DOCTORAATSPROEFSCHRIFT

2010 | Interfacultair Instituut Verkeerskunde

An epidemiological approach to explain crash risk and crash severity for different types of road users at roundabouts

Proefschrift voorgelegd tot het behalen van de graad van
Doctor in de Verkeerskunde, te verdedigen door:

Stijn DANIELS

Promotor: prof. dr. Geert Wets

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Nil sine labore

(Horatius, 35 A.C.)

Preface

Seven years ago, after some years of experience in the domain of transportation policy, I took up the challenge to manage the Policy Research Centre on Traffic Safety that was founded at that moment and that was hosted by Hasselt University.

Soon I got taste for more. In my early career, I had become aware of quite some knowledge gaps and research needs in the domain of transportation policy and I got more and more interested in a rigorous and profound way to deal with these issues. The idea to start a PhD-project emerged. The topic of traffic safety at roundabouts appeared to be timely, policy relevant and susceptible for thorough scientific research.

During the past five years, I have spent countless hours and days in elaborating this thesis. Finishing it feels like an achievement, but not an end point.

Numerous people contributed in some way to this project. I want to thank my promoter, prof. dr. Geert Wets and my supervisor prof. dr. Tom Brijs. We went a long way together since the founding of the Transportation Research Institute and the Bachelor-Master in Transportation Sciences at Hasselt University. Special thanks as well to dr. Erik Nuyts who was also a member of my PhD-commission. I could benefit largely from his previous scientific work, his knowledge and experience.

Furthermore I want to thank my internal jury members prof. dr. Koen Vanhoof and dr. Ellen Jongen as well as my external jury members dr. Rune Elvik and prof. dr. Dominique Lord for their constructive comments on this dissertation.

Special thanks as well to my colleagues at IMOB, who provided an inspiring environment for carrying out this research.

Furthermore I want to thank my parents, family and friends for supporting me in this effort and in so many other things.

Finally, I owe much, if not everything, to my wife Katrien. She supported my decision to undertake this work and encouraged me in all circumstances to persevere. She and our children Jasper and Sofie have been a great help in making this work possible, each in their own way.

Stijn Daniels

May 28th, 2010

Executive summary

Although roundabouts exist almost as long as cars do, they only became common in continental Europe during the 80’s and the 90’s of the twentieth century. In North America they even emerged only recently. Knowledge and insights on traffic operations and safety on roundabouts have evolved considerably. Roundabouts have some intrinsic properties that are believed to improve traffic safety when they are constructed: they reduce speeds considerably and they decrease the number of possible conflict points between road users. Apart from their effects on traffic safety, roundabouts are considered to be adequate intersection types for accommodating high traffic flows, particularly in case of high quantities of left turning traffic.

Nevertheless some uncertainties exist on the safety effects of roundabouts. Particularly for bicyclists and pedestrians the effects are less clear. Also the effects of some design elements are not yet fully understood. These elements justified the execution of a PHD project on safety issues at roundabouts. The main objective of this dissertation was therefore to extend existing scientific knowledge on safety performance of roundabouts, based on state-of-the-art empirical research.

After an introduction the manuscript continues with an explanatory Chapter 2 on geometrical aspects of roundabouts. This is useful since a number of concepts needs some clarification and also to achieve consistency in the used terminology.

Chapter 3 provides an overview of existing knowledge on traffic safety aspects of roundabouts, based on a review of the scientific literature.

Subsequently, the empirical research efforts are described. Since this appeared to be an important issue in the research community as well as among practitioners, I thought it was useful to start with an evaluation of safety effects of roundabouts for one particular user group: bicyclists. Chapter 4 presents the results from an observational empirical Bayes before- and after study on injury crashes with bicyclists at roundabouts. This study design takes into account the stochastic nature of crashes and accounts for general safety trends and regression-to-the-mean-effects. Conversions of intersections into roundabouts turn out to have caused a significant increase of 27% in the number of injury crashes with bicyclists on or nearby the roundabouts. The increase is even higher for crashes involving fatal or serious injuries (41-46%). Compared to the

formerly proven favourable effects of roundabouts on safety in general, this result is unexpectedly poor. However, the effects of roundabouts on bicycle crashes differ depending on when these roundabouts are built inside or outside built-up areas. Inside built-up areas the construction of a roundabout did increase the number of injury crashes involving bicyclists by 48%. For crashes inside built-up areas with fatal or serious injuries, an average increase of 77% is noticed. However, outside built-up areas the zero-hypothesis of 'no safety effect for bicyclists' cannot be rejected (best estimate: + 1% crashes, not significant). Furthermore, roundabouts that are replacing traffic signals perform worse compared to roundabouts on other types of intersections.

Chapter 5 describes the results of analyses based on additionally collected information about the design type of the cycle facilities and some geometrical features of the investigated roundabouts. This happened through linear regression analyses on the effectiveness-indices resulting from the before-and-after study. Regarding all injury crashes with bicyclists, roundabouts with cycle lanes appear to perform significantly worse compared to three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths). Nevertheless, an increase of the severest crashes is noticed, regardless of the design type of the cycle facilities.

Before- and after-studies like they are discussed in these chapters provide a convenient way to calculate effects of certain measures. However, the calculations show considerable differences in safety performance of particular roundabouts or particular groups of roundabouts. It is therefore interesting to know which factors might explain the differences between roundabouts. An attempt to do so is done by fitting cross-sectional risk models on the available data. This work is presented in Chapter 6. Poisson and gamma modelling techniques are used, the latter one since underdispersion in the crash data is observed. The results show that the variation in crash rates is relatively small and mainly driven by the traffic exposure. Vulnerable road users are more frequently than expected involved in crashes at roundabouts and roundabouts with cycle lanes are clearly performing worse than roundabouts with cycle paths. Confirmation is found for the existence of a safety in numbers-effect for bicyclists, moped riders and – more unsure – for pedestrians at roundabouts.

After completing this, an attempt was done to extend the available dataset substantially. The results of the analyses based on the extended dataset are provided in Chapter 7. The originally investigated sample was extended to 148 roundabouts. The same modelling techniques as in the previous chapter are used and separate models are fitted again for crashes with six different types of road users: bicyclists, motorcyclists, light and heavy four-wheel vehicles, moped riders and pedestrians. A further distinction is made between single-vehicle and multiple-vehicle crashes. The results confirm largely the results of the previous models, but add also some interesting information. Moped riders and motorcyclists are strongly overrepresented in single-vehicle crashes as well as in multiple-vehicle crashes whereas bicyclists are clearly overrepresented in multiple-vehicle crashes. In the investigated dataset, roundabouts with cycle paths are performing better than roundabouts with other types of cycle facilities, particularly in comparison with roundabouts with cycle lanes close to the roadway. Furthermore, the results confirm the ‘safety in numbers’ effect for different types of road users. This effect makes that, although the total number of crashes is higher in case of higher traffic volumes on a certain location, the individual risk for each road user decreases.

In Chapter 8, the focus shifts to the level of severity of crashes that were recorded at the roundabouts. Severity can be expressed as the probability that, given a crash happening, the outcome will be of certain seriousness. The severity of 1491 crashes on 148 roundabouts is examined in order to investigate which factors might explain the severity of crashes or injuries and to relate these factors to the existing knowledge about contributing factors for injury severity in traffic. Logistic regression and hierarchical binomial logistic regression techniques are used. A clear externality of risk appears to be present in the sense that vulnerable road user groups (pedestrians, bicyclists, moped riders and motorcyclists) are more severely affected than others. Fatalities or serious injuries in multiple-vehicle crashes for drivers of four-wheel vehicles are much rarer. Injury severity increases with higher age, crashes at night, crashes outside built-up areas and crashes at roundabouts with grade-separated facilities for bicyclists are more severe. Single-vehicle crashes seem to have more severe outcomes than multiple-vehicle crashes. However, systematic differences in the reporting rate of crashes are likely to exist and may have affected the stated results. Correlations with important, but unobserved variables like the impact speeds in the crashes might exist as well and could provide an alternative explanation for some results.

The manuscript ends with a number of general conclusions, some policy recommendations and some recommendations for further research.

The stated results may raise a policy dilemma in the sense that, given the poor performance for bicyclists, it could be questioned whether the construction of roundabouts should be promoted or discouraged. A strictly rational approach would probably mean that an overall reduction should prevail, even if one particular subgroup is not benefitting. But such an approach is likely to be contested, not at least within a sustainability development perspective. Based on the stated results, it might be careful not to construct roundabouts at locations where cyclist safety is of particular concern and in that case rather to balance pros and contras of other types of design such as signal-controlled intersections. If a well-considered decision is made to construct a roundabout, this should be no roundabout with cycle lanes.

It can reasonably be assumed that the stated results are valid for the whole population of roundabouts on regional roads in Flanders-Belgium. It is more unclear whether the stated effects would be valid for other countries and regions as well. At least, the results of the present work could serve as an indication for effects that are likely to occur in other settings as well. However, this issue deserves further investigation.

Also further research on different aspects of roundabout design and related safety performance will be required. Useful research directions are related to the extension of the existing models with extra data and variables. Other topics deserving further research are the safety effects of two-lane roundabouts and defining the concept of ‘complexity’ on intersections. In-depth analyses of crashes on roundabouts could contribute to a better understanding of underlying reasons for the over involvement of cyclists in crashes at roundabouts. Ideally, any future research in this domain should be done in a cross-country perspective in order to incorporate better existing differences in roundabout design guidelines and practices. In the longer run, this may lead to more universal design guidelines.

The present research was based on observed crash data and was of an epidemiological nature. It aimed to describe possible problems and effects of variations in design elements. It is my opinion that a useful future and supplementary approach could consist of examining the potential of some surrogate measures to assess the safety performance of some roundabout designs. Particularly factors (e.g. not frequently occurring design elements) that are most likely not substantial in explaining crash rates at an aggregate level of “all crashes at all roundabouts” might be assessed in a more valid and detailed way by observing their effects on human behaviour than on their final crash outcomes. Such an approach would improve the understanding of the occurrence of crashes by defining relations of crashes with events that precede crashes (conflicts, behaviours) and higher-order conditions that influence the occurrence of these preceding events. An improved knowledge hereof would contribute gradually to the establishment of conceptual, law-like relationships between variables describing features of the traffic system (roadway, vehicles and human (inter)actions) and the level of traffic safety.

Nederlandse samenvatting

Hoewel rotondes al zolang als auto's bestaan, verschenen ze pas massaal in het straatbeeld in continentaal Europa sinds de jaren 80 en 90 van de vorige eeuw. In Noord-Amerika deden ze zelfs maar recentelijk hun intrede. De kennis van en de inzichten over rotondes zijn aanzienlijk geëvolueerd. Omwille van enkele intrinsieke eigenschappen kan verwacht worden dat de aanleg van een rotonde leidt tot een verbeterde verkeersveiligheid. Rotondes reduceren de rijsnelheid en leiden tot een geringer aantal conflicten tussen weggebruikers. Bovendien zijn rotondes geschikte kruispunttypes om intense verkeersstromen te verwerken, vooral in geval van een hoge proportie links afslaand verkeer.

Niettemin zijn er steeds enkele onzekerheden blijven bestaan in verband met verkeersveiligheid op rotondes. Dat geldt vooral voor de effecten voor voetgangers en fietsers. Tevens bestaat nog onzekerheid over de effecten van bepaalde geometrische elementen. Deze elementen vormden het uitgangspunt bij de start van dit doctoraatsproject. De hoofddoelstelling was om de bestaande wetenschappelijke kennis over de veiligheidseffecten van rotondes te beschrijven en uit te breiden aan de hand van state-of-the-art empirisch onderzoek.

Het proefschrift start met een inleiding en een beschrijvend hoofdstuk 2 over de geometrische aspecten van rotondes. Dit is nuttig omdat een aantal begrippen uitleg vereist, maar ook omdat consistentie gewenst is in de gebruikte terminologie.

Hoofdstuk 3 biedt een overzicht van de bestaande kennis over verkeersveiligheidseffecten van rotondes, gebaseerd op een doorlichting van de bestaande wetenschappelijke literatuur.

Vervolgens komt het uitgevoerde empirisch onderzoek aan bod. Omdat dit een belangrijk topic bleek te zijn, zowel in de onderzoekswereld als bij praktijkmensen, leek het zinvol om dit doctoraatsonderzoek te starten met een evaluatie van de effecten van rotondes op de verkeersveiligheid voor één specifieke gebruikersgroep, met name fietsers. Hoofdstuk 4 presenteert de resultaten van een empirisch Bayesiaanse voor- en nastudie van letselongevallen met fietsers op 91 rotondes. Deze onderzoeksmethode houdt rekening met de stochastische aard van ongevallen, met algemene trends in verkeersveiligheid en met het mogelijke regressie-naar-het-gemiddelde effect. Het omvormen van kruispunten tot rotondes blijkt een significante stijging van

27% van het aantal letselongevallen met fietsers op en nabij de rotondes te hebben veroorzaakt. De toename blijkt zelfs hoger voor wat de ongevallen betreft met doden en zwaargewonden (41-46%). Dit is een onverwacht zwak resultaat in het licht van de vroeger bewezen gunstige algemene veiligheidseffecten van rotondes. Niettemin blijkt het effect van rotondes op ongevallen met fietsers te verschillen naargelang de locatie binnen of buiten bebouwde kom. Binnen bebouwde kom bedraagt de stijging van het aantal letselongevallen 48%. De gemiddelde stijging van het aantal dodelijke en zware ongevallen met fietsers bedraagt binnen de bebouwde kom zelfs 77%. Buiten bebouwde kom kan de nulhypothese van "geen veiligheidseffect voor fietsers" echter niet verworpen worden gegeven een beste, maar niet significante, schatting van 1% stijging van het aantal ongevallen. Voorts presteren rotondes die verkeerslichten vervangen zwakker dan rotondes die andere kruispuntvormen vervangen.

Hoofdstuk 5 beschrijft de resultaten van analyses op basis van bijkomende data over de verschillende types fietspaden en enkele geometrische elementen van de onderzochte rotondes. Dit gebeurde via lineaire regressie-analyses op de effectiviteits-indices uit de voor- en nastudie. Rotondes met aanliggende fietspaden blijken significant zwakker te presteren dan drie andere types fietsvoorzieningen (gemengd verkeer, vrijliggende fietspaden en volledig gescheiden fietspaden). Voor de zwaarste ongevallen was er niettemin een stijging van het aantal ongevallen, ongeacht het type fietsvoorzieningen.

Voor- en nastudies zoals ze aan bod komen in Hoofdstuk 4 en Hoofdstuk 5 bieden een geschikte methode om de effecten van bepaalde maatregelen te berekenen. Nochtans bleek uit de berekeningen dat er aanzienlijke individuele verschillen bestaan tussen de rotondes. Daarom was het interessant te weten welke factoren het verschil tussen rotondes bepalen. Dit gebeurde door cross-sectionele risicomodellen te fitten voor de beschikbare data. Deze analyses komen aan bod in Hoofdstuk 6. Daarbij zijn zowel Poisson als gamma modelleringstechnieken gebruikt, deze laatste omdat er onderdispersie in de data bleek aanwezig te zijn. De resultaten tonen dat de variatie in het aantal ongevallen relatief klein is en voornamelijk wordt bepaald door de blootstelling aan het risico. Zwakke weggebruikers zijn vaker dan verwacht betrokken bij verkeersongevallen op rotondes en rotondes met aanliggende fietspaden presteren duidelijk zwakker dan rotondes met vrijliggende fietspaden. Verder bevestigen de onderzoeksresultaten het "safety-in-numbers"-effect voor fietsers, bromfietsers en – minder zeker – voetgangers op rotondes.

Nadat deze analyses waren uitgevoerd bood zich een interessante opportuniteit aan om de dataset uit te breiden met 58 rotondes tot in totaal 148 rotondes. De resulterende analyses zijn opgenomen in Hoofdstuk 7. De gebruikte technieken bleven grotendeels dezelfde, inclusief de afzonderlijke modellen voor zes verschillende types weggebruikers: fietsers, motorrijders, lichte en zware vierwielige voertuigen, bromfietsers en voetgangers. Daarnaast werd onderscheid gemaakt tussen eenzijdige en meerzijdige ongevallen. De resultaten bevestigen in grote mate de resultaten voor de beperktere dataset, maar voegen er ook nieuwe informatie aan toe. Bromfietsers en motorrijders blijken zowel oververtegenwoordigd te zijn in eenzijdige als in meerzijdige ongevallen terwijl fietsers duidelijk oververtegenwoordigd zijn in meerzijdige ongevallen. In de uitgebreide dataset blijken rotondes met vrijliggende fietspaden beter te presteren dan andere rotondes, vooral dan in vergelijking met rotondes met aanliggende fietspaden. Verder bevestigden de resultaten het 'safety-in-numbers-effect' voor verschillende types weggebruikers. Dit effect zorgt ervoor dat, hoewel het totale aantal ongevallen per locatie toeneemt bij toenemende verkeersvolumes, het individuele risico voor weggebruikers daalt.

In Hoofdstuk 8 verschuift de focus naar de ernst van de geobserveerde ongevallen op de rotondes. De ernst wordt uitgedrukt als de kans dat, indien een ongeval gebeurt, dit resulteert in een letsel van een zekere ernst. In dit hoofdstuk worden analyses uitgevoerd van 1491 ongevallen op 148 rotondes om daaruit af te leiden welke factoren de ernst van deze ongevallen of de daarmee gepaard gaande letsels bepalen. Hiertoe gebruikte technieken zijn logistische regressie en hiërarchisch binomiale regressie. Er blijkt sprake te zijn van een externaliteit van het risico aangezien zwakke weggebruikers (voetgangers, fietsers, bromfietsers en motorrijders) gemiddeld zwaarder gewond geraken dan andere weggebruikers. Dodelijke of zware verwondingen in meerzijdige aanrijdingen op rotondes voor bestuurders van vierwielige voertuigen zijn veel zeldzamer. De ernst van het letsel neemt toe met de leeftijd. Nachtelijke ongevallen, ongevallen buiten de bebouwde kom en ongevallen op rotondes met volledig gescheiden fietspaden kennen een ernstiger afloop. Eenzijdige ongevallen zijn ernstiger dan meerzijdige ongevallen, maar dit verschil zou kunnen verklaard worden door verschillen in de rapporteringsgraad voor beide types. Correlaties met relevante, maar niet gekende variabelen kunnen bestaan en zouden een alternatieve verklaring kunnen bieden voor sommige resultaten.

Het proefschrift besluit met een aantal algemene conclusies, enkele beleidsaanbevelingen en suggesties voor toekomstig onderzoek.

De gevonden resultaten kunnen leiden tot een zeker dilemma voor het beleid in die zin dat men zich zou kunnen afvragen of het aanleggen van rotondes best wordt aangemoedigd dan wel ontmoedigd in de wetenschap dat de meeste weggebruikers daar wel bij varen, maar dat minstens één gebruikerscategorie - met name de fietsers - daar de dupe van is. Op basis van de gevonden resultaten wordt aanbevolen om geen rotondes te bouwen op plaatsen waar de veiligheid voor fietsers een bijzonder punt van zorg is. Indien er toch een weloverwogen keuze voor een rotonde wordt gemaakt, is dit best geen rotonde met aanliggende fietspaden.

Er kan redelijkerwijze gesteld worden dat de gevonden resultaten valide zijn voor de gehele populatie van rotondes op gewestwegen in Vlaanderen. Het is minder zeker of de gevonden resultaten ook bruikbaar zijn voor andere landen en regio's. Op zijn minst kunnen de resultaten uit dit werk als indicatie dienen. Niettemin verdient dit verder onderzoek.

Tegelijkertijd zal verder onderzoek nodig zijn over verschillende aspecten van het ontwerp van rotondes. Een nuttige denkpiste bestaat er alleszins in om de huidige dataset verder uit te breiden. Andere aspecten waar verder onderzoek zich aandient zijn de effecten van tweestrooksrotondes en het definiëren van het concept 'complexiteit' op kruispunten. Diepte-analytisch onderzoek van ongevallen met fietsers zou kunnen bijdragen tot een beter inzicht in de achterliggende redenen voor de oververtegenwoordiging van fietsers in ongevallen op rotondes. Idealiter zou eender welk onderzoek in dit verband in een internationaal perspectief gedaan worden zodat bestaande verschillen in de richtlijnen en de praktijken voor het aanleggen van rotondes in rekening kunnen gebracht worden. Op de langere termijn kan dit leiden tot universelere richtlijnen voor ontwerp.

Dit onderzoek was gebaseerd op geobserveerde ongevallendata en van epidemiologische aard. Het doel was om mogelijke problemen en effecten van variaties in ontwerpelementen te beschrijven. Een nuttige toekomstige en supplementaire aanpak zou erin zou kunnen bestaan om het potentieel te onderzoeken van surrogaat methoden als middel om de veiligheidsprestatie van bepaalde vormen van rotondes te evalueren. Dit zou vooral van nut kunnen zijn om het precieze effect te observeren van bepaalde factoren (zoals ontwerpelementen die niet vaak voorkomen) die waarschijnlijk niet substantieel zijn op het geaggregeerde niveau van "alle ongevallen op alle rotondes". Een dergelijke benadering zou een beter begrip mogelijk maken door relaties te definiëren tussen ongevallen en fenomenen die aan ongevallen vooraf gaan (conflicten, gedragingen) en hogere-orde omstandigheden die op hun beurt het optreden van deze voorafgaande factoren beïnvloeden. Meer inzicht hierin zou geleidelijk aan kunnen leiden tot het beschrijven van conceptuele en universeel geldende verbanden tussen kenmerken van het verkeerssysteem (weg, voertuigen en menselijke (inter)acties) en het niveau van verkeersveiligheid.

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Chapter 1. Introduction

It felt appropriate to start this manuscript with an introductory description of roundabouts and a short overview of their present and past application. It will be shown that roundabouts are gaining popularity, but are still not applied to the same extent everywhere. Furthermore, some argumentation is given about the choice of safety effects of roundabouts as a research topic for this PhD-project. Subsequently, the structure of the manuscript is explained.

Parts of this introduction have been published in Daniels & Wets (2005; 2006a; 2006b).

1.1. ROUNDABOUT GENERALITIES

A roundabout can considered to be a circular intersection on which traffic is circulating in one direction around a central island.

Roundabouts almost exist as long as cars do. Nevertheless, knowledge and insights on traffic operations and safety on roundabouts have evolved considerably. Roundabouts in their actual design originate from large traffic circles as they were built in France in the beginning of the 19th Century. In 1903 the Paris architect Eugène Hénard developed the principle of an intersection where all the road users (at that time mainly horses and coaches) had to make a circulatory movement around an obstacle in the middle (Alonzo, 1995; Brown, 1995).

Later on, especially in Great Britain, much experience was acquired with roundabouts (Brown, 1995; Certu, 2000; Thai Van & Balmefrezol, 2000). With increasing traffic, roundabouts tended to lock up. Give-way-priority to the circulatory traffic on roundabouts was therefore generalised in Great Britain in 1966.

Roundabouts have become common in continental Europe during the 80’s and the 90’s of the twentieth century (Brilon & Vandehey, 2000; Brown, 1995; CERTU, 2000; Daniels & Wets, 2006; MET, 2003; Thai Van & Balmefrezol, 2000) and a further increase in the number of roundabouts is consistently reported in all the mentioned sources. In North America the use of roundabouts is still rather limited (Persaud et al., 2001; Pellecuer & St.-Jacques, 2008), although it is increasing (Rodegerdts et al., 2007).

1.2. RESEARCH OBJECTIVES

As described above, roundabouts are becoming increasingly popular in many countries. Their popularity is based on some of their favourable properties in comparison with other types of intersections. Those elements are provided more into detail in section 1.3 hereunder. Many authors and textbooks argue in favour of the construction of roundabouts. For instance, Hakkert & Gitelman (2004) argue: "Intersection accidents can most effectively be addressed by the widespread conversion of intersections to roundabouts, of course, where the right conditions for such a conversion exist." Shinar (2007) notes that "Traffic calming techniques through highway design changes appear to be the most effective means of slowing drivers, especially through the use of single-lane roundabouts. Their effectiveness in crash reduction has been so great and consistent, that they are rapidly replacing uncontrolled and controlled intersections". As will be shown in Chapter 3, roundabouts have some intrinsic properties that should allow improving traffic safety when they are constructed. Apart from their effects on traffic safety, roundabouts are considered to be adequate intersection types for accommodating high traffic flows, particularly in case of high quantities of turning traffic (Bird, 2001; PIARC, 2003).

Although the benefits of roundabouts were extensively described some warnings have been raised as well about their safety performance. Ogden (1996) mentions possible problems with bicyclists and, to a lesser extent, with pedestrians. Furthermore safety problems might occur in case of inappropriate designs such as too sharp merging angles, steep approach gradients and inadequate sight conditions (Ogden, 1996). Shinar (2007) advocates research on the possible effects of roundabouts on safety for older road users.

A number of elements were believed to justify a PHD-project on safety issues at roundabouts:

- While the effect of roundabouts on crashes in general was rather extensively investigated, this was not the case for the effects on particular road users. The 'Handbook of Road Safety measures' (Elvik & Vaa, 2004) mentions only a very few, not scientifically published, studies that have evaluated the effects of roundabouts on crashes for different types of road users. The available studies failed to take into account major confounding elements such as general trends and regression-to-the-mean effects and were therefore likely to be at least somewhat biased.

- Roundabouts appear to induce a higher number of bicyclist-involved accidents than might be expected by the occurrence of bicycles in overall traffic. In Flanders-Belgium bicyclists appear to be involved in almost one third of reported injury accidents at roundabouts (1118 reported accidents with bicyclists; 3558 in total, data 1991–2001), while according to the regional travel behaviour survey (Zwerts and Nuyts, 2004) only 14.6% of all trips (5.7% of distance traveled) are made by bicycle. In Great Britain, the involvement of bicyclists in accidents on roundabouts was found to be 10–15 times higher than the involvement of car occupants, taking into account the exposure rates (Brown, 1995). It was unclear which elements could explain this phenomenon: an increased crash risk or an increased injury severity?

- Much of the knowledge in this domain seems to have been developed outside the scope of traditional scientific literature and is not always very well empirically supported. Ogden (1996, p.11) argues that in general "...the road safety problem... calls for a response based on a scientific analysis of the problem, not one based on judgment and emotion – or as used to be said, one based on the PHOG approach of Prejudice, Hunch, Opinion and Guesswork". Other authors argue that road safety evaluation research does not have a strong theoretical foundation or a strong tradition for using experimental study designs that make it impossible to rule out methodological interpretations of the findings (Elvik & Vaa, 2004). These arguments indicate that even widely accepted knowledge might benefit from confirmation by empirical scientific research.

- Although some efforts were done in the past, a lack of knowledge persisted on the possible contribution of some design elements (number of legs, number of lanes, markings, central island shape and size, roadway dimensions, facilities for pedestrians and cyclists...) to the safety performance of roundabouts (Brown, 1995; Elvik & Vaa, 2004).

- Design guidelines for roundabouts differ from one country to another, which makes that research results from one country are not necessarily valid for another country and still some efforts are needed to gradually establish better universal knowledge on this topic. For instance with respect to entry flaring and provisions for bicyclists important differences between design guidelines seem to exist (Kennedy, 2007).

- Design guidelines have evolved over time and the more recently constructed roundabouts are likely to be designed according to more recent guidelines. Since design guidelines should have benefited from ever-improving research results, expertise and scientific knowledge, the design of modern roundabouts should therefore reflect these improved insights. Consequently, explaining factors for the crashes at roundabouts could have evolved over time as well.

Consequently the main objective for this thesis can be worded as “extending existing knowledge on safety effects and safety performance of roundabouts, based on state-of-the-art empirical research”.

1.3. APPLICABILITY OF ROUNDABOUTS

Roundabouts are believed to be a safe and efficient design for intersections. The simplicity and ease of operation of normal roundabouts make them well understood by drivers (PIARC, 2003). Roundabouts enable drivers also to make U-turns to correct wrong destination choices or to provide access to destinations on the reverse side of the road.

Different authors and guidelines describe operational circumstances in which roundabouts are believed to be better or worse design types than other intersection designs such as signal-controlled intersections or give-way intersections.

Circumstances in which roundabouts are believed to be appropriate intersection types are intersections with high volumes of left turning traffic (for traffic driving on the right, vice versa in case of traffic driving on the left), intersections with more than four legs and intersections on which other designs would lead to important delays for one or another direction. Furthermore roundabouts are believed to improve traffic safety at locations with high numbers of crashes and they could be used as a part of a traffic management strategy to reduce vehicle speeds in certain areas (Brown, 1995; CERTU, 2000; CROW, 1998; FHWA, 2000; MET, 1999; MVG, 1997; Ogden, 1996; PIARC, 2003).

Some authors and guidelines describe also some advantages at higher levels of the traffic system or even related to urban planning. Roundabouts could act as ‘collecting and distribution points’ or even as physical landmarks in order to recognize borders of urban or built-up areas (Brown, 1995; CERTU, 2000; MVG, 1997).

Nevertheless, a number of circumstances are also defined in which roundabouts could perform less well or would not be a suitable alternative for other designs, often compared with signal-controlled intersections (Brown, 1995; CERTU, 2000; CROW, 1998; FHWA, 2000; MET, 1999; MVG, 1997; Ogden, 1996). Circumstances in which roundabouts are believed to be less suitable are when either the topography or the available public space doesn’t allow an adequate construction. Also when traffic flows are unbalanced or in case of high numbers of pedestrians a roundabout is considered to be less appropriate. Moreover, roundabouts are not recommended at an isolated intersection in a network of signal-controlled intersections or when a signal-controlled intersection is located nearby the roundabout which could result in traffic queues locking the roundabout.

1.4. STRUCTURE OF THE MANUSCRIPT

The main objective for this dissertation is to describe and extend existing knowledge on safety effects and safety performance of roundabouts.

The manuscript will start with an introduction on geometrical aspects of roundabouts. This is useful since a number of concepts need some clarification and since consistency is needed in the adopted terminology. This introduction is provided in Chapter 2.

Chapter 3 provides an overview of existing knowledge on traffic safety aspects of roundabouts, based on a screening of the existing scientific literature.

Subsequently, the empirical research efforts will be described. Since it appeared to be an important issue among researchers as well as among practitioners, it was chosen to start with an evaluation of safety effects of roundabouts for one particular user group: bicyclists. Chapter 4 presents the results of an observational before and after study on injury crashes with bicyclists at 91 roundabouts. Chapter 5 describes the results of analyses based on additionally collected information about the design type of the cycle facilities and some geometrical features of the investigated roundabouts.

Before- and after-studies like they are discussed in these chapters provide a convenient way to calculate effects of certain measures. However, the calculations showed considerable differences in safety performance of particular roundabouts or particular groups of roundabouts. It was therefore interesting to know which factors might explain the differences between roundabouts. An attempt to do so was done by fitting cross-sectional risk models on the available data. This work is presented in Chapter 6. After completing this, a nice opportunity of extending the dataset appeared to be available. The results of the analyses with the extended data are provided in Chapter 7.

In 0, the focus shifts to the level of severity of crashes that were recorded at the roundabouts. Severity can be expressed as the probability that, given a crash happening, the outcome will be of certain seriousness. The severity of 1491 crashes on 148 roundabouts is examined in order to investigate which factors might explain the severity of crashes or injuries and to relate these factors to the existing knowledge about contributing factors for injury severity in traffic.

The manuscript finishes with some general conclusions, policy recommendations and recommendations for further research.

Chapter 2. Geometric aspects of roundabouts

A roundabout consists of a number of geometric elements that may have influence on both safety and traffic operations: a central island, a truck apron, the circulatory roadway, bicycle and/or pedestrian facilities, exit and entry lanes... The presence and the dimensions of those elements determine to a large extent the operational performance of the roundabout. But they are assumed as well to have impact on the safety performance of roundabouts. Hereunder, the most essential geometrical elements of roundabouts are listed and described, particularly those elements that will be of further importance throughout this manuscript.

2.1. ROUNDABOUT FEATURES

For the purpose of this project, guidelines for roundabout design from several regions and countries were examined. Like it is also the case for other applications in road design, no universal practice nor international consensus seems to exist about some aspects of roundabout design. Nevertheless, an attempt is made to synthesize the relevant elements of roundabout design, not by providing exact measures and calculation methods, but by dealing with some underlying principles that are suitable for a more universal description. The consulted design guidelines originate from the three Belgian regions Flanders (MVG, 1997), Wallonia (MET, 1999) and Brussels (Dupriez & Vertriest, 2009); the Netherlands (CROW, 1998; 2002); France (CERTU, 1999); the United Kingdom (GBHA, 1993; 1997) and the USA (FHWA, 2000).

Most design guidelines refer to some general principles that determine the design of a roundabout. Although the emphasis may vary according to the source, the following principles seem to appear in all the examined design guidelines:

- The speeds on the roundabout and on the entry lanes should be sufficiently low and homogenous for all present road users. This enables to achieve optimal capacity and decreases the risk on conflicts.
- The design vehicle is the largest vehicle that should be able to use the roundabout in normal circumstances. The size of the design vehicle determines the geometric features of the roundabout: central island diameter, entry/exit radii, road width etc.

- The presence of non-motorised road users (mainly pedestrians and bicyclists) determines the need for specific facilities. In practice, this is largely related to the presence of sidewalks and pedestrian crossings. Specific facilities for bicyclists are, except for a few countries, not common.
- The alignment of approaches and entries. A roundabout is generally considered to be optimal when the centrelines of all approach legs pass through the centre of the inscribed circle.

Furthermore, it is worth to mention that in all the considered countries priority is given to the circulating traffic on roundabouts.

Apart from these general principles, a whole series of particular design elements is of importance. Figure 1 Shows the basic geometric features of a roundabout. A description of the most important elements is given hereunder.

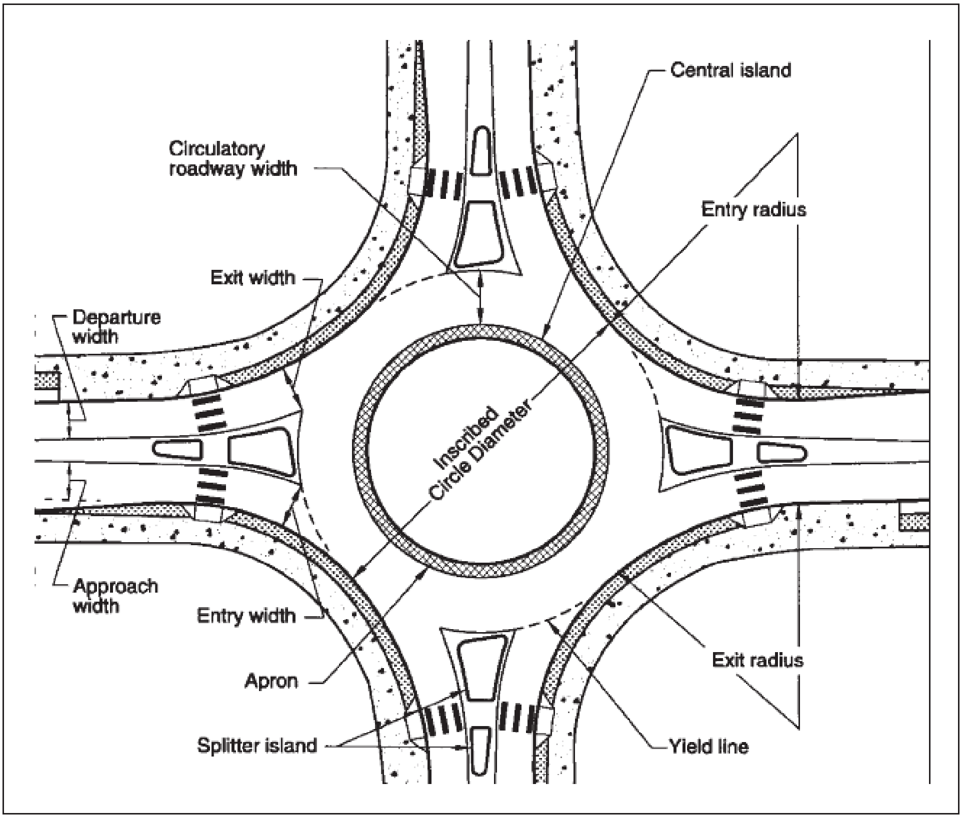

Figure 1 Basic geometric roundabout features. Source: FHWA

2.1.1. Central island

The central island is the raised area in the centre of a roundabout around which traffic circulates. The central island might contain a traversable apron. A circulatory shape for the central island is recommended, although not necessarily present everywhere (e.g. not in the case of oval roundabouts, see section 2.3). A circulatory shape favours constant speeds and limits the number of manoeuvres while driving on the roundabout. The central island should preferably be raised since it this improves the visibility of the roundabout for approaching traffic. Shrubs and/or vertical elements (e.g. artwork) might further improve the visibility. An adequate lighting of roundabouts and/or the use of retro-reflective materials are recommended in each of the examined guidelines.

The size of the central island is an important geometric variable of the roundabout since it determines largely the amount of lateral deflection (= lateral movement of the entering traffic). A larger central island generates logically a larger roundabout. Throughout this manuscript, the central island radius is the radius of the central island, including the apron if present.

2.1.2. Apron

The central island can be constructed in such a way that the outer part is slightly raised and therefore can be traversed. The traversable outer part is called a (truck) apron in that case. The construction of an apron is recommended for smaller roundabouts. The main reason not to opt for a widened roadway in such cases is the fact that the lateral deflection for private cars could be too limited and speeds would be too high. The straighter the driving path is through the roundabout, the less will be the achieved speed reduction. Consequently, an ideal apron can easily be traversed by trucks and busses, but deteriorates the comfort level for car drivers in such a way that its use is discouraged for car users.

2.1.3. Inscribed circle diameter

The distance across the circle inscribed by the outer edge of the circulatory roadway is considered to be the inscribed circle diameter (FHWA, 2000). The inscribed circle diameter is the most common variable to describe the size of a roundabout. Larger roundabouts facilitate the accommodation of larger vehicles, but tend to allow higher speeds as well. In the different guidelines, inscribed circle diameters from 13 meters (mini-roundabouts) to 80 meters were found.

2.1.4. Road width/lane width

The road can be divided into more than one lane through the use of road markings. Lane widths should be constant throughout the roundabout (CERTU, 1999). As a rule of thumb, the roundabout lane width should never be smaller than the width of the approaching lanes (FHWA, 2000). The French and US guidelines recommend to apply a road width on a single-lane roundabout of 120% of the lane width of the entry lane (CERTU, 1999; FHWA, 2000).

2.1.5. Alignment of approaches and entries

A roundabout is generally considered to be optimal when the centrelines of all approach legs pass through the centre of the inscribed circle. Nevertheless, the section of the entry lane that is closest to the roundabout is sometimes flared to the circulatory roadway and allows therefore smoother traffic operations since the entering traffic and the circulating traffic are moving with more homogenous speeds. This shape is particularly common on roundabouts in the UK and the US and on large roundabouts in France (Brown, 1995; FHWA, 2000). In the Flanders region and in the Netherlands, flaring is applied to a much lesser extent since more emphasis is laid on the speed reducing effect of the perpendicular approach design (CROW, 1998; MVG, 1997). The speed reducing effect is argued to be particularly favourable for crossing pedestrians and bicyclists (MVG, 2007).

2.1.6. Entry/exit lanes

Splitter islands on the entry and exit lanes guide traffic, prevent possible conflicts between approaching and entering traffic, provide a shelter for crossing pedestrians and bicyclists and can be used as a place for mounting signs. Moreover, roundabout capacity is favourably affected since wider splitter islands enable approaching drivers to detect easier whether oncoming circulating vehicles will leave the roundabout or continue their way. Most guidelines recommend the use of splitter islands, except for very small roundabouts. (CERTU, 1999; MVG, 1997; FHWA, 2000). Only the UK guidelines are less conclusive and leave the decision whether to put splitter islands or not to the appraisal of the roundabout designer (GBHA, 1993).

Unless more lanes are needed through capacity reasons, entries and exit roads are preferably single-lanes. In a number of cases, bypasses are constructed to allow traffic in some directions to operate independently of other directions.

2.2. FACILITIES FOR PARTICULAR ROAD USER TYPES

2.2.1. Bicyclists

Although huge differences exist between design practices in different countries, some basic types of designs for bicyclists at roundabouts can be distinguished. They are ordered into four categories:

1. Mixed traffic;
2. Cycle lanes close to the roadway;
3. Separate cycle paths;
4. Grade-separated cycle paths.

The most basic solution is to treat bicyclists the same way as motorised road users, which means that bicycle traffic is mixed with motorised traffic and bicyclists use the same entry lane, carriageway and exit lane as other road users. It is further called the "mixed traffic" solution (see Figure 2). In many countries this is the standard design as no specific facilities for bicyclists are provided. In some countries it is common to apply the mixed traffic solution, even when cycle lanes or separate cycle paths are present on approaching roads. In that case, the cycle facilities are bent to the road or truncated about 20-30 meter before the roundabout (CROW, 2007).

A second possible solution are cycle lanes next to the carriageway, but still within the roundabout (Figure 3 , see also Figure 7). Those lanes are constructed on the outer side of the roundabout, around the carriageway. They are visually recognizable for all road users. They may be separated from the roadway by a road marking and/or a small physical element or a slight elevation. They may also be constructed in a different pavement or differently coloured (red, green, blue…). However the cycle lanes are essentially part of the roundabout because they are very close to it and because the manoeuvres bicyclists have to make are basically the same as the manoeuvres for motorised road users. A specific case occurs when the cycle lanes are differently coloured but not separated by a line marking from the carriageway. This solution is called a 'cycle suggestion lane'. From a legal point of view (at least in Belgium) roundabouts with such a cycle suggestion lane could be considered as roundabouts with mixed traffic since bicyclists are not obliged to use the cycle lane and may use the carriageway. Nevertheless, in practice the presence of a coloured pavement is supposed to attract bicyclists to that part of the road. Therefore they are classified as roundabouts with cycle lanes.

When the distance between the cycle facility and the carriageway becomes somewhat larger (the operational criterion used in this study is: more than 1 meter), the cycle facility cannot be considered anymore as belonging to the roundabout. This is called the separate cycle path-solution. The 1 meter-criterion corresponds with the Flemish guidelines for cycle facilities (MVG, 2006). Since the distance between the separate cycle path and the roadway may mount to some meters (e. g. the Dutch design guidelines recommend 5 meter) (CROW, 2007), specific priority rules have to be established when bicyclists cross, while circulating around the roundabout, the entry or exit lanes.

While it is universally accepted to give traffic circulating on the roundabout priority to traffic approaching the roundabout (offside priority), such is not always the case for bicyclists on separate cycle paths. In some cases, priority is given to the bicyclists when crossing the entry/exit lanes, in other cases bicyclists have to give way. The former is called the "separate cycle paths - priority to bicyclists solution" (Figure 4), the latter the "separate cycle paths - no priority to bicyclists solution" (Figure 5 , see also Figure 8) (CROW, 1998). When bicyclists have priority, this is supported by a rather circulatory shape of the cycle path around the roundabout allowing smooth riding (Figure 4). When bicyclists have no priority, the bicycle speed is reduced by a more orthogonal shape of the crossing with the exit/entry lane (Figure 5).

Finally, in a limited number of cases grade-separated roundabouts are constructed allowing bicycle traffic to operate independently from motorised traffic (Figure 6). This can for instance be done by constructing some small tunnels that enable bicyclists to cross under the roadway.

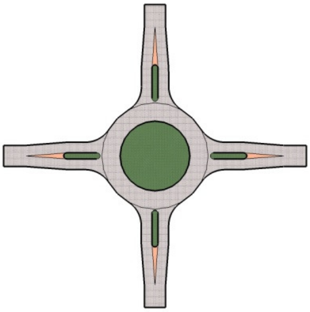

Figure 2 Roundabout with mixed traffic

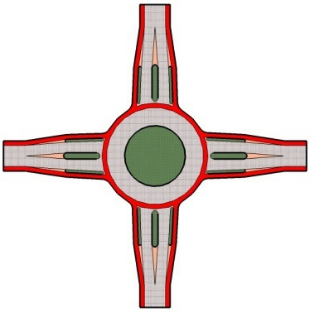

Figure 3 Roundabout with cycle lanes

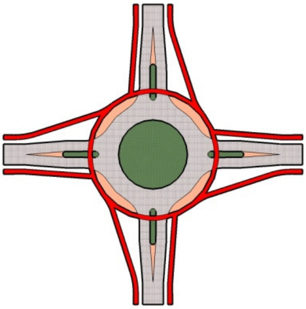

Figure 4 Roundabout with separate cycle paths – priority to bicyclists

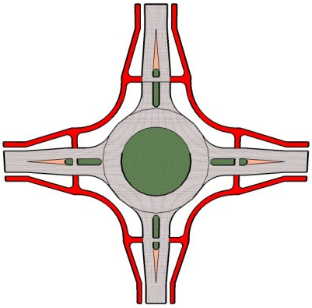

Figure 5 Roundabout with separate cycle paths – no priority to bicyclists

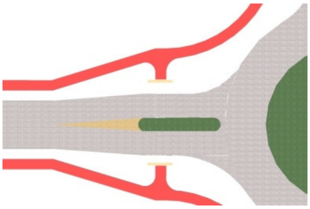

Figure 6 Roundabout with grade-separated cycle paths

Figure 7 Roundabout with cycle lanes

Figure 8 Roundabout with separate cycle paths (no priority for bicyclists)

2.2.2. Pedestrian facilities

Pedestrian facilities on roundabouts are mainly intended to allow pedestrians to cross the different legs. If they are present, it is generally recommended to construct splitter islands that provide a shelter for crossing pedestrians and that allow pedestrians to cross entry and exit lanes in two times. It is recommended to construct pedestrian crossings on the approaches on a minimum distance varying from 4 meter (MET, 1999) to 7.5 meter (FHWA, 2000) from the roundabout, allowing exiting vehicles to stop without locking the roundabout.

Around roundabouts sidewalks may be constructed or cycle facilities might be shared by moped riders, cyclists and pedestrians.

2.2.3. Provisions for trucks and exceptional transport

Roundabouts should be able to accommodate the largest vehicles that are legally allowed to be present in traffic. Consequently, important geometric variables like the size of the central island, the road width and the entry/exit path curvature will eventually be determined by the requirements of the largest vehicles that need to pass. This might come into conflict with the safety objectives of speed reduction for lighter vehicles since the latter are sometimes able to drive with higher speeds on roundabouts than would ideally be the case according to the before mentioned design principles (CROW, 1998; FHWA, 2000). One way to deal with this issue is to construct truck aprons like mentioned in section 2.1.2. As to exceptional transport, it is sometimes recommended to construct gated roadways through the central island that allow to accommodate exceptionally large vehicles without requiring too much compromises with respect to the design principles (CROW, 1998; MVG, 1997).

2.2.4. Public transport

Requirements for trucks are generally valid as well for busses. However, the use of truck aprons might cause loss of comfort for public transport users. Sometimes, reserved bus or tram lanes are constructed through the central island, which allow passing straight through the roundabout. In such a case, the roundabout needs to be equipped with additional traffic signals in order to set the priority rules (CROW, 1998).

2.3. ROUNDABOUT TYPES

According to their size, different types of roundabouts can be distinguished. The simplest classification is according to the number of lanes: single-lane, two-lane or multiple-lane roundabouts.

Other classifications are related with the inscribed circle diameter of the roundabout. However, no universal classification scheme seems to exist. Mini-roundabouts seem to be the only exception since they are more or less consistently described as roundabouts with an inscribed circle diameter of less than 25 meter (CERTU, 1999; FHWA, 2000; MET, 1999; MVG, 1997). However, GBHA (1993) defines a mini-roundabout as a roundabout having a one-way circulatory carriageway around a flush or slightly raised circular marking less than 4m in diameter. None of the guidelines defines a maximum size for roundabouts.

Apart from the classic circulatory roundabouts, some particular shapes appear to exist. Oval roundabouts are characterised by an oval shaped central island. Although non-circulatory central islands are not recommended, oval roundabouts are sometimes applied for more complex intersections, often with more than 4 legs or with legs that are not in line with each other (CROW, 1998; FHWA, 2000). A turbo roundabout is characterized by a spiral shaped central island that forces traffic to choose the appropriate lane before entering the roundabout (CROW, 2002). It is mainly intended to increase roundabout capacity in case of dominant traffic flows in one direction.

2.4. CONCLUSIONS ON ROUNDABOUT GEOMETRY

The screening of the roundabout design guidelines in different countries reveals that the basic principles determining the design of roundabouts are similar for the different countries. For instance, a principal choice for radial approaches is made everywhere and all guidelines mention advantages of circulatory central islands and separate facilities for pedestrians and bicyclists with respect to traffic safety. Moreover, a consensus seems to exist about principal aspects that contribute to road safety and capacity issues such as the effects of certain angles of approaches, lateral displacement or potential conflict points. However, the way in which these principles are concretised in the design recommendations seems to differ from country to country. The most important differences possibly exist with respect to the design of entry paths (flaring or not) and the design of cyclist facilities. These differences could be attributed to mainly two, partly interrelated, aspects: on the one hand the presence of certain road users in traffic, on the other hand the level of public attention that is paid to certain objectives, in particular the degree to which either safety or traffic operations are considered to be decisively important. This difference is reflected in what has been called the UK approach with tangential approaches and wider carriageways on the roundabout allowing higher speeds versus the tighter European continental approach of radial approaches and minimal entry flares (Lawton et al., 2004). As will be discussed in Chapter 9, this indicates some challenges for future research.

Chapter 3. Roundabouts and traffic safety: Existing knowledge

As stated in the introduction, the focus of this manuscript is on traffic safety aspects of roundabouts, mainly in relation to their geometric design. While the previous chapter was dedicated to roundabout geometry, the current chapter provides an overview of the existing scientific knowledge about traffic safety aspects of roundabouts.

The chapter starts with an overview of theoretical safety effects and issues that can be expected at roundabouts, based on known concepts regarding conflicts and speeds. Subsequently, an overview is given of the existing scientific literature on roundabout safety. A special emphasis is put on the safety aspects for bicyclists since this issue received particular attention in different studies and will return several times as an important issue in the following chapters.

3.1. THEORETICAL SAFETY EFFECTS OF ROUNDABOUTS

There are different reasons why roundabouts could be safer than other types of intersections (FHWA, 2000; Elvik & Vaa, 2004). Generally they can be divided into two groups: effects on speeds and effects on conflicts between road users.

Effects on speeds:

- The speeds of the different vehicles on the roundabout are low and homogenous. This means that the relative speeds (speeds of the different road users in comparison to each other) are low. As the same goes for vulnerable road users, such as bicyclists, this is considerably different from the situation on conventional intersections where often large differences in speeds are recorded.

- Traffic entering a roundabout is forced to slow down, due to the lateral displacement it has to make. The resulting absolute speed is low and gives time to road users to overview the situation and to anticipate to potential conflicts.

Effects on conflicts:

- Roundabouts modify or eliminate potential conflict points between road users. Particularly the potentially dangerous conflicts are eliminated, like right-angle collisions or frontal collisions.
- All traffic on the roundabout is one way. Road users only need to look to the traffic coming from one direction and to wait for a time gap to enter the roundabout.
- Roundabouts eliminate left-turning movements (in countries driving on the right, otherwise vice versa).
- Traffic entering the roundabout has to give priority to the circulating traffic. This causes approaching traffic to be cautious when entering the roundabout.

On a roundabout, crossings of road users are eliminated as potential conflicts. The number of locations where traffic flows merge or diverge is only the half of the number of conflict points on conventional four-leg intersections. In total, the number of conflict points on a single-lane roundabout is reduced from 32 to 8 in comparison with a conventional intersection.

Apart from conflicts with other road users, other types of conflicts might occur. The central island of a roundabout, for example, appears to be an obstacle that might induce a raised level of single-vehicle crashes.

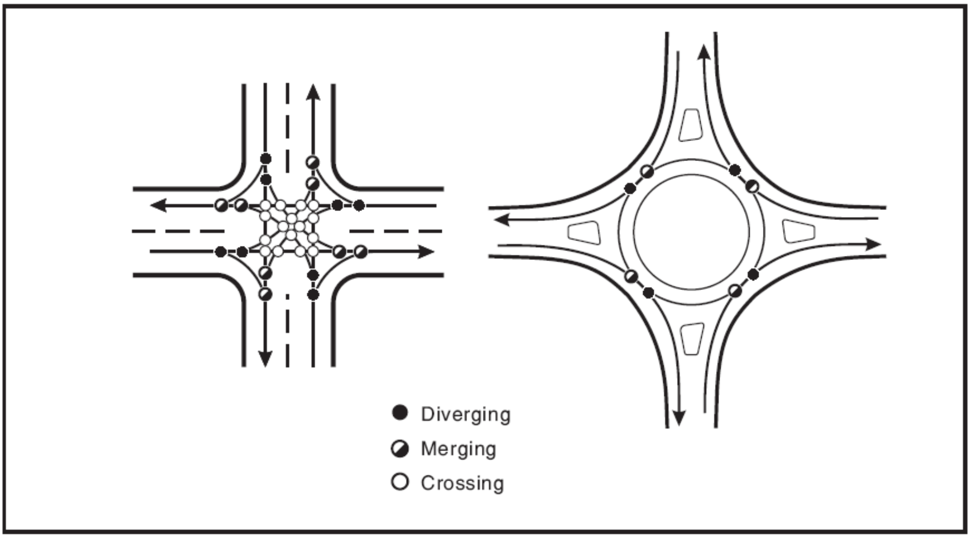

Figure 9 Vehicle conflicts on a single-lane roundabout. Source: FHWA (2000)

Safety aspects on double-lane roundabouts are somewhat different. In comparison to single-lane roundabouts they have additional conflict points due to the changing of lanes on the roundabout and to the double approaching or exit lane (although the latter are not necessarily present).

With respect to pedestrians, roundabouts reduce a certain number of potential conflicts that occur on conventional intersections:

- Conflicts between high-speeding vehicles and pedestrians crossing the street.
- Conflicts between right-turning vehicles and pedestrians crossing the street (on signal-controlled as well as other intersections).
- Conflicts between left-turning vehicles and pedestrians crossing the street (on signal-controlled as well as other intersections).

The situation for bicyclists is somewhat different. The number of conflicts with bicyclists depends on the design of the roundabout. If there are no particular cycle facilities, bicyclists are mixed with other road users on the roundabout. Consequently they meet the same conflict points as other (motorised) road users. Nevertheless, the number of conflicts could be higher than for other road users, due to the higher differences in speeds between bicyclists and motorised road users and also due to the poorer visibility of bicyclists in comparison with motorised vehicles. (Brown, 1995; FHWA, 2000).

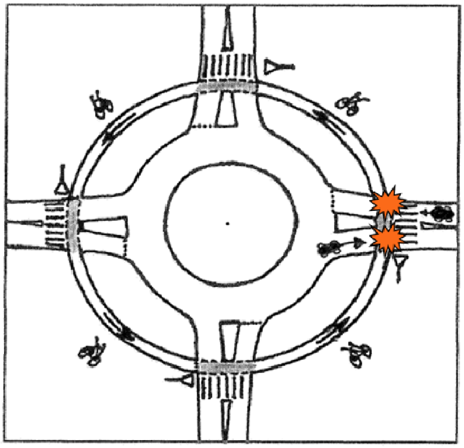

Figure 10 Conflicts with bicyclists. Source: adapted from CERTU (1999)

3.2. RESEARCH RESULTS ON ROUNDABOUT SAFETY

This chapter continues with a description of research results about safety effects of roundabouts. The description is organised according to a number of elements like depicted below. Also some considerations are given on the inherent quality and limitations of the two most important types of included studies.

3.2.1. Roundabouts and safety: relevant elements

The safety effects of roundabouts can be decomposed into a number of elements like described schematically in Figure 11 . A roundabout can either be newly constructed or an intersection can be converted into a roundabout. Within the group of roundabouts a large variation of design types is possible according to some geometric features like central island radius, curvature of entry and exit lanes, number of lanes, lane width, type of cycle facilities, road markings and lighting (see Chapter 2). Every roundabout is attributed by a certain distribution of speeds and possible conflicts between road users. Apart from these elements a roundabout exerts some possible effects on operational characteristics such as traffic operations, intersection capacity, emissions and urban design. The latter effects are out of the scope of this dissertation and therefore not further discussed here. Some events at roundabout lead to on crashes. Those crashes have some consequences, basically divided according to the presence of injuries. Those crashes might affect different types of road users.

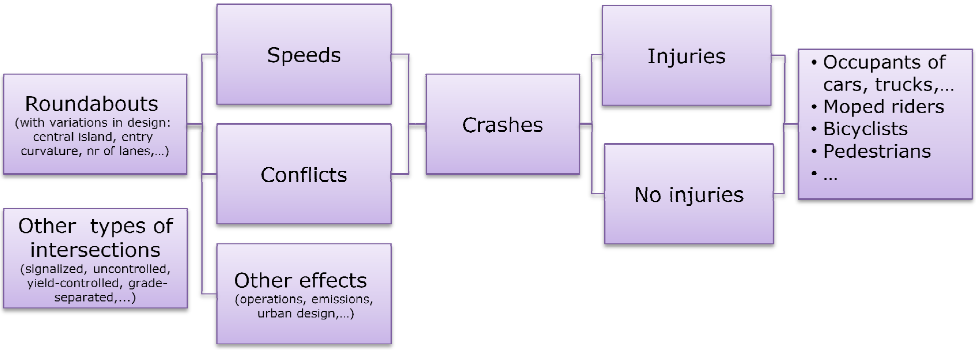

Figure 11 Roundabouts and traffic safety - decomposition

3.2.2. Selection of studies

Most common technique in road safety analysis to evaluate safety effects of a treatment is the observational before and after study. In an observational before and after study crash frequencies before and after a certain measure (e.g. change in road design) are compared to each other. However it would be wrong just to compare crash frequencies before and after the measure, since there are 3 confounding effects that should be taken into account (Hauer, 1997):

1. Crashes are of a stochastic nature. Even when no safety measure is taken on a particular location and the characteristics of passing traffic would remain the same, a natural fluctuation in the number of crashes will occur. This fluctuation is only based on chance. To analyse safety effects properly, one should consequently not rely only on the counted number of crashes (e.g. the number of crashes in one year). It is needed to estimate values, as well for the number of crashes that occurred before as for the number of crashes after the measure.

2. As traffic is not a well-controlled experimental environment, there are always some general trends that might also influence the number of crashes on the area under investigation. For example, there could be changes in traffic volume, a higher or lower level of driving under influence, modifications in enforcement level, laws etc… These general trends are likely to result in a changing number of crashes on a location, even when no specific measures are taken. In order to isolate the effect of a specific measure, one should consequently distinct the effect of the measure itself from the effect of general trends.

3. Road authorities tend to treat locations not randomly. They use ranking systems, usually based on available crash frequencies or crash rates, to determine what locations need a particular treatment. Consequently, the locations with a specific treatment (e.g. roundabouts) ought not to be considered as a random sample, as this sample consists of locations that were selected based on their crash records. Due to the stochastic nature of crashes, one could expect that the number of crashes on that type of locations would decrease – at least partly, even if no specific measure would be taken. This effect is called ‘regression to the mean’. As this effect could also occur on locations with a treatment, it is obvious that the change in the number of crashes should not be attributed fully to the treatment itself. In that case a certain part of the effect has to do with

chance elements and would also have occurred if no measure would have been taken.

To avoid wrong estimations, an observational before-and-after study should take into account the above-mentioned effects. If not, the study results are less reliable. Simple before-and-after studies, which do not control for any confounding factors should never be trusted (Elvik, 2002; Hakkert & Gitelman, 2004).

Another approach is followed by fitting cross-sectional risk models, often called accident or crash prediction models. The purpose of these models is to reveal some structural relationships between particular design or traffic characteristics on the one hand and the level of safety of roundabouts on the other hand. Most often, the crash frequency of a study sample is explained through the use of regression modelling techniques, nowadays most often Poisson regression and negative binomial regression (Reurings et al., 2006). In most models, the investigated parameters are traffic volume and some geometric data, such as number of lanes, curvature or lane width. Hauer (2005) describes extensively the limitations of using observational cross-section data, in particular by fitting multiple regression models:

- Throughout the history of crash modeling, regressions based on observational cross-section data have failed to produce consistent results.
- Observation units are not randomly selected to be converted into type A or type B, meaning that some response-relevant differences that are revealed in cross-section models might have been present already from the before-situation or might correlate with other, possibly unobserved, factors. Confounding is therefore likely to exist in cases in which not all possible response-relevant variables are captured in the cross-section models or in cases in which the function linking the responses to their relevant attributes is not known.

While it is possible for observational before-after studies to provide an acceptable empirical foundation for cause-effect beliefs, this is not the case for studies using cross-section data. Hauer (2005) concludes therefore that it is highly questionable to attribute any causal relationship to relations that were found in cross-section data. Nevertheless, statistical modelling of crashes has made methodological progress and remains an important area of assessing safety of transportation facilities (Abdel-Aty & Pande, 2007; Mitra & Washington, 2007).

The most straightforward way to decide upon including studies would be to include only those that meet severe scientific criteria such as having addressed the abovementioned issues or that were publish in peer reviewed journals. At least this was the basic approach. However, such an approach would have resulted in only a very limited amount of information. Therefore, the sample was enriched with studies that, although they did not meet all the desired criteria, were believed to have been carried out properly and to have yielded useful results.

3.2.3. Effects of the addressed type of intersection

Road authorities tend to convert specific types of intersections into roundabouts. A decision to build a roundabout could depend on the number of legs, the amount of traffic, the composition of the traffic (cars, trucks, bicycles…), the location or the history of crashes. Some studies found the reduction of the number of victims to be higher on roundabouts outside built-up areas than on roundabouts inside the built-up area (Schoon & van Minnen, 1993; MET, 2003). The decrease in the number of injury crashes was found to be higher on intersections that were yield-controlled before they were converted into a roundabout than on signalized intersections. (Schoon & van Minnen, 1993; Elvik, 2003). However, these effects were stated by the authors to be uncertain. Converting intersections into roundabouts could also have more effect on crashes in four-leg intersections than in three-leg intersections, although also this effect is unsure (Elvik, 2003).

3.2.4. Effects on speeds

The theoretically assumed effects on speeds have been proven by research. Average car speeds decrease significantly when an intersection is converted in to a roundabout. The speed decrease is higher when measured closer to the roundabout (Hydén & Várhelyi, 2000; van Minnen, 1994). For distances above 300 meter, speed effects couldn’t be measured anymore. The speed of approaching cars is highly influenced by the lateral displacement forced by the roundabout. The lateral displacement is determined by the diameter of the central island and the angle of the approaching lane. The speed reducing effect is already large at a 2 meter deflection (Hydén & Várhelyi, 2000).

3.2.5. Effects on conflicts

The number of traffic conflicts seems to increase rather than to decrease when an intersection is converted into a roundabout (van Minnen, 1994). Nevertheless, this author found conflicts to be less severe than before. The number of conflicts with vulnerable road users (pedestrians and bicyclists) hardly changed (van Minnen, 1994). Other research reported a status quo in the number of conflicts between cars, but recorded oppositely a decrease in the number of conflicts, both between bicyclists and cars and between pedestrians and cars (Hydén & Várhelyi, 2000). In the perspective of the theoretically expected reduction of conflict points (e.g. from 32 to 8 for 4-leg roundabouts) these results are somewhat surprising. At least this means that the number of conflicts is not directly proportional to the number of conflict points. Given that the number of conflict points theoretically reduces from 32 to 8, finding an equal number of conflicts after construction of a roundabout is meaning that the number of conflicts per conflict point on average multiplied by four.

According to van Minnen (1994) people comply well with priority rules on roundabouts, as long as the entering traffic volume is not too large. With higher volumes, the number of offences against priority rules increases remarkably.

3.2.6. Effects on injury crashes

During the past decades, quite some research was done about the safety effects of introducing roundabouts on intersections. Although numbers and percentages often vary strongly, there are quite some studies indicating a strong reduction of injury crashes after construction of a roundabout (Green, 1977, cited in Brown, 1995; Persaud et al, 2001; MET, 2003; Elvik, 2003; De Brabander et al, 2005). The decrease is higher for crashes with killed and serious injuries than for crashes with only slight injuries (Green, 1977, cited in Brown, 1995; Persaud et al, 2001; MET, 2003; Elvik, 2003; De Brabander et al., 2005).

There seems to exist a directly proportional relationship between measured speeds and the number of crashes on a roundabout. The number of injured has even a quadratic relationship with the speeds. Furthermore a positive relationship was measured between traffic volume and the number of crashes (Brüde & Larsson, 2000).

3.2.7. Effects on non-injury crashes

Discussion exists about the effects of roundabouts on crashes with property damage only. An empirical Bayes before-and-after-study on 23 roundabouts in the USA (Persaud et al, 2001) found a significant reducing effect of roundabouts on all types of crashes (property damage and injury crashes). Nevertheless, other authors conclude that the average effect of roundabouts on non-injury crashes is highly uncertain (Elvik, 2003, based on a meta-analysis of 28 studies).

3.2.8. Effects on different types of road users

Not so much has been done about the safety effects of roundabouts for different types of road users. According to Schoon & van Minnen (1993) the safety effects of roundabouts are not equally distributed over the different types of road users: safety effects for car occupants and pedestrians are much better than safety effects for bicyclists and mopeds. Nevertheless the registered effects for mopeds and bicyclists were still favourable.

Oppositely, Hydén & Várhelyi (2000) reported a large reduction in injury crash risk for bicyclists and pedestrians, based on conflict observations, whereas they found no risk reduction for car occupants.

3.2.9. Research results concerning safety for bicyclists

Similar to the results of general roundabout safety, the results for bicyclists can be classified following the schema in Figure 11 .

EFFECTS OF THE ADRESSED TYPE OF INTERSECTION

Roundabouts with smaller traffic volumes (less than 10000 vehicles per day and less than 1000 bicyclists per day) are safer for bicyclists than roundabouts with higher traffic volumes (Brüde en Larsson, 2000).

EFFECTS ON CONFLICTS

As an alternative to the observational before and after study based on reported crashes, some investigations were made using a traffic conflict observation technique. A conflict observation study (Van Minnen, 1994) revealed that the number of conflicts with bicyclists and mopeds did not decrease after the construction of a roundabout. Nevertheless this study reported a shift to less serious conflicts.

In another Dutch research project, observations were made on the priority giving behaviour between motorised vehicles and bicyclists on roundabouts with separated cycle lanes (van Minnen & Braimaster, 1994). On roundabouts with priority for bicyclists (see Figure 4 on page 13) about 20% of the bicyclists, despite their priority status, appeared to stop and give priority to motorised vehicles. However, on roundabouts without priority to bicyclists (Figure 5), bicyclists received priority in 33% of the cases. This effect appeared to be much higher in case or traffic approaching the roundabout (46% of the cases) than in case of exiting traffic (14% of the cases).

A higher number of car drivers gave priority to bicyclists when the cycle lane was close to the roadway than in case of a separate cycle path (Räsänen en Summala, 2000).

Bicyclists tend to offence some traffic rules when entering or leaving roundabouts. In 2% till 13% of the observed cases in a Dutch study, bicyclists used the cycle crossing in the prohibited direction (van Minnen & Braimaster, 1994). Furthermore, more than 40% of the bicyclists gave no priority when entering the roundabout (Hydén & Várhelyi, 2000).

EFFECTS ON CRASHES

Roundabouts seem to induce a higher level of bicyclist-involved crashes than could be expected based on the presence of bicycles in total traffic. In Great-Britain the involvement of bicyclists in crashes on roundabouts was found to be 10 till 15 times higher than the involvement of car occupants, taken into account the exposure rates (Maycock and Hall, 1984, cited in Brown, 1995).

Opposite to the favourable results that were noticed for traffic on roundabouts in general (see before), the results for bicyclists were at a considerably lower level. Schoon en Van Minnen (1993) studied safety records of 185 roundabouts and reported a bicyclist's traffic victims reduction of 30% compared to the period before construction of the roundabout, while overall traffic victims decreased with 95% (car occupants), motorcycles (63%), pedestrians (63%) and other road users (64%). Unfortunately, this study could not correct for possible effects of trends and regression to the mean.

Some efforts were made to determine whether one or another priority rule on roundabouts with separated cycle lanes was safer for bicyclists. Crash rates for bicyclists seemed to be higher (0.16 victims per million passages) on roundabouts with priority for bicyclists (Figure 4) compared with roundabouts where the crossing bicyclist had to give priority (0.04 victims per million passages, Figure 5) (van Minnen & Braimaster, 1994). Dijkstra (2005) compared two scenario’s, differing from each other in the way crossing bicyclists got priority or not, and concluded that a scenario including the adoption of priority to bicyclists on all roundabouts would lead to a slightly higher number of serious injuries compared to a scenario in which bicyclists would have to give way on all roundabouts with separate cycle paths.

TYPE OF CYCLE FACILITIES

Schoon en Van Minnen (1993) investigated also the number of bicycle crashes related to the type of cycle facilities on roundabouts: no particular cycle facilities, a cycle lane close to the roadway and a separate cycle path. They concluded that differences in the crash frequency between the different types were small. However, when looking at injuries instead of crashes they concluded that separate cycle paths performed better than both the ‘mixed traffic’ and ‘cycle lane’ alternatives.

EFFECTS OF DESIGN ELEMENTS

Generally, smaller and one-lane-roundabouts seem to be safer for bicyclists then larger or multi-lane roundabouts (Brüde en Larsson, 1996). Although smaller roundabouts seem to be safer than larger ones, the opposite is true for the dimension of the central island. Roundabouts with a central island of more than 10 meter were found to be safer for bicyclists than roundabouts with smaller central islands (Brüde en Larsson, 2000).

3.3. CONCLUSIONS

Based on the existing research, a number of conclusions can be drawn with respect to the effects of the construction of roundabouts on traffic safety.

- The most reliable studies on the effects of roundabouts are before- and after-studies that take into account the stochastic nature of crashes, correct for general trends in traffic, changes in traffic volume and for regression to the mean. Unfortunately, quite a number of studies did not account for one or more of these aspects.

- Roundabouts generally improve traffic safety. De Brabander et al. (2005) provide an estimate for roundabouts on regional roads in Flanders-Belgium. The number of crashes with at least a slightly injured decreased with on average 34% after construction of a roundabout. The number of crashes with at least a seriously injured decreased with on average 38%.

- The screened studies report consistently about a more favourable effect of roundabouts on the most serious crashes (generally those with fatally or seriously injured) than for less serious crashes. The effect on the number of crashes with property damage only is highly unsure.

- The conversion of an intersection into a roundabout leads to significant speed reductions in the neigbourhood of the intersection until a distance of 300 meter. Speeds on the roundabout are related to the size of the lateral displacement on the roundabout. The lateral displacement is determined by the size of the central island and the entry radius.

- The crash reduction tends to be higher on intersections that were previously not equipped with traffic signals than on intersections that were signal-controlled.

- The construction of a roundabout is likely to decrease the number of crashes with bicyclists as well. However, this conclusion is not sure. The observed decrease in the number of crashes with bicyclists is lower than the observed reduction in the number of crashes with other road users.

- No conclusive evidence seems to exist concerning the difference in safety performance according to the type of cycle facility: separate cycle paths, cycle lanes close to the roadway, mixed traffic. Roundabouts with separate cycle paths are likely to be safer for bicyclists than roundabouts with cycle lanes or roundabouts with mixed traffic.

- Cycle paths with priority for bicyclists show on average a somewhat higher frequency of crashes with bicyclists than roundabouts with cycle lanes.

- The frequency of crashes with pedestrians is lower on roundabouts than on signal-controlled intersections.

- A directly proportional relationship exists between the actual speeds and the number of crashes at roundabouts. The number of crashes is positively related with the traffic volume.

- A smaller central island is likely to be more favourable for traffic safety than a larger one. However, a larger central island is likely to be more beneficial for cyclists.

Those research results confirm largely the theoretical hypothesis about the favourable safety effects of roundabouts. The number of crashes decreases and the severity of crashes is lower at roundabouts, which is most likely due to the stated speed reduction.

However, no full confirmation of the established theories was found for the observed traffic conflicts: although the construction of a roundabout reduces theoretically the number of conflict points from 32 to 8 (single-lane roundabouts at 4-leg intersections) (Elvik & Vaa, 2004; FHWA, 2000), the executed conflict observations (van Minnen, 1994; Hydén & Várhelyi, 2000) reveal that the number of conflicts on roundabouts does not decrease. This means logically that the number of occurring conflicts per conflict point exceeds the number of conflicts per conflict point at classic intersections.

Chapter 4. Safety effects of converting intersections into roundabouts on crashes with bicyclists

In this chapter the results are presented from an observational before and after study on injury crashes with bicyclists at 91 roundabouts. An empirical Bayes before and after design was applied since this technique is believed to be able to overcome adequately some well known problems and threats to validity of other designs. The presented research in this chapter was published in Daniels et al. (2008).

The chapter starts with an introduction on existing knowledge on safety performance of roundabouts that was based on before and after-studies. After a description of the used dataset, the used method is extensively explained. Subsequently the results are provided and discussed.

4.1. EXISTING KNOWLEDGE ON SAFETY EFFECTS OF ROUNDABOUTS

Roundabouts in general have a favourable effect on traffic safety, at least for crashes causing injuries. During the last decades several studies were carried out into the effects of roundabouts on traffic safety. A meta-analysis on 28 studies in 8 different countries revealed a best estimate of a reduction of injury crashes of 30-50% (Elvik, 2003). Other studies, not included in the former one and using a proper design, delivered similar results (Persaud et al., 2001; De Brabander et al., 2005). All those studies reported a considerably stronger decrease in the number of severest crashes (fatalities and crashes involving serious injuries) compared to the decrease of the total number of injury crashes. The effects on property-damage only crashes are however highly uncertain (Elvik, 2003).

Less is known about the safety effects of roundabouts for particular types of road users, such as bicyclists (Daniels and Wets, 2005). Roundabouts seem to induce a higher number of bicyclist-involved crashes than might be expected from the presence of bicycles in overall traffic. In Great-Britain the involvement of bicyclists in crashes on roundabouts was found to be 10 to 15 times higher than the involvement of car occupants, taking into account the exposure rates (Brown, 1995). In the Netherlands safety records of 185 roundabouts were studied and a reduction of 30% was reported in the number of victims among bicyclists to the period before construction of the roundabout, while the overall number of traffic victims decreased by 95% (car occupants), 63% (motorcyclists), 63% (pedestrians) and 64% (other road users) (Schoon and van Minnen, 1993). Unfortunately, the study design could not take into account the possible effects of general trends in traffic safety and the regression-to-the-mean-effect.

In Flanders-Belgium bicyclists appear to be involved in almost one third of reported injury crashes at roundabouts (1118 reported crashes with bicyclists; 3558 in total, period 1991-2001), while in general only 14.6% of all trips (5.7% of distances) are made by bicycle (Zwerts and Nuyts, 2004). The apparent overrepresentation of bicyclists in crashes on roundabouts was the main cause to conduct an evaluation study on the effects of roundabouts, specifically on crashes involving bicyclists. The main research question was whether the resulting effect would be the same as for crashes in general, both for the totality of injury crashes as for the severest crashes (crashes resulting in fatal or serious injuries). It is important to know whether roundabouts have a different impact on the safety of different types of road users in order to develop adequate decision criteria for situations when a roundabout should be constructed or not. Supplementary questions were whether the effect would be different if the roundabout was constructed inside or outside built-up area (as traffic conditions inside built-up area may be considerably different from conditions outside built-up area, e.g. number of bicyclists, average speed of cars, road width, presence of trucks, etc.). A final aim was to find out whether the effects on the number of crashes involving bicyclists would be different on intersections that were signal-controlled before the conversion to a roundabout compared to locations with no traffic signals in the before-situation.

4.2. USED DATA

A sample of 91 roundabouts in the Flanders region of Belgium was studied. The roundabout data were obtained from the Flemish Infrastructure Agency (part of the Ministry of Mobility and Public Works). The sample was selected according to the following successive selection criteria applied on the initial dataset:

- Roundabouts constructed between 1994 and 2000.
- 3 or 4 roundabouts selected randomly in each of the 28 administrative road districts in the Flanders region.

All the investigated roundabouts are located on regional roads (so called numbered roads) owned by either the Flemish Infrastructure Agency either the provinces. This type of roads is characterized by significant traffic, where other, smaller and less busy roads are usually owned by municipalities. The Annual Average Daily Traffic on the type of roads in question is 11 611 vehicles per day (AWV, 2004). No information was available about the AADT on the selected roundabouts. Both single-lane as well as double-lane roundabouts may occur on the roads that were selected in the sample, although the former type is more common. The dataset provides no information on the number of lanes on the roundabout. Also, no information was available about the type of bicyclist facility present at the roundabouts.

For the purpose of this study only those roundabouts that were constructed between 1994 and 2000 were taken into account. Crash data were available from 1991 until the end of 2001. Consequently a time period of crash data of at least 3 years before and 1 year after the construction of each roundabout was available for the analysis. For each roundabout the full set of available crash data in the period 1991-2001 was included in the analysis. Table 1 shows the distribution of the construction years for the roundabouts in the sample.

Table 1 Number of roundabouts per construction year – study sample

Construction year	Nr. of roundabouts
1994	17
1995	21
1996	16
1997	8
1998	7
1999	14
2000	8
Σ	91

Exact location data for each roundabout were available so that crash data could be matched with the roundabout data. 40 roundabouts from the sample are located inside built-up area (area inside built-up area boundary signs, general speed limit of 50km/h), 51 outside built-up area (general speed limit of 90 or 70 km/h) (see table 2). 22 roundabouts were constructed on intersections that were signal-controlled in the before-situation, 69 roundabouts were constructed on non-signal-controlled intersections. On the investigated regional roads nearly all intersections are at least controlled in some way, either stop-controlled or yield-controlled which are both common. Uncontrolled intersections (with priority for traffic from the right) principally do not occur on regional roads in Flanders. No specific data on the type of control in the before situation were available, except from the knowledge that they were not signal-controlled.

Apart from the different speed limits other arguments exist to make a distinction between roundabouts inside versus outside built-up area. Important differences in land use, share of different transportation modes (e.g. bicyclists), age and gender of road users might exist. Moreover some constraints for roundabout construction such as available public space are likely to be more restrictive inside built-up area.

Table 2 Treatment Group Locations (Roundabouts)

	No traffic signals before	Traffic signals before	TOTAL
Inside built-up area	33	7	40
Outside built-up area	36	15	51
TOTAL	69	22	91

Two comparison groups were composed, consisting of 76/96 intersections inside/outside built-up area serving as a comparison group for roundabouts inside/outside built-up area (see table 3). For the comparison groups, intersections on regional roads were selected in the neighbourhood of the roundabout locations. Preference for comparison group locations was given to intersections on the same main road as the nearby roundabout location with the same type of crossing road. The road categories were found on a street map. In order to avoid possible interaction effects of the comparison group locations with the observed roundabout locations, comparison group locations had to be at least 500 meter away from the observed roundabout locations. Apart from the confirmation they aren’t roundabouts, no information is available about the type of traffic regulation on the intersections in the comparison group. On these types of roads either signal-controlled or priority-ruled intersections (one direction has priority) may occur.

Table 3 Comparison Group Locations

	Number of locations
Inside built-up area	76
Outside built-up area	96
TOTAL	172

Detailed crash data were available from the National Statistical Institution for the period 1991-2001. This database consists of all registered traffic crashes causing injuries. Only crashes where at least one bicyclist was involved were included. Crashes were divided into 3 classes based on the severest injury that was reported in the crash: crashes involving at least one fatally injured person (killed immediately or within 30 days after the crash), crashes involving at least one seriously injured (person hospitalized for at least 24 hours) and crashes involving at least one slightly injured. No distinction was made about which road user was injured, the bicyclist or any other road user such as a car occupant, a motorcyclist, another bicyclist or whoever.

Locations of crashes on numbered roads are identified by the police by references to the nearest hectometre pole on the road. All the crashes that were exactly located on the hectometre pole of the location were included in this study. Subsequently crashes that were located on the following or the former hectometre pole were added, except when the observed crash could clearly be attributed to another intersection. This approach was chosen in order to include possible safety effects of roundabouts in the neighbourhood of the roundabout as they might occur (Hydén and Várhelyi, 2000). Consequently the results should be considered as "effects on crashes on or near to roundabouts". At least one road on each location, both for the treatment group as for the comparison group, was a numbered road.

The same selection criteria were applied for crashes on locations in the comparison group as for crashes on locations in the treatment group.

The total number of crashes included in the treatment group was 411, of which 314 with only slight injuries, 90 with at least one serious injury and 7 with a fatal injury (see table 4). The total number of crashes in the comparison group is 649, of which 486 with only slight injuries, 142 with serious injuries and 21 with fatal injuries.

Table 4 Number of Crashes considered (before and after period together)

	Treatment group	Comparison group
Number of crashes involving at least 1 slight injury	314	486
Number of crashes involving at least 1 serious injury	90	142
Number of crashes involving at least 1 fatal injury	7	21
TOTAL	411	649

Tables 5 and 6 give the number of crashes for the treatment group, split up by the location inside and outside built-up area and by the before-situation at the location (traffic signals or not). In table 5 this was done for all injury crashes, in table 6 only for the most severe crashes, i.e. crashes involving serious or fatal injuries.

Table 5 Number of crashes – roundabouts

	Traffic signals before				No traffic signals before				TOTAL
	TOTAL	Period before constr.	Year of constr.	Period after constr.	TOTAL	Period before constr.	Year of constr.	Period after constr.	
Inside built-up area	50	26	6	18	186	82	10	94	236
Outside built-up area	67	34	4	29	108	59	10	39	175
TOTAL	117	60	10	47	294	141	20	133	411

Table 6 Number of severe crashes (with fatal or serious injuries) – roundabouts

	Traffic signals before				No traffic signals before				TOTAL
	TOTAL	Period before constr.	Year of constr.	Period after constr.	TOTAL	Period before constr.	Year of constr.	Period after constr.	
Inside built-up area	10	7	0	3	41	18	1	22	51
Outside built-up area	18	13	1	4	28	18	4	6	46
TOTAL	28	20	1	7	69	36	5	28	97

Table 7 shows the number of crashes for the comparison group, split up by the location inside or outside built-up area. Table 8 shows the distribution of the crashes in the comparison group per year, both for all injury crashes and for severe crashes.

Table 7 Number of Crashes – Comparison Group

	Number of injury crashes	Number of crashes with killed or seriously injured
Inside built-up area	340	74
Outside built-up area	309	89
TOTAL	649	163

Table 8 Number of Crashes per year – Comparison Group

Year	Number of injury crashes	Number of crashes with killed or seriously injured
1991	65	19
1992	68	13
1993	65	19
1994	58	16
1995	54	18
1996	54	13
1997	70	18
1998	62	15
1999	49	13
2000	48	13
2001	56	6
TOTAL	649	163

The average yearly number of crashes with bicyclists on the roundabout locations in the before-situation was 0.51 (inside built-up area) / 0.3 (outside built-up area) (Table 9). In the period after construction of the roundabout the yearly averages were 0.6 (inside built-up area) / 0.3 (outside built-up area).

During the full considered period the average yearly number of crashes in the comparison group was 0.41 (inside built-up area) and 0.29 (outside built-up area) (Table 10). Figure 12 gives an impression of the distribution of locations with respect to the number of count crashes both in the before and after period.

Table 9 Average yearly number of crashes – Roundabout locations

	Before construction	After construction
Inside built-up area	0.51	0.60
Outside built-up area	0.33	0.30

Table 10 Average yearly number of crashes – Comparison group locations

	Inside built-up area	Outside built-up area
1991	0.49	0.29
1992	0.64	0.20
1993	0.49	0.29
1994	0.33	0.34
1995	0.39	0.25
1996	0.33	0.30
1997	0.45	0.38
1998	0.38	0.34
1999	0.29	0.28
2000	0.29	0.27
2001	0.39	0.27
FULL PERIOD	0.41	0.29

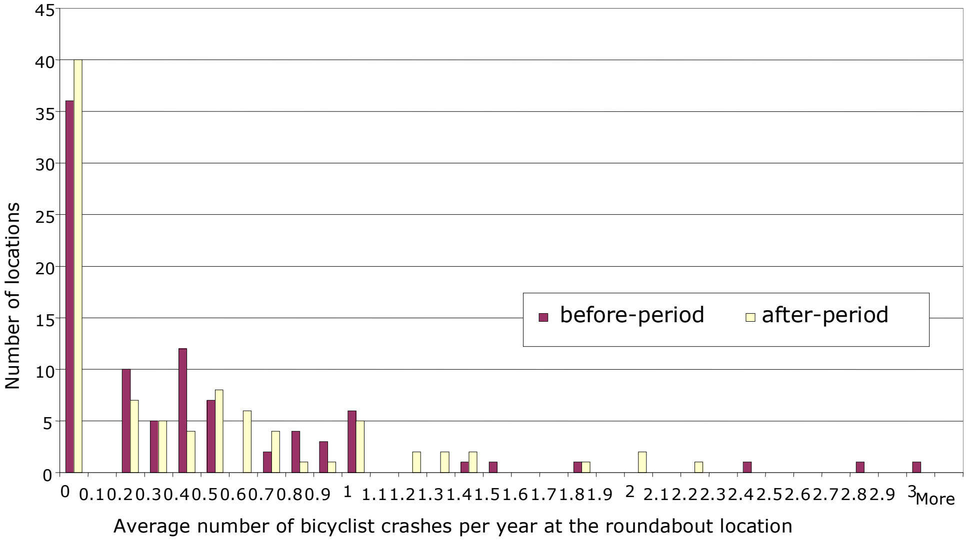

Figure 12 Annual number of crashes involving bicyclists per location before and after roundabout construction

4.3. METHODOLOGY

The objective was to ascertain the effect of a measure (construction of roundabouts) on a particular type of crashes (crashes involving bicyclists). The study was designed as an Empirical Bayes before and after study with a comparison group, controlling for general trends in traffic safety and possible effects of regression-to-the-mean (Hauer, 1997; Elvik, 2002; Nuyts and Cuyvers, 2003).

The Empirical Bayes procedure for safety estimation combines crash counts with knowledge about the safety of comparable locations. In principle, this approach needs estimates of the Safety Performance Function (SPF) for the comparison locations (Hauer, 1997; Hauer et al., 2002). Unfortunately no traffic volume data were available or could be collected for the comparison locations. Consequently no Safety Performance Function could be developed and a different approach was adopted, based on the crash observations on the locations in the comparison group. The alternative approach combined the crash counts at the treated intersections with the observed crash counts for the comparison locations. An underlying assumption was that the treatment locations and the comparison locations were relatively homogeneous in the before-situation and therefore that their (expected) crash counts were comparable. Although fitting a crash prediction model in order to estimate the

Safety Performance Function should be the preferable option, the used method was defendable and in any case the best that was possible given the data restrictions.

Table 9 and Table 10 reflect the average yearly number of crashes both in the treatment groups and the comparison groups. The average crash counts in the before-situation both for locations inside and outside built-up areas seem to correspond to a large extent with the counts in the comparison groups. This is an indication that the locations in the comparison groups were useful (in the absence of contra-indications) as an information source in order to apply a correction for the possible selection bias in the treatment groups.

Another possible solution for the selection bias (causing regression-to-the-mean-effects that need to be corrected) might have been to remove from the sample those years that likely were the basis for treatment decisions, for example the last year or the last two years before the conversion. This would have led to losing some crash data, but a correction for the regression-to-the-mean effect would not have been needed. However, a major difficulty with this alternative approach would have lied in the actual use of accident data by the Roads and Traffic Agency. As accident statistics are only available within a (serious) delay, road authorities do not have recent information about the crash history on certain sites. The delay mounted during the last decade in Belgium to 2 till 4 years being not the same for each accident year (Belgian Road Safety Institute, oral communication). A second problem in case I would have eliminated “years with more than expected crashes” is the delay between planning/designing a roundabout and actually constructing it. Depending on tactical (e.g. budgets, political priorities) and more operational considerations (e.g. weather conditions, inviting and negotiating tenders for work) there is a supplementary (but not fixed) delay between the design of a roundabout and the actual construction. Due to these reasons it’s hardly possible to reliably eliminate one or another specific period n from X tot (X-n) years before construction of the roundabout in order to eliminate the regression-to-the-mean effect.

The first step in the adopted procedure was to calculate the effectiveness for each location in the treatment group separately. Consequently the results were combined in a meta-analysis. This allowed combining the results for roundabouts that were constructed in different years.

The effectiveness is expressed as an odds-ratio of the evolution in the treatment group after the measure has been taken compared to the evolution in the comparison group in the same time period (Eq. 4-1).

$$EFF_l = \frac{TREAT_{l,after}/TREAT_{l,before,regr}}{COMP_{after}/COMP_{before}} \quad \text{(Eq. 4-1)}$$

The values of $TREAT_{l,after}$, $COMP_{after}$ and $COMP_{before}$ are count values and can simply be derived from the data. The value for $TREAT_{l,after}$ is the count number of crashes that happened on the location l during the years after the year when the roundabout was constructed. The values for $COMP_{after}$ and $COMP_{before}$ are the total count numbers of crashes for all locations in the comparison group respectively after and before the year during which the roundabout has been constructed. The values for the year during which the roundabout was constructed are always excluded, both in the treatment group and in the comparison group. For each roundabout the before-period (after-period) in the comparison group was selected that matches with the before-period (after-period) of the roundabout. Therefore no normalisation to years averages or similar rates in Equation 4-1 is necessary and total counts can be used.

The use of the comparison group allows for a correction of general trend effects that could be present in the crash evolution on the studied locations.

The value of $TREAT_{l,before,regr}$ reflects the estimated number of crashes on the treatment location l before construction of the roundabout, taking into account the effect of regression-to-the-mean. The regression-to-the-mean effect is likely to occur at locations where a decision has been taken to construct a roundabout as the Infrastructure Agency considers an increased number of crashes among others as an important criterion for constructing a roundabout at a certain location. The value is calculated as a result of the Empirical Bayes formula (Eq. 4-2):

$$TREAT_{l,before,regr} = \mathrm{w} * \left(\mu_{(\mathrm{TREAT_l+COMP})} * \mathrm{T}\right) + (1-\mathrm{w}) * \left(\textstyle\sum_{t=1}^{T} \mathrm{TREAT_{l,t}}\right) \quad \text{(Eq. 4-2)}$$

with $$w = \frac{1}{1+k*\mu_{(TREAT_l+COMP)}*T} \quad \text{(Eq. 4-3)}$$

and $$\mathrm{k} = \frac{\sigma^2{}_{(TREAT_l+COMP)} - \mu_{(TREAT_l+COMP)}}{\mu^2_{(TREAT_l+COMP)}} \quad \text{(Eq. 4-4)}$$

T equals the number of years in the before period. The value k (Eq. 4-4) expresses the overdispersion factor. This value reflects the amount in which the data are more spread than it would be the case in a perfect Poisson-distribution. Section 4.4 provides a numerical example of the derivation of the values k and w and the application of the method for one location. The value k must be positive and is calculated from the data itself. k-values were derived for each location separately, using all available crash data. In the case that all injury crashes were considered, the average value for k on the investigated locations was 1.12. However, in some cases, the k-value that was derived for individual locations appeared to be close to zero or even sometimes turned out to be negative. In the former case, this could reveal a problem of erroneous pure Poisson characteristics due to the small size of the sample and the low sample mean (Lord, 2006). In the latter case this is even contradictory to the basic assumption of the negative-binomial distribution of crashes (variance larger than the mean). As the use of a different value for k might lead to different results and an unreliably estimated overdispersion parameter could significantly undermine estimates (Lord, 2006), three scenarios were used in all cases where no k-value could be derived from the data themselves. In the first scenario an extremely small, but positive fixed value for k was used ($k=10^{-10}$). In the second scenario the same value for k was used for crashes involving fatalities or serious injuries as for all crashes (as all cases where no k-value could be derived from the data applied to crashes with fatalities and serious injuries). In the third scenario an extreme high value for k was used ($k= 10^{10}$). Using this approach, a sensitivity analysis was performed on the impact of k on the results by comparing the results through an assessment of the most extreme different possible conditions. It can be argued that the “in between value” that was derived from the data for all injury crashes is the most probable value since the others are fully arbitrary and unrealistically extreme.

The value w (Eq. 4-3) reflects the weighting of the group in comparison to the weighting of the location itself when estimating the number of crashes on the observed location before construction of the roundabout.

Equation 4-2 expresses the estimated number of crashes at the observed location in a time period T. Equation 4-2 equals the weighted sum of the number of crashes on the individual location and the average of a comparable location (i.e. the average of location and the comparison group). The higher the value k in Equation 4-3 or the number of years T in the before-period, the lower the weight (value w) for the comparison group and accordingly the higher the weight (1-w) for the number of crashes on the roundabout location itself. Note that an extreme high value for k means that the value w in Equation 4-3 almost equals to zero which corresponds a hypothesis of “no regression-to-the-mean-effect” as in such a case in Equation 4-2 only count data from the treatment location itself are used.

Consequently the value of EFF_l can be calculated. This value reflects the best estimate for the impact of the construction of a roundabout at location l. $Ln(EFF_l)$ denotes the natural logarithm of EFF_l. As EFF_l has a lognormal distribution (Fleiss, 1981) the variance s_l^2 of $Ln(EFF_l)$ can be calculated as

$$s_l^2 = \frac{1}{TREAT_{l,after}} + \frac{1}{TREAT_{l,before,regr}} + \frac{1}{COMP_{after}} + \frac{1}{COMP_{before}} \quad \text{(Eq. 4-5)}$$

This method creates problems in cases in which one of the crash counts becomes zero. In those cases a number of 0.5 was added to each of the denominators in Equation 4-6 (Fleiss, 1981; Elvik, 1997).

The 95% confidence interval can be derived as

$$CI_{EFF_l} = exp\,[LN(EFF_l\,) \pm 1.96 * s_l] \quad \text{(Eq. 4-7)}$$

This method was applied to calculate best estimates and confidence intervals for each roundabout location separately. After doing this, a fixed-effects meta-analysis was carried out in order to retrieve generalized impacts on groups of locations. The generalized effect is expressed as

$$EFF_{ALL} = exp\left(\frac{\sum_{i=1}^{n} w_l * LN(EFF_l\,)}{\sum_{i=1}^{n} w_l}\right) \quad \text{(Eq. 4-8)}$$

with $w_l = \frac{1}{s_l^2}$ (Eq. 4-9)

The confidence interval for EFF_{ALL} is derived in a similar way as in equation 4-6.

$$CI_{EFF_{ALL}} = exp\left(\frac{\sum_{i=1}^{n} w_l * LN(EFF_l\,)}{\sum_{i=1}^{n} w_l} \pm 1.96 * \frac{1}{\sqrt{\sum_{l=1}^{n} w_l}}\right) \quad \text{(Eq. 4-10)}$$

4.4. NUMERICAL EXAMPLE

Assume a treatment location $TREAT_l$ that was converted into a roundabout in 1998. The following crash data are available for $TREAT_l$ and for comparable locations C1 to C9:

Table 11 Crash data for location TREAT$_l$ and for comparable locations C1-C9

	1991	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
TREAT$_l$	0	0	0	0	0	0	0	0	3	1	0
C1	0	0	1	0	2	0	0	0	0	1	0
C2	0	0	0	0	0	0	0	0	0	1	0
C3	1	0	2	0	0	1	0	1	1	2	1
C4	0	3	0	0	0	0	0	0	0	0	0
C5	0	0	0	0	0	0	1	1	0	0	0
C6	0	2	0	0	0	0	0	0	0	0	0
C7	1	0	0	0	0	0	0	0	0	0	0
C8	0	0	2	0	1	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	1	2	0	0

Then

TREAT$_{l,after}$ = 4	(sum of all crashes on TREAT$_l$ in the years after the roundabout construction)
COMP$_{after}$ = 8	(sum of all crashes on C1 to C9 in the years after the roundabout construction)
COMP$_{before}$ = 17	(sum of all crashes on C1 tot C9 in the years before the roundabout construction)
$\mu_{(TREAT_l+COMP)}$ = 0.24	(mean yearly number of crashes on TREAT$_l$ and C1 tot C9 in the before-period)[1]
$\sigma^2{}_{(TREAT_l+COMP)}$ = 0.39	(variance of crash counts in the before-period for both the treatment location and the comparison locations)[1]

$$\mathrm{k} = \frac{\sigma^2{}_{(TREAT_l+COMP)} - \mu_{(TREAT_l+COMP)}}{\mu^2_{(TREAT_l+COMP)}} = 2.6$$

$$w = \frac{1}{1+k*\mu_{(TREAT_l+COMP)}*T} = \frac{1}{1+2.6*0.24*7} = 0.19$$

---

[1] The information on TREAT$_l$ is also included. Since this location was no roundabout before 1998, it is considered to be similar to the locations in the comparison group in the before-period.

$TREAT_{l,before,regr} = \mathrm{w} * \left(\mu_{(\mathrm{TREAT_l+COMP})} * \mathrm{T}\right) + (1-\mathrm{w}) * (\sum_{t=1}^{T} \mathrm{TREAT_{l,t}})$ = 0.19*0.24*7 + (1-0.19)*0 = 0.32

Consequently the estimated effectiveness-index on this location would be

$EFF_l = \frac{TREAT_{l,after}/TREAT_{l,before,regr}}{COMP_{after}/COMP_{before}} = \frac{4/_{0.32}}{8/_{17}} = 26.56$

4.5. RESULTS

Both treatment group and comparison group were divided into locations inside and outside built-up area. Consequently analyses were made for roundabouts inside built-up area using all locations in the comparison group inside built-up area as a comparison group for this estimation. The treatment locations were divided into two groups, depending whether the investigated intersection was equipped with traffic signals or not in the before-situation. The effectiveness-index was calculated for each treatment location using the described methodology. After calculating the effectiveness-index for all the locations in the same group a meta-analysis was made for the whole group.

Table 12 shows the results of the analyses. The best estimate for the overall effect of roundabouts on injury crashes involving bicyclists on or nearby the roundabout is an increase of 27%. The best estimate for the effect on crashes involving fatal and serious injuries is an increase of 41 to 46%, depending on the used k-value.

Performing the meta-analysis for all locations inside built-up area reveals an increase of crashes of probably 48% (effectiveness-index 1.48) after the roundabout construction. The result is significant at the 5% level.

On intersections inside built-up area and not equipped with traffic signals before, a significant increase of crashes involving bicyclists of 55% is noted. On intersections with traffic signals before, the best estimate is an increase of 23% of crashes. However, this result is clearly not significant. Estimations were also made for the group of the most serious crashes, i.e. crashes involving fatal and serious injuries. The results show a significant 77% increase in crashes involving bicyclists inside built-up area.

Subsequently the same procedure was followed for locations outside built-up area. When it comes to all injury crashes the overall best estimate of the impact is close to one, which means that the zero-hypothesis of “no effect” cannot be rejected at all. Nor a significant effect can be seen for crashes involving fatal and serious injuries. The overall best estimate shows an increase of 15 to 24% of severe crashes. Nevertheless, the confidence interval is broad and even a decrease in crashes cannot statistically be excluded.

In order to reveal whether there are any significant differences in the results for different before-situations (traffic signals or not) or different locations (inside or outside built-up area), a series of two-tailed t-tests with two samples assuming unequal population variances was performed. Table 13 shows the results. Significant differences are found for “all crashes causing injuries” outside built-up area (a best estimate of index 1.27 on intersections with traffic signals before versus an index of 0.89 on intersections without traffic signals before).

Table 12 Effectiveness-indices

		Traffic signals before	No traffic signals before	All locations
Inside built-up area	All injury crashes	1.23 [0.62-2.45] (ns)	1.55 [1.10-2.17] (*)	1.48 [1.09-2.01] (*)
	Crashes with fatally and seriously injured	1.63 [0.45-5.90] (ns)	1.81 [0.99-3.29] (ns)	1.77 [1.03-3.05] (*)
Outside built-up area	All injury crashes	1.27 [0.68-2.38] (ns)	0.89 [0.56-1.42] (ns)	1.01 [0.69-1.47] (ns)
	Crashes with fatally and seriously injured	1.78 [0.72-4.38] (ns) ° 1.62 [0.68-3.88] (ns) °° 1.36 [0.55-3.33] (ns) °°°	1.06 [0.59-1.91] (ns) ° 1.06 [0.59-1.91] (ns) °° 1.05 [0.57-1.99] (ns) °°°	1.24 [0.76-2.03] (ns) ° 1.21 [0.74-1.97] (ns) °° 1.15 [0.69-1.92] (ns) °°°
All locations	All injury crashes	1.25 [0.79-1.99] (ns)	1.28 [0.97-1.68] (ns)	1.27 [1.00-1.61] (*)
	Crashes with fatally and seriously injured	1.73 [0.83-3.61] (ns) ° 1.62 [0.79-3.34] (ns) °° 1.44 [0.69-3.01] (ns) °°°	1.38 [0.91-2.10] (ns) ° 1.38 [0.91-2.10] (ns) °° 1.40 [0.91-2.16] (ns) °°°	1.46 [1.01-2.10] (*) ° 1.44 [1.00-2.07] (*) °° 1.41 [0.97-2.05] (ns) °°°

ns = non significant, * = $p \leq 0.05$
° Use of fixed k = 10^{-10}
°° Use of k-value = k for all injury crashes
°°° Use of fixed k = 10^{10}

Table 13 t-tests

			t-statistic	p-value	
Inside built-up area	All injury crashes	signals vs no signals before	0.23	0.83	ns
	Crashes with fatally and seriously injured	signals vs no signals before	-0.14	0.89	ns
Outside built-up area	All injury crashes	signals vs no signals before	2.19	0.04	*
	Crashes with fatally and seriously injured °	signals vs no signals before	1.23	0.23	ns
All locations	All injury crashes	signals vs no signals before	1.59	0.12	ns
	Crashes with fatally and seriously injured °	signals vs no signals before	0.66	0.51	ns
All locations	All injury crashes	inside vs outside built-up area	1.78	0.08	ns
	Crashes with fatally and seriously injured °	inside vs outside built-up area	1.79	0.08	ns
Signals before	All injury crashes	inside vs outside built-up area	-0.02	0.99	ns
	Crashes with fatally and seriously injured°	inside vs outside built-up area	0.17	0.87	ns
No signals before	All injury crashes	inside vs outside built-up area	2.37	0.02	*
	Crashes with fatally and seriously injured°	inside vs outside built-up area	2.04	0.05	*

ns = non significant, * = p≤0.05, ** = p≤0.01

° used results with k = k_all crashes for locations outside built-up area

Furthermore significant differences are found for locations inside versus outside built-up area at intersections that were not equipped with traffic signals before (both for “all injury crashes” and “crashes with fatally or seriously injured”).

4.6. DISCUSSION

I am aware of only one previous before-and-after study investigating the effects of roundabouts on different types of road users. This study (Schoon and van Minnen, 1993) provided indications of a less favourable effect of roundabouts on injuries among bicyclists compared to other road users. But this study did not take into account possible trend effects in road safety nor stochastic elements or regression-to-the-mean effects. According to the results presented in this chapter, the effect does not look favourable at all. This finding could provide an explanation for the higher-than-expected prevalence of injury crashes involving bicyclists on roundabouts as I found it in the crash data in Flanders and as it was also been noted in some other countries (Brown, 1995; CETUR, 1992). However, it is recommendable to perform similar studies in other countries in order to confirm whether results are comparable.

Our best estimate for the overall effect of roundabouts on the number of injury crashes involving bicyclists is an increase of 27% (95% C.I. [0%; 61%]. The effect on severe crashes is even worse: an increase of 41-46% . It is interesting to compare these results with a former study (De Brabander et al., 2005) that studied the effects of roundabouts on safety among all types of crashes in the same region and used a strongly comparable dataset. This study revealed an overall decrease of 34% of crashes causing injuries (95% C.I. [-43%; -28%]) and a decrease of 38% [-54%; -15%] for crashes involving fatal and serious injuries.

Apart from the mere fact that the construction of a roundabout appears to increase the number of crashes with bicyclist, the increase seems to be higher for the most severe crashes like is indicated by the figures in Table 12 The estimates are consistently worse for the severest crashes compared with all the injury crashes. This is an atypical finding compared with research results for effects of roundabouts on all types of crashes that generally report an even higher reduction of the severest crashes. Although atypical, this finding is not illogical in the sense that the nature of crashes with bicyclists can be assumed to be very different from the crashes with other types of road users. The outcome of crashes in general is strongly determined by the biomechanical forces that are exerted to the involved human bodies. These forces are in essence dependent on the mass and speed of the moving bodies (kinetic energy $E_k = mv^2$) (Evans, 2004). Since the construction of a roundabout reduces vehicle speeds, it is logical that mainly the number of the most severe crashes is reduced. However crashes with bicyclists at roundabouts are often collisions between cyclists circulating around the roundabout colliding with motorised vehicles entering or leaving the roundabout (see for instance the crash analysis in CETUR, 1992). Even at low speeds such a crashes are likely to cause severe injuries.

These contradictory results for crashes involving bicyclists and all crashes raise the question whether it is recommendable or not – at least from a safety point of view – to construct roundabouts. Although roundabouts turn out to be a safe solution in general, the results for bicyclist's safety are clearly poor.

The effects on bicyclist's safety differ depending on the location of the roundabouts. It is unquestionable that the effect of roundabouts inside built-up area is bad. Outside built-up area the effect on safety for bicyclists is about zero: not better nor worse compared to the before-situation. However, also there seems to be a tendency towards a deterioration (best estimates +1% for all injury crashes, +15-24% for crashes with fatally and seriously injured, although clearly not significant).

Another issue is to judge the effect depending on the type of intersection (with or without traffic signals) in the before-situation. Inside built-up area there is no clear effect. Outside built-up area the differences are more distinct. Intersections with traffic signals in the before-situation perform significantly worse in comparison to non-signalised intersections.

One must take into account that an estimated effect is always a "most likely" effect that may conceal many differences between individual locations. Figure 13 illustrates this. The figure shows the estimations for the effectiveness-index for the individual roundabout locations (all crashes, 91 data points) and their weight (value w_l in Equation 4-8) in the meta-analysis. It is obvious that results at individual intersections differ considerably. The lowest estimated effect is a 80% decrease (index 0.2), the highest an increase of 787% (index 8.87). Generally, it could be expected that the data points with the highest weights (lowest variance of the effectiveness-index) are closer to the general best estimate, which should show a more or less normal distribution. To a large extent this seems to be the case.

The variations between the individual results can be explained mainly by the stochastic nature of crashes as rare events, but there might also be something more. Looking at Figure 13 , there are some indications of a double peak in the curve. This could reveal the presence of distinct subgroups in the sample of roundabouts with different safety effects. Looking at the second peak, in the neighbourhood of coordinates (5.27; 1.89), all intersections are located inside built-up area. However, as one of the major conclusions in this study is that roundabouts inside built-up area perform weaker compared to roundabouts outside built-up area when it comes to the safety of bicyclists, a higher representation of locations inside built-up area in the group of the worst performing locations shouldn’t be really surprising. The available data don’t enable to give an accurate explanation for the second peak in the curve. Unknown influencing factors may exist. For example, no information was available about the type of bicyclist facility (motorised traffic and bicyclists mixed together – the so called mixed traffic solution, adjoining – close to the roadway - cycle tracks or physically separated cycle paths) present at the roundabouts studied, while specific design characteristics may have an important effect on crashes for specific groups of road users (Daniels and Wets, 2005). Also the number of lanes on the roundabout, which was not known in this case, might influence the results as double-lane roundabouts tend to reduce crashes less in comparison to single lane roundabouts (Persaud et al, 2001). More research on this topic should be carried out.

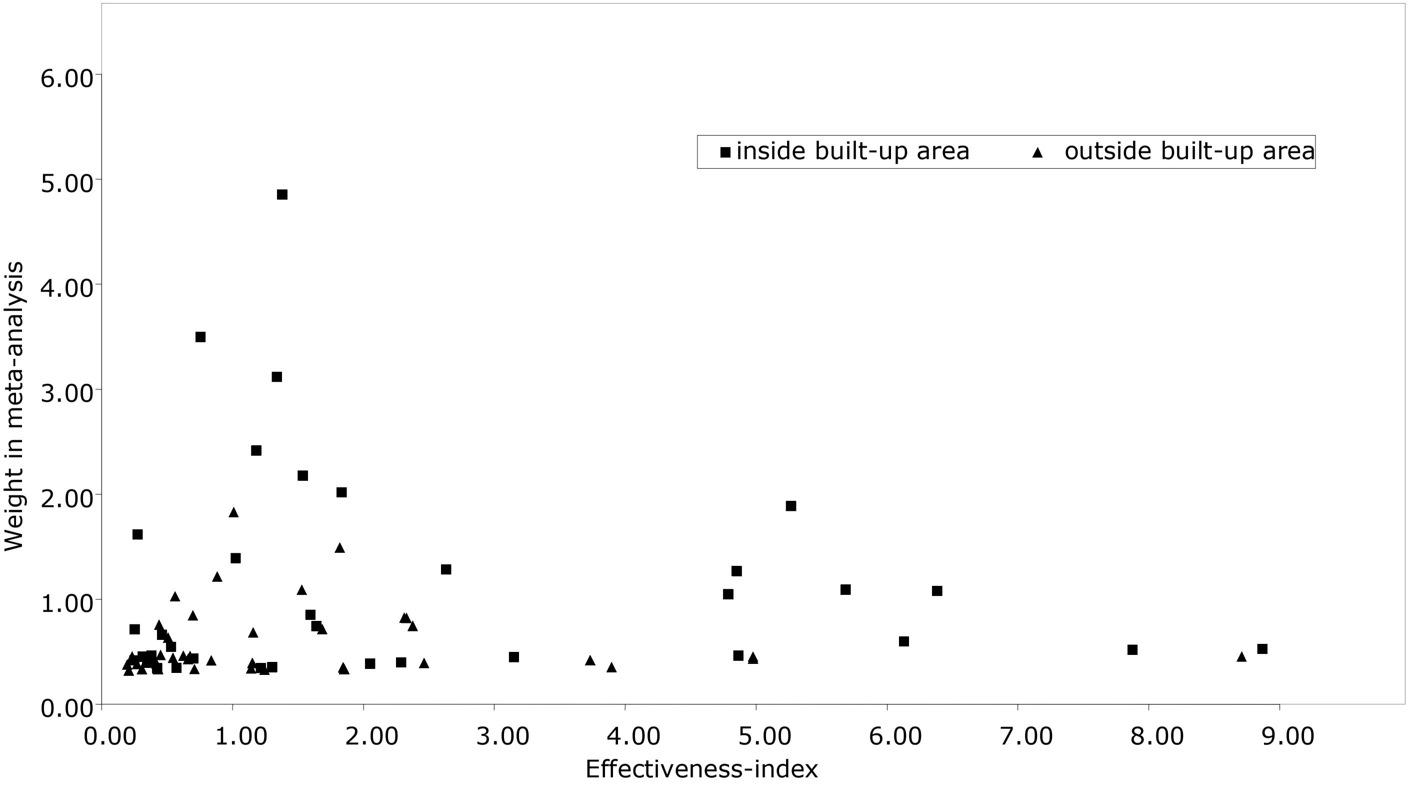

Figure 13 Funnel Graph – Best Estimates of the Effectiveness-Index – All Roundabouts – All Crashes.

One of the restrictions of this study is the lack of data about the evolution of traffic volume on the locations studied, particularly the evolution of motorised traffic and bicyclist traffic. By using a large comparison group it was possible to account for both general trends in traffic volume as well as possible evolutions in modal choice. But, at a local scale level, one cannot exclude the effect of roundabouts on exposure, for motorised traffic as well as for bicyclists. It is possible that some bicyclists or car drivers will change their route choice after the construction of a roundabout, either resulting in an increased use of the roundabout or a decrease in the use, depending on personal preferences. Either changes in the route choice could make the results in this study weaker (if roundabouts for instance would attract bicyclists this would create a higher exposure for bicyclists at the site, but a corresponding lower risk elsewhere, in which case I am too pessimistic in my estimates) but the results might also be stronger (if bicyclists would use roundabouts less than the previous types of intersections, in which case our estimations are even too modest). As no data on exposure were available, I couldn’t account for possible changes in the choice of route. Further research in this area is nevertheless recommended.

4.7. CONCLUSIONS

As roundabouts are in general improving safety on intersections, there are few reasons for doubting the added-value of roundabouts as far as safety is concerned. But, looking at the poor results for bicyclist crashes and keeping in mind the attention that many governments pay to vulnerable road users, roundabouts don’t seem to be an appropriate solution in all circumstances in which they were built in the past. At least in built-up area where speeds are lower and bicyclists are more numerous, road authorities should look at pros and cons carefully before constructing a roundabout. Further research should reveal whether it is possible to define more specific circumstances in which roundabouts should be constructed or not and whether some geometric features of roundabouts correlate with less or more crashes involving bicyclists.

Chapter 5. Crashes with bicyclists: influence of some location characteristics and the design of cycle facilities.

In the previous chapter, the results were presented from a before-and-after analysis of injury crashes with bicyclists at roundabouts. A considerable increase in the number of injury crashes with bicyclists was noticed. The results were unexpected and emphasized the need to deepen the insights in the reasons behind the poor performance of roundabouts with respect to safety for bicyclists.

The present chapter describes the results of analyses based on additionally collected information about the design type of the cycle facilities and some geometrical features of the investigated roundabouts. This research was published in Daniels et al. (2009).

The reader is referred to Chapter 2 for an introduction about the basic geometrical features of roundabouts, particularly the different types of cycle facilities that will be discussed in this chapter. The chapter starts with a specification of the problem statement. This is followed by a description of the available data and the adopted methodology. Consequently the results are provided and related to existing knowledge and previous research.

5.1. PROBLEM STATEMENT

In Chapter 4, the results of a before-and-after analysis of injury crashes with bicyclists at roundabouts were presented. Based on a sample of 91 roundabouts on regional roads in Flanders-Belgium, a considerable increase in the number of injury crashes with bicyclists was noticed (best estimate: + 27% with a 95% C.I. of [+0%; +61%] for all injury crashes). For the severest crashes, those with fatal and serious injuries (i.e. a hospitalisation of at least 24 hours) the results were even worse (best estimate of the increase of 41-46%). The results were unexpected, although earlier findings suggested possible specific safety problems for bicyclists at roundabouts (see for example Brilon, 1997; Brüde and Larsson, 2000; Layfield and Maycock, 1986; Schoon and van Minnen, 1993).

However, some questions stayed open after the study. A major discussion point has been the influence of different design types of cycle facilities at roundabouts. In practice, considerable differences between countries seem to exist regarding the applied road design in order to conduct bicyclists through roundabouts. It indicates that no commonly accepted solution has been reached so far.

Other remaining research questions had to do with the possible influence of geometrical variables such as the number of lanes at the roundabout and the pavement colour of the cycle facility.

The present chapter describes the results of analyses based on additionally collected information about the design type of the cycle facilities and some geometrical features of the investigated roundabouts. The main research objective in this part was to investigate whether differences between geometrical designs correlated with a different safety effect for bicyclists.

5.2. DATA COLLECTION

A sample of 90 roundabouts in the Flanders region of Belgium was studied. The roundabout data were obtained from the Infrastructure Agency (part of the Ministry of Mobility and Public Works). The used dataset is the same, except for one location, as the dataset that was used in the previous chapter. Additionally acquired data included the presence and the types of cycle facilities, the number of lanes at the roundabout, the presence of lines or barriers between the roundabout and the cycle facility (in case of cycle lanes), the priority rules for bicyclists (in case of separate cycle paths) and the pavement colour.

The data were used to estimate possible differences in the safety performance (effectiveness-indices obtained from a before-after analysis) of roundabouts according to the present accommodation for bicyclists. A second goal was to detect possible explaining factors for the differences in the performance of different roundabouts.

Table 14 Number of roundabouts in the study sample

	Number of lanes		
	1	2	TOTAL
Inside built-up area	39	1	40
Outside built-up area	44	6	50
TOTAL	83	7	90

Both single-lane and double-lane roundabouts occur in the sample, although the former type is far more common (Table 14).

Information was collected about the type of cycle facility that is present at the roundabouts. Pictures were made of each of the 90 roundabouts. According to the type of the cycle facilities, each roundabout was assigned to one of the four before-mentioned categories (Table 15).

Table 15 Number of roundabouts in the study sample - number of lanes and type of cycle facility

	Number of lanes		
	1	2	TOTAL
Mixed traffic	8	1	9
Cycle lane	38	2	40
Separate cycle path	35	3	38
Grade-separated	2	1	3
TOTAL	83	7	90

Table 16 Intersection design before roundabout construction

	Number of locations
Traffic signals	21
No traffic signals	69
Total	90

Of the 90 roundabouts, 21 were replacing traffic signals (Table 16). The other roundabouts were built on other types of intersections (intersections with stop signs, give way-signs or general priority to the right).

For the purpose of this study only roundabouts that were constructed between the year 1994 and 2000 were taken into account. Crash data were available from 1991 until the end of 2001. Consequently a time period of crash data of at least 3 years before and 1 year after the construction of each roundabout was available for the analysis. For each roundabout the full set of available crash data in the period 1991-2001 was included in the analysis. Table 17 shows the distribution of the construction years for the roundabouts in the sample.

Table 17 Construction year according to design type

Construction year	Mixed traffic	Cycle lanes	Separate cycle paths	Grade-separated	TOTAL
1994	3	10	4		17
1995	2	11	8		21
1996	1	8	6	1	16
1997		2	5	1	8
1998	1	4	2		7
1999	1	3	8	1	13
2000	1	2	5		8
TOTAL	9	40	38	3	90

Exact location data for each roundabout were available so that crash data could be matched with the roundabout data. 40 roundabouts from the sample are located inside built-up areas (areas inside built-up area boundary signs, in general with a speed limit of 50km/h), 50 outside built-up areas (in general with speed limits of 90 or 70 km/h).

Extra information was collected according to the type of cycle facilities. For roundabouts with cycle lanes this extra information applied to:

- The presence of a line marking between carriageway and cycle lane;
- The presence of one or another physical barrier (e.g. a kerbstone, small concrete elements, verdure) or an elevation between carriageway and cycle lane.

When the distance between the cycle lane and the carriageway mounted to more than 1 meter, the roundabout was classified as one with separate cycle paths. Details about the roundabouts with cycle lanes in the sample are given in Table 18 .

Table 18 Details - Roundabouts with cycle lanes

	Physical barrier	No barrier	TOTAL
Marking	15	22	37
No marking	1	2	3
Total	16	24	40

Table 19 Details - Roundabouts with separate cycle paths

	Inside built-up area	Outside built-up area	Total
Priority to bicyclists	5	13	18
No priority to bicyclists	3	17	20
Total	8	30	38

A subdivision in the group of roundabouts with separate cycle paths was made according to when they were constructed with or without priority for bicyclists crossing the exit and entry lanes (see Table 19).

Furthermore the colour of the cycle facility (when present) was collected (Table 20). In Flanders it is common to colour cycle facilities red, although it is not compulsory. Other colours do not occur. In the case of the cycle lanes, all but one are coloured. In the group of the separate cycle paths there are some more instances of uncoloured pavements, but they remain a small minority.

Table 20 Number of roundabouts with coloured cycle facilities according to design type

	Coloured	Not coloured
Mixed traffic	not applicable	
Cycle lanes	39	1
Separate cycle paths	32	6
Grade-separated	2	1
TOTAL	73	8

The comparison group consisted of 649 crashes with bicyclists at 172 intersection locations and is identical to the comparison group in the previous study. The total number of crashes included in the treatment group (= roundabout locations) was 411, of which 314 with only slight injuries, 90 with at least one serious injury and 7 with a fatal injury (see Table 21).

Table 21 Number of considered crashes (period 1991-2001)

Nature of the severest injury in the crash	Roundabouts	Comparison group
Slight	314	486
Serious	90	142
Fatal	7	21
TOTAL	411	649

Table 22 shows the number of crashes for the treatment group (both before and after conversion into a roundabout), split up by the design type of the cycle facilities at the roundabout and by the severest injury caused by the crash.

Table 22 Number of crashes at the roundabout locations - before and after conversion

	Crashes with slight injuries	Crashes with serious injuries	Fatalities	Total
Mixed traffic	31	9	0	40
Cycle lanes	160	35	3	198
Separate cycle paths	121	41	4	166
Grade-separated	2	5	0	7
TOTAL	314	90	7	411

5.3. METHODOLOGY

The adopted study design was that of an Empirical Bayes before-and-after study with injury crashes with bicyclists as a measurement variable. The adopted methodology is the same as in Chapter 4. The use of comparison groups enabled to control for general trends in traffic safety and possible regression-to-the-mean effects. No correction for specific developments in traffic volume was possible. In the first stage, the effectiveness for each roundabout location was calculated separately. Subsequently, the results were combined in a meta-analysis.

The before-and-after design allowed to determine effectiveness-indices for each roundabout in the sample. The effectiveness is expressed as an odds-ratio of the evolution in the treatment group after conversion into a roundabout compared to the evolution in the comparison group in the same time period. An effectiveness-index above 1 respectively below 1 indicates an increase, respectively a decrease in the number of crashes compared to the average evolution on similar locations where no roundabout was constructed, while an index of 1 equals the zero-hypothesis of no effect.

Since additional data about geometric features of the roundabout were available some regression models could be fitted in order to explain the variance of the estimated values of the effectiveness-indices according to differences in the number of lanes, pavement colour, location inside/outside built-up area etc. Later on, the dataset could be extended by information on the traffic volume of the examined locations, both volume of motorised vehicles and the volume of bicyclists. This information was included as well in the meta-regression models.

The models were fit through a generalised linear modelling procedure (SAS) assuming a normal response variable distribution and an identity link. Since the results for the effectiveness-indices that were found in the previous chapter showed a lognormal distribution, the chosen dependent variable in the regression analyses was the natural logarithm of the effectiveness-index.

5.4. RESULTS

Table 23 and Table 24 show the results of the analyses for all injury crashes and severe injury crashes respectively. The best estimate for the overall effect on injury crashes involving bicyclists on or nearby the roundabout is an increase of 27% ($p = 0.05$). The best estimate for the effect on crashes involving fatal and serious injuries (Table 24) is an increase of 42-44% ($p = 0.05$-0.06), depending on the applied dispersion-value k. None of the partial results for any of the subgroups in Table 24 is significant at the 5% level. However, all the results for the separate subgroups show an increase in the number of fatal and serious crashes, except in one scenario for roundabouts with grade-separated cycle facilities (showing a status quo).

Overall, the number of injury crashes at roundabouts with cycle lanes turns out to increase significantly (+93%, 95% CI [38 to 169%]. However, for the other 3 design types (mixed traffic, separate cycle paths, grade-separated cycle paths) the best estimate is a decrease of 17% in the number of crashes, although not significant (Eff. index 0.83 with 95% CI [0.59-1.16]) (result of a separate meta-analysis on the values for those categories, not reflected in the table). Some separate analyses were made for the results within subgroup of the cycle lanes as well as within the subgroup of the cycle paths, reflecting the possible influencing effects of some particular design variables such as the type of distinction between roadway and the cycle facility (in case of cycle lanes) and the applicable priority rule (in case of cycle paths). Also these results are provided in Table 23 and Table 24 . For reasons of clarity the presented results in Table 24 for these subgroups are only those for the dispersion parameter k = value k for all injury crashes.

Table 23 Results – all injury crashes.

	Nr. of locations	Effectiveness- index [C.I.] (p-value)
MIXED TRAFFIC	9	0.91 [0.45-1.84] (0.79)
CYCLE LANES		
Line + barrier	15	2.06 [1.23-3.44] (0.01)
Line + no barrier	22	1.85 [1.16-2.94] (0.01)
No line + barrier	1	2.63 [0.47-14.89] (0.27)
No line + no barrier	2	0.90 [0.10-8.15] (0.93)
All cycle lanes	40	1.93 [1.38-2.69] (<0.01)
SEPARATE CYCLE PATHS		
Priority to bicyclists	18	0.79 [0.45-1.41] (0.41)
No priority to bicyclists	20	0.86 [0.50-1.48] (0.59)
All separate cycle paths	38	0.83 [0.56-1.23] (0.35)
GRADE-SEPARATED	3	0.56 [0.11-2.82] (0.48)
ALL ROUNDABOUTS	90	1.27 [1.00-1.61] (0.05)

Table 24 Results – crashes with fatal and serious injuries.

	Nr. of locations	Effectiveness- index [C.I.] (p-value)
MIXED TRAFFIC	9	1.77 [0.55-5.66] (0.34) ° 1.79 [0.56-5.74] (0.33) °° 1.89 [0.59-6.10] (0.28) °°°
CYCLE LANES		
Line + barrier	15	1.58 [0.67-3.71] (0.30) °°
Line + no barrier	22	1.13 [0.53-2.39] (0.75) °°
No line + barrier	1	3.18 [0.10-100.66] (0.51)°°
No line + no barrier	2	2.13 [0.19-24.09] (0.54) °°
All cycle lanes	40	1.37 [0.79-2.37] (0.26) ° 1.37 [0.79-2.35] (0.26) °° 1.34 [0.78-2.31] (0.29) °°°
SEPARATE CYCLE PATHS		
Priority to bicyclists	18	1.14 [0.50-2.59] (0.76) °°
No priority to bicyclists	20	1.74 [0.79-3.86] (0.17) °°
All separate cycle paths	38	1.43 [0.81-2.52] (0.22) ° 1.42 [0.80-2.51] (0.23) °° 1.46 [0.83-2.56] (0.19) °°°
GRADE SEPARATED	3	1.84 [0.26-12.76] (0.54) ° 1.31 [0.23-7.54] (0.76) °° 1.00 [0.18-5.49] (>0.99) °°°
ALL ROUNDABOUTS	90	1.44 [1.00-2.09] (0.05) ° 1.42 [0.99-2.05] (0.06) °° 1.42 [0.99-2.03] (0.06) °°°

° use of fixed dispersion parameter k =10^{-10}
°° use of dispersion parameter k = value k for all injury crashes
°°° use of fixed dispersion parameter k=10^{10}

Subsequently a meta-regression procedure was applied. Maximum likelihood linear regression models (SAS-procedure GENMOD) were fitted in order to estimate the relationship between the estimated value for the effectiveness per location and some known characteristics of the roundabout locations. The available independent variables are listed in Table 25 .

Table 25 Independent variables

Abbreviation	Description
INSIDE	0 = outside built-up area; 1= inside built-up area
MIXED	0 = no mixed traffic; 1= mixed traffic
CYCLLANE	0 = no cycle lane; 1 = cycle lane
CYCLPATH	0 = no separate cycle path; 1 = separate cycle path
GRADESEP	0= no grade-separation; 1 = grade-separation
SIGNALS	0 = no traffic signals; 1 = traffic signals before roundabout construction
RED	0 = not coloured, 1 = red-coloured cycle facilities (not applicable when MIXED = 1)
TWOLANES	0 = 1 lane; 1 = 2 lanes on the roundabout
LINE	0 = no marking or not applicable; 1 = marking between roadway and cycle lanes
BARR	0 = no physical element or not applicable; 1 = physical element between roundabout and cycle lanes
PRIOR	0 = no priority for bicyclists; 1= priority when crossing exit or entry lanes

All variables were dummies and could take the value 0 or 1. The estimated effectiveness per location (EFF_l) was used as the dependent variable in the model. EFF_l was a continuous, non-negative variable, showing a more or less lognormal distribution. A natural log transformation was done and the value $LN(EFF_l)$ was further used for the analysis.

The functional form of the fitted model can be described as

$$LN(EFF_l) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon$$

where $x_1, \ldots, x_n$ denote the independent variables (all dummies) and $\beta_0, \ldots, \beta_n$ were the estimation parameters.

In order to account for the uncertainty in the individual effectiveness-estimates, the inverse of the variance of the individual effectiveness-estimates($w_l = \frac{1}{s_l^2}$), see Eq. 4-11 on page 44, was included as a weight variable (Elvik, 2005).

The generalized linear modelling procedure was applied starting from an initial set of variables including: INSIDE, MIXED, CYCLLANE, CYCLPATH, GRADESEP, SIGNALS and TWOLANES. At a later stage data came available on the traffic volume on the investigated roundabout locations. Although these data reflect only the situation after the roundabout construction they are assumed to be powerful indicators for the traffic volume in the before situation as well. Traffic volume information was available for both motorized vehicles (variable ADT) and for bicyclists (variable BICYCL_VOL).

Possible second-order effects were checked by including a number of interaction terms in the models. The interaction terms were each time calculated as the product of the values of two dummy variables, resulting in a value one in case both dummy variables had the value one, and a value zero in the other cases. Included interaction terms were cross variables for the different cycle facility types (MIXED, CYCLLANE, CYCLPATH and GRADESEP) on the one hand and the variables INSIDE, SIGNALS and TWOLANES on the other hand (thus MIXED*INSIDE, CYCLLANE*INSIDE etc.). Furthermore interaction terms were used to include some variables that are only applicable to one particular category of roundabouts: CYCLPATH*PRIOR (in case of cycle paths), CYCLLANE*BARR and CYCLLANE*LINE (both in case of cycle lanes). In a first step a model was fitted with all those variables, resulting in a AIC-value of 259.61. Subsequently the correlation matrix was inspected and in case of variables with a high correlation ($\rho>0.6$), the variable with the smallest contribution to the model fit was eliminated unless both variables had a substantial individual contribution to the model fit. Furthermore non-significant variables ($p>0.1$) were gradually eliminated. Table 26 shows the results for the best fitting model without traffic volume variables.

Table 26 Regression results of LN(EFF_I) for all roundabouts (N=90), all crashes with bicyclists

Parameter	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept	-0.50	0.17	8.32	<0.01
CYCLLANE	0.89	0.17	26.17	<0.01
TWOLANES	0.59	0.38	2.47	0.12
INSIDE	0.30	0.17	3.08	0.08
SIGNALS	0.26	0.20	1.64	0.20

Deviance = 40.89 df = 85 AIC 244.59 BIC 259.58

The main effect for CYCLLANE is positive and significant at the 1%-level. The main effects for TWOLANES, INSIDE and SIGNALS are positive but clearly less significant. The sign of the revealed effects is positive, meaning that roundabouts with cycle lanes, two-lane roundabouts, roundabouts inside built-up areas and roundabouts that replaced signal-controlled intersections, compared with the other designs, have had a worse performance with respect to crashes with bicyclists (positive predicted value for LN(EFF_I). Due to the negative intercept, the default value for the outcome estimate is negative, meaning that in the model for all injuries the default estimate for the effect is a decrease in the number of crashes, except for the roundabouts in the four aforementioned cases.

Table 27 shows the results for the best fitting model including the traffic volume variables. It appears that the bicyclist volume becomes strongly significant, whereas the volume of motorised vehicles adds little to the model fit and was highly insignificant and therefore excluded from the model. Another important consequence is that the variable SIGNALS looses significance and that the variables TWOLANES and INSIDE becomes significant at the 2%, respectively 1%-level. The volume of bicyclists is strongly significant and generates a small negative effect on the estimated effectiveness-index, meaning that locations with more bicyclists perform better than locations with fewer bicyclists in terms of safety for bicyclists.

Table 27 Regression results of LN(EFF_I) for all roundabouts (N=90), all crashes with bicyclists, including traffic volume variables

Parameter	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept	-0.41	0.17	6.05	0.01
CYCLLANE	0.85	0.17	25.76	<0.01
TWOLANES	0.74	0.37	4.09	0.04
INSIDE	0.52	0.18	7.88	0.01
BICYCL_VOL	-0.0002	0.0001	7.29	0.01
SIGNALS	0.23	0.20	1.41	0.24

Deviance = 37.82 df = 84 AIC 239.57 BIC 257.07

After fitting the models for all injury crashes the same procedure was followed for the effectiveness-indices of the subsample of crashes with fatally or seriously injured. The chosen variables and procedures were identical to the before-mentioned. The dependent variables were the effectiveness estimates from the scenario where k = value k for all injury crashes. Again a weighted regression procedure was applied with the inverse of the variance of the individual results as the weighting variable. This resulted in a model containing two variables (CYCLPATH and the interaction term CYCLPATH*PRIOR) and showing a much weaker fit than the model for all crashes (Table 28). Although clearly non significant, the interaction term CYCLPATH*PRIOR (cycle paths with priority to bicyclists) seems to moderate the unfavourable result of roundabouts with a cycle path. However, due to the lack of significance, the results of this model seem too unreliable for any well-grounded conclusion.

Table 28 Regression results of LN(EFF) for all roundabouts (N=90), KSI crashes with bicyclists

Parameter	Estimate	Standard Error	Chi-square	Pr > ChiSq
Intercept	0.19	0.17	1.35	0.24
CYCLPATH	0.38	0.33	4.43	0.25
CYCLPATH*PRIOR	-0.45	0.42	1.22	0.27
Deviance = 42.30	DF = 87	AIC 302.19	BIC 312.19	

5.5. DISCUSSION

In Chapter 4 the effects of roundabouts on crashes involving bicyclists were estimated. The extra information about the cycle facilities on roundabouts in the present study enabled to relate the results of the previous study to different designs of cycle facilities.

In the data, a clear difference in the performance level is visible for roundabouts with cycle lanes compared to other types when all injury crashes with bicyclists are considered. The presence of cycle lanes correlates with a higher value of the effectiveness-index which indicates an increase in the number of bicycle crashes. This effect was suggested earlier, e.g. by Brilon (1997), but was so far not supported by very extensive analyses of crash data. However, in their cross-sectional study, Hels & Orozova-Bekkevold (2007) found no significant effect of the presence of a cycle facility on the number of bicyclist crashes.

Although a clear statistical relationship was found, the present results should be interpreted carefully. The model for all crashes fits quite well and shows different convincingly significant variables. The model that includes the information for the traffic volume performs clearly better than the model without traffic volume information, both in terms of statistical fit by comparing the AIC or BIC-values and by its intuitive appeal. The relevance of the cyclists volume for the results might indicate a 'safety in numbers-effect for bicyslists which is discussed further in the following chapters.

The model for the severest crashes is too weak to allow any well-grounded conclusion. Moreover the reliability of the underlying data, i.e. the estimated values for the effectiveness-indices, is highly questionable. The results for the individual locations for the crashes with killed or seriously injured have systematically low significance values (see Table 24) and moreover they are affected by the applied overdispersion parameter (see for example the influence of the applied overdispersion parameter on the estimates for the group of the grade-separated roundabouts).

Based on the model for all crashes it can therefore be concluded that mainly roundabouts with cycle lanes, two-lane roundabouts and roundabouts inside built-up areas perform worse.

For the two remaining types of cycle facilities (mixed traffic and grade-separated), the models didn't reveal a distinct effect, which might be due to the scarcity of the data (9 and 3 observations respectively).

van Minnen and Braimaster (1994) investigated the give-way behaviour of motorists and bicyclists at roundabouts with separate cycle paths. Both the designs with and without priority to bicyclists were included. The observations revealed that in a considerable number of cases the formal rules were not obeyed, both by motorists and bicyclists. van Minnen (1995) found in a cross-sectional study a difference between the performance of roundabouts with separate cycle paths with priority to bicyclists and separate cycle path-roundabouts without priority to bicyclists. When priority is given to bicyclists the number of serious injury crashes seems to be higher than if not (Dijkstra, 2005). However, the above presented model for the most serious crashes produces possibly deviating results since the sign of the interaction variable CYCLPATH*PRIOR is negative, meaning that within the group of the cycle path roundabouts priority for bicyclists moderates the unfavourable effect. Nevertheless, this last effect is far from significant and it suffers from the above-mentioned severe uncertainties.

A Dutch before and after-study found no major differences in the evolution of crashes with bicyclists between three different roundabout design types (mixed traffic, cycle lanes, separate cycle paths) (Schoon and van Minnen, 1993). Unfortunately this study did not incorporate trend effects in the number of crashes and disregarded the stochastic nature of crashes. Regarding the numbers of victims, it was concluded that at roundabouts with a considerable traffic volume, a separate cycle path design was safer than both other types. Therefore the authors recommended the use of separate cycle path designs. In a Swedish cross-sectional study it was concluded that the bicyclist crash rate at roundabouts with cycle crossings (i.e. roundabouts with a cycle path design) was lower compared to roundabouts with bicyclists riding on the carriageway (Brüde and Larsson, 2000).

Two roundabouts in the sample are in the case of a ‘suggestion lane’. They are considered to be a part of the group with the cycle lanes. A sensitivity analysis on the results was performed by recalculating meta-analyses and assigning those two roundabouts to the group of mixed traffic. However, no important differences were found.

Earlier findings (Brüde and Larsson, 2000) suggested a weaker result for two-lane roundabouts compared to single-lanes. Our study reveals a similar tendency, but the results must be qualified as only indicative since they are insufficiently significant.

Roundabouts replacing signal-controlled intersections tend to score somewhat weaker than roundabouts replacing other types of intersections. A meta-analysis by Elvik (2003) revealed that the general favourable effect of roundabouts - although for all road users, not only for bicyclists - was greater on intersections previously controlled by yield signs than on signal-controlled intersections. In the present case, the same order of effect can be seen: also for crashes with bicyclists roundabouts replacing traffic signals perform worse compared to roundabouts on other types of intersections.

Two-lane roundabouts perform worse than single –lanes. However, a limitation of this study is the absence of information about other, not included, variables that could be relevant. Possible relevant variables are vehicle speeds, radius of the central island, road width on the roundabout and on the entry/exiting lanes, entry/exit radii. Some of these variables might even correlate with variables in our models and therefore provide alternative explanations for the stated effects. For example, speeds on two-lane roundabouts might be higher and could therefore provide an alternative explanation for the effect of the TWOLANE-variable in our model.

In practice it appears that lack of available space or budgetary constrictions often put a limit on the possibility to construct more space-consuming cycle facilities, particularly on locations inside built-up area, where more cyclists are present. This last argument may also provide an explanation for the tendency of a worse effect on locations inside built-up area (variable INSIDE) that is found in the present study.

Some other variables and interaction terms were not significant in any of the models. Worth mentioning among these are the colour of the cycle facility (possibly relevant in the case of cycle lanes, cycle paths and to a lesser extent at grade-separated roundabouts) and the interaction terms CYCLLANE*BARR and CYCLLANE*LINE that are describing the nature of the separation between roadway and cycle lane within the group of the cycle lane roundabouts. However, also here the scarcity of the data might decrease the power of the study to find out some differences in safety performance. Generally little is known concerning the effects of line markings and physical elements between roadway and cycle lane. Schoon and van Minnen (1993) found a slightly lower number of crashes at cycle lane-roundabouts with small humps between the roadway and the cycle lane.

The effects of some other variables have been investigated in different studies. Hels and Orozova-Bekkevold (2007) found a significant positive relationship between the drive curve as a proxy for potential vehicle speeds and the number of bicyclist crashes. A similar effect was reported by Layfield and Maycock (1986). Brüde and Larsson (2000) found a central island radius for single-lane roundabouts of more than 10 meter most beneficial for reducing bicycle crashes.

After regarding some effects of roundabouts on bicyclist safety and considering some influential variables, one might question what causes the weaker score of roundabouts for bicyclists. A dominant type of crashes with bicyclists at roundabouts is the one with a circulating bicyclist that collides with an exiting or entering motor vehicle (CETUR, 1992; Layfield and Maycock, 1986). Hels & Orozova-Bekkevold (2007) found that a large part of the crashes were vehicle-failed-to-give-way crashes. They suggest a possible major role of what has been called ‘looked-but-failed-to see’ crashes. Other concepts might be helpful to explain some parts of the effects, such as the ‘law of rare events’ (Elvik, 2006), stating that relatively rare events (like motorists – bicyclists encounters at roundabouts can considered to be) are more likely to increase crash rates. Further research in this area is recommended as a better knowledge of causal mechanisms is likely to facilitate adequate countermeasures.

5.6. CONCLUSIONS

The main conclusions of this chapter can be summarized in four points:

1. The data for the study sample suggest that the construction of a roundabout generally increases the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities.
2. Roundabouts with cycle lanes perform obviously worse compared to the three other design types (mixed traffic, separate cycle paths and grade-separated cycle paths).
3. Two-lane roundabouts and roundabouts inside built-up areas perform worse than single-lane roundabouts and roundabouts outside built-up area. There exists some tendency for roundabout replacing signal-controlled intersections to perform also worse, but this effect is highly unsure. Some alternative explanations for the influence of these variables may exist.
4. Further research, preferably based on larger samples and applied in different settings, such as in other countries and under other traffic conditions is needed in order to assess the validity of the results in general. Further research is also needed in order to reveal possible causal mechanisms for crashes with bicyclists at roundabouts.

Chapter 6. Explaining variation in safety performance of roundabouts

Before- and after-studies like they were discussed in Chapter 4 and in Chapter 5 provide a convenient way to calculate effects of certain measures. However, the calculations showed considerable differences in safety performance of particular roundabouts or particular groups of roundabouts. It is therefore interesting to know which factors might explain the differences between roundabouts. An attempt to do this is presented in the current chapter by fitting cross-sectional risk models on the available data. The presented results in this chapter are published in Daniels et al. (2010).

The remainder of the chapter is organized as follows. The next sections describe the data that were collected and the way it was done. Subsequently the analysis method is explained and the results are provided. Finally the results are discussed and conclusions are drawn.

6.1. INTRODUCTION

Roundabouts have become an accustomed type of intersection design in many countries, although they are not yet applied to the same extent everywhere. The number of roundabouts seems to increase steadily in countries and regions where they are already common while they are gaining popularity in regions where they were not applied in the past (Brilon & Vandehey, 1998; Brown, 1995; Pellecuer & St-Jacques, 2008; Rodegerdts et al., 2007; Thai Van & Balmefrezol, 2000). In a number of circumstances, roundabouts are assumed to be more beneficial than other intersection types, both in terms of traffic operations and traffic safety (Bird, 2001; Ogden, 1996; PIARC, 2003).

With respect to traffic safety, the conversion of an intersection into a roundabout has been proven to reduce the number of crashes with injuries or fatalities (De Brabander, 2005; R. Elvik, 2003; Persaud, Retting, Garder, & Lord, 2001). However, research has also shown that effects for particular user groups, such as bicyclists, are less favourable or even unfavourable (Daniels et al., 2009; Daniels et al., 2008; Schoon & van Minnen, 1993).

Those general effects have typically been established by observational before- and after-studies and meta-analyses on the resulting estimates. Nevertheless, before- and after-studies frequently showed considerable differences in safety performance of particular roundabouts or particular groups of roundabouts. Obviously, chance factors might explain a part of the heterogeneity in the results. Crashes are rare events and from an analytical point of view, the number of crashes on the disaggregate level of particular locations is low and easily affected by pure chance elements. However, heterogeneity in the safety performance of intersections such as roundabouts might also be explained, at least partly, by some structural differences between locations. Several authors have suggested structural differences in roundabout safety performance according to exposure elements (traffic volume), but also according to some geometric features of roundabouts. Examples of explanatory models for crash counts at roundabouts are described in Brüde & Larsson (2000), Kennedy (2007) and Rodegerdts et al. (2007).

Some other authors attempted to fit models for particular user groups. Most of these models were related to bicyclists, probably since a weaker safety record for bicyclists at roundabouts has often been suggested (Brüde & Larsson, 1996, 2000; Hels & Orozova-Bekkevold, 2007; Layfield & Maycock, 1986; Turner, Roozenburg, & Francis, 2006).

The common purpose of all those attempts was to reveal some structural relationships between particular design or traffic characteristics on the one hand and the level of safety of roundabouts on the other hand. In most models, the investigated parameters were traffic volume and some geometric data, such as number of lanes, curvature, number of legs and the central island size. Generally, clear relationships were found between traffic volume (AADT) and crash frequencies. However, within the group of geometric data, few variables showed a more or less structural relationship with the crash frequency.

Three reasons justify a renewed attempt to investigate explaining factors for safety at roundabouts. Firstly, the amount of research in this domain is all in all rather limited. Secondly, design guidelines for roundabouts differ from one country to another, which makes that research results from one country are not necessarily valid for another country and still some efforts are needed to gradually establish better universal knowledge on this topic. Thirdly, design guidelines have evolved over time and the newest roundabouts can be supposed to be designed according to more recent guidelines. Since design guidelines should have benefited from research results that have been found during the past decades, the design of modern roundabouts should therefore reflect improved insights in some elements that affect safety performance.

Consequently, explaining factors for the crashes at roundabouts could have evolved over time as well.

The influence of design elements on safety is typically investigated by the fitting of cross-sectional risk models, i.e. models in which the variation in safety performance of a study sample is explained through the use of regression modelling techniques, nowadays most often Poisson regression and negative binomial regression.

The main purpose in the present chapter is to explain the variance in safety performance of roundabouts through the use of state-of-the-art cross-sectional risk models based on crash data, traffic data and geometric data of a sample of 90 roundabouts in Flanders-Belgium. The main target is to investigate which variables might explain a structural part of the variation in crash rates at roundabouts and to which extent the stated effects would correspond with earlier research results elsewhere. Moreover, an attempt is also made to add some variables that were not or not always included in prior analyses and that potentially could influence the safety level of roundabouts. In particular, this last element refers to some design characteristics of cycle facilities that are commonly used in a few European countries.

6.2. DATA COLLECTION

90 roundabouts on regional roads in Flanders-Belgium were selected through a stratified random sample procedure (three or four roundabouts for each of the 28 administrative road districts) out of a database of the Roads and Traffic Agency. The included roundabouts were the same as in Chapter 5, but important extra information was added to the database. For the purpose of the present part, each roundabout in the sample was visited and photographed, traffic counts were executed and additional geometric data were collected on the spot. Information on the construction year of the roundabout was available from the database. All investigated roundabouts were constructed between 1994 and 2000.

Collected data were a number of variables, expressed as dummies and describing some particular features of the roundabouts: a raised central island, a traversable truck apron (with, if present, the width of the apron), an oval shape of the central island, a gated roadway through the central island to accommodate oversized trucks, a bypass for right-turning traffic in one or more directions, and whether the roundabout was located inside or outside built-up area. Geometric data consisted also of the number of lanes on the roundabout, the road width, the central island diameter, the inscribed circle diameter (distance across the circle inscribed by the outer edge of the circulatory roadway) and the number of legs.

Furthermore some variables were collected in order to describe the present facilities for bicyclists and pedestrians. Four types of cycle facilities were distinguished: roundabouts with mixed traffic (motor vehicles and bicyclists use the same roadway), cycle lanes (lanes reserved for bicyclists close to the roadway), cycle paths (dedicated paths for bicyclists on a distance of more than one meter from the roadway) and grade-separated roundabouts (with tunnels for bicyclists). The reader is referred to Chapter 2 for a detailed description of the different types of cycle facilities and some illustrations. For each roundabout the type of cycle facilities was recorded as well as the presence of line markings or small barriers between the roundabout and the cycle facility (in case of cycle lanes), the priority rules for bicyclists when crossing the exit/entry lanes (in case of separate cycle paths) and the pavement colour. Moreover, the width of the cycle facility – when present - was measured as well as its distance from the roadway. Finally, pedestrian facilities like the presence of a sidewalk around the roundabout, the presence of a zebra marking on the entry or exit lanes and – when present - the distance between the zebra marking and the outer edge of the circulatory roadway were measured. The collected variables are listed in Table 29 .

No particular data were collected that enabled to determine the actual speeds at the roundabouts. Worth mentioning is that roundabouts in Flanders are generally constructed with perpendicular approaches in combination with central islands that are large enough to impose considerable lateral movements (deflections) on entering vehicles. Consequently, speeds of any types of vehicles at roundabouts are reduced considerably.

Traffic data were collected as follows: at each examined roundabout all entering traffic was counted by one or two observers during one hour by day (between 8:00 and 18:00). Traffic modes were classified in light vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Light vehicles comprised mainly private cars, but also minibuses and all kind of vans. Heavy vehicles were trucks, trailers, busses and tractors. A particular reason for the distinction between motorcycles and mopeds is their different driving path through a roundabout. Mopeds are often allowed to use cycle facilities when these are present, while this is not the case for motorcycles. Furthermore, the engine power of mopeds is legally limited in such a way that no speeds higher than 45 km/h can be reached on horizontal roads. Calibration counts were held on two roundabouts during one day (08:00-18:00).

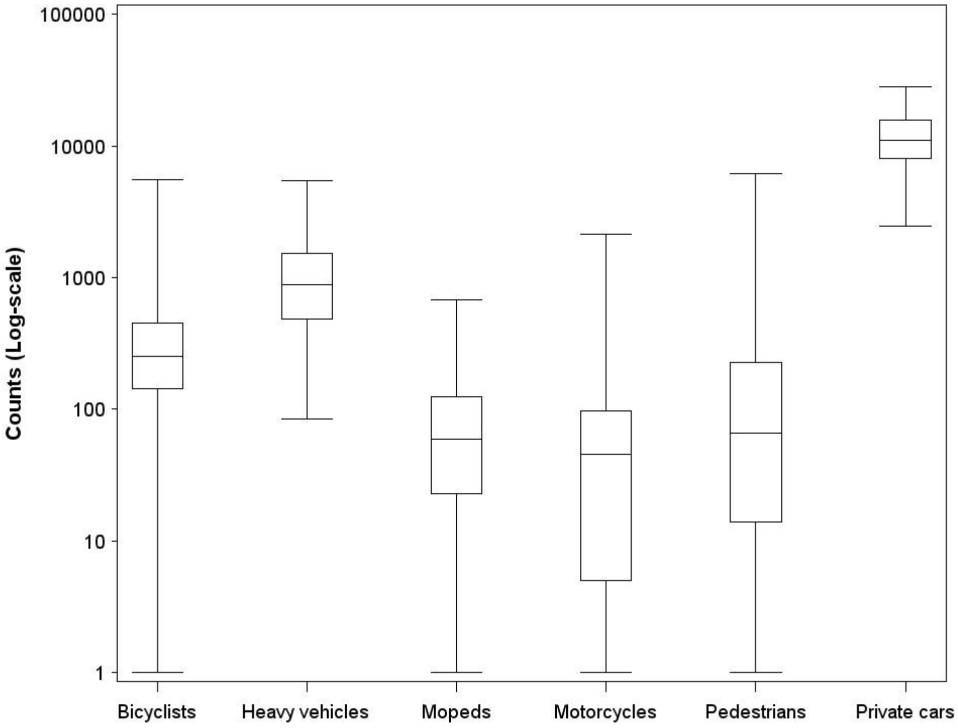

Figure 14 Box plot of average daytime traffic volume counts on the examined roundabouts

Table 29 Explanatory variable description

Variable (ABBREVIATION)	Nr. of observations	Descriptive statistics
Annual average number of injury crashes on the roundabout	90	Mean: 1.37; VAR: 1.39; Min: 0; Max: 5.89
Annual average number of crashes with private cars on the roundabout	90	Mean: 1.14; VAR: 1.05; Min: 0; Max: 5.67
Annual average number of crashes with bicyclists	90	Mean: 0.42; VAR: 0.21; Min: 0; Max: 2.22
Annual average number of crashes with moped riders on the roundabout	90	Mean: 0.29; VAR: 0.19; Min: 0; Max: 3.22
Annual average number of crashes with bicyclists or moped riders on the roundabout	90	Mean: 0.68; VAR: 0.60; Min: 0; Max: 4.89
Annual average number of crashes with heavy vehicles on the roundabout	90	Mean: 0.10; VAR: 0.02; Min: 0; Max: 0.56
Annual average number of crashes with motorcycles on the roundabout	90	Mean: 0.08; VAR: 0.02; Min: 0; Max: 0.44
Annual average number of crashes with pedestrians on the roundabout	90	Mean: 0.07; VAR: 0.02; Min: 0; Max: 0.56
Annual average number of single-vehicle crashes	90	Mean: 0.28; VAR: 0.13; Min: 0; Max: 2.25
Annual average number of multiple-vehicle crashes	90	Mean: 1.09; VAR: 1.06; Min: 0; Max: 5.22
Inside built-up area? (INSIDE) (1 = Yes; 0 = No, thus outside)	90	Yes: 39; No: 51
Central island min. 0.5 m raised? (ELEV) (1 = Yes; 0 = No)	90	Yes: 70; No: 20
Traversable truck apron present? (APRON) (1 = Yes; 0 = No)	90	Yes: 83; No: 7
Apron width (in meters) (APRONWIDTH)	83	Mean: 1.85; S.D.: 0.55; Min: 0.9; Max: 3.8
Central island diameter (in meters) (CENTRDIAM)	90	Mean: 25.29; S.D.: 12.72; Min: 8.00; Max: 96.75
Inscribed circle diameter (in meters) (OUTDIAM)	90	Mean: 40.46; S.D.: 13.52; Min: 22.50; Max: 111.50

Variable (ABBREVIATION)	Nr. of obser-vations	Descriptive statistics
Number of legs (3LEG, 4LEG, 56LEG) (1 = Yes; 0 = No)	90	3-leg: 20; 4-leg: 60; 5-or 6-leg: 10
Gated roadway through the central island? (EXCEPT) (1 = Yes; 0 = No)	90	Yes: 4; No: 86
Bypass present in some directions? (BYPASS) (1 = Yes; 0 = No)	90	Yes: 15; No: 75
Oval roundabout? (OVAL) (1 = Yes; 0 = No)	90	Yes: 4; No: 86
Two-lane roundabout? (TWOLANE) (1 = Yes; 0 = No, thus single-lane)	90	Yes: 7; No: 83
Road width on the roundabout (all lanes together, in meters) (ROADWIDTH)	90	Mean: 6.46 ; S.D.: 1.10; Min: 4.80; Max: 10.00 (single-lanes) Mean: 8.21 ; S.D.: 0.80; Min: 7.30; Max: 9.85 (two-lanes)
Construction year of the roundabout (YEAR)	90	Median: 1996; range [1994;2000]
Traffic signals present before roundabout construction? (SIGNALS) (1 = Yes; 0 = No)	90	Yes: 21; No: 69
Mixed Traffic? (MIXED) (1 = Yes; 0 = No)	90	Yes: 9; No: 81
Cycle lanes? (CYCLLANE) (1 = Yes; 0 = No)	90	Yes: 40; No: 50
Cycle paths? (CYCLPATH) (1 = Yes; 0 = No)	90	Yes: 38; No: 52
Grade-separated? (GRADESEP) (1 = Yes; 0 = No)	90	Yes: 3; No: 87
Cycle lane width (in meters) (CYLANEWIDTH) (only in case of cycle lanes)	40	Mean: 1.73; S.D.: 0.28; Min: 1.20; Max: 2.60
Cycle path width (in meters) (CYPATHWIDTH) (only in case of cycle paths)	38	Mean: 1.86; S.D.: 0.38; Min: 1.05; Max: 2.60
Priority for cyclists when crossing entry/exit lanes? (PRIOR) (only in case of cycle paths) (1 = Yes; 0 = No)	38	Yes: 18; No: 20
Distance between roundabout roadway and cycle path (in meters) (DISTROADCYCLSEGM) (only in case of cycle paths)	38	Mean: 2.91; S.D.: 2.61; Min: 0.60; Max: 15.00

Variable (ABBREVIATION)	Nr. of obser-vations	Descriptive statistics
Distance between roadway and cycle path at crossings (in meters) (DISTROADCYCLCROSS) (only in case of cycle paths)	38	Mean: 5.68; S.D.: 7.65; Min: 1.10; Max: 50.00
Cycle facility coloured red? (RED) (not applicable in case of mixed traffic) (1 = Yes; 0 = No)	81	Yes: 74; No: 7
Pavement of cycle facility different from roadway? (PAVEMENT) (not applicable in case of mixed traffic) (1 = Yes; 0 = No)	81	Yes: 28; No: 53
Interrupted line marking present between roadway and cycle lane? (only in case of cycle lanes) (MARKING) (1 = Yes; 0 = No)	40	Yes: 37; No: 3
Physical elements between roadway and cycle lane? (only in case of cycle lanes) (PHYS) (1 = Yes; 0 = No)	40	Yes: 17; No: 23
Width of physical elements (in meters) (only if CYCLLANE=1 and PHYS =1) (PHYSWIDTH)	17	Mean: 0.63; S.D.: 0.35; Min: 0.20; Max: 1.40
Sidewalk present around the roundabout? (SIDEWALK) (1 = Yes; 0 = No)	90	Yes: 55; No: 35
Zebra markings present on exit/entry lanes? (ZEBRA) (1 = Yes; 0 = No)	90	Yes: 57; No: 33
Distance between roadway and zebramarkings (in meters) (ZEBRADIST)	57	Mean: 6.67; S.D.: 8.65; Min: 0.50; Max: 67.00
Nr. of entering motor-vehicles 8:00-18:00 (ADT) (corrected for yearly ADT-evolution)	90	Mean: 13416; S.D.: 6266; Min: 2549; Max: 32173
Nr. of pedestrians 8:00-18:00 (PED)	90	Mean: 292; S.D.: 765; Min: 0; 6205
Nr. of bicyclists 8:00-18:00 (BIC)	90	Mean: 526; S.D.: 842; Min: 0; Max: 5598
Nr. of mopeds 8:00-18:00 (MOP)	90	Mean: 100; S.D.: 128; Min: 0; Max: 680
Nr. of motorcycles 8:00-18:00 (MCY)	90	Mean: 129; S.D.: 326; Min: 0; Max: 2161
Nr. of light vehicles 8:00-18:00 (LGT)	90	Mean: 12139; S.D.: 5765; Min: 2472; 28227
Nr. of heavy vehicles 8:00-18:00 (HVY)	90	Mean: 1176; S.D.: 979; Min: 84; Max: 5498

The results of the calibration counts were used to calculate adjustment factors that brought all the hourly traffic counts to a common 10 hour (08:00-18:00) level. Subsequently, the counts for private cars, heavy vehicles and motorcycles were added up in order to estimate a value for the Average Daily Traffic (ADT), representing the motorised, fast traffic. This approach enabled to obtain a useful classification of the sample of roundabouts according to their traffic volume, although this approach has obviously its limitations, see the discussion part. As a result, traffic volume data were available for six different traffic modes. Figure 14 shows box-plots of the frequency of different traffic modes and the variability of the observed values.

The traffic counts were done during spring 2008 whereas the crash data for the examined roundabouts were spread over the period from the year after the construction year of the roundabout up to and including 2004, the last year of available data. In order to match the periods of the crash counts with the periods of the traffic counts another calibration procedure was followed. Firstly, the 'average roundabout year' was calculated per individual roundabout by considering the, rounded off, median year of available crash data per roundabout. For example, the 'average roundabout year' of a roundabout constructed in 1999 was 2002 (median of 2000 till 2004). Subsequently the calculated ADT per roundabout was divided by the mean evolution index of traffic on comparable roads in Flanders (AWV, 2008) for the period from the 'average roundabout year' till 2007 (2007 representing the volumes that match best with the traffic counts held during Spring 2008). Since similar time series data were only available for aggregate ADT-values and not for particular traffic modes, the correction was only done for the aggregate values. Consequently, the value ADT10H in Table 29 was corrected for trend evolutions in traffic volume, but the traffic volumes for the particular traffic modes (values BIC, PED, MOP,...) were not.

Data from all registered injury crashes (Statistics Belgium) were available for the investigated period. The ministry of Mobility and Public Works routinely geo-codes (i.e. assigns spatial XY-coordinates) all crash data since 1996. The 90 roundabout locations were localised and geo-coded by the researchers through the use of Google Earth. Subsequently the roundabout data were linked in a GIS-system (ArcMap) with the geo-referenced crash data for the period 1996-2004. All crashes within a distance of 100 meters of the centre of the roundabout were included in the dataset. After subtraction of the crashes that occurred before the roundabouts were constructed, the dataset consisted of 932 injury crashes. Annex 2 provides an example of the linking procedure of the crash data and the location data.

Table 30 shows some frequency statistics of the crash data and the involvement of different types of road users. The crashes were classified according to the same six road user groups as the traffic counts: light vehicles, heavy vehicles, motorcycle, mopeds, bicycles and pedestrians. Light vehicles were involved in 82.9% of all registered injury crashes at the investigated roundabouts. Bicyclists were present in 30% of the crashes and mopeds in 21.5%. No other user group occurred in more than 10% of the crashes. Since usually more than one road user is involved in a crash, the sum of the frequency counts and the percentages in Table 30 exceed the totals in the first row.

In comparison with their average share in traffic on the observed locations moped riders ($\chi^2 = 1962$, $p<0.01$), bicyclists ($\chi^2 = 1220$, $p<0.01$), motorcyclists ($\chi^2 = 206$, $p<0.01$) and pedestrians ($\chi^2 = 29$, $p<0.01$) were more frequently involved in crashes. Light ($\chi^2 = 1.67$, ns) and heavy vehicles ($\chi^2 = 0.54$, ns) were less frequently involved, but these differences are not significant.

Table 30 Frequency statistics of crashes in the roundabout dataset according to type of involved road user

	Counts	% of total	Avg/year/ roundbt.	Variance
Injury crashes at the 90 roundabouts	932	100	1.37	1.39
Injury crashes with at least a				
light vehicle	773	82.9	1.14	1.05
bicycle	280	30.0	0.42	0.21
moped	200	21.5	0.29	0.19
bicycle or moped	463	49.7	0.68	0.60
heavy vehicle	70	7.5	0.10	0.02
motorcycle	58	6.2	0.08	0.02
pedestrian	44	4.7	0.07	0.02

Table 31 Frequency statistics of crashes in the roundabout dataset according to crash type

	Counts[1]	% of total	Avg/year/ roundbt.	Variance
Single-vehicle crashes	189	20.3	0.27	0.13
Multiple-vehicle crashes	737	79.1	1.09	1.06

[1] For 6 crashes the type is unknown

Since they can be believed to show different patterns, information was also sought for single-vehicle crashes and multiple-vehicle crashes separately. About eight in ten crashes at the roundabouts were multiple-vehicle crashes (Table 31). Table 32 shows the frequencies of single-vehicle crashes for each road user type and compares the shares of the different traffic modes in the crash counts with their share in traffic. The two most important single-vehicle crash types were those with light vehicles and motorcycles. A small p-value for the chi-square test of homogeneity of the two populations indicates strong evidence of heterogeneity: mopeds, bicycles and motorcycles were more frequently involved in single-vehicle crashes than expected on the basis of their traffic share, whereas light vehicles were involved less. The odds-ratios are provided as well in order to get more information about the strength of the association, showing that mainly motorcyclists (OR 19.2) and moped riders (OR 13.2) are overrepresented in single-vehicle crashes.

The collision matrix for multiple-vehicle crashes is shown in Table 33 . Light vehicles are involved in more than eight in ten (656 on 737) multiple-vehicle crashes. In 60% of the multiple vehicle crashes either a bicyclist or a moped rider was involved. The three dominant collision types were those between light vehicles mutually, light vehicles against bicyclists and light vehicles against mopeds. No other collision type is found in more than 5% of the multiple-vehicle crashes. The chi-square tests and odds-ratios show that mainly mopeds (OR 47.1) and bicyclists (OR 14.5) are overrepresented in multiple-vehicle crashes.

Table 32 Frequency of single-vehicle crashes per user group

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Other/ unknown	TOTAL
Single-vehicle crashes	118	10	28	16	16	1	189
%	62.4	5.3	14.8	8.5	8.5	0.5	100
Traffic volume	12139	1176	129	100	526	292	14362
Share in roundabout traffic (in %)	84.5	8.2	0.9	0.7	3.7	2	100
OR[1] (p-value[2])	0.3 (<0.01)	0.6 (0.15)	19.2 (<0.01)	13.2 (<0.01)	2.4 (<0.01)	0.3 (0.14)	

[1] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 single-vehicle crashes for the road user type divided by single-vehicle crashes of all the other road users and Ω_2 volume of road users at the roundabouts divided by volume of all the other road users

[2] p-value of the chi-square test with null hypothesis H_0: proportion of single-vehicle crashes per road user type homogeneous with share in roundabout traffic. H_0 rejected if $p<0.05$

Table 33 Collision matrix for multiple-vehicle crashes (N= 737)

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Pedestrian	Other/ unknown	Σ
Light vehicle	217	24	21	143	207	23	16	651
Heavy vehicle	24	2	2	10	19	3	1	61
Motorcycle	21	2	0	2	2	0	0	27
Moped	143	10	2	3	17	6	2	183
Bicycle	207	19	2	17	8	7	2	262
Pedestrian	23	3	0	6	7	0	0	39
Other/ unknown	16	1	0	2	2	0	0	21
Σ	651	61	27	183	262	39	21	
% of crashes	88.3	8.3	3.7	24.8	35.5	5.3	2.8	100
Traffic volume per day	12139	1176	129	100	526	292		14362
Share in roundabout traffic (in %)	84.5	8.2	0.9	0.7	3.7	2		100
OR[1] (p-value[2])	1.4 (0.01)	1.0 (0.93)	4.2 (<0.01)	47.1 (<0.01)	14.5 (<0.01)	2.7 (<0.01)		

[1] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 single-vehicle crashes for the road user type divided by single-vehicle crashes of all the other road users and Ω_2 volume of road users at the roundabouts divided by volume of all the other road users

[2] p-value of the chi-square test with null hypothesis H_0: proportion of single-vehicle crashes per road user type homogeneous with share in roundabout traffic. H_0 rejected if $p<0.05$

6.3. METHODOLOGY

Regression models were fitted using the available geometric and traffic variables. The dependent variable was the average annual number of crashes per roundabout (N=90). Crash data have in the last decade most often been modelled by Poisson or negative binomial regression models. Much literature dealt with the phenomenon of overdispersion that is often found in crash data. Generally it is concluded that negative binomial modelling should be preferred above Poisson-modelling when the data are overdispersed, i.e. when the variance is significantly larger than the mean (S. Washington, Karlaftis, & Mannering, 2003). In our dataset however, no overdispersion in the data seemed to be present. On the contrary, the variance of the average annual number of crashes turned out to be more or less equal to the mean, at least when all crashes were considered (see Table 30). However, mainly when subgroups of crashes were considered, the data appeared even to be underdispersed.

In a first step Poisson loglinear models were fit to explain crash rates at roundabouts. All exposure variables were transformed to their natural logarithm. Some models were also fit without transforming the exposure variables, but the transformed data delivered a better fit. The relative shares of the different traffic modes (percentage of motorcycles, pedestrians,...) were initially considered as explanatory variables as well, but they were omitted later since they turned out to correlate often strongly with the absolute exposure values and to yield no improvements in the models.

As a result, the functional form of the chosen models was the following:

$$E(\lambda) = e^{\alpha}.Q_1{}^{\beta_1}.Q_2{}^{\beta_2}.e^{\sum_{i=1}^{n}\gamma_i.x_i} \qquad \text{(Eq. 6-1)}$$

with E(λ) = expected annual number of crashes

Q_1 = ADT (motor vehicles)

Q_2 = traffic volume for particular vehicle types (bicyclists, mopeds,...)

x_i = other explanatory variables

α, β_1, β_2, γ_i = model parameters

Since underdispersion was found in the crash data, some additional models were fit by using gamma probability models like proposed earlier by Oh et al. (2006).

Gamma models allow for variances that are not constant or equal to the mean, but rather proportional to the square of the mean (Myers et al., 2002). Gamma probability models allow for both overdispersion and underdispersion in the data.

The gamma model makes use of the gamma probability distribution (Agresti, 2002) that for a given λ

$$f(\lambda; \varphi; \mu) = \frac{(\varphi/\mu)^{\varphi} . e^{(-\varphi.\lambda/\mu)} . \lambda^{\varphi-1}}{\Gamma(\varphi)}; \lambda \geq 0 \qquad \text{(Eq. 6-2)}$$

with $E(\lambda) = \mu$ and $VAR(\lambda) = \frac{\mu^2}{\varphi}$

φ is the dispersion parameter. Underdispersion exists if $\varphi > 1$, overdispersion if $\varphi < 1$, equidispersion if $\varphi = 1$

All models were fitted by using the GENMOD-procedure in SAS and made use of the log link function. The following modelling procedure was followed: initially, all possible explanatory variables were included in the models. Next, variables were removed step by step according to the following criteria:

- Inspection of the correlation matrix. In case of strong correlation ($\rho \geq 0.6$) one of the two correlating variables was eliminated, in principle the variable with the smallest individual significance and under the condition that the model fit did not deteriorate significantly. If the remaining variable was eliminated in a further step in the modelling process, the correlating variable was re-introduced in the model and subsequently checked for its significance. In case of strong correlations between geometric variables and exposure variables the last ones were kept in the models since there are well established grounds (e.g. Fridstrøm et al., 1995; Greibe, 2003) to consider them as important predictors .
- Non – significant variables, each time with a more severe criterion.
- Goodness of fit of the models was evaluated by the Akaike Information Criterion (AIC). The best fitting model was the model with the lowest value for the AIC.

The list of available explanatory variables consisted of 40 possible covariates. Interaction terms were constructed in order to model variables that were only relevant in specific cases, e.g. the variable PHYS (physical elements between roadway and cycle facility) that was only recorded in case of a cycle lane roundabout (CYCLLANE=1).

The variable YEAR (construction year of the roundabout) was initially modelled as a categorical variable, delivering individual parameter estimates for all but one years (compared with the reference year). Since it appeared that in most models the relationship between the annual average of crashes and the construction year showed a more or less linear shape, the variable YEAR was scaled into a series with the first year (1994) =1, the second year = 2 etc. and subsequently included in the models as a continuous variable. This enabled a single parameter estimate for the variable YEAR which did in practice not affect the model fits and which enabled a more straightforward interpretation of the results.

Furthermore, models were checked on their stability and the comprehensibility of the estimated effects. Variables were assessed in terms of their correlations with some other candidate variables and in terms of their theoretical appeal (Maher & Summersgill, 1996).

6.4. RESULTS

The results are provided in Table 34 and Table 35 . The results for the Poisson models and the gamma models are both provided. The model for all crashes shows two significant exposure variables: ADT and bicyclist volume. Furthermore the presence of a cycle lane affects the number of crashes positively. The variables SIGNALS (roundabouts replacing signal-controlled intersections) and 3LEG (roundabouts with three legs) are significant at the 9%-level in the gamma model, but do not occur in the Poisson model. The coefficient for the exposure variables is less than one in the Poisson model, suggesting an increase with higher traffic volumes at a decreasing rate. However, the gamma model shows a different result with an estimate for β_1 above 1. The parameter estimates for the bicyclist volumes are similar for the Poisson models and the gamma models.

Specific models were fit for crashes with particular road users: bicycles, mopeds, motorcycles, heavy vehicles, light vehicles and pedestrians. The models for crashes with light vehicles are very similar to the models for all crashes, which was not unexpected due to the dominancy of crashes with private cars in the entire dataset. Crashes with bicyclists are explained by the ADT and the volume of bicyclists, both in the Poisson and gamma models. Two additional variables turned out to be significant in the gamma models, LN(MOP) and CYCLLANE, both with positive parameter estimates. The number of crashes with mopeds is, apart from the exposure variables, dependent from the construction year of the roundabout. The parameter sign is negative, meaning that fewer crashes with mopeds seem to occur at more recently constructed roundabouts. Higher numbers of crashes with mopeds seem to occur at 3-leg roundabouts. Roundabouts that replaced signal-controlled intersections (SIGNALS) correlate with a higher number of crashes for different road user types, although not always consistently for the Poisson and the gamma models, and not always strongly significant.

A number of similarities relating to vehicle dimensions, speed properties, use of cycle facilities and position on the road can be assumed to exist between bicyclists and moped riders. An extra model was therefore fitted for all crashes where at least one bicyclist or moped rider was involved. Besides the two exposure variables (ADT and BICMOP, the joint volume of bicycles and mopeds), three geometric variables appeared to be relevant in this model: the presence of a cycle path (with a negative parameter sign), SIGNALS (only in the Poisson model) and 3LEG.

The best fitting models for both the crashes with motorcycles and with heavy vehicles were ADT-only models. In the Poisson model for crashes with pedestrians no variable was significant at the 5%-level. In the gamma model the variables CYCLLANE, SIGNALS, 3LEG (with, on the contrary of some other models, a negative parameter) and INSIDE (roundabout inside built-up area) were significant.

Furthermore separate models were fit for single-vehicle crashes and for multiple-vehicle crashes. The results are provided in 0. The number of single-vehicle crashes turns out to be explained by the ADT, by the presence of a pass-through for exceptional transport (EXCEPT) and in cases of oval roundabouts (OVAL), the latter two only in the gamma model. Multiple-vehicle crashes are affected by the ADT, by the presence of two-wheelers (bicyclists in the gamma model, bicyclists and mopeds together in the Poisson model) and furthermore by the variables CYCLPATH (Poisson model) / CYCLLANE (gamma model), 3LEG and, only in the Poisson model, SIGNALS.

Table 34 Parameter estimates for Poisson and gamma-models with particular road users

Variables[1]	All crashes	Crashes with light vehicles	Crashes with bicyclists	Crashes with mopeds	Crashes with mopeds or bicyclists	Crashes with motor-cycles	Crashes with heavy vehicles	Crashes with pedestrians
Intercept	-9.20 (<0.01) *-11.68 (<0.01)*	-9.41 (<0.01) *-11.72 (<0.01)*	-10.06 (<0.01) *-14.85 (<0.01)*	-9.15 (0.06) *-15.35 (<0.01)*	-9.53 (<0.01) *-13.84 (<0.01)*	-15.68 (0.06) *-25.70 (<0.01)*	-14.05 (0.06) *-15.55 (<0.01)*	-22.68 (0.04) *-31.07 (<0.01)*
LN(ADT)	0.89 (<0.01) *1.16 (<0.01)*	0.88 (<0.01) *1.13 (<0.01)*	0.78 (0.03) *1.19 (<0.01)*	0.73 (0.16) *1.38 (<0.01)*	0.74 (0.02) *1.20 (<0.01)*	1.38 (0.11) *2.44 (<0.01)*	1.23 (0.11) *1.39 (<0.01)*	1.99 (0.08) *2.77 (<0.01)*
LN(BIC)	0.14 (0.04) *0.11 (0.03)*	0.15 (0.05) *0.13 (0.02)*	0.27 (0.04) *0.24 (0.05)*					
LN(BICMOP)					0.33 (<0.01) *0.33 (<0.01)*			
LN(MOP)			*0.21 (0.05)*	0.29 (0.07) *0.24 (0.01)*				
LN(PED)								*0.27 (<0.01)*
CYCLPATH					-0.65 (0.02) *-0.65 (0.01)*			
CYCLLANE	0.40 (0.03) *0.38 (0.02)*	0.40 (0.04) *0.38 (0.02)*	*0.58 (0.05)*					*1.57 (<0.01)*
SIGNALS	*0.35 (0.09)*	0.40 (0.10) *0.37 (0.08)*		0.94 (0.07)	0.63 (0.05)			
YEAR				-0.23 (0.05) *-0.19 (0.02)*				
3 LEGS	*0.32 (0.09)*	*0.33 (0.09)*		0.90 (0.07) *1.06 (0.01)*	0.63 (0.05) *0.62 (0.05)*			*-1.28 (0.01)*
INSIDE								1.71 (0.07)
AIC	228.36 *198.10*	211.28 *167.63*	129.91 *-42.67*	106.42 *-167.52*	166.74 *63.08*	47.86 *-496.63*	53.61 *-448.91*	41.15 *-590.48*
Dispersion parameter[2] (φ)	*0.52*	*0.57*	*1.80*	*2.38*	*1.44*	*3.57*	*3.65*	*3.14*

[1] values in normal typeface are results from the Poisson-models, values in italics are from the gamma models; ( ) p-values; explanatory variables only included if $p \leq 0.10$, except for LN(ADT) that is always included.

[2] for the gamma models. Overdispersion if $\varphi < 1$, underdispersion if $\varphi > 1$, equidispersion if $\varphi = 1$

Table 35 Parameter estimates for Poisson and gamma-models with single/multiple-vehicle crashes

Variables[1]	Multiple-vehicle crashes	Single-vehicle crashes
Intercept	-10.72 (<0.01) *-14.52 (<0.01)*	-8.09 (0.05) *-10.18 (<0.01)*
LN(ADT)	0.98 (<0.01) *1.37 (<0.01)*	0.72 (0.10) *0.93 (<0.01)*
LN(BICMOP)	0.23 (0.01)	
LN (BIC)	*0.19 (0.01)*	
CYCLPATH	-0.42 (0.05)	
CYCLLANE	*0.47 (0.03)*	
3 LEGS	0.48 (0.06) *0.53 (0.03)*	
SIGNALS	0.50 (0.05)	
EXCEPT		*2.78 (0.03)*
OVAL		*-4.44 (<0.01)*
AIC	204.35 *160.24*	106.53 *-123.33*
Dispersion parameter[2] (φ)	*0.90*	*2.09*

[1] values in normal typeface = Poisson-models, values in italics = gamma models; ( ) = p-values; explanatory variables only included if p≤ 0.10

[2] for the gamma models. Overdispersion if φ<1, underdispersion if φ>1, equidispersion if φ=1

For those response variables that showed an overdispersion some negative binomial models were also fit. The results were very similar to the Poisson models and are not presented for reasons of brevity.

The reader should note that some variables show strong correlations which makes that they are to some extent mutually exchangeable. Examples of strongly correlating variables were the duo's CYCLPATH / CYCLLANE and LN(BIC) / LN(BICMOP). In the case of the multiple-vehicle crashes the Poisson model delivered the variable CYCLPATH as an explanatory variable whereas the gamma model delivered a correlating variable, CYCLLANE. Some trials revealed that those variables could be substituted by each other without losing too much of the goodness-of-fit, but it was preferred to present the best fitting models and to comment upon some interpretations hereunder.

6.5. DISCUSSION

6.5.1. Modelling approach

The gamma probability models show better fits than the Poisson models in terms of their AIC-value. The gamma models tend equally to include more variables than the Poisson-models. Theoretically, underdispersion and even equidispersion are not expected in crash data and one might question whether the observed underdispersion is an artefact of the data or reveals a high structural homogeneity of the examined locations. Although the gamma probability models seemed to be able to fit the observed data in this particular dataset better, it was useful as well to fit Poisson models in order to show the effects of different assumptions for the random structure of the data and to avoid a tendency toward overfitting the data. As a conclusion it seems that, the identified relevant variables throughout the different models are rather consistent for both types of regression models. Figure 15 shows the predicted yearly crash numbers for the 90 roundabouts for the three possible model approaches (Poisson, negative binomial and gamma). The used model is each time the model for all crashes, but limited to one explanatory variable (ADT). The figure shows similar results for the three models in the observed range of ADT-values, although it seems as well that the curves of the Poisson and the negative binomial models resemble each other, while the gamma model is yielding higher predictions in case of higher ADT-values and somewhat lower predictions in the lower range of ADT's.

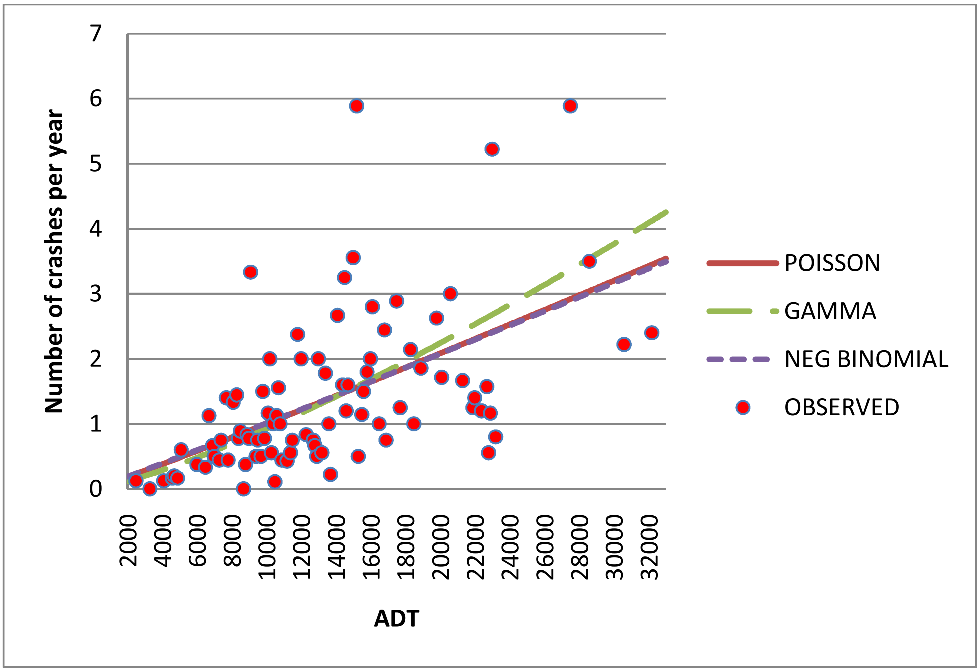

Figure 15 Predicted yearly crash numbers related to ADT (exposure-only model for all crashes)

Attempts were made to deal with multicollinearity which was an expected phenomenon in this dataset. Especially some variables that turned out to be significant predictors for some models were checked on their correlations with other variables in the dataset. For instance the variable SIDEWALK (presence of a footpath alongside the roundabout) turned out to be significant, in particular when no exposure variable for cyclists or moped riders was included. A logistic regression of the odds of SIDEWALK =1 upon a series of explanatory variables showed the variables LN_ADT (-), LN_PEDESTRIANS (+) and ZEBRA (+) to be significant. This raised the question to which degree the presence of a sidewalk was measuring another concept, most likely merely exposure variables like ADT and the presence of pedestrians. It was therefore decided to replace SIDEWALK by an exposure variable in cases when this had only a minor influence on the model fit.

6.5.2. Influencing risk variables

Traffic volume (ADT) was a significant predictor in most of the fitted models. It was only less significant in those models where the number of observations was low such as in the models for pedestrians or heavy vehicles. When traffic volume was poorly significant, no other variables came into the model. Therefore it can be concluded that the ADT was technically by far the most important variable in the models, which corresponds with many earlier findings in traffic safety research.

Less straightforward to interpret is the parameter estimate of the ADT. In most cases of the Poisson-models the estimate is below 1 which suggest a positive, but less than proportional relationship between the ADT and the crash rate. However, all but one of the gamma probability models show parameter estimates above 1 which would suggest that the number of crashes would increase at an increasing rate with an increasing ADT. Existing research seems to show a comparable ambiguity since parameters below as well as above 1 for crashes at roundabouts were found (Brüde & Larsson, 2000; Maycock & Hall, 1984).

Apart from the ADT, the volume of bicyclists and/or mopeds turned out be a significant predictor as well. Surprisingly this is not only true for the specific models for bicyclists or mopeds but also for the crashes with light vehicles (mostly private cars) and the multiple-vehicle crashes. This highlights the important role of encounters between light vehicles on the one hand and bicycles and mopeds on the other hand like it was already shown in the collision matrix in Table 33 .

The parameter estimate of the cyclist/moped volume is consistently below 1 which supports the notion of a 'safety in numbers' effect for crashes with two-wheelers like it was reported elsewhere (Brüde & Larsson, 1993; Jacobsen, 2003; Turner et al., 2006).

Roundabouts with cycle lanes (N=40) are clearly performing worse than roundabouts with cycle paths (N=38). The other two design types, mixed traffic (N=9) and grade-separated (N=3) showed no particular effect but their limited presence in the dataset could be a major explanation. The limited numbers of mixed traffic and grade-separated roundabouts in the sample explains equally the correlation between the two most dominant groups, cycle lanes and cycle paths. This correlation causes some troubles in order to interpret whether roundabouts with cycle lanes are performing worse than the other types, or conversely, whether roundabouts with cycle paths are doing better than the other three types. Although CYCLLANE is more dominantly present in the models, this study stays inconclusive on this matter. More explicit results were found in the before-and-after study of crashes at the same roundabouts (Daniels et al., 2009), where was found that roundabouts with cycle lanes performed worse compared to the three other design types. It should be mentioned that the present data enabled to correct for differences in exposure which excludes one still existing and important possible confounding variable for being responsible for the differences in safety performance of the different cycle facilities. It might therefore be concluded that the present results are confirming the findings in the previous chapter with respect to the role of the different types of cycle facilities, i.e. mainly the elevated risk level at roundabouts with cycle lanes. Together with the findings in the previous chapter, the present results seem to confirm the theses about the doubtfulness of cycle lanes at roundabouts like suggested in previous work (Brilon, 1997; Brüde & Larsson, 1996; van Minnen, 1995).

However, it should be noticed as well that this study, like every observational study, could be affected by some possible confounding elements. The existence of unknown but relevant variables for which variables in the model act as unexpected proxies, could provide an alternative explanation for the relevance of the variables CYCLLANE or CYCLPATH. Since locations are not randomly selected to be converted into a roundabout with cycle lanes or cycle paths, some response-relevant differences might have been present already from the before-situation (Hauer, 2005). In other words, particular reasons might exist why road authorities decide to construct roundabouts with a particular design instead of some alternatives and those reasons are not always well-known. The existing formal guidelines do not give conclusive guidance on this and too little is known about the informal decision rules that might be applied when the conversion of intersections into roundabouts is considered. Future research could reveal more about these implicit criteria. A possible hypothesis is that in a number of cases, cycle lanes are preferred above cycle paths due to lack of available public space and/or due to excessive expropriation costs. But in those cases some other features like smaller roadways, more parking manoeuvres, less optimal entry or exit radii or non-orthogonal roundabout legs could also be structurally more present and be responsible for an unknown part of the found effect.

The variable SIGNALS is significant in different models, what suggests that roundabouts replacing traffic signals perform worse than other roundabouts. Again this result is consistent with the previous chapter where was found that roundabouts that were replacing signal-controlled intersections have had a worse evolution compared with roundabouts on other types of intersections. Elvik (2003) came to the same conclusion based on a meta-analysis of 28 studies. Nevertheless, the interpretation of this variable should still be interpreted cautiously since the variable SIGNALS refers to a previously (before the roundabout construction) existing difference that was not observable anymore in the examined situation after the roundabout construction. One possible explanation might be related to the violation of one of the basic rules of an experimental design, i.e. the randomness of the assignment of study subjects to the treatment or control group. Engineers are not randomly selecting intersections neither to place traffic signals, nor to convert them afterwards to roundabouts. This could mean that there were particular reasons to equip the concerned intersections once with traffic signals and afterwards to convert the signal-controlled intersections into roundabouts. Those particular reasons could be related to traffic safety, but also to other elements, such as smoother traffic operations. Consequently this could mean that the SIGNAL-variable in our dataset acts as a proxy for other, influencing but unknown variables. Traffic volume is included in our models and its influence is therefore accounted for. A remaining candidate relevant, but unknown parameter could be the degree of ‘complexity’ of a certain intersection since it could explain why the number of crashes on some locations is higher than expected on the basis of the ADT. Further research on this topic is recommended.

Worth to mention is the distinct role of three-leg roundabouts (3LEG) that was found in some models, in all but one cases with a positive sign, suggesting that three-leg roundabouts perform worse than roundabouts with four or more legs. This finding corresponds with the finding by Elvik (2003) that converting intersections to roundabouts had a greater decreasing effect on injury crashes in four-leg intersections than in three-leg intersections.

The variables EXCEPT and OVAL occur only in one model. In practice they relate only to very small subgroups of roundabouts since both features are each only present in four cases. Therefore their presence in this model has a considerable likelihood to be influenced by chance elements and is not further discussed.

The variable YEAR (construction year of the roundabout) showed a significant contribution in the models for crashes with moped riders and had a negative sign, suggesting a lower number of crashes, at more recently constructed roundabouts. An important comment should be made here: our models are fitting the average annual number of crashes after the roundabout construction which means that, since the roundabouts were constructed in different years, the annual crash data for each roundabout are not reflecting exactly the same time period. Crash data from more recently constructed roundabouts are thus on average more recent than crash data from older roundabouts. Consequently, an alternative explanation for the negative sign of YEAR in the model for mopeds could also be the existence of a general downward trend in the number of crashes with mopeds at roundabouts and is not necessarily related with a better performance of more recently constructed roundabouts.

Note also that the exposure variable for the volume of pedestrians was not present in the Poisson-model for pedestrian crashes, which might explain why some other, correlating variables like INSIDE were significant in that model. The parameter estimate for the pedestrian volume in the gamma model is below 1, which again corresponds with the "safety in numbers" – thesis for crashes with vulnerable road users. 3LEG had only a negative parameter sign in the model for the crashes with pedestrians.

6.5.3. Variables that were NOT found to be important

Subsequently, it is important to have a look at variables that were not meaningful in any of the presented models, in some cases maybe unexpected. Perhaps the most important among those variables are the ones that describe the roundabout dimensions: inscribed circle diameter, central island diameter, the road width or the number of lanes. Particularly the number of lanes was in previous research reported to be a relevant variable (Brüde & Larsson, 2000), but the present results do not confirm the earlier findings on this point. In Daniels et al. (2009) roundabout with two lanes tended equally to perform worse but since no exposure variable was included, the number of lanes could act there as a proxy for traffic volume.

6.5.4. Study limitations

It is clear that a study based on a relatively small sample of locations in one particular country should not pretend to be valid for all possible roundabout designs wherever applied. Nevertheless, I believe that the results confirm some earlier findings but also shed a new light on some others. In that sense this study should be considered as one in a series of efforts - made and to be made by many in different countries - that should gradually enable to develop consistent theories and guidelines about safety issues at roundabouts.

The registered variables were based partly on those that were used in similar studies and for another part derived from and limited to the practical possibilities to collect information about them. This means as well that information could not be collected about all possible useful variables. Mainly some parameters to reflect actual or potential vehicle speeds at roundabouts were not present in the used dataset and were earlier reported to be important (Hels & Orozova-

Bekkevold, 2007; Layfield & Maycock, 1986; Maycock & Hall, 1984). However, Rodegerdts et al. (2007) found no reliable relationship between speeds and the crash frequency at roundabouts where actual speeds were measured.

Another limitation relates to the traffic counts that were derived from the one hour – measurements at the roundabout locations. Undoubtedly, the inference of ADT-values from one hour-counts brings some extra portion of uncertainty in the results. At least this limitation should be kept in mind when interpreting the parameter estimates for the exposure variables.

A further restriction lies in the poor knowledge of some changes in the roundabout design that may have been made after the initial construction of the roundabout. Although major changes are not common, adaptations at a certain moment after the roundabout construction such as changes in road markings (e.g. to create an extra lane on the roundabout), improved road lighting or signposting are sometimes made. No information on this was available, making that this could not be accounted for. It can be assumed that some of the treatments that were done after the roundabout construction were – intentionally or not – affecting road safety.

6.6. CONCLUSIONS

The main conclusions of this chapter can be summarized as follows:

- Vulnerable road users (mopeds, motorcycles, bicycles, pedestrians) are more often involved in injury crashes at roundabouts then could be expected based on their presence in traffic. Moped riders and motorcyclists are overrepresented in single-vehicle crashes whereas moped riders an bicyclists are overrepresented in multiple-vehicle crashes.

- Variations in crash rates at roundabouts are relatively small and mainly driven by the traffic exposure.

- In the investigated dataset, roundabouts with cycle lanes are clearly performing worse than roundabouts with cycle paths.

- Confirmation is found for the existence of a safety in numbers-effects for bicyclists, moped riders and, more unsure, for pedestrians at roundabouts.

- Some variables turned out to be no meaningful predictors for the number of crashes in the studied sample, in particular the ones that describe the roundabout dimensions: inscribed circle diameter, central island diameter, road width or the number of lanes.

- Due to the nature of a cross-sectional study it cannot be excluded that significant variables in the dataset act as a proxy for other, influencing but unknown variables. This might be particularly be the case for the variables SIGNALS (roundabouts replacing signal-controlled intersections) and 3LEG (roundabouts with three legs). This might even not be excluded for the revealed differences between cycle lanes and cycle paths but is less likely in that case due to the better theoretical appeal of the influence of the design types and due to the consistency of this finding with the results of the previous before-and-after-study.

- Continued research on safety effects of different roundabout types and in different countries is recommended

Chapter 7. Extended crash prediction models for roundabouts

The fitted models in the previous chapter show interesting information, but suffer from some shortcomings as well. One of the major limitations often encountered in crash prediction models is related to the number of locations that can be included. An effort was therefore made to acquire data on an additional set of roundabouts. As a result, a dataset of 148 roundabouts including geometric information, crash data and exposure data became available. Moreover one additional year of crash data could be incorporated. The present chapter presents the results of the cross-section analyses based on this extended dataset. These results were also submitted for publication (Daniels et al., n.d.).

The remainder of the chapter is organized as follows. The next sections describe the data that were collected and the way it was done. Subsequently the analysis method is explained and the results are provided. Finally the results are discussed and conclusions are drawn.

Elements that correspond strongly to the information presented in the previous chapter will only be repeated very briefly in order to put the focus on modified or added elements and to avoid needless repetition. Nevertheless, the provided information in the present chapter should be sufficiently complete to stand on itself and to allow a comprehensive understanding of the performed analyses and the resulting conclusions.

7.1. DATA

The dataset was based on the previously composed dataset of 90 roundabouts (see Chapter 6), that was extended. The dataset consisted of three categories: geometric data, traffic counts and crash data. Extra data for the three categories could be collected for an extra sample of 58 roundabouts. The nature of the available data on geometry and traffic volume was identical to that of the previous dataset. Apart from the extension of the number of objects in the dataset, crash information from one extra year (2005) was included. In the remainder of this chapter I will use the terms ‘existing’ and ‘additional’ data to refer respectively to the previously composed dataset of 90 roundabouts and the additional data on 58 roundabouts. With ‘extended dataset’ I will refer to the full dataset of 148 roundabouts.

Each roundabout in the sample was visited and photographed, traffic counts were executed and geometric data were collected on the spot. Information on the construction year of the roundabout was available from the Roads and Traffic Agency's database. All investigated roundabouts were constructed between 1990 and 2002. The collected variables are listed in Table 36 .

Values for the variable SIGNALS (traffic signals present in the before-situation) were not available for the additional roundabout sample. This variable was therefore excluded for further analysis in this chapter.

Average daily traffic data (08:00-18:00) were estimated for each roundabout based on a traffic count of all entering traffic during one hour. Traffic modes were classified into light vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Light vehicles comprised mainly private cars, but also minibuses and all kinds of vans. Heavy vehicles were trucks, trailers, busses and tractors. The followed procedure was identical to the one that was adopted in the previous chapter.

The 148 roundabout locations were localised and geo-coded in Google Earth. Subsequently the roundabout data were linked in a geographical information system (ESRI ArcMap) with the geo-referenced crash data (available from Statistics Belgium) for the period 1996-2005. All crashes within a distance of 100 meters of the centre of the roundabout were included in the dataset. After subtraction of the crashes that occurred before the roundabouts were constructed, the extended dataset consisted of 1491 injury crashes.

Table 37 shows elementary descriptive statistics of the previously existing versus the extended dataset. The mean (μ) number of crashes dropped from 1.37 to 1.22, while the variance (σ^2) decreased somewhat from 1.39 to 1.33. A comparison between the two columns in this table shows that the addition of one year extra crash data does not explain the differences. A difference seems to exist between both used datasets since on average approximately 25% fewer crashes seem to occur in the group of 58 added roundabouts than in the group of the 90 roundabouts.

Table 36 Explanatory variable description

Variable (ABBREVIATION)	Nr. of observations	Descriptive statistics
Inside the built-up area? (INSIDE) (1 = Yes; 0 = No, thus outside)	148	Yes: 55; No: 93
Central island min. 0.5 m raised? (ELEV) (1 = Yes; 0 = No)	148	Yes: 115; No: 33
Traversable truck apron present? (APRON) (1 = Yes; 0 = No)	148	Yes: 141; No: 7
Central island diameter (in meters) (CENTRDIAM)	148	Mean: 25.22; S.D.: 12.30; Min: 8.00; Max: 96.75
Inscribed circle diameter (in meters) (OUTDIAM)	148	Mean: 40.29; S.D.: 12.85; Min: 22.50; Max: 111.50
Number of legs (3LEG, 4LEG, 56LEG) (1 = Yes; 0 = No)	148	3-leg: 32; 4-leg:100; 5-or 6-leg: 16
Gated roadway through the central island? (EXCEPT) (1 = Yes; 0 = No)	148	Yes: 4; No: 144
Bypass present in some directions? (BYPASS) (1 = Yes; 0 = No)	148	Yes: 22; No: 126
Oval roundabout? (OVAL) (1 = Yes; 0 = No)	148	Yes: 8; No: 140
Two-lane roundabout? (TWOLANE) (1 = Yes; 0 = No, thus single-lane)	148	Yes: 15; No: 133
Road width on the roundabout (all lanes together, in meters) (ROADWIDTH)	133	Mean: 6.38 ; S.D.: 1.26; Min: 4.00; Max: 13.40 (single-lanes)
	15	Mean: 7.78 ; S.D.: 1.41; Min: 6.50; Max: 9.85 (two-lanes)
Construction year of the roundabout (YEAR)	148	Median: 1996; range [1990;2002]
Mixed Traffic? (MIXED) (1 = Yes; 0 = No)	148	Yes: 13; No: 135
Cycle lanes close to the roadway? (CYCLLANE) (1 = Yes; 0 = No)	148	Yes: 64; No: 84

Variable (ABBREVIATION)	Nr. of obser-vations	Descriptive statistics
Cycle paths, separated from the roadway ? (CYCLPATH) (1 = Yes; 0 = No)	148	Yes: 66; No: 82
Grade-separated cycle facilities ? (GRADESEP) (1 = Yes; 0 = No)	148	Yes: 4; No: 144
Sidewalk present around the roundabout? (SIDEWALK) (1 = Yes; 0 = No)	148	Yes: 71; No: 77
Zebra markings present on exit/entry lanes? (ZEBRA) (1 = Yes; 0 = No)	148	Yes: 75; No: 73
Nr. of pedestrians 8:00-18:00 (PED)	148	Mean: 246; S.D.: 645; Min: 0; Max: 6205
Nr. of bicyclists 8:00-18:00 (BIC)	148	Mean: 470; S.D.: 765; Min: 0; Max: 5598
Nr. of mopeds 8:00-18:00 (MOP)	148	Mean: 76; S.D.: 108; Min: 0; Max: 680
Nr. of motorcycles 8:00-18:00 (MCY)	148	Mean: 98; S.D.: 260; Min: 0; Max: 2161
Nr. of light vehicles 8:00-18:00 (LGT)	148	Mean: 11627; S.D.: 5818; Min: 2201; Max: 30944
Nr. of heavy vehicles 8:00-18:00 (HVY)	148	Mean: 1155; S.D.:1237; Min: 74; Max: 10929

Table 37 Average annual number of crashes per roundabout (N=148)

	1996-2004	1996-2005
N=90 (existing data)	$\mu = 1.37$, $\sigma^2 = 1.39$	$\mu = 1.35$, $\sigma^2 = 1.31$
N=58 (extra data)	$\mu = 1.03$, $\sigma^2 = 1.46$	$\mu = 1.01$, $\sigma^2 = 1.33$
N=148 (full dataset)	$\mu = 1.23$, $\sigma^2 = 1.44$	$\mu = 1.22$, $\sigma^2 = 1.33$

Some differences in both data samples might consequently exist. They could be related to the applied selection criteria. The existing dataset of 90 roundabouts was randomly selected from a dataset of all existing roundabouts on regional roads in Flanders that were constructed between 1994 and 2000. The additional dataset was selected from the same original dataset and consisted of the in the dataset remaining roundabouts on regional roads in three of the five Flemish provinces (Antwerp, Flemish Brabant and Limburg). Additionally, 9 roundabouts were included that were constructed in 2001 or 2002.

The descriptive statistics like reflected in Table 36 were compared between the two samples by means of significance tests for the difference between two proportions (z-tests). Compared to the original 90 roundabout dataset, the 58 added locations turned out to be more often located outside built-up areas (72% of the cases instead of 57% before, $z=1.93$, p 0.05). However, when the 9 roundabouts that were constructed after 2000 were excluded from the added sample of 58, the proportions of roundabouts outside built-up areas became almost equal (72% versus 69%, $z= 0.34$, p 0.73). This could indicate that road authorities started to convert more often intersections outside built-up areas into roundabouts more recently. A difference was also found for the average daily traffic (ADT) that was lower in the additional dataset (12004) then in the existing dataset (13416). This difference appears not to be related to the higher proportion of roundabouts outside the built-up area in the new dataset. On the contrary, roundabouts outside built-up areas have throughout the extended dataset higher average ADT's then roundabouts inside built-up areas (13566 and 11674 respectively). Furthermore, it should be noticed that identical calculation and calibration procedures for the traffic volume in both datasets were applied (see Chapter 6).

A conclusion based on these elements is that the new dataset differs to some extent from the existing dataset in the sense that the added roundabouts were on average less busy and more often located outside built-up areas. It will be checked further in this chapter to what extent the conclusions derived from the analyses of the existing data will remain valid for the extended dataset. All analyses in the remainder of this chapter will be made for the entire extended dataset of 148 roundabouts.

Table 38 shows the average annual number of crashes per roundabout in the extended dataset, for each different road user type separately. The crashes were classified according to the same six road user groups as the traffic counts: light vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Light vehicles were involved in 85% of all registered injury crashes at the investigated roundabouts. Bicyclists were present in 28% of the crashes and mopeds in 18%. No other user group occurred in more than 10% of the crashes. Since usually more than one road user is involved in a crash, the sums of the crash counts (column 1) and the percentages (column 2) in Table 38 exceed the totals in the first row.

Table 38 Frequency statistics of crashes in the roundabout dataset according to type of involved road user

	Crash counts	Proportion of total crashes	Avg/year/ roundbt. (Minimum-Maximum)	Variance	Proportion of traffic volume	χ^2	p[1]
Injury crashes at the 148 roundabouts	1491	100	1.22 (0-5.70)	1.33			
Injury crashes with at least one							
light vehicle	1261	0.846	1.04 (0-5.50)	1.08	0.850	0.23	0.63
bicycle	410	0.275	0.33 (0-2.20)	0.17	0.034	1423.66	<0.01
moped	270	0.181	0.21 (0-2.90)	0.13	0.006	1857.59	<0.01
heavy vehicle	111	0.074	0.09 (0-0.50)	0.02	0.084	1.77	0.18
motorcycle	97	0.065	0.08 (0-0.50)	0.01	0.007	354.89	<0.01
pedestrian	61	0.041	0.05 (0-0.60)	0.01	0.018	35.60	<0.01

[1] significance of the chi-square test with null hypothesis H_0: proportion of crashes per road user type equals share in roundabout traffic. H_0 rejected if $p \leq 0.05$

Table 39 Frequency statistics of crashes in the roundabout dataset according to crash type

	Counts[1]	% of total	Avg/year/ roundbt.	Variance
Single-vehicle crashes	329	22.1	0.29	0.26
Multiple-vehicle crashes	1151	77.2	0.92	0.94

[1] For 11 crashes the type is unknown

Moped riders, bicyclists, motorcyclists and pedestrians were more frequently involved in crashes than would be expected based on their average share in traffic on the observed locations. Light and heavy vehicles were almost as frequently involved as expected.

Crashes were subdivided according to the number of involved road users. Almost eight in ten of the reported crashes at the roundabouts were multiple-vehicle crashes (Table 39).

0shows the frequencies of single-vehicle crashes for each road user type and compares the shares of the different traffic modes in the crash counts with their share in traffic. The two most important single-vehicle crash types were those with light vehicles and motorcycles. A small p-value for the chi-square test of homogeneity of the two populations indicates strong evidence of heterogeneity. Mopeds and motorcycles were more frequently involved in single-vehicle crashes than expected on the basis of their traffic share, whereas the four-wheeled vehicles (light and heavy) were less involved. The magnitude of the odds ratios for motorcyclists (OR 23.1) and moped riders (OR 13.4) shows that the revealed effects were not only significant but substantial as well. Compared to the existing dataset, two results changed: firstly, the result for the heavy vehicles became significant at the 5%-level and secondly, the odds ratio for the bicyclists decreased and is not longer significant at the 5%-level. A clearer distinction seems therefore possible between road user groups that show (strong) over-involvement in single-vehicle crashes (mopeds and motorcycles) and groups showing under-involvement (four-wheel vehicles) relative to their traffic participation.

The collision matrix for multiple-vehicle crashes is shown in Table 41 . Light vehicles are involved in 90% of all multiple-vehicle crashes, bicyclists in 34% and mopeds in 21%. The most dominant collision types were those between light vehicles mutually, light vehicles against bicyclists and light vehicles against mopeds. No other collision type is found in more than 5% of the multiple-vehicle crashes.

Also in Table 41 , odds ratios were calculated for the relative occurrence of crashes in comparison with the traffic participation for each road user type. In order to estimate the probability of occurrence of road user types in crashes, it was assumed that exactly two road users or vehicles were involved in every multiple-vehicle crash. The calculated odds ratios show that mainly moped riders, bicyclists and motorcyclists are overrepresented in multiple-vehicle crashes when compared with their traffic participation. Figure 16 depicts this graphically.

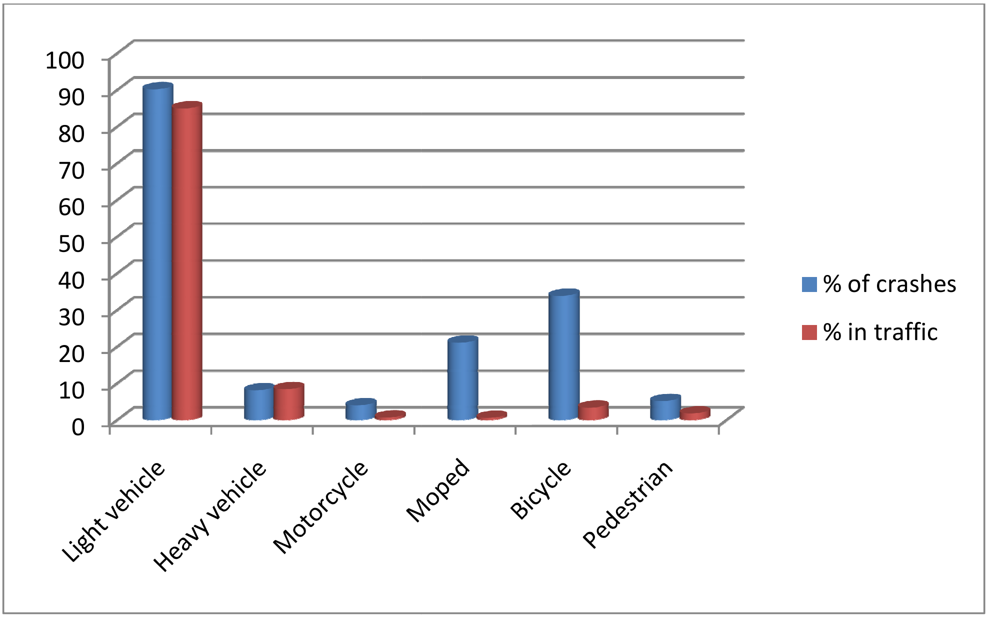

Figure 16 Crash involvement and traffic share for different road user types in multiple –vehicle collisions

Table 40 Frequency of single-vehicle crashes per user group (N=329)

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Other/ unknown	TOTAL
Number of single-vehicle crashes	223	17	47	23	17	2	329
% of all single-vehicle crashes	67.8	5.2	14.3	7	5.2	0.6	100
Average volume	11627	1155	98	76	470	246	13672
Share in roundabout traffic (in %)	85	8.4	0.7	0.6	3.4	1.8	100
OR[1] (p-value[2])	0.4 (<0.01)	0.6 (0.03)	23.1 (<0.01)	13.4 (<0.01)	1.6 (0.08)	0.33 (0.11)	

[1] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 single-vehicle crashes for the road user type divided by single-vehicle crashes of all the other road users and Ω_2 volume of road users at the roundabouts divided by volume of all the other road users

[2] p-value of the chi-square test with null hypothesis H_0: proportion of single-vehicle crashes per road user type homogeneous with share in roundabout traffic. H_0 rejected if $p \leq 0.05$

Table 41 Collision matrix for multiple-vehicle crashes (N= 1138)[1]

	Light vehicle	Heavy vehicle	Motor-cycle	Moped	Bicycle	Pedes-trian	Σ
Light vehicle	407	41	35	189	316	38	1026
Heavy vehicle	41	4	3	11	29	4	92
Motorcycle	35	3	0	3	3	1	45
Moped	189	11	3	7	21	9	240
Bicycle	316	29	3	21	10	7	386
Pedestrian	38	4	1	9	7	0	59
Σ	1026	92	45	240	386	59	
% of crashes[2]	90.2	8.1	4	21.1	33.9	5.2	
Traffic volume	11627	1155	98	76	470	246	13672
Share in roundabout traffic (in %)	85.0	8.4	0.7	0.6	3.4	1.8	100
Probability (in %) of at least one road user of this type in a random selection of 2 road users[3]	97.8	16.2	1.4	1.1	6.8	3.6	
Odds ratio[4]	0.9	0.5	2.9	19.2	5	1.4	

---

[1] One or both road user types were not known for 13 crashes. These were not included

[2] to read as “involved in x % of the total number of crashes. Since two or more different types of road users are involved in many crashes, the sum of the percentages in this row exceeds 100.

[3] Calculated by applying the probability rule P(A or B) = P(A) + P(B) – P(A and B) for non-mutually exclusive events A and B

[4] Odds-ratio: ratio Ω_1/Ω_2 of the odds Ω_1 % of crashes with this road user type and Ω_2 probability of at least one road user of this type in a random selection of two road users

An interesting subsequent step was to assess whether the real crash involvement for the different combinations of road user types corresponded with the expected involvement based on the traffic participation of each road user type. This was done by evaluating the frequency of collisions for each possible combination of road user types in comparison with the frequency of encounters between those vehicle types. Therefore the following procedure was adopted:

In a first step, the number of encounters between at least 2 road users was theoretically derived from the available exposure data. To this end, the assumptions made by Elvik et al. (2009) were adopted and slightly modified:

1. Multiple-vehicle collisions are not possible without encounters of at least two vehicles. An encounter is defined as a quasi-simultaneous arrival at the roundabout, i.e. within an interval of 1s. Opposite to the approach by Elvik et al., conflicts (e.g. those leading to rear-end crashes) were assumed to be also possible in case of two vehicles coming from the same direction.

2. Traffic volumes are not time-dependent.

3. Individual arrivals are independent and the arrivals per unit of time follow a Poisson-process.

4. The proportions of the different road user types in traffic in the period 08:00-18:00 are reflecting the real daily proportions on a 24 hour basis.

Given the average daily (10 hours) number of entering vehicles at the roundabouts of 13672 (all directions and all road user types together), the mean number of arrivals λ per second equals $\lambda = \frac{13672}{10*60*60\ \mathrm{s}}$ = 0.38

Then, the probability of x arrivals per second can be written as $\mathrm{P(x)} = \frac{\lambda^{\mathrm{x}}.\mathrm{e}^{-\lambda}}{\mathrm{x!}}$

Consequently, the probability of an encounter of at least 2 road users in the considered period of 1 second is given by P(x>1) = 1 - P(x=0) - P(x=1) = 1-0.6841-0.2597 = 0.0562

The resulting expected number of encounters per day (10h) then equals 0.0562 * 13672 = 768.

Subsequently, the expected proportion of encounters between two different road user types (e.g. light vehicle X heavy vehicle, bicycle X bicycle) to the total number of encounters is calculated. This is done by multiplying the respective shares in roundabout traffic (Table 38) and relating them subsequently to the calculated total number of encounters. For instance, to get the estimated probability of encounters between mopeds and light vehicles, multiply 0.006 with 0.85 and 2 = 0.0102 (multiply by 2 to incorporate one possible permutation). Then, the estimated number of encounters for each road user combination is easily estimated by multiplying the estimated probability with the estimated total number of encounters (N=768). For instance the estimated number of encounters between mopeds and light vehicles is 0.0102*768 ≈ 8. The results are provided in Table 42 .

In a second step, odds ratios are estimated for the crash frequency of each possible combination of road user types compared with the relative involvement in encounters. The results are also shown in Table 42 . For instance, the odds ratio of 10.31 for the combination mopeds and heavy vehicles means that 10 times more crashes are count than would be expected based on the estimated number of encounters of both vehicle types in traffic. The table shows that the count number of crashes is lower than expected for three combinations of vehicle types: light vehicle * light vehicle (0.21), heavy vehicle * light vehicle (0.22) and heavy vehicle * heavy vehicle (0.49). All other collision types occur more frequently than expected.

It can be noticed that these estimations are somewhat distorted since the number of crashes is related to a period of 24 hours per day whereas the traffic volume estimations and proportions are only valid for a period of 10 hours per day. Particularly, it is likely that the proportion of pedestrians and two-wheeled road users is lower during night than during daytime. However, if this would be true, the stated figures for the relative crash involvement would be even be an underestimation of the real distortions.

Table 42 Estimated frequency of encounters and relative crash involvement for each possible combination of road user types[1]

	Light vehicle	Heavy vehicle	Motorcycle	Moped	Bicycle	Σ
Light vehicle	555 (0.21)					555
Heavy vehicle	110 (0.22)	6 (0.49)				116
Motorcycle	9 (2.56)	1 (2.17)	0			10
Moped	8 (20.71)	1 (10.31)	0 (32.21)	0 (192.77)		9
Bicycle	45 (6.19)	4 (4.47)	0.5 (5.33)	0.5 (48.78)	1 (7.48)	51
Pedestrian	24 (1.09)	2 (1.16)	0 (3.38)	0 (39.2)	1 (4.99)	27
Σ	751	14	0.5	0.5	2	768

[1] Reflected values = a (b) with

a = Estimated daily number of encounters between represented road user types

b = (Odds) ratios of the odds of multiple-vehicle crashes for collisions between the represented road user type divided by all other collisions and the odds of the expected daily number of encounters for the represented road user types divided by all other encounters

7.2. REGRESSION MODELLING

Regression models were fitted using the available geometric and traffic variables. The dependent variable was the average annual number of crashes per roundabout (N=148). In a first step, Poisson loglinear models were fit to explain crash rates at roundabouts. Since underdispersion was found in the crash data, additional models were fit by using gamma probability models that are able to account for underdispersion (Oh et al., 2006).

The functional form of the chosen models was the following:

$$E(\lambda) = e^{\alpha}.\, {Q_1}^{\beta_1}.\, {Q_2}^{\beta_2}.\, e^{\sum_{i=1}^{n} \gamma_i . x_i} \qquad \text{(Eq. 7-1)}$$

with E(λ) = expected annual number of crashes

Q_1 = ADT (motor vehicles)

Q_2 = traffic volume for particular vehicle types (bicyclists, mopeds,...)

x_i = other explanatory variables

α, β_1, β_2, γ_i = model parameters

The gamma model makes use of the gamma probability distribution (Agresti, 2002) that for a given λ

$$f(\lambda; \varphi; \mu) = \frac{({}^{\varphi}/_{\mu})^{\varphi} . e^{(-\varphi . \lambda/\mu)} . \lambda^{\varphi - 1}}{\Gamma(\varphi)};\ \lambda \geq 0 \qquad \text{(Eq. 7-2)}$$

with $E(\lambda) = \mu$ and $VAR(\lambda) = \frac{\mu^2}{\varphi}$

φ is the dispersion parameter. Underdispersion exists if φ > 1, overdispersion if φ <1, equidispersion if φ = 1.

All models were fitted by using the GENMOD-procedure in SAS and made use of the log link function. In Chapter 6, the adopted modelling approach was a stepwise backward elimination procedure starting from initial models with all possible variables. In the resulting models only variables were reflected that showed a significance value below or equal to 0.10, except for the ADT that was always included. The best fitting models (in terms of their AIC-value) were represented, which resulted in the fact that the Poisson and gamma models contained not necessarily the same variables and were therefore not always easy mutually comparable.

The current models were somewhat differently fitted: a forward selection procedure was followed like proposed by Hauer (2004a). Initially, only the variables ADT (motorized vehicle traffic) and the exposure variable for the specific vehicle category (e.g. motorcyclist volume for the model predicting the crashes with motorcyclists) were included. The exposure variables were transformed to their natural logarithm, which meant they were incorporated in the multiplicative part of the model as shown in equation (1). Subsequently, the "spreadsheet" approach (Hauer, 2004a) was followed in order to check any candidate variable for entering the models. This approach started from the exposure-only model. The predicted crash rates and the observed crash rates for each observation in the model were subsequently listed in a spreadsheet, together with all the values of the different variables. Then, each relevant possible value was evaluated for entering in the model. This was done as follows: firstly, 'bins' were created for each possible value (in case of dummies or discrete variables with a small number of possible values) or group of values (in other cases). Then, the sum of all the observed crashes in the bins was compared with the sum of all predicted crashes and it was evaluated whether this showed a systematic difference for all the evaluated bins. If so, this indicated that the candidate variable could be meaningful in the model. Subsequently, the variable was introduced in the model, together with all the other variables that were selected this way.

Subsequently, the Poisson and gamma models were fitted with the resulting list of variables. In case of strong correlation ($\rho \geq 0.6$) one of the two correlating variables was eliminated, in principle the variable with the smallest individual significance. If the remaining variable was eliminated in a further step in the modelling process, the correlating variable was re-introduced in the model and subsequently checked for its significance. In case of strong correlations between geometric variables and exposure variables the last ones were kept in the models since there are well established grounds, e.g. in (Fridstrøm et al., 1995; Greibe, 2003) to consider them as important predictors.

Variables that were neither significant at the 10% level in the Poisson nor in the gamma-model were eliminated, except for the exposure variables who were always included. If a variable was significant in either the Poisson model or the gamma model, it was included in both models in order to maintain comparability between the two models. The goodness of fit of the subsequent models was evaluated by the Akaike Information Criterion (AIC). The best fitting model was in principle the model with the lowest value for the AIC. However, due to the abovementioned constraints, the final models were not necessarily those with exactly the lowest AIC-value.

The variable YEAR was scaled into a series with the first year (1994) =1, the second year = 2 etc. and subsequently included in the models as a continuous variable. This approach was also followed in the previous chapter and yielded better results than using YEAR as a categorical variable. The followed procedure enabled a single parameter estimate for the variable YEAR which enabled a more straightforward interpretation of the results.

Table 43 and Table 44 show the results. The results for the Poisson models and the gamma models are both provided. It was considered to include all variables that were at least significant in one of the fitted models in all the other models as well. This would offer the advantage that the values for some variables could, even if not significant, easily be compared between different models. However, this was not done because including all the variables listed in Table 43 and Table 44 deteriorated the individual significance level of some variables severely and deteriorated the model fit. Moreover the theoretical basis for including some variables in some models was very unclear: for instance including a variable like the presence of cycle paths in the models for motorcyclists would not correspond with common sense.

The first column of Table 43 presents the most general model, the one for all crashes. The crash rate appears to be influenced by two exposure variables: the motor vehicle exposure ADT and the bicyclist exposure (BIC), although not significantly by the latter one. Furthermore, the presence of a cycle path influences the number of crashes negatively and more crashes occur at roundabouts with three legs. These findings are very consistent with the findings in the previous chapter.

Specific models were fit for crashes with particular road users: bicycles, mopeds, motorcycles, heavy vehicles, light vehicles and pedestrians. The models for crashes with light vehicles showed strong similarities with the models for all crashes, which was not unexpected due to the dominancy of crashes with light vehicles in the entire dataset. However, one extra variable enters the model for crashes with light vehicles: the presence of a bypass, which correlates with a higher number of crashes.

Crashes with bicyclists are explained by the ADT and the volume of bicyclists, both in the Poisson and gamma models. Furthermore, the number of crashes with bicyclists turns out to be lower on roundabouts with separate cycle paths. See section 7.3 for some comments on this result. The number of crashes with mopeds is, apart from the exposure variables, dependent on the construction year of the roundabout (YEAR) and seems to be higher on roundabouts with 3 legs (3LEGS). Furthermore, fewer crashes with mopeds occur at roundabouts where the central island is raised than those where this is not the case (ELEV). Apart from the exposure variables (ADT and MCY), the crash rate for motorcyclists was dependent on the shape of the central island: fewer crashes seemed to occur at oval roundabouts (OVAL).

Only exposure and the year of construction seemed to have an effect on the crash rate for trucks. Crashes with pedestrians seem to be influenced by the ADT and by the pedestrian volume (PED). Furthermore the number of crashes with pedestrians seems to be higher at roundabouts inside built-up areas (INSIDE) then on roundabouts outside the built-up area.

Furthermore separate models were fit for single-vehicle crashes and for multiple-vehicle crashes. The results are provided in Table 44 . The number of single-vehicle crashes turns not longer out to be only explained by the ADT. A larger diameter of the central island (CENTRDIAM) is correlated with a higher single-vehicle crash rate. The presence of a cycle path (CYCLPATH), the presence of an oval central island (OVAL) and roundabouts that were located inside built-up area (INSIDE) were correlated with fewer single-vehicle crashes. Multiple-vehicle crashes are affected by the ADT, by the presence of bicyclists and furthermore by the variables CYCLPATH, 3LEGS, YEAR, BYPASS and ZEBRA which are the same variables as in the existing dataset.

Table 43 Parameter estimates for Poisson and gamma-models with particular road users (N=148)

Variables[1]	All crashes	Crashes with light vehicles	Crashes with bicyclists	Crashes with mopeds	Crashes with motorcycles	Crashes with heavy vehicles	Crashes with pedestrians
Intercept	-10.05 (<0.01) *-10.64 (<0.01)*	-9.27 (<0.01) *-9.91 (<0.01)*	-11.01 (<0.01) *-14.23 (<0.01)*	-15.47 (<0.01) *-15.40 (<0.01)*	-12.61 (0.03) *-22.79 (<0.01)*	-10.97 (0.06) *-9.48 (<0.01)*	-19.90 (0.02) *-28.69 (<0.01)*
LN(ADT)	1.06 (<0.01) *1.10 (<0.01)*	0.99 (<0.01) *1.04 (<0.01)*	0.91 (<0.01) *1.22 (<0.01)*	1.46 (<0.01) *1.49 (<0.01)*	1.10 (0.07) *2.22 (<0.01)*	0.70 (0.35) *0.39 (029)*	1.62 (0.07) *2.50 (<0.01)*
LN(BIC)	0.05 (0.18) *0.08 (0.12)*		0.26 (0.01) *0.32 (<0.01)*				
LN(MOP)				0.23 (0.07) *0.21 (0.01)*			
LN(MCY)					-0.10 (0.48) *-0.23 (0.02)*		
LN(HEAVY)						0.36 (0.35) *0.58 (0.03)*	
LN(PED)							0.20 (0.37) *0.25 (<0.01)*
CYCLPATH	-0.45 (<0.01) *-0.33 (0.06)*	-0.52 (<0.01) *-0.33 (0.07)*	-0.54 (0.09) *-0.59 (0.04)*				
YEAR				-0.15 (0.09) *-0.21 (0.01)*		-0.17 (0.22) *-0.17 (0.01)*	
3 LEGS	0.37 (0.04) *0.59 (0.01)*	0.42 (0.03) *0.58 (0.01)*		0.47 (0.29) *0.70 (0.07)*			
INSIDE							1.15 (0.29) *1.39 (<0.01)*
BYPASS		0.43 (0.04) *0.36 (0.17)*					
ELEV				-0.58 (0.17) *-0.74 (0.08)*			
OVAL					-1.72 (0.57) *-2.06 (<0.01)*		
AIC	369.10 *315.11*	340.79 *262.68*	179.18 *-305.16*	140.11 *-575.52*	76.14 *-978.17*	81.21 *-953.34*	52.68 *-1306.19*
Dispersion parameter[2] (φ)	*1.12*	*1.22*	*2.93*	*3.53*	*4.35*	*4.55*	*4.43*

[1] values in normal typeface = Poisson-models, values in italics = gamma models; ( ) = p-values

[2] for the gamma models. Overdispersion if φ<1, underdispersion if φ>1, equidispersion if φ=1

Table 44 Parameter estimates for Poisson and gamma-models with single/multiple-vehicle crashes

Variables[1]	Multiple-vehicle crashes	Single-vehicle crashes
Intercept	-10.50 (<0.01) *-12.33 (<0.01)*	-5.84 (0.06) *-6.99 (<0.01)*
LN(ADT)	1.04 (<0.01) *1.21 (<0.01)*	0.44 (0.18) *0.62 (0.02)*
LN (BIC)	0.12(0.05) *0.15 (0.02)*	
CYCLPATH	-0.32 (0.08) *-0.25 (0.22)*	-0.66 (0.05) *-0.51 (0.08)*
3 LEGS	0.45 (0.03) *0.60 (0.02)*	
YEAR	-0.09 (0.04) *-0.08 (0.05)*	
BYPASS	0.41 (0.06) *0.43 (0.14)*	
OVAL		-2.24 (0.15) *-1.56 (0.01)*
ZEBRA	0.37 (0.05) *0.22 (0.32)*	
CENTRDIAM		0.03 (0.01) *0.01 (0.27)*
INSIDE		-0.63 (0.15) *-0.72 (0.03)*
AIC	311.13 *190.68*	176.93 *-304.39*
Dispersion parameter[2] (φ)	*1.48*	*2.87*

[1] values in normal typeface = Poisson-models, values in italics = gamma models; ( ) = p-values; explanatory variables only included if $p \leq 0.10$

[2] for the gamma models. Overdispersion if $\varphi<1$, underdispersion if $\varphi>1$, equidispersion if $\varphi=1$

7.3. DISCUSSION

7.3.1. Modelling approach

Like in the analyses of the existing dataset, both Poisson and gamma models were fit. The modelling procedure was somewhat modified in order to obtain as much as possible information from the data. However, the adaptations did not substantially influence the results. The underdispersion that was found in the existing dataset persisted. The observed underdispersion indicates that the variation of the crash rates at the investigated roundabouts is low. It appears that the parameter estimates of the variables in the Poisson and the gamma models are generally close to each other. However, the significance values of the parameters differ sometimes considerably between the both models. In essence, it might be concluded that the modelling procedure and the results were quite consistent for the extended dataset compared with the existing dataset.

7.3.2. Multicollinearity

Attempts were made to deal with multicollinearity which was an expected phenomenon in this dataset. Principally, multicollinearity is a tough issue and one can theoretically not be certain about which variables to include in a model when two or more variables correlate strongly (Verbeek, 2004). A first type of expected multicollinearity in our models relates to the correlation of infrastructure variables with traffic exposure. For instance, larger roundabouts (larger values for OUTDIAM) are related to higher traffic volumes (ADT) and more pedestrians (PED) are present at roundabouts inside built-up areas (INSIDE). Due to the well established importance of exposure in crash prediction modelling, I decided to include at least one exposure variable in each model before looking at any infrastructure variable. In case of a strong correlation, the infrastructure variable would have been removed. A second type of multicollinearity relates to correlations between different exposure variables. In principle, each model comprised two exposure variables. However, the addition of a second road user type was not possible in the model for light vehicles and the model for single-vehicle crashes due to the fact that the suitable candidate second covariate (the number of light vehicles LIGHT) correlated strongly with the ADT and its inclusion deteriorated the individual significance values severely. A third type of multicollinearity is found between the infrastructure variables. For instance the size of the central island (CENTRDIAM) appears to correlate to a large extent with the size of the entire roundabout (OUTDIAM) which made it impossible to include both variables together in the models in a reliable way.

However, CENTRDIAM an OUTDIAM are not *by definition* dependent on each other and thus not substitutable. In these cases, I chose to include that variable in the particular models that was believed to be the principally most relevant. Another example is the duo CYCLPATH / CYCLLANE. It was preferred to include CYCLPATH consistently in all models since this was found to be the best explaining variable in most of the different cases. Some more comments on this are given below.

7.3.3. Influencing exposure variables

Traffic volume (ADT) was a significant predictor in most of the fitted models. It was only less significant in those models where the number of observations was low such as in the models for pedestrians or heavy vehicles. Therefore it can be concluded that the ADT was technically by far the most important variable in the models, which corresponds with many earlier findings in traffic safety research.

The coefficient for the motorized vehicle exposure (ADT) is not consistently above or below 1 in most of the models. A coefficient of 1 would suggest an increase in crash rate (crashes per year) that is proportional to the traffic volume, whereas a coefficient of above respectively below 1 would equal an increase that is respectively higher or lower than proportional to the traffic volume increase. For the single-vehicle crashes, however, the coefficient for the ADT is well below 1, suggesting that the average number of single-vehicle crashes per passing vehicle is lower on busier roundabouts. In existing research, ADT-parameters below as well as above 1 for crashes at roundabouts were found (Brüde & Larsson, 2000; Maycock & Hall, 1984).

Also the exposure variables for the specific road user types appeared to contribute significantly to the models. This was the case for the bicyclist volume, the number of moped riders and the number of pedestrians (only significant in the gamma model), each time in the model for the respective group of road users. These results are roughly the same as in the previous dataset. Additionally to the previous dataset, the volume of trucks and the volume of motorcyclists entered the respective models, although far from significant in the case of the Poisson model. It can be noticed that all the parameter estimates for the specific road user types are considerably below 1, which could support the "law of rare events" (Elvik, 2006), stating that the more rarely a certain traffic hazard is encountered the greater its effect is on the crash rate. This law implies as well that the rarer some types of road users are encountered in traffic, the higher the risk of a collision with those road users per encounter. This would mean that the ‘safety in numbers effect’ that was discussed in the previous chapter and seemed to be confirmed for bicyclists, motorcyclists and moped riders, needs to be extended to some other road user categories.

The exposure variable for the volume of bicyclists entered also the models for all crashes and for multiple-vehicle crashes. This highlights the important role of the most dominant type of encounters in the crash statistics, being the collisions between light vehicles mutually and those between light vehicles and bicycles as it appears from the collision matrix in Table 41 .

7.3.4. Are cycle paths better or cycle lanes worse?

In the previous chapter, I still stated that roundabouts with cycle lanes were clearly performing worse than roundabouts with cycle paths. But I added that, although the variable CYCLLANE was more dominantly present in the models, the chapter stayed inconclusive on the question whether roundabouts with cycle lanes were performing worse than other types or roundabouts with cycle paths were performing better than other types. In the present chapter, it seems that the variable CYCLPATH has gained importance and contributes better to the model fit. Again, the other two design types, mixed traffic (N=13) and grade-separated (N=4) showed no particular effect but their limited presence in the dataset could still be a major explanation. The limited numbers of mixed traffic and grade-separated roundabouts in the sample explain equally the correlation between the two most dominant groups, cycle lanes and cycle paths. This correlation obscures the interpretation of the revealed effects. More explicit and better controlled results were found in the before-and-after study of crashes at roundabouts (see Chapter 5), where was found that roundabouts with cycle lanes performed worse compared to the three other design types.

7.3.5. Other risk variables

Three-leg roundabouts appear to perform worse than roundabouts with four or more legs. This finding corroborates the findings in the previous chapter since the variable 3LEGS showed very comparable parameter estimates and smaller significance values. The most likely explanation for this finding seems to be that speeds at 3-leg roundabouts could be somewhat higher since approach and exit angles are in principle somewhat wider (on average on 120°) than in case of a four leg roundabout (on average on 90°).

Again, some variables appeared only in one models for subgroups. An interesting result is that fewer crashes with motorcyclists and less single-vehicle crashes seem to occur at oval roundabouts (OVAL). A straightforward explanation for this result seems not to be available. Human errors are expected to occur more often on roundabouts with non-circulatory central islands since more manoeuvring actions are required (FHWA, 2000; Kennedy, 2007). Therefore, central island shapes that deviate from a strictly circulatory shape are generally not recommended. Particularly motorcyclists might have more difficulties in negotiating roundabouts with non-circulatory central islands. Consequently, a lower crash rate at roundabouts with oval central islands is not really expected. Possibly, it might be the result of risk overcompensation. However, it should be noticed that this result was far from significant in the Poisson models and therefore seems to be considerably influenced by the modelling assumptions. At least it needs some further research.

More multiple-vehicle crashes seem to occur at roundabouts with zebra markings (ZEBRA) on the entries and the exits. Roughly the same comments apply to this result. It is counterintuitive and might be explained by overcompensation, but at the same time the result is too unsure (since insignificant for the gamma model) to allow drawing many conclusions.

More crashes with light vehicles and more multiple-vehicle crashes (which are to a certain extent overlapping groups) appear to occur at roundabouts with bypasses for traffic in some direction (BYPASS). A possible explanation for this is related to higher speeds and some extra – perhaps less expected – conflict points that are met at such a roundabout. This finding seems to support the statement in different design guidelines for roundabouts that bypass lanes should be avoided since the entries and the exits bypass lanes can increase the number of conflicts (FHWA, 2000).

The variable YEAR (construction year of the roundabout) showed a significant contribution in different models. Like it was discussed in the previous chapter, the most likely explanation for this is that fewer crashes (of certain types) occur at more recently constructed roundabouts.

An interesting result is the higher number of single-vehicle crashes on roundabouts with larger central islands (1 to 3% extra single-vehicle crashes per meter central island diameter extra) (CENTRDIAM). A larger central island necessitates a stronger lateral vehicle deflection when entering a roundabout and is therefore expected to reduce speeds more strongly. Obviously, it may lead as well to a higher single-vehicle crash risk, which seems to be supported here.

More crashes with pedestrians seem to occur at roundabouts inside the built-up area (INSIDE), even if there is accounted for the pedestrian volume. There seems to be no simple explanation for this. Again, the significance of this result is strongly dependent on the adopted distributional assumptions. Furthermore, fewer single-vehicle crashes occur inside built-up areas. This might be related to lower speeds that can be expected to be present inside built-up areas compared with locations outside built-up areas.

Apart from the variable SIGNAL where no information was available for in the additional dataset, only the variable EXCEPT (gated roadway for exceptional transport through the central island) was present in the existing models and did not longer appear in one of the models for the extended dataset. However, the removal of EXCEPT was not unexpected since this result was highly unsure in the previous model wherein it appeared.

7.3.6. Two-lane roundabouts

The variable TWOLANES (two-lane roundabouts) did not enter any of the models, neither in the existing dataset nor in the extended dataset. However, the mere fact that a certain variable is not *significant* must not directly lead to the conclusion that this variable could not be *important*. In statistical terms, the fact that the zero-hypothesis is not rejected should not lead to the conclusion that the zero-hypothesis has to be accepted (Hauer, 2004b). Nevertheless, the modelling practice revealed that the variable TWOLANES was never coming close to significance, which makes it less likely that a further extension of the used dataset would suddenly show some effect of this variable.

In the previous chapter, I mentioned that the number of lanes in existing research showed some tendencies to be relevant (Brüde & Larsson, 2000; Daniels et al., 2009; Persaud et al., 2001). But I argued as well that the number of lanes could act as a proxy for traffic volume in those studies. Based on all those elements, I stated that at least no confirmation was found for higher crash rates at double-lane roundabouts and that further research would be needed. Based on the present analyses, I believe that this conclusion should be maintained.

7.3.7. Study limitations

Finally, some limitations of this study should be taken into account. Although I tried to overcome them in a best possible way, they might have affected the stated results also in the extended models. Firstly, it is clear that a study based on a relatively small (even if extended) sample of locations in one particular country should not pretend to be valid for all possible roundabout designs wherever applied. Secondly, important concepts might be overlooked since information on a number of circumstances or risk factors was not present in the data. For instance, no information could be collected about actual or potential vehicle speeds at roundabouts, although this might be an important variable (Hels & Orozova-Bekkevold, 2007; Layfield & Maycock, 1986; Maycock & Hall, 1984). However, Rodegerdts et al. (2007) found no reliable relationship between speeds and the crash frequency at roundabouts where actual speeds were measured.

The inference of ADT-values from one hour-counts brings some extra portion of uncertainty in the results, which was already the case in the previous chapter. Finally, possible changes in the roundabout design that may have been made after the initial construction of the roundabout might act as a confounder.

7.4. CONCLUSIONS

This study was an extension of the study in Chapter 6. The original dataset of 90 roundabouts was extended to 148 roundabouts, all located on roads owned by the regional road authority in Flanders-Belgium. The added dataset was checked for similarities and differences with the existing dataset. It is concluded that both datasets showed some differences, but enabled to be mixed together and to fit reliable crash prediction models for the entire dataset as an important extension of the existing dataset. The following conclusions can be made:

- Vulnerable road users (moped riders, motorcyclists, bicyclists, pedestrians) are more often involved in injury crashes at roundabouts then could be expected based on their presence in traffic. Moped riders and motorcyclists are strongly overrepresented in single-vehicle crashes whereas moped riders, bicyclists and motorcyclists are overrepresented in multiple-vehicle crashes.
- Variations in crash rates at roundabouts are relatively small and mainly driven by the traffic exposure.

- In the investigated dataset, roundabouts with cycle paths are performing better than roundabouts with other types of cycle facilities, particularly in comparison with roundabouts with cycle lanes close to the roadway.

- Confirmation is found for the existence of a ‘safety in numbers’ effect for bicyclists, moped riders, motorcyclists, heavy vehicles and for pedestrians at roundabouts.

- The overall number of crashes is more or less proportional to the number of motorized vehicles (ADT). The mean number of single-vehicle crashes per passing vehicle is lower on busier roundabouts.

- Three-leg roundabouts appear to perform worse than roundabouts with four or more legs.

- More crashes with light vehicles and more multiple-vehicle crashes (which are to a certain extent overlapping groups) seem to occur at roundabouts with bypasses for traffic in some direction.

- Fewer crashes seem to occur at more recently constructed roundabouts.

- The larger the central island, the more single-vehicle crashes seem to occur.

- No confirmation is found for higher crash rates at double-lane roundabouts. Further research on this topic is needed.

- Due to the nature of a cross-sectional study it cannot be excluded that significant variables in the dataset act as a proxy for other, influencing but unknown variables.

- Continued research on safety effects of different roundabout types and in different countries is recommended.

These conclusions confirm largely the conclusions in the previous chapter. However, some conclusions were somewhat modified. The most important adaptations are related to the fact that the ‘safety in numbers’ effect appeared to be valid for almost all road user types and to the more pronounced role of the cycle path-roundabouts compared with the cycle lanes. Finally, the size of the central island did enter one model, which meant that at least some variable that is describing the size of the roundabout seems to be influential.

Chapter 8. Modelling crash severity at roundabouts

The fitted crash prediction models in the previous chapters tried to explain the variance in the yearly crash rates at roundabouts in order to reveal which structural factors (mainly exposure and geometric variables) influenced these rates. In these chapters, abstraction was made from the severity of the crashes. Only models for injury crashes were fit, regardless of the severity of the related injuries.

The present chapter describes the results of analyses that took explicitly the severity of crashes into account. The objective of this analysis was to investigate which factors contributed to the severity of crashes and injuries at roundabouts. This research was submitted for publication in a scientific journal (Daniels et al., n.d.)

8.1. INTRODUCTION

Traffic safety aspects of roundabouts have been investigated earlier. Generally, it was found that roundabouts are able to reduce injury crashes considerably, although not for all user groups (Daniels et al., 2008; Daniels et al., 2009; Elvik, 2003; Persaud et al., 2001). In the previous chapters, crash prediction models were fit for all injury crashes at roundabouts (Daniels et al., n.d.). The results showed that vulnerable road users (moped riders, motorcyclists, bicyclists and pedestrians) are more frequently than expected involved in crashes at roundabouts. Roundabouts with cycle lanes close to the roadway are clearly performing worse than roundabouts with off-road cycle paths. Nevertheless, the variation in crash rates at the examined roundabouts was relatively small and mainly explained by the traffic exposure. Furthermore, confirmation was found for the existence of a safety in numbers-effect for bicyclists, moped riders and – unsure – for pedestrians at roundabouts.

In this chapter, the focus is on the level of severity of crashes that were recorded at the roundabouts. Severity can be expressed as the probability that, given a crash happening, the outcome will be of certain seriousness. The objective of the analyses in the present chapter was to investigate which factors might explain the severity of crashes and injuries at roundabouts and to relate these factors to the existing knowledge on explaining factors for injury severity in traffic.

The chapter is organized as follows. The next section describes the data that were collected and the way it was done. Subsequently, the different analysis methods and levels are described and the results are provided. Finally the results are discussed and conclusions are drawn.

8.2. DATA COLLECTION

Information was available on crashes at 148 roundabouts on regional roads in Flanders-Belgium. The dataset departed from a previously composed dataset of 90 roundabouts (Daniels et al., n.d.), that was extended. The nature of the available data on geometry and traffic volume was identical to that of the previous dataset. A short summary of the data collection procedure is provided below.

Each roundabout in the sample was visited and photographed, traffic counts were executed and geometric data were collected on the spot. Information on the construction year of the roundabout was available from the Roads and Traffic Agency’s database. All investigated roundabouts were constructed between 1990 and 2002. The collected variables are listed in Table 36 .

Average daily traffic data were estimated for each roundabout based on a traffic count of all entering traffic during one hour. Traffic modes were classified into light vehicles, heavy vehicles, motorcycles, mopeds, bicycles and pedestrians. Light vehicles comprised mainly private cars, but also minibuses and all kinds of vans. Heavy vehicles were trucks, trailers, busses and tractors.

The 148 roundabout locations were localised and geo-coded in Google Earth. Subsequently the roundabout data were linked in a geographical information system (ArcMap) with the geo-referenced crash data (available from Statistics Belgium) for the period 1996-2005. All crashes within a distance of 100 meters of the centre of the roundabout were included in the dataset. After subtraction of the crashes that occurred before the roundabouts were constructed, the dataset consisted of 1491 injury crashes. Table 45 shows the average annual number of crashes per roundabout for each different road user type.

Like in most European countries, the Belgian crash data distinct between 3 levels: crashes resulting in fatal injuries (at least someone in the crash killed immediately or – as a consequence of the crash - within 30 days after the crash), crashes resulting in serious injuries (at least someone in the crash was seriously injured, i.e. in a hospital for at least 24 hours) and crashes with slight injuries (any type of injuries, but not belonging to one of the previous categories) (European Commission, 2006; FOD Economie, 2009). Apart from the crash level, analyses were done as well on the subject level, i.e. all the involved road users in the examined crashes.

Table 45 Average annual injury crash rates per roundabout (N=148)

Per roundabout, annual average number of	Mean	Variance
all injury crashes	1.22	1.33
crashes with light vehicles	1.04	1.08
crashes with bicyclists	0.33	0.17
crashes with moped riders	0.21	0.13
crashes with heavy vehicles	0.09	0.02
crashes with motorcycles	0.08	0.01
crashes with pedestrians	0.05	0.01
single-vehicle crashes	0.29	0.26
multiple-vehicle crashes	0.92	0.94

Table 46 shows frequency statistics of the crash data, related to the number of involved road users. Most dominant are the crashes with only one involved vehicle (single-vehicle crashes) (22%) and two-vehicle crashes (72%). Table 47 shows the frequency of injuries of different levels for the single-vehicle crashes and the multiple-vehicle collisions. Car occupants account for most of the killed and severely injured in single-vehicle crashes, whereas the two-vehicle crash data show particularly a considerable proportion of bicyclists among the killed. All the transport modes that are listed in the table are legally considered to be vehicles, except for pedestrians. Crashes with only pedestrians (e.g. falls) are legally considered to be no traffic crashes. Pedestrians are therefore not present in the examined single-vehicle crash data. However, in the case of a crash with one vehicle and a pedestrian, I considered it to be a multiple-vehicle crash since at least two human actors were involved.

Table 46 Frequency statistics of crashes in the roundabout dataset according to number of involved parties

Number of involved parties	Number of crashes
1	322
2	1068
3	95
4	6
Σ	1491

Basic goal of this study was to explore the crash severity at roundabouts. In the next section this is done in a rather intuitive way, whereas in the subsequent sections regression models are applied in order to establish formal relationships in the data. A distinction is made between severity on the crash level and on the subject level (= for those who were involved in the crash).

Table 47 Frequency of injuries in the dataset[1]

Travel mode	Killed	Seriously injured	Lightly injured	Not injured	SUM
Bicycle	0;12	6;47	11;325	0;17	17;401
Light vehicle	5;1	45;24	157;424	27;1034	234;1483
Heavy vehicle	1;0	2;0	13;6	2;91	18;97
Moped	0;1	5;17	17;210	1;18	23;246
Motorcycle	2;2	7;6	36;35	2;3	47;46
Pedestrian	0;1	0;17	0;38	0;4	0;60
Other	1;0	0;0	3;23	3;6	7;29
SUM	9;17	65;111	237;1061	35;1173	346;2362

[1] Represented values = x;y with x = absolute number of injuries in single-vehicle crashes, y = absolute number of injuries in multiple-vehicle crashes

8.3. RISK EXTERNALITY

In general, an externality is present whenever some economic agent's (Y's) welfare (utility or profit) function includes real variables whose values are chosen directly by others (X) without particular attention to the effect upon the welfare of agent Y they affect (Schipper et al., 2001). Applied to traffic safety, the concept of externality can be described as the fact that travel performed by one group of road users imposes an additional risk on other groups of road users (Elvik, 2008).

Table 48 and Table 49 provide descriptive statistics of the concept of externality, applied to the multiple-vehicle crashes in the dataset, for the severest injuries (seriously or fatally injured) and for all injuries respectively. E.g. the value 35/3 in Table 49 for the combination light vehicles / heavy vehicles means that 35 drivers of light vehicles were at least slightly injured in collisions with heavy vehicles while in the same collisions 3 drivers of heavy vehicles were injured.

For the purpose of describing the externality concept in this section and in the analyses on the subject level in section 8.5, only information on the driver's injuries (thus not for the passengers) was included. This was done in order to eliminate random effects of the number of passengers and in order to enable the analyses on a variable such as Alcohol (reflecting the result of an alcohol test) that was only available for drivers. Crashes with more than two involved parties were principally included as well. If only two different road user categories were involved in these crashes, the collision was considered to have happened between the two different parties. If, for instance, a collision occurred between a car and two moped riders, the crash was considered to have happened between a moped rider and a car. If more than two different road user types were involved in the same crash, the crash was not included in Table 48 and Table 49 since no detailed information was available about the course of the crash, which hindered a correct assignment of the crash to one or another category. The tables show that only a few crashes belonged to this last category.

Table 48 Externality of risk – Number of killed or seriously injured in two-party collisions[1]

Killed or seriously injured in/on/as	Heavy vehicle	Light vehicle	Motorcycle	Moped	Bicycle	TOTAL ∑=127
Heavy vehicle	0					0
Light vehicle	6/0	19				25
Motorcycle	2/0	6/0	0			8
Moped	1/0	15/0	0/0	1		17
Bicycle	10/0	46/0	1/0	2/0	0	59
Pedestrian	1/0	14/0	1/0	1/0	1/0	18

[1] Presented values x/y with x= killed or seriously injured as driver/rider of (row) in collisions with (column) and y = killed or seriously injured as driver/rider of (column) in collisions with (row). 1 seriously injured moped rider in a three-vehicle crash (car-truck-moped) was not included.

Table 49 Externality of risk – Number of injured in two-party collisions[1]

At least slightly injured in/on/as	Heavy vehicle	Light vehicle	Motorcycle	Moped	Bicycle	TOTAL ∑=1160
Heavy vehicle	3					6
Light vehicle	35/3	405				449
Motorcycle	3/0	35/2	0			43
Moped	11/0	185/3	3/2	10		224
Bicycle	29/0	316/2	3/3	20/11	12	382
Pedestrian	4/0	37/2	1/0	8/4	6/2	56

[1] Presented values x/y with x= killed or injured as driver/rider of (row) in collisions with (column) and y = killed or injured as driver/rider of (column) in collisions with (row). 23 injured in categories other/unknown and 6 injured in crashes with more than two different road user types were not included.

Table 48 shows that bicyclists represent almost the half of all the killed or seriously injured in multiple-vehicle collisions at the investigated roundabouts. Furthermore, the tables show imbalances between the injury severities according to the different road user types. When only the severest injuries are considered as it is the case in Table 48 , the injured is always the occupant of the lightest vehicle. When all injuries in the crash are considered (Table 49), this phenomenon persists although somewhat less explicit.

8.4. SEVERITY AT THE CRASH LEVEL

On the crash level, the severity is expressed as the severity of the worst injury that was reported in the crash, regardless of the question which party was affected or what was the role of the involved (driver/rider or passenger). The objective was to check which factors would influence the severity of the crash. Variables related to the crash (e.g. type and number of involved road users, light conditions) as well as variables related to the roundabout (e.g. number of legs, inscribed circle diameter, type of cycle facilities) were available. These characteristics can be assumed to represent a hierarchical data structure whereby observations (=crashes) within the same group (= on the same roundabout) are more alike than crashes across groups. Consequently, correlations might exist among crashes occurring at the same roundabout, since these crashes may share (possibly unobserved) characteristics of the roundabout.

Logistic regression analyses have often been used to model crash severity. One of the prerequisites of a traditional logistic regression framework is that the residuals from the model are independent across observations (Verbeek, 2004). However, the observations in the used dataset might correlate within the groups (= roundabouts). Therefore a hierarchical 2-level binomial logistic model was adopted like proposed by Kim et al. (2007).

The structure of the fitted model was the following:

Let

Y_{ij}	binary outcome variable for the i^{th} crash on roundabout j
$p_{ij} = \sum Y_{ij} / \mathrm{n}$	probability of the resulting binomial (0,1) outcome Y_{ij}
β_p , γ_0, γ_q	model parameters,

X_{pij} covariates ($X_1,\ldots, X_P$) on the crash level

R_{qj} covariates ($R_1,\ldots, R_Q$) on the roundabout level

u_j random effect at the roundabout level $u_j \sim N(0,\sigma_u^2)$

Then

$$LN\left(\frac{p_{ij}}{1-p_{ij}}\right) = \alpha_j + \sum_{p=1}^{P} \beta_p . X_{pij} \quad \text{(level 1-model)} \qquad \text{(Eq. 8-1)}$$

$$\text{And } \alpha_j = \gamma_0 + \sum_{q=1}^{Q} \gamma_q . R_{qj} + u_j \quad \text{(level 2-model)} \qquad \text{(Eq. 8-2)}$$

The multilevel model was fitted by the use of the GLIMMIX procedure in SAS 9.2. Dependent variable was the probability that the outcome of the crash, measured as the most severe injury reported in the crash, was either fatal or at least serious ($Y_{ij}=1$) or not ($Y_{ij}=0$). A forward stepwise regression procedure was adopted. Odds-ratios ($OR = e^{\beta_p}$ or e^{γ_q}) were calculated to determine the rate of increase ($OR>1$) or decrease ($0 \leq OR<1$) of the probability of the outcome when the value of the independent variables X_{pj} or R_{qj} increases with one unit. Values further away from 1 represent stronger associations. In case OR=1, the outcome is independent of the variable X_p or R_q.

The results are provided in Table 50 . The table shows the odds-ratios and their significance values (measuring the result of the hypothesis test H_0: OR = 1). Two models are presented: the first reflecting the likelihood of having a fatal or serious injury in the crash, the second with the probability of a fatally injured in the crash. Values that are significant at the level $p \leq 0.05$ are printed in bold. After fitting both models separately, all variables that were significant at the 5%-level in one of both models were included in the other model as well. This approach allowed to assess the consistency of some results over the two categories and to obtain as much information from the data as possible. It should be noticed that fitting a model with too many covariates in case of an event only occurring in a few cases (like in Y= killed, where Y=1 occurs only in 27 of 1491 observations), might lead to biased estimations and poor standard errors (Agresti, 2002). The results of the model for Y=killed should therefore be interpreted with much caution. The results show that the probability of a killed or at least a seriously injured in the crash increases rather consistently in case of single-vehicle crashes (SINGLE) or in crashes wherein a pedestrian (PEDESTRIAN), a bicyclist (BICYCLIST), a truck or bus (HEAVY) or a motorcyclist (MOTORCYCLE) is involved. Moreover the severity seems to increase in case of a roundabout with grade-separated cycle facilities (GRADESEP) and in case of a crash at night on locations without street lighting. Furthermore, a larger inscribed circle diameter (OUTDIAM) of the roundabout could be somewhat more protective in case of a crash, but this result is highly uncertain.

The intra-class correlation coefficient ρ expresses the proportion of residual variability that is associated with the level 2 (roundabout) unit. It was calculated according to the procedure described in Kim et al. (2007) and Goldstein et al. (2002). A higher value of ρ indicates a stronger clustering of the data. The results in Table 50 show that the largest part of the variance is explained on the crash-level (level 1) whereas the between-group (level 2) variability is limited. Since the level 2 variability does not significantly differ from zero, it is even very uncertain whether a hierarchical structure is really present in the data.

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Table 50 Hierarchical binomial logistic regression results for the odds of Y=1 in the crash (N=1491)

	Y = killed or severely inj. Odds ratio [95% C.I.] (p-value)	Y = Killed Odds ratio [95% C.I.] (p-value)
Level 1 - crash		
Bicyclist = Yes vs. No	**2.16** [1.48-3.14] (<0.01)	**4.42** [1.62-12.03] (<0.01)
Pedestrian = Yes vs. No	**4.76** [2.56-8.83] (<0.01)	2.28 [0.26-19.93] (0.46)
Heavy vehicle = Yes vs. No	**2.16** [1.30-3.58] (<0.01)	**14.75** [6.01-36.20] (<0.01)
Motorcycle = Yes vs. No	1.51 [0.86-2.68] (0.15)	**4.23** [1.18-15.23] (0.03)
Single-vehicle = Yes vs. No	**3.26** [2.21-4.82] (<0.01)	**5.21** [1.88-14.42] (<0.01)
Light conditions[1]		
Dawn, dusk	0.52 [0.23-1.18] (0.12)	
Night – street lighting on	1.20 [0.83-1.74] (0.34)	
Night – no street lighting	**7.29** [2.20-24.22] (<0.01)	
Day	Reference case	
Level 2 - roundabout		
OUTDIAM[2]	1.00 [0.98-1.01] (0.76)	**0.94** [0.89-0.99] (0.01)
GRADESEP = Yes vs. No	2.30 [0.73-7.28] (0.16)	**16.46** [2.73-99.08] (<0.01)
Observations	1491	1491
Observed nr. of Y=1	213	27
Proportion of Y=1	0.14	0.02
Intra-class correlation r	0.04	0.08

[1] Including this variable in the model for Y = killed did not allow model convergence

[2] Odds-ratio assessed as one meter offset from the mean = 41.07m

8.5. SEVERITY AT THE SUBJECT LEVEL

Models were fit on the subject level as well, i.e. on the level of the people involved in the crashes. Dependent variable was the probability that, for each subject involved as a driver/rider (of a truck, car, motorcycle, bicycle...) or a pedestrian in a crash, the outcome was a severe or fatal injury. For many crashes two or even more observations at the subject level were available, since multiple vehicle crashes were dominantly present in the dataset.

Available data on the subject level were gender, age, road user type, alcohol use and injury severity. Variables that in previous research (see 8.6) proved to be influential on crash severity were forced into the model. Those variables were age, gender and alcohol use. Since alcohol use could only be measured for drivers and thus not for passengers, the latter one were not included in the analyses.

Again, a certain hierarchical structure could be present in the dataset and one could identify a subject level, a crash level and a roundabout level. However, structural biases due to this structure were very unlikely. The roundabout level was not likely to be more important than in the model at the crash level reflected in Table 50 . At the crash level, intra-unit correlation was very unlikely, given the maximum of 4 observations for the same crash (see Table 46). Therefore, the adopted modelling procedure was a classic forward stepwise logistic regression. The results are shown in Table 51 . Since only the data for drivers/riders were included, it follows by logic that the numbers of killed and severely injured in Table 51 were somewhat lower than those in the analyses on the crash level. The injury severity on the subject level appears to be affected by the road user type. Injuries for pedestrians, bicyclists, moped riders and motorcyclists seem to be significantly worse than for car drivers, whereas injuries for bus and truck drivers are - although not significantly - less severe. Age is positively related with injury severity. Single-vehicle crashes and crashes outside the built-up area have more severe outcomes than multiple-vehicle crashes or crashes inside built-up areas. A gender-effect is highly uncertain. The probability to get killed or seriously injured seems to be significantly higher when no alcohol test is executed and tends to be higher in case of a positive alcohol test. Light conditions seem to be influential in that sense that crashing in night conditions tends to be more serious. Comments on these results are provided in section 8.6.

A supplementary model was fitted for the odds of being killed as a consequence of the crash at the subject level. Including the same variables as the model for killed and seriously injured resulted again in a model with questionable properties (see section 8.4), but was done in order to enable comparisons between the two models.

8.6. DISCUSSION AND CONCLUSIONS

I examined injury severity at different levels: subject, crash and roundabout. Throughout the analyses, some variables showed quite consistent effects on injury severity. Particularly the road user type and the number of involved in the crash (one or more) were predominantly related with the injury severity. Before drawing too simple conclusions based on this finding, attention should be given to an important limitation in the analysis of crash severity data. The number of reported crashes of a certain severity can be considered as the product of the real number of crashes of a certain severity and the reporting rate. The reporting rate is not a constant and depends on many factors such as the crash severity, road user type, time of the day, day of the week and the number of involved road users. Particularly the crash severity is a crucial element in determining the reporting rate: the more severe the crash, the higher the reporting rate (Elvik & Mysen, 1999). Using data about reported crashes, it is therefore a priori impossible to say whether a change or a difference in crash counts (for instance between road user types A and B) reflects either a change or a real underlying difference in crash frequency or a difference in the reporting rate (Hauer, 2006). Obviously, this issue is of importance for our analyses. At least one should be aware of the consequences of possible different reporting rates according to each of the included factors in the models (age, gender, road user type, day/night crashes...). However, since not all variables are likely to be influenced to the same extent by this phenomenon, I will provide some considerations below, relate them to previous research on the issue of crash reporting and subsequently argue why some conclusions can be made or not.

8.6.1. Single versus multiple vehicle

In the examined dataset, single-vehicle crashes are correlated with more severe outcomes. This might be explained by some systematic but mainly unobserved differences between single and multiple-vehicle crashes (e.g. in average crash speeds, personality traits or emotions), but a different reporting rate of single-vehicle crashes in comparison with multiple-vehicle crashes might provide an important alternative explanation. The existing literature showed consistently lower reporting rates for single vehicle crashes than for multiple vehicle crashes (Alsop & Langley, 2001; Amoros et al., 2006; Elvik & Mysen, 1999). Unfortunately, the magnitude of the underreporting is unclear and varies according to the involved road user type. Amoros et al. (2006) found odds ratios of 0.78, 0.32 and 0.06 for the reporting rate of single-vehicle crashes compared with multiple vehicle crashes with cars, motorcycles and bicycles respectively. With respect to our results, it is therefore impossible to conclude whether or to which degree the difference in severity between single-vehicle and multiple-vehicle crashes is related to either a different reporting rate or to real existing differences in severity.

8.6.2. Road user type

Risk externality appeared to be dominantly present in our data, regardless of the level on which the outcomes were examined (subject or crashes). Light-weight and more vulnerable road users (pedestrians, bicyclists, moped riders and motorcyclists) are far more present in the crash statistics compared with motorised vehicles. This seems to be a clear example of the laws on mass ratio and relative driver fatality risk (Evans & Frick, 1993) stating that (1) the lighter the vehicle, the less risk to other road users and (2) the heavier the vehicle, the less risk to its occupants.

Table 51 Logistic regression results for the odds of Y=1 on the subject level (N=2719)

Expl. variable	**Categories**	**Frequency**	**Y= killed or severely injured** **Odds ratio [95% C.I.] (p-value)**	**Y = killed** **Odds ratio [95% C.I.] (p-value)**
Gender	Male	1807	0.96 [0.68-1.37] (0.84)	2.49 [0.79-7.88] (0.12)
	Female	880	reference case	reference case
	Unknown	32	1.83 [0.12-26.98] (0.66)	<0.01 [<0.01-∞] (0.99)
Alcohol test	Refused	5	<0.01 [0-∞] (0.98)	0.44 [<0.01-∞] (>0.99)
	Not executed	1650	**2.04** [1.18-3.54] (0.01)	∞ [<0.01-∞] (0.94)
	Positive	104	1.76 [0.76-4.11] (0.19)	0.24 [<0.01-∞] (>0.99)
	Negative	527	reference case	reference case
	Unknown	433	**1.94** [1.02-3.71] (0.04)	∞ [<0.01-∞] (0.94)
Light conditions	dawn, dusk	154	0.72 [0.32-1.63] (0.43)	1.23 [0.15-9.93] (0.84)
	night - street lighting on	606	1.42 [0.97-2.11] (0.08)	**3.46** [1.41-8.53] (0.01)
	night- no street lighting	19	**5.13** [1.52-17.33] (0.01)	<0.01 [<0.01-∞] (0.99)
	day	1919	reference case	reference case
	Unknown	21	0.79 [0.09-7.23] (0.84)	<0.01 [<0.01-∞] (0.98)
Type of road user	Pedestrian	62	**15.46** [7.76-30.81] (<0.01)	6.25 [0.65-59.64] (0.11)
	Bicyclist	423	**6.87** [4.49-10.50] (<0.01)	**10.57** [3.47-32.22] (<0.01)
	Moped rider	272	**3.54** [2.05-6.10] (<0.01)	1.81 [0.20-16.32] (0.60)
	Motorcyclist	97	**2.71** [1.41-5.22] (<0.01)	**5.90** [1.47-23.62] (0.01)
	Light vehicle driver	1709	reference case	reference case
	Heavy vehicle driver	115	0.58 [0.17-1.94] (0.37)	2.20 [0.25-19.33] (0.48)
	Other/unknown	30	0.93 [0.11-7.72] (0.95)	<0.01 [<0.01-∞] (0.99)
Age	0-14	94	0.56 [0.22-1.40] (0.21)	1.60 [0.27-9.56] (0.60)
	15-29	917	reference case	reference case
	30-44	786	1.08 [0.69-1.70] (0.72)	2.19 [0.69-6.93] (0.18)
	45-59	487	**1.82** [1.15-2.87] (0.01)	1.28 [0.32-5.13] (0.73)
	60-74	255	**3.15** [1.88-5.27] (<0.01)	2.64 [0.56-12.42] (0.22)
	>75	90	**3.10** [1.50-6.41] (<0.01)	**6.70** [1.36-32.95] (0.02)
	Unknown	90	0.39 [0.06-2.51] (0.32)	∞ [<0.01-∞] (0.98)
Nr. of parties in the crash	1	346	**7.16** [4.73-10.84] (<0.01)	**3.88** [1.36-11.06] (0.01)
	2 or more	2373	reference case	reference case
Built-up area	Inside	1056	**0.66** [0.47-0.94] (0.02)	0.78 [0.33-1.87] (0.58)
	Outside	1663	reference case	reference case
Observations			2719	2719
Observed Nr. of Y=1			203	26
Proportion of Y=1			0.07	0.01
Hosmer and Lemeshow test			χ^2= 10.88 (df =8, p = 0.21)	χ^2= 4.86 (df =6, p = 0.56)

The different models show consistently that the outcome severity of a crash is strongly dependent on the road user type. Pedestrians, bicyclists and motorcyclists have a higher probability of getting seriously injured in a crash. But again, these results may partly be attributed to differences in reporting rates according to the road user type since mainly the less severe crashes with pedestrians, bicyclists and lighter vehicles are known to be reported less (Alsop & Langley, 2001; Amoros et al., 2006; Elvik & Mysen, 1999). However, it should be noticed that bicyclists represent almost the half of all the killed or seriously injured in multiple-vehicle collisions at the investigated roundabouts, while they represent only 3.4 % of the present traffic volume.

8.6.3. Roundabout geometry

The variables OUTDIAM (inscribed circle diameter) with odds ratio 0.94 and GRADESEP (grade-separated cycle facilities) with odds ratio 16.46 were significant in the model for Y = killed on the crash level, which suggested that the probability of a fatality in the crash was somewhat lower in the case of a larger roundabout and strongly higher in the case of a crash on a roundabout with grade-separated cyclist facilities. Both results need some comments.

The role of the inscribed circle diameter could be explained by the fact that a larger obstacle free area improves the 'forgiving' capacity of a road since it provides for the same crash with the same impact more time and space for the involved vehicle(s) to slow down and therefore – according to Newtonian mechanics – reduces the amount of energy in the crash (Evans, 2004). Nevertheless, this result is unsure since the model for Y= killed or severely injured shows an estimated odds ratio of 1 for the variable OUTDIAM, meaning that the severity would be independent of the size of the roundabout.

The grade-separated cycle facilities (GRADESEP) showed only a significant effect in the model for Y= killed, but the result in the model for Y = killed or seriously injured showed the same tendency. Roundabouts with grade-separated cycle paths are constructed with tunnels allowing bicyclists to cross the roads without any conflict with motorised vehicles. At the first sight one would not expect a higher crash severity on this type of roundabouts. A possible explanation for this result could be related to some variables that correlate with the application of this intersection type. Roundabouts with grade-separated cycle facilities are likely to be constructed in cases in which the safety of cyclists is a particular concern, which could mean that they are constructed on locations with high volumes of motorised traffic and/or on arterial roads with high mean speeds. Those circumstances might explain the severity of the crashes that occur.

Inspection of the dataset learns that 3 people were killed on this type of roundabout whereas only 4 roundabouts were of this type (see Table 36). One of them was a private car driver in a single-vehicle crash, in two other cases motorcyclists were killed in collisions, once with a truck, another time with a private car.

8.6.4. Alcohol use

The results for the alcohol use deserve some extra attention. Previous research has shown that alcohol use may increase severity risk and thus not only the mere risk of a crash (Bédard et al., 2002; Waller et al., 1986), which provides a logical explanation for the tendency towards an odds ratio higher than 1 in case of a positive alcohol test. However, driving under influence is known to correlate with other behaviours such as speeding (Evans, 2004; Shinar, 2007). Since for instance speeding is not controlled for in the present study, it may on its turn be responsible for a part of the increased severity that is captured in the variable for alcohol use.

The significant positive effect in case of a not executed alcohol test needs some explanation. In a number of cases, the non execution might conceal an alcohol intoxication that was not measured or registered. This might indicate that alcohol testing is still not sufficiently a routine in case of car crashes. But another part of the explanation is likely to be related to the fact that not all victims were able to take part in the alcohol test by the police, for instance due to the severity of their injuries or due to the fact that they were carried to a hospital. The crash data don’t contain information, neither on whether a subject was carried or not to a hospital nor on the particular reasons for the non execution of an alcohol test. Inspection of the data reveals that the group of 1650 subjects for who no alcohol test was executed contains 141 killed and seriously injured for who the execution of an alcohol test on the crash location was not very likely. Other, less severely injured might have been carried directly to a hospital as well, without being tested on the crash location. Results of possible blood tests in hospitals are not registered in the police data that are used for official crash reporting.

8.6.5. Gender and age

In our data, gender did not show a consistent nor significant effect on the risk of serious or fatal injuries. Yet, research has found higher probabilities for females to get killed in crashes with the same impact than males (Evans, 2004). Again, the reporting rate could in the present case be somewhat influential, although most studies revealed no meaningful differences between reporting rates between males and females (Alsop & Langley, 2001; Amoros et al., 2006).

Age did have an effect, although it was not significant for each category. The higher the age category, the higher the odds ratio was for all categories above 29, with the age group 15-29 as a reference category. For the age group below 15, the odds ratios delivered no clear picture. The increased severity for higher age categories corresponds with existing knowledge (Bédard et al., 2002; Evans, 2004).

Possible differences in the reporting rate could again provide an alternative explanation for the stated effect of age. Amoros et al. (2006) found a slight association between age and reporting rate with a somewhat higher reporting rate for older age categories. Other studies found no effect for age, but used smaller samples (Daniels et al., submitted) or found only a lower reporting rate for the age category 0-14 (Alsop & Langley, 2001) which is likely to have some alternative explanation, although these last authors controlled for road user type. If the reporting rate for crashes with subjects in younger categories in our sample would be somewhat lower than for older subjects, this would mean that the reported severity of the crashes with younger subjects in our sample tends to be somewhat overestimated in comparison with the severity for the older subjects' crashes (under the assumption that the most severe crashes are more correctly reported, regardless of the age category). In that case, the stated effects for age in Table 51 seem even to be underestimated. Anyway, a slight difference in reporting rate is not likely to affect the stated effects of age.

8.6.6. Light conditions

The stated results in Table 51 show a tendency toward more severe crashes at night. Obviously, this variable could act as a confounder for some other, unobserved but correlated variables such as differences in speeds (for instance due to less busy traffic conditions), in travel purposes or in driver characteristics at night. Other possible explaining variables that are likely to be different are present in the model and are therefore controlled for: road user type, alcohol use, age and gender. Again, the reporting rate might be influential as well. Amoros et al. (2006) found an estimated significant 9% higher probability for crashes at night to be reported compared with daylight crashes. But if this estimation would be valid for our dataset and assuming that more severe crashes are more correctly reported, regardless of their time of occurrence, the stated effect in Table 51 would only be reinforced.

8.6.7. Built-up area

The logistic regression results show that crashes inside built-up areas are significantly less severe than crashes outside the built-up area. Differences in reporting rate are not very likely for this variable. The most likely interpretation for this result seems that the distinction inside versus outside the built-up area correlates with other, not incorporated variables. Since mainly approaching speeds at roundabouts are expected to be much lower inside then outside built-up areas, this seems to be a plausible factor.

8.7. CONCLUSIONS

To sum up, the following conclusions can be made:

- A clear externality of risk seems to be present in the investigated dataset. The crash severity is strongly dependent of the involved types of road users. Pedestrians, bicyclists, moped riders and motorcyclists have a higher probability of getting seriously injured in a crash. Bicyclists represent almost the half of all the killed or seriously injured in multiple-vehicle collisions at the investigated roundabouts.
- Fatalities or serious injuries in multiple-vehicle crashes for drivers of four-wheeled vehicles at roundabouts are relatively rare.
- A higher age does increase the probability of a severe or fatal injury. This result corresponds with existing knowledge.
- Crashes at night, crashes outside the built-up area and crashes at roundabouts with grade-separated cycle facilities turn out to be more severe. Correlations of these variables with unobserved but important variables, in particular with impact speeds, might be present and explain their role in the models better.
- Systematic differences in the reporting rate of crashes according to road user type, the number of involved road users and crash severity are likely to exist and may cause the stated results to be under- or overestimations of the real effects on crash severity. Particularly prone to a bias due to a different reporting rate, are the more severe outcomes for single-vehicle crashes. It is therefore impossible to conclude whether single-vehicle crashes were in general more severe or not. Other results, such as the effects of the road user type, age, geometry and light conditions are less likely to be substantially influenced by a different reporting rate.

Chapter 9. General conclusions

The previous chapters described different approaches for the empirical assessment of the safety performance of roundabouts. Clearly, the main research objective of this thesis was to improve knowledge and insights on safety issues at roundabouts. The designs and methods that were applied were seen in the first place as helpful tools. Improvement of these tools as such was not aimed. Although the central study object was identical throughout the whole document, the viewpoints in the subsequent chapters were different since different analysis methods (crash prediction models, before-after studies, crash severity models) were adopted in order to obtain as much as possible information about influencing factors on safety performance of roundabouts. Moreover, the scopes of the chapters were not always equal since Chapter 4 and Chapter 5 were dedicated to the particular effects on crashes with bicyclists whereas the analyses in the following chapters had a more general focus. Each of these approaches enabled partial conclusions, but showed some uncertainties and limitations as well. In the final part of this manuscript, it is therefore useful to put some pieces of the puzzle together in order to obtain a more complete view on the revealed results.

This chapter is divided in three sections. The first chapter treats the general conclusions that can be drawn, based on the executed analyses. In the second section, some policy recommendations are provided. Finally, some ideas are provided for future research in this field.

9.1. CONCLUSIONS

The cross-section analyses in Chapter 6 and Chapter 7 show that variations in crash rates at roundabouts are relatively small and mainly driven by traffic exposure. The overall number of crashes is proportional to the number of motorized vehicles. The mean number of single-vehicle crashes per passing vehicle is lower on busier roundabouts.

Vulnerable road users (moped riders, motorcyclists, bicyclists, pedestrians) are more often involved in injury crashes at roundabouts then could be expected based on their presence in traffic. Moped riders and motorcyclists are strongly overrepresented in single-vehicle crashes whereas moped riders, bicyclists and motorcyclists are overrepresented in multiple-vehicle crashes.

A clear externality of risk appeared to be present. The crash severity turned out, according to the analyses in Chapter 8, to be strongly dependent on the involved types of road users. Pedestrians, bicyclists, moped riders and motorcyclists have a higher probability of getting seriously injured in a crash. Bicyclists represent almost the half of all the killed or seriously injured in multiple-vehicle collisions at the investigated roundabouts. Fatalities or serious injuries in multiple-vehicle crashes for drivers of four-wheeled vehicles are relatively rare.

The executed analyses confirm the existence of a 'safety in numbers' effect for different road user types at roundabouts (Chapter 6 and Chapter 7). At least, this effect is visible for bicyclists, moped riders, motorcyclists, heavy vehicles and for pedestrians. Most likely, this seems to be an application of the "law of rare events", stating that the more rarely a certain traffic hazard is encountered the greater its effect is on the crash rate.

The before-and-after analyses in Chapter 4 showed that the construction of a roundabout generally increased the number of severe injury crashes with bicyclists, regardless of the design type of cycle facilities. Although the existing literature and guidelines contain many concerns about safety issues for bicyclists at roundabouts, this was an unexpected result. Previous research still showed a favourable, but much smaller effect of roundabouts on the number of crashes with bicyclists. The present result raises a policy dilemma since the effects of roundabouts on crashes for all road users together were previously sufficiently proven to be favourable, whereas this is clearly not the case for one particular subgroup.

Roundabouts with cycle lanes close to the roadway perform worse than roundabouts with other types of cycle facilities, particularly in comparison with roundabouts with cycle paths on a larger distance from the roadway. Although it is not clear in the crash prediction models in Chapter 6 and Chapter 7 whether the cycle lanes are performing worse than the other three types (mixed traffic, cycle paths and grade-separated) or, slight oppositely, the cycle paths are performing better than the three other types, the results of the before-after analyses in Chapter 5 were more clarifying. It is therefore concluded that roundabouts with cycle lanes perform worse than the other types.

Like was shown in Chapter 5 roundabouts that are replacing signal-controlled intersections have had a worse evolution for cyclists compared with roundabouts on other types of intersections. More in general, it appeared in Chapter 6 that roundabouts replacing signal-controlled intersections correlated with a higher number of crashes for all road user types than other roundabouts. Nevertheless, this variable might have acted as a confounder for a higher complexity of intersections that were previously equipped with traffic signals and did for some reason not appear to work properly.

Furthermore Chapter 6 and Chapter 7 showed that more crashes occur at three-leg roundabouts compared with roundabouts with four or more legs. Some other infrastructural variables relate as well to a higher number of crashes: the larger the central island, the more single-vehicle crashes seem to occur. More crashes with light vehicles and more multiple-vehicle crashes (which are to a certain extent overlapping groups) seem to occur at roundabouts with bypasses for traffic in some direction. Finally fewer crashes seem to occur at more recently constructed roundabouts.

The analyses of the crash severity in Chapter 8 showed that a higher age of the involved did increase the probability of a severe or fatal injury, which corresponded with existing knowledge. Furthermore crashes at night, crashes outside the built-up area and crashes at roundabouts with grade-separated cycle facilities turned out to be more severe. However, correlations of these variables with unobserved but important variables, in particular with impact speeds, might have been present and could explain their role in the models better. Systematic differences in the reporting rate of crashes according to road user type, the number of involved road users and crash severity are likely to exist and may have caused the stated results on crash severity to be under- or overestimations of the real effects. Particularly prone to a bias due to a different reporting rate, were the more severe outcomes for single-vehicle crashes. It is therefore impossible to conclude whether single-vehicle crashes were in general more severe or not. Other results, such as the effects of the road user type, age, geometry and light conditions were less likely to be substantially influenced by a different reporting rate.

9.2. SOME POLICY RECOMMENDATIONS

The scientific domain in which this work was executed is likely to yield some interest from those who are in charge of road infrastructure management. Moreover some of the revealed results might shed a new light on some previously established knowledge on this topic. It is therefore useful to propose some policy recommendations based on the stated results. However it might be argued as well that the conclusions above show that some uncertainties persist about the direction and the magnitude of certain effects. Moreover, possible confounders complicate the interpretation of the results. Therefore it could be argued from a strictly scientific point of view that deriving conclusive policy recommendations is in essence not possible based on particular results of some particular studies. In that sense, an option could be to abstain from any statement and to declare that the topic should be investigated further before a full scientific basis could be provided for a rational road infrastructure policy.

Nevertheless I believe that this dissertation can provide some useful elements that could be integrated in roundabout design guidelines and practices. These elements must be seen in the perspective of a gradually progressing scientific knowledge on some contributing factors to the safety performance of roundabouts. Together with previous results, they provide the current knowledge on this issue. Hopefully this knowledge will further develop in the future. Meanwhile, the best available knowledge should be reflected in design standards and practices.

The before-and-after analyses showed that the construction of a roundabout generally increases the number of injury crashes with bicyclists. The increase appeared to be mainly an issue on roundabouts with cycle lanes. Nevertheless, for the most severe crashes, the increase appeared to be rather general. At the same time there is no reason to question the well established favourable effects of roundabouts on crashes in general. Consequently, the stated results in this thesis may raise a policy dilemma in the sense that it could be questioned whether the construction of roundabouts should be promoted or discouraged. A strictly rational approach would probably argue that an overall reduction of crashes should prevail, even if one particular subgroup (i.e. bicyclists) is not benefitting. But this approach might evoke strong counterarguments, not at least since the promotion of cycling is believed to fit in a policy on sustainable development (see for instance Banister, 2008).

Based on the stated results, I want to give a double policy recommendation with respect to the issue of the cycle facilities. Firstly, it might be careful not to construct roundabouts at locations where cyclist safety is of particular concern. In those circumstances other types such as signal-controlled intersections are more preferable. Examples of such locations are intersections inside built-up areas in low speed zones with high shares of pedestrians and cyclists. Secondly, if a well-considered decision is made to construct a roundabout, this should be not a roundabout with cycle lanes close to the roadway.

Another policy question is what should be done with existing roundabouts with cycle lanes. A recommendation that no roundabouts with cycle lanes should be constructed does not necessarily imply that every existing roundabout with cycle lanes should be redesigned in the short term into something else. Apart from possible cost-benefit considerations, it must be stated that no straightforward evidence exists that simply converting roundabouts with cycle lanes to another cycle design type without adapting other geometric variables would improve the safety for bicyclists. For instance, when a roundabout with cycle lanes is converted into a mixed traffic roundabout only by resurfacing the road or by erasing markings, the roadway will become wider and is likely to enable higher speeds that could in turn be responsible for a worse safety record. The fact that roundabouts with mixed traffic in the present study perform better than the roundabouts with cycle lanes could does not contradict this last argument.

Other policy recommendations relate as well to geometric variables. The fitted models showed effects for some manipulatable variables such as the number of legs or the presence of a bypass.

Bypasses correlate with more crashes. They should be avoided unless capacity requirements are not longer fulfilled. In that case, special attention should be given to possible conflicts between merging vehicles or conflicts between car drivers and crossing cyclists or pedestrians.

Three-leg roundabouts perform worse than roundabouts with four or more legs. I cannot imagine a real reason why a roundabout with three legs would show an intrinsic poorer safety record than a roundabout with more legs. Probably this type of roundabouts is often constructed with flaw approach angles and is therefore allowing higher speeds in some directions. From a safety perspective, it is therefore recommended to keep the angle of the approaches tight enough to reduce speeds sufficiently and to avoid heterogeneous speeds at roundabouts.

Larger central islands correlate with a higher number of single-vehicle crashes. However it is highly questionable whether reducing the size of central islands would result in a net benefit with respect to safety since –ceteris paribus - smaller central islands are related with higher speed at roundabouts due to the smaller imposed lateral deflection.

At least on the level of safety in the Flanders region where the investigated locations were all located, the stated results are valid for the whole population of roundabouts on regional roads. It is more unclear whether the results are valid for other countries and regions as well. One should be aware that the investigated design types are also used elsewhere and that an apparent overrepresentation of bicyclists in crashes at roundabouts was reported in several countries. At least, the results of the present work could serve as an appropriate indication for effects that are likely to occur in other settings as well.

9.3. PERSPECTIVES FOR FURTHER RESEARCH

The hope is that the present work provided some contribution to a better understanding of crash occurrence and severity at roundabouts. But in no way, this was an endpoint. Some important research questions were not dealt with or could not be answered. New questions appeared. Further research on different aspects of roundabout design and related safety performance will be required. This section provides a short view on possibly useful research directions.

9.3.1. Improved data

The size of the composed datasets for the different analyses (90 roundabouts, later extended to 148) was at least as large as what was previously common in this domain. However, for appropriate statistical analysis, a sample size of 90 or even 148 is still limited. Although the assembled dataset enabled to generate meaningful conclusions and new insights, many uncertainties are left. They will need further clarification in the future. By applying different analysis methods I aimed to reveal as much as possible from the existing structure in the data. To some this might look as overanalyzing the data, but every different technique showed some different things and enabled to get a better picture of the whole. However, available opportunities should be seized to further extend databases like the assembled one in the future.

Undoubtedly, further extensions should comprise larger samples of roundabouts with a particular geometry such as mini-roundabouts or the emerging type of turbo-roundabouts. The effects of those particular groups on safety performance might differ from the more common roundabout types and are not yet documented very well. Furthermore, increases in the sample size, the included number of variables and in the underlying data quality could enable to establish particular effects of roundabout lighting types on crashes at night or in bad visibility circumstances.

In the fitted cross-sectional models, it could not be excluded that significant variables in the dataset acted as proxies for other, influencing but unknown variables. Efforts should be done to include these variables in future models. In particular, some measures for real speeds at roundabouts are likely to contribute to both crash frequency and severity.

In the executed analyses, no confirmation was found for higher crash rates at double-lane roundabouts. In previous research, some effects for double-lane roundabouts were reported but this variable was often likely to be a confounder for traffic volume. Still, design guidelines express concerns about safety issues at double-lane roundabouts. At least this topic merits more profound research. Ideally, such a research would incorporate also crashes with property-damage only.

More in general, the addition of property-damage only crashes would allow establishing the general effects of roundabouts on this type of crashes. The effect is expected to be less pronounced than the effect on injury crashes. However, it should be investigated whether the effect is still favourable.

Since the present work showed clear evidence about the weaker position of bicyclists at roundabouts, a next step in research could be to reveal more deeply the underlying causal mechanisms for crashes with bicyclists at roundabouts. The present research was based on aggregate crash data and was of an epidemiological nature. It aimed to describe possible problems and effects of variations in design elements, but did not include in-depth analyses of crashes or events that preceded crashes on roundabouts. A supplementary approach could be to investigate some events or behaviours more into depth, for instance the yielding behaviour of car/truck drivers and bicyclists at roundabouts with certain designs. The latter approach could provide more insight in which road user behaviours and interactions are present in different roundabout settings, why they are done and why some of these behaviours lead to crashes.

I recommend constructing no longer roundabouts with cycle lanes close to the roadway. However, I argued that this does not necessarily mean that simply replacing existing cycle lanes with cycle paths or mixed traffic would improve the safety performance. This topic could be investigated further. Ideally, this could happen by a before and after analysis of a sufficient sample of roundabouts with cycle lanes that were (or will be) converted into roundabouts with other types of cycle facilities.

In the conclusions it was stated that a higher degree of ‘complexity’ of intersections could provide an alternative explanation for the apparent role of the fact that a roundabout was replacing a signal-controlled intersection. It would be therefore a challenge to try to give an operational definition of the complexity of an intersection and to examine possible ways to measure this concept.

9.3.2. Methodological improvements

The fitted cross-sectional models for roundabouts revealed the existence of underdispersion (variance smaller than the mean) in parts of the used dataset. Mainly the datasets with a very low sample mean (e.g. crashes for pedestrians) were affected by this phenomenon. The underdispersion of real-world observations causes some troubles both in a technical way - since commonly applied models are not able to account for it - but also in a more theoretical way since underdispersion could reveal a lack of structural variation.

In highway safety research, traditional Poisson and negative binomial models are the most common stochastic models to analyse observed crash data. Since underdispersion was encountered, I used gamma models to account for it. Lord et al. (2008; 2010) tested the application of Conway-Maxwell-Poisson models that are able to account for both over- and underdispersion. Their results indicate that the COM-Poisson models fitted better than the gamma models. It might be useful to check the performance of the COM-Poisson models also for datasets like the one that was developed in this thesis.

Another issue related with the phenomenon of underdispersion is even more fundamental. It could be argued that, if the variance does not exceed the mean, there is no systematic variation in the number of crashes. In that case there seems to be no systematic variation in the data anymore that can be explained by fitting risk models. Traditional crash risk models are based on the assumption that the random variability in datasets shows a Poisson distribution and any systematic variation comes from a higher dispersion (Fridstrøm et al., 1995; Hauer, 2001; Mitra & Washington, 2007). An observed underdispersion would therefore mean that there is nothing to explain anymore. Lord (2006) showed that low sample means combined with small sample sizes can seriously affect estimated dispersion parameters. Since the underdispersion that I encountered in the risk models was stronger in case of the models with the lowest sample means, there are reasons to believe that the observed underdispersion was related to the low sample mean problem and thus an artefact of the data. I preferred to remain on the safe side and to include the output for both the Poisson models and the gamma models since they each reflect a different approach to the assumed dispersion parameter. The fact that their results were relatively consistent supports the robustness of the conclusions that were derived. But still the issue remains on which approach should be preferred from a theoretical viewpoint. So far, no formal guidance seems to exist for this.

9.3.3. International perspective

Ideally, any future research in this domain should be done in a cross-country perspective in order to incorporate better existing differences in roundabout design guidelines and practices. The hope is that such a research would enable not only a better scientific knowledge on contributing factors, but would encourage as well more universally accepted design standards. The screening of the roundabout design guidelines in different countries in Chapter 2 revealed that the basic principles determining the design of roundabouts are similar for the different countries. Moreover, an increasing amount of knowledge seems to exist about issues such as the effects of certain angles of approaches, lateral displacement or potential conflict points. However, the way in which these principles are concretised in the design recommendations appeared to differ from country to country. The most important differences possibly exist with respect to the design of entry paths (flaring or not) and the design of cyclist facilities. Future research should reveal more formally which differences in roundabout design practices persist throughout countries and what consequences this has on traffic operations and safety. One limitation of the current thesis has certainly been that only a sample of roundabouts in one country has been investigated. A valuable future research challenge would therefore be to investigate a mixed sample of roundabouts from different countries, designed and built according to different guidelines, on their performance on both safety and traffic operations. Such a project would obviously require an international approach.

9.3.4. Surrogate safety measures

However, it seems that even the performance of the above mentioned research will not be sufficient in order to achieve a full understanding of all possible safety effects of roundabouts. Different authors have described very well the limitations of statistical crash analyses. Among the most important is the lack of possible control on many confounding variables due to the observational setting. Furthermore there use to be structural limitations of the underlying crash data such as underreporting, time-varying explanatory variables, low sample means, over/underdispersion and an excess of zeros. During the present PHD-project, it became clear that even a substantial extension of a composed dataset did not enable to understand substantially better the contributing effect of some basic design variables. Moreover it appeared that many findings in previously published papers were based on findings in cross-sectional risk models that were rather based on established correlations then on well-proven causal relationships. The question remains open how many extra data need to collected to show the effect of for instance particular shapes of the central island or the effects of some different priority rules for bicyclists. A supplementary approach could consist of examining the potential of some surrogate measures to describe the safety performance of some designs. An example of such an approach is provided in a recent paper (Sakshaug et al., n.d.). Possible surrogate measures are traffic conflicts or behaviours that are crash-correlated. Particularly factors that are most likely not substantial in explaining crash rates at an aggregate level of “all crashes at all roundabouts” might be assessed in a more valid way by observing their effects on human behaviour than on their final crash outcomes. Cases might be found in differences in roadway widths, in apron size and in distances between roadway and cycle facilities. Although stating effects directly on crashes should be considered to be a priori superior to stating effects based on some surrogate measures for crashes, the latter approach shows perspectives, both for practical and scientific purposes. Consequently I believe that this approach merits to be further developed.

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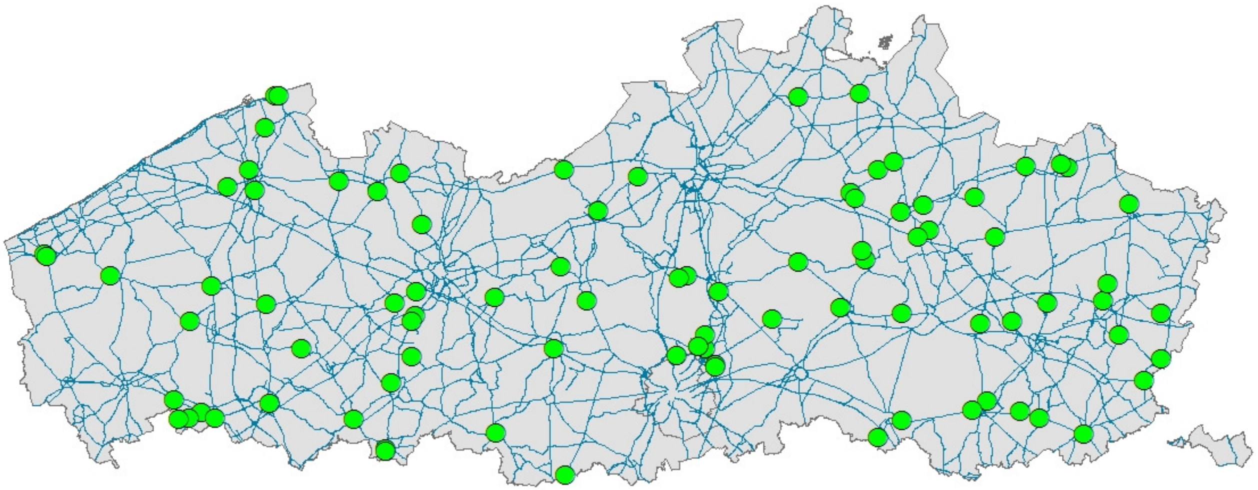
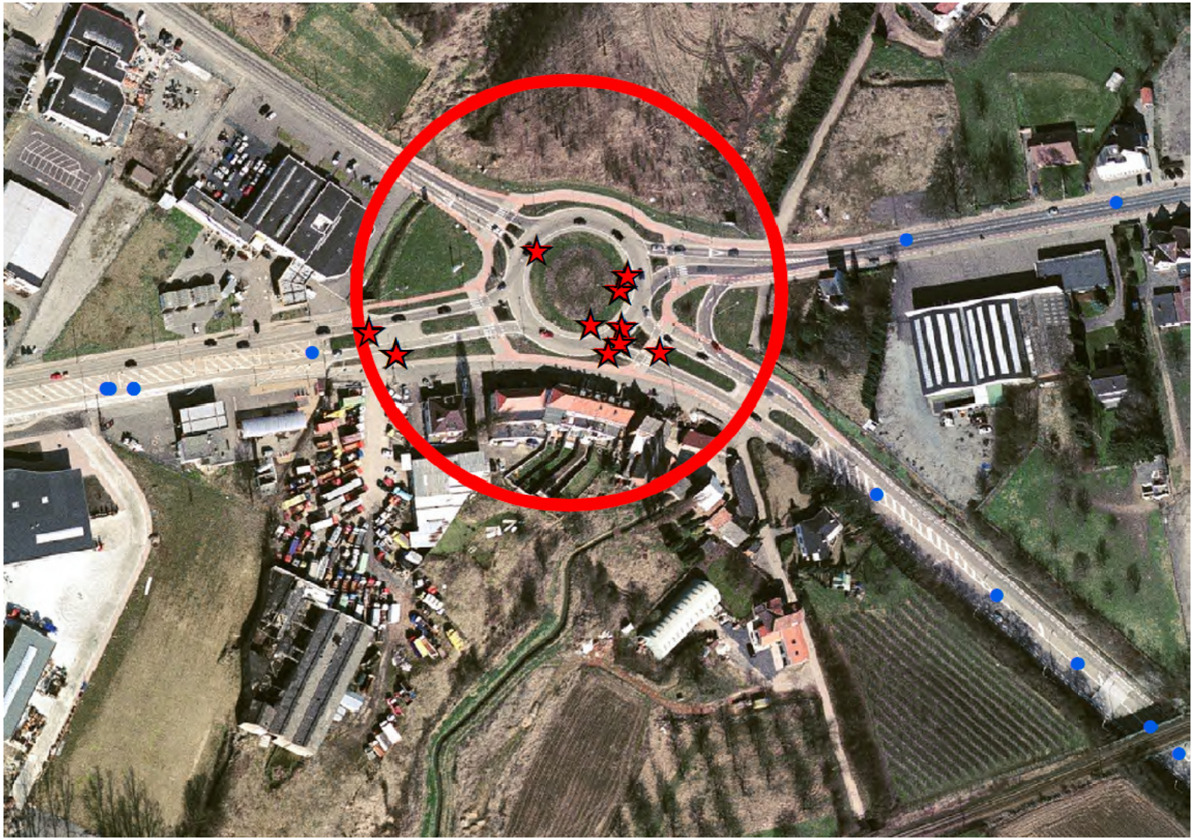
ANNEX 1 – MAP OF ROUNDABOUT LOCATIONS (N= 90)



ANNEX 2 – EXAMPLE OF GIS-LINK OF LOCATION AND CRASH DATA



ANNEX 3 – LIST OF EXAMINED ROUNDABOUTS

DESCRIPTION	MUNICIPALITY
ROT N405 AALST (HOUTEN HAND): N405 NINOVESTWG X N405A VILLALAAN X CHURCHILLSTWG	AALST
BEVRIJDINGSLAAN - BILZERWEG	AS
N9C X VLIEGWEZENLAAN	ASSE
N9 PONTBEEKLAAN X ZUIDERLAAN	ASSE
ROT N8 X N453 X N36	AVELGEM
ROTONDE N136 X SOEF	BALEN
ROTONDE R25 X N21B	BEGIJNENDIJK
ROT N70 X KLOOSTERSTRAAT	BEVEREN
N730 BELISIA TUNNEL	BILZEN
N730 PARKLAAN EIKENLAAN	BILZEN
N2 X N700	BILZEN
HASSELTSESTR-LAMBERTUSLAAN	BILZEN
DORPSSTRAAT-KERKPLEIN	BOCHOLT
ROT N777 DAALHOFSTRAAT X BERGSTRAAT	BORGLOON
ROTONDE N079 SINT_TRUIDERSTEENWEG X N784 NEREMSTRAAT	BORGLOON
ROTONDE N131 X EESTER	BRECHT
ROTONDE N76 X N731 X N76H	BREE
HAVENRANDWEG ZUID X ZONNEBLOEMWEG	BRUGGE
ROT N9 OOSTENDSESTEENWEG X SCHEEPSDAALLAAN X N371	BRUGGE
ROT N342 SPOORWEGSTRAAT X CASENBROOTLAAN	BRUGGE
INGANG CAMPUS	DIEPENBEEK
LEUVENSEPOORT	DIEST
HASSELTSEPOORT	DIEST
ROT N35 X STEENBAKKERIJSTRAAT	DIKSMUIDE
ROT N499 X RAVERSCHOOTSTRAAT	EEKLO
ROT N456 X SLEIDINGE DORP	EVERGEM
ROTONDE R14 X N71	GEEL
ROTONDE R14 X N19	GEEL
R14 - KONING ALBERTSTRAAT	GEEL

DESCRIPTION	**MUNICIPALITY**
R14 - N126 WINKELOM	GEEL
ROTONDE N744 X ONAFHANKELIJKHEIDSLAAN	GENK
HOEVENZAVELLAAN - ACHTERSTRAAT	GENK
N702	GENK
ONDERWIJSLAAN - DUMONTLAAN	GENK
N779 CMINE	GENK
COPPEELAAN - HENGELHOEFSTRAAT	GENK
ROTONDE N43 X HEMELRIJKSTRAAT	GENT
ROT N495 ZONNEBLOEMSTRAAT X WEVERIJSTRAAT	GERAARDSBERGEN
N202 ST ANNALAAN ROMEINSE STEENWEG	GRIMBERGEN
ROTONDE N21 X JENNEKENSTRAAT	HAACHT
N2 COMPLEX E314	HALEN
COMPLEX 25 WEST	HAM
COMPLEX 25 OOST	HAM
HASSELT(STOKROOI) : N729 STOKROOIEWEG(KMP:3.325) X ST AMANDUSSTRAAT X WATERLOZESTR	HASSELT
LANGWEG HERCKENRODESINGEL	HASSELT
ROTONDE N10 X N15	HEIST-OP-DEN-BERG
ROTONDE N153 X AUGUSTIJNENLAAN	HERENTALS
ROTONDE N123 X N153	HERENTALS
STEVOORTWEG-RIDDERSTRAAT	HERK - DE - STAD
N716 SINT-TRUIDERSTEENWEG	HERK - DE - STAD
KIEZELWEG-ST-JANSSTRAAT SCHULEN	HERK - DE - STAD
ROTONDE N717 SCHULEN NEERSTRAAT ST JORISLAAN	HERK-DE-STAD
ROTONDE N285 X VAN CAUWENBERGHELAAN	HERNE
ROTONDE N15 X N152	HERSELT
N29 X N221	HOEGAARDEN
N29 COMPLEX E40 ZUID	HOEGAARDEN
ROT N36 X N313	HOOGLEDE
ROT N367 X OUDE DORPSWEG	JABBEKE
ROT N456 X VROUWSTRAAT	KAPRIJKE
ROTONDE N19 X N19G TURNHOUTSEBAAN	KASTERLEE
ROTONDE N123 X N134	KASTERLEE
N2XN725	KERMT

DESCRIPTION	MUNICIPALITY
N73XN751	KINROOI
ROT N34 X MEERLAAN	KNOKKE-HEIST
ROT N34 X KONINGSLAAN X PARMENTIERLAAN	KNOKKE-HEIST
N10 X VAN HOOLSTRAAT	KONINGSHOOIKT
N10 X BURG. HENSSTRAAT	KONINGSHOOIKT
ROT ROMEINSELAAN X ZWEVEGEMSESTRAAT	KORTRIJK
ROTONDE N174 X A13 X NIJVERHEIDSWEG	LAAKDAL
N141 X N174	LAAKDAL
ROTONDE N2 X N78	LANAKEN
ROTONDE N78 X N78A	LANAKEN
TOURNEBRIDE NOORD	LANAKEN
N78XGROENSTRAAT	LANAKEN REKEM
ROT N47 X LINDENLAAN	LEBBEKE
ROTONDE N72XN73XN141	LEOPOLDSBURG
N73	LEOPOLDSBURG
ROT N32 X N35	LICHTERVELDE
ROTONDE N712 N NEECKLAAN X N746 STATIONSTRAAT	LOMMEL
N712XN715	LOMMEL
N71 X MERCATORSTRAAT	LOMMEL
N717 X OOSTEREINDESTRAAT	LUMMEN
OPOETEREN DILSERWEG - ZANDSTRAAT	MAASEIK
ROTONDE N763 SMEETSLAAN X RINGLAAN	MAASMECHELEN
COMPLEX E314	MAASMECHELEN
A201 MACHELEN - HERMESLAAN	MACHELEN (DIEGEM)
ROTONDE N9 X N44A X N410A	MALDEGEM
ROTONDE KON. ALBERTPLEIN N001 X N001A	MECHELEN
B101 - BEDRIJVENLAAN	MECHELEN
ROTONDE N102 X N126	MEERHOUT
ROT N8 X LEOPOLDPLEIN X FABIOLALAAN	MENEN
ROTONDE N124 X 132 LEOPOLDSTRAAT X LEEST	MERKSPLAS
ROT N60 X BEGONIASTRAAT	NAZARETH
ROTONDE N60 X N60C OUDE STEENWEG	NAZARETH
ROTONDE N76 X WEG NAAR ZWARTBERG	OPGLABBEEK

DESCRIPTION	**MUNICIPALITY**
ROT N60 X PRUIMELSTRAAT	OUDENAARDE
N790 HAAGDOORNDIJK X FABRIEKSTRAAT	OVERPELT
N712 KON ALBERTLAAN X N790 HAAGDOORN X N712A LEOPOLDLAAN (GAMMA)	OVERPELT
N712	OVERPELT
N73B	PEER
N73 X N747	PEER
ROT N35 X STATIONSSTRAAT	PITTEM
ROT N48 X N60B	RONSE
ROT N36 X SNOEKCLAAN	RONSE
N19 - STATIONSSTRAAT	ROTSELAAR
N212 - WEG MESSELBROEK	SCHERPENHEUVEL - ZICHEM
ROTONDE N10 X N212	SCHERPENHEUVEL-ZICHEM
ROTONDE N43 X N437	SINT-MARTENS-LATEM
ROT N16 X N70	SINT-NIKLAAS
ROTONDE STAAIEN (N3 60,1 X N3E X ZOUTLEEUWSESTEENWEG	SINT-TRUIDEN
ROTONDE N722 X TERBIEST	SINT-TRUIDEN
ROT N403 X N49ZUID	STEKENE
HAVENLAAN - KANAALWEG	TESSENDERLO
EERSELS-RODE HEIDE	TESSENDERLO
N174-SPARRENWEG	TESSENDERLO
N725-INDUSTRIEWEG	TESSENDERLO
INDUSTRIEWEG-PAALSEWEG	TESSENDERLO
N2 X N223	TIELT - WINGE
ROTONDE R27 X N3 RING OOST	TIENEN
R27 X GRIJPENLAAN	TIENEN
R27 X N29	TIENEN
ROTONDE LUIKERSTEENWEG (N20 19,2) X WIJKSTRAAT	TONGEREN
ROMEINSE KASSEI - RKL	TONGEREN
ROT N39 X BENOITLAAN X DEHAENELAAN	VEURNE
ROT N8G X LINDENDREEF X P. BENOITLAAN	VEURNE

DESCRIPTION	MUNICIPALITY
ROT N8G X N392VEURNE : N392 (KM 1,459) ZUIDBURGWEG X N8G IEPERSE STWG X KAN. J. CLOUSTRAAT	VEURNE
ROTONDE N1 X R22	VILVOORDE
ROTONDE R22 X N211	VILVOORDE
ROTONDE N21 X TUCHTHUISSTRAAT	VILVOORDE
ROTONDE N1 X N211	VILVOORDE
ROTONDE N202 X RAVENLAAN	VILVOORDE
R22 WOLUWELAAN X MONNETLAAN	VILVOORDE
ROT N8 X N58 GELUWE	WERVIK
ROT N58 X N303	WERVIK
ROT N58 X N311	WERVIK
ROTONDE N152 X GEVAERTLAAN	WESTERLO
ROT N407 X COOPPALAAN	WETTEREN
ROT N357 X BREESTRAAT	WIELSBEKE
ROTONDE N16 X BLAASVELDSTRAAT	WILLEBROEK
ROTONDE N16 X N183 BLAASVELD	WILLEBROEK
ROTONDE A201 X N262	ZAVENTEM
ROTONDE N262 X HEIDESTRAAT	ZAVENTEM
ROTONDE N47 X DENDERMONDEBAAN X OOSTELIJKE OMLEIDING	ZELE
ROT N435 X AMELOTSTRAAT	ZINGEM
N715A HOUTHALENSEWEG X KLEINE HEMMENWEG X SPRINKWATERSTRAAT	ZONHOVEN
ROT N8 X N303 MENENSTRAAT X WERVIKSTRAAT	ZONNEBEKE
ROTONDE N77 X N730 MP 19800	ZUTENDAAL
N70 BEVERSEBAAN	ZWIJNDRECHT

N =148