roundabout are adequate before the yield line, because there is vegetation (i.e. trees) placed on the two opposite sides of the central island to restrict the sight distance.

For sight distances at the roundabout, the relationship between geometric design element and relevance of safety that potentially lead to accidents for cyclists can be evaluated as acceptable, but the drivers should be more cautious and attentive (be aware of the presence of cyclists) when approaching the entries at Riksvägen South and Finspångsvägen West prior to exit the roundabout with right turn movement.

**Entry curve radius**

![Figure 4. 7. Entry radii at Riksvägen South (Top) and Finspångsvägen West (Bottom)](image)

On the subject of entry curves, based on the review in section 2.6.2, we grasp that the design of entry curves is an important factor in determining the operation of a roundabout and its’ safety and capacity. According to *Roundabouts: An informational Guide* (Robinson et al. 2000), the recommended entry radii for double-lane roundabouts in urban settings are ranging from 30 to
60 meters. But based on the measurements of each entry on Google Maps, entry radii are below the recommended values. Since most of the cyclist related accidents occurred at the entries of Riksvägen South and Finspångsvägen West, entry curve radii at these two locations are presented, as illustrated in Fig 4.7. Compared to the recommended entry radii, the entry curve radii at these two entries are relatively small. Even though small entry radii at double-lane roundabout may produce low entering speeds, as mentioned earlier, but it often leads to path overlap on motorized vehicle of the outer circulating lane into the inner lane (through observation, this movement occurred), and it could potentially lead motorized vehicles crash into curbs. Thus it will possibly increase the chance of collision with cyclists that are crossing the roundabout. Therefore, the relationship between entry curve radius and relevance of safety that potentially lead to accidents for cyclists at this roundabout can be assessed as not safe towards cyclists.

**Exit curve radius**

![Figure 4.8 Exit radii at Riksvägen South (Top) and Finspångsvägen West (Bottom)](image)

According to the review on section 2.6.2, exit curves on the other hand, the recommended values for exit curve radius at double-lane roundabouts are not provided in the guideline. Based on the review, it indicates that the radii of the exit curves should be smaller than the radii of entry curves in urban areas to maintain low speeds at the crosswalk on exits for maximizing safety for vulnerable road users. Since the recommended design values of entry curve radius
are not provided, based on the recommended entry curve radii in the guideline (range from 30 to 60 meters), we can assume that the recommended values for exit curve radius at double-lane roundabouts are approx. 40-45 meters (using the median value between 30-60 meters of entry curve radii), since exit curve radii are suggested to be comparatively smaller than entry curve radii. Through the observation of the measurements of exit curve radii on Google maps, values of each exit of the roundabout are under 20 meters, as exhibited in Fig 4. 8. In this case, the observed values are relatively small compared to the recommended values in such a large roundabout, it may have the same concerns as the aforementioned entry curve radii at the roundabout. Hence, it will increase the accident risks for cyclists on crossings on exit lanes, so the exit curve radii at this roundabout are not safe towards cyclists in terms of relevance that potentially lead to accidents for cyclists.

**Central island**

As shown in Fig 4. 9, the central island diameter of the roundabout is approx. 69 meters. Based on the review of geometric variables in section 2.6.2, the recommended size of central island diameter for a multi-lane roundabout should range from 20 meters to 40 meters, within this range, it provides the best safety for cyclists. In terms of shapes of central islands, it should preferably be built in circular shape for promoting constant speeds on circulatory roadway at roundabouts. However, at Finspångsrondellen, it is an oval-shaped central island, which indicates it can allow higher speeds on straight sections of the roadway and reduced speeds on the arcs of the roadway, thus this will produce relatively large speed differences for drivers on the circulating roadway, especially when drivers exit the roundabout, it may lead to loss of
control accidents that involved with cyclists. Also, it will make entering vehicles difficult to judge the gap acceptance and speed from the circulating traffic.

In terms of the size of the central island at the location, it is overly exceeded the recommended size for a double-lane roundabout. High circulating speed will be permitted if roundabouts are too large due to the size and shape of central islands, and it will increase crash risk and injury severity for cyclists at roundabouts. Therefore, size of the central island at the location is not safe towards cyclists in terms of relevance that potentially lead to accidents for cyclists.
5. Conclusions

This chapter presents the summary of findings based on the research objectives of this work and conclusions drawn from the findings and limitations of the thesis work.

In terms of traffic safety issues/concerns encountered by cyclists at roundabouts, depending on designs of roundabouts, cyclists will experience different kinds of conflicts either as pedestrians or vehicles when traveling through the roundabout. At mixed traffic roundabouts and roundabouts with adjacent cycle lanes, cyclists will travel through the roundabouts as vehicles, they will experience similar conflicts to those for motorized vehicles. In the literature the study identified that, at mixed traffic roundabout, the major concern for cyclists is the entering vehicles are not yielding to cyclists who are circulating. Another concern for cyclists is when a bicyclist is circulating in parallel with a driver on the circulatory roadway while the driver exits the roundabout. At roundabouts with separated cycle paths, cyclists will cross through the roundabouts as pedestrians, conflicts between motorized vehicles and cyclists emerge at the cross sections between the bicycle crossings and the entry/exit lanes. The main concern is the safety effects for cyclists tend to differ based on the arrangement of priority for cyclists at the roundabouts. The study in the literature showed that the accident reduction rate is much higher for cyclists when cyclists are without priority at the roundabout compared to when priority is assigned to cyclists. The second concern is the perceived accident risks for cyclists is relatively high when cyclists cruise through the roundabout in closewise direction while drivers enter or exit the roundabouts at the same time.

In terms of the common traffic safety issues faced by cyclists in general, the first common issue is the actual number of casualties for cyclists are overly underrated by the police worldwide. There is a need to improve the awareness of the police reporting accident data for cyclists without bias internationally, since good data can give nonbiased analysis towards traffic safety problems for road users, in this work, which means proper measures can be applied to specific traffic safety problems for cyclists at roundabouts. The second common issue is cyclists whose age are equal to or over 65 years old taking up high percentage of fatalities in accidents, especially for male riders across Europe. Statistics may widely differ from country to country in which can be determined by the cycling infrastructures of a country and the use of bicycles. The third common issue is the usual causes which lead to risks and injuries for cyclists are high speed differences, misuse or lack of use of bicycle helmets, and misbehavior from cyclists.

In terms of the differences between roundabouts and traffic circles, the literature showed that, at roundabouts, entering traffic have to give way to circulating traffic, vehicle speeds are controlled by their physical features (not by signs or pavement markings), eliminate left turn movements for entering traffic, provide raised splitter islands on all approaches for safety purpose, no parking is allowed on the circulating roadway, and no cyclist/pedestrian activities happen on the central island. At traffic circles, depending on its size, some small traffic circles allow left turn movement for entering traffic, unable to accommodate large vehicles, do not give right of way for circulating traffic, do not provide raised splitter islands, and do not control
speed. Certain large traffic circles allow parking on circulating roadway and provide cyclist/pedestrian crossings on the central island.

In terms of traffic safety effects at roundabouts in comparison to conventional intersections, there are two dominant factors that stand out the most for roundabouts in regards to traffic safety effect, which are speeds and conflicts. Compared to conventional intersections, influence of these two factors can substantially reduce accident rate and mitigate injury severity at roundabouts for most of the road users. Roundabouts with good design can offer speed reduction and speed consistency that conventional intersections hardly provide. Roundabouts can eliminate crossing conflicts that are able to lead to severe accidents, but conventional intersections possess these conflicts.

Based on the literature review, roundabouts with mixed traffic design are safe towards cyclists if average daily vehicle volume is less than 8000. Adjacent cycle lane roundabouts have had worse safety performance towards cyclists compared to other roundabout designs that integrated with cyclists, unless the daily traffic is under 8000, then the safety difference is less clear. Even though roundabouts with grade separated cycle paths show positive influence on safety performance for cyclists, but most researchers did not give opinions on this design. On the other hand, the separated cycle paths design is recommended by several researchers for improving safety level for cyclists at roundabouts, especially with high traffic volume.

Based on the case study in Norrköping city, the overall safety performance for cyclists at these four identified roundabouts (Packhusrondellen, Fenixrondellen, Finspångsrondellen, Stockholmsrondellen) is acceptable in a 8-year period, according to Table. 8. In Sweden, majority of the roundabouts are designed with separated cycling paths. Fenixrondellen as urban single-lane roundabout shows the best safety performance towards cyclists among the identified roundabouts. And Finspångsrondellen as double-lane roundabout is the most hazardous towards cyclists compared to the rest of the roundabouts. Other than carrying relatively high daily vehicle volume that increasing accident risks for cyclists at the location, and based on the safety assessment of certain geometric elements of the roundabout, there are also several geometric elements that are evaluated as not safe towards cyclists (potentially lead to accidents for cyclists) such as inscribed circle diameter, entry width, entry curve radius, exit curve radius, central island diameter. It therefore is recommended for the designer and road authorities to follow through the overall design principles of the design guide line and adapt to site-specific conditions of this particular roundabout in order to reduce accident risks and mitigate injury level for cyclists at the location.

On the subject of the main objective of the work, the conclusion that can be drawn from this research based on the literature review and the case study is single-lane roundabouts with separated cycling paths provide better performance under high vehicle volume in terms of reducing accident risks and mitigating injury severity for cyclists compared to other roundabout configurations, but there is no straightforward evidence shown that which roundabout configuration offers the best safety performance towards cyclists.
6. References


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