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DOCTORAL DISSERTATION
Identification and in-depth analysis of patterns of behaviour, conflicts and accidents on intersections

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Executive summary

The main purpose of this doctoral dissertation is to identify and provide an in-depth analysis of patterns of behaviour, conflicts and accidents on intersections.

Intersections are an integral part of the road traffic system. These locations facilitate movement of different road users in conflicting directions and allow to change travel direction. Because of this distinguished characteristic, intersections present a discontinuity and are considered as one of the most dangerous parts of the road network. The fact that these sites are regarded as high-risk locations stems from the complex nature of intersections. Due to the convergence of multiple vehicle streams, road users are required to make multiple decisions in a limited amount of time and often at high speeds. Furthermore, the numerous intersection types (i.e. roundabouts, signalized intersections, non-signalized intersections, etc.) that are present within the road network further enhance their complex nature.

Road safety at intersections also seems to be a persistent problem. In Europe, the overall number of accident and injured road users has decreased over the years whereas the number of accidents, fatally and severely injured road users at intersections has remained relatively constant over the past years. This is also the situation in Flanders, Belgium. Therefore, these locations are awaiting a solution to improve road safety.

The traditional approach to study road safety at intersections can be described as reactive and collision-based. However, this approach has many disadvantages. Road safety research can therefore strongly benefit from road safety techniques, which make use of empirical non-crash data. The term ‘non-crash’ in this context means that these data are not based on accidents, but rather rely on other occurrences in traffic that are causally related to accidents (i.e. near-accidents). In contrast to accident data, these techniques allow to examine the interaction process between the different components of the road traffic system and provide insights in the situational aspects that precede accidents. In that respect, these proactive techniques provide a more comprehensive analysis of the road safety situation at intersections, as they are able to capture how safety problems arise and unfold. Within this research, the following proactive road safety techniques are applied to investigate intersection safety: the on-site traffic conflict observation technique, the on-site behavioural observation technique and a driving simulator study. Besides these proactive techniques, the reactive road safety technique based on accident data will also be used to gain insights in the road safety situation at intersections.

Therefore, the following four studies conducted within the frame of this doctoral dissertation have not only provided improved insights into intersection safety but also led to detailed insights in the use of crash and empirical non-crash data to study policy-relevant road safety issues.

In chapter 2, an exploratory study is performed in order to gain more insights in the dominant accident patterns at roundabouts by including the accident location in the analysis. An analysis of 399 injury and property damage–only accidents on 28 roundabouts in Flanders, Belgium, was carried out based on detailed accident descriptions; that is, accident data and collision diagram information. The accident data were sampled from police-reported accident at roundabouts in the region of Flanders, Belgium (period 2005–2010). More specifically, accident characteristics, location characteristics and the exact position of the accident were determined for a subset of roundabout locations. For this purpose, a protocol was developed to divide the roundabout location into 11 detailed and different segments. Furthermore, the information of the collision diagrams was also used to distinguish eight different accident types. The eight roundabout accident types were examined by injury severity, accident location within the roundabout, type of roundabout, type of cycle facility and type of involved road user.

The results revealed that four dominant accident types occurred at roundabouts: rear-end accidents, single-vehicle collisions with the central island, collisions with vulnerable road users and entering–circulating accidents. Accidents with vulnerable road users and collisions with the central island were characterised by significantly higher proportions of injury accidents. Rear-end accidents predominantly occurred in the zones before entering the roundabout (segment 1 and 2) while nearly all accidents in the zones close to the central island (segment 4) were single-vehicle collisions with this island. Vulnerable road user accidents mostly took place in the zone where drivers left the roundabout and crossed the path of circulating cyclists (segments 6 and 7). Entering–circulating accidents primarily dominated the location where the entry lane is connected to the circulatory road (segment 3). Road users who were the most at risk to be involved in serious injury crashes at roundabouts were cyclists and moped riders. Furthermore, it was also found that certain roundabout design characteristics were related to accident occurrence.

Chapter 3 focuses on identifying accident patterns on signalized intersections. For this purpose, 1295 police-reported injury and property damage–only crashes at 87 signalized intersections in Flanders, Belgium (period 2007-2011) were analysed. The analysis was carried out based on detailed accident descriptions, that is, accident data and collision diagrams. The information from the collision diagrams was used to distinguish six different crash types and to create an accident location typology to divide the signalized intersection into 13 detailed segments. Logistic regression modelling techniques were used to identify relations between accident types, their accident location on certain signalized intersection segments, the accident severity and the different features that affected accident occurrence.

The results revealed four dominant accident types: rear-end, side (i.e. left-turn plus right-angle), head-on and vulnerable road user accidents. Additionally, side, head-on and vulnerable road user accidents had a higher probability of resulting in injury accidents. Vulnerable road user accidents also had a higher probability of resulting in severe injuries. The findings also showed that there was a link between the occurrence of the dominant accident types and their location on the signalized intersection. Rear-end accidents predominantly occurred before the intersection (segments 1-3) and on the bypass (segments 12-13). Side and head-on accidents mostly took place on and in the vicinity of the intersection plane (segments 4-6). Vulnerable road user accidents primarily occurred at the crossing facilities after the intersection plane (according to the perception of the motorised road users) (segments 7-8) or on the bypass (segment 12). The results also revealed important signalized intersection features that affected accident occurrence.

In chapter 4, more insights are provided into drivers' behavioural responses to speed and red-light cameras. Worldwide, signalized intersections have been equipped with enforcement cameras in order to tackle red-light running and often also to enforce speed limits. However, various impact evaluation studies of red-light cameras (RLCs) showed an increase of rear-end collisions (up to 44%). Therefore, the principal objective of this study was to provide a better insight in possible explaining factors for the increase in rear-end collisions caused by placing combined speed and red-light cameras (SRLCs). For this purpose, drivers' behavioural responses to SRLCs were studied in a before and after study at two signalized intersections where SRLCs were about to be installed.

The implementation of SRLCs was evaluated on-site by observing and analysing driver behaviour in traffic conflict situations and in normal encounters (period 2012-2013). One signalized intersection was also rebuilt in a driving simulator equipped with an eye tracking system. At this location, two test conditions (i.e., SRLC and SRLC with a warning sign) and one control condition (i.e., no SRLC) were examined. The data of 63 participants were used to estimate the risk of rear-end collisions by means of a Monte Carlo Simulation. The results of the on-site observation study revealed decreases in the number of red and yellow light violations, a shift (i.e., closer to the stop line) in the dilemma zone and a time headway reduction after the installation of the SRLC. Based on the driving simulator data, the odds of rear-end collisions (compared to the control condition) for the conditions with SRLC and SRLC + warning sign amounted to 6.42 and 4.01, respectively. The results of the driving simulator study also revealed that drivers brake more abruptly in the presence of a SRLC. To conclude, the real-world and driving simulator observations indicated that the risk of rear-end collisions increases when SRLCs were installed. However, an indication was found that this risk might decrease when a warning sign is placed upstream.

In chapter 5, a behavioural analysis of vehicle-vehicle interactions at right-hand priority intersections and priority-controlled intersections is presented. The purpose of this study was to gain a better insight into safety differences between both types of intersections. Data about yielding, looking behaviour, drivers' age and gender, approaching behaviour, type of manoeuvre, order of arrival, and communication between road users were collected by on-site observations at one priority-controlled intersection and one right-hand priority intersection in Flanders, Belgium (period November to December 2011). Logistic regression models were built to identify variables that affect the probability that a violation against the priority rules will occur and the probability that a driver will look to the side when entering the intersection.

This behavioural analysis of vehicle-vehicle interactions revealed that the number of right-of-way violations was significantly higher at the observed right-hand priority intersection (27% of all interactions) than at the priority-controlled intersection (8%). Furthermore, the results revealed that the presence of an informal right-of-way at the right-hand priority intersection was responsible for the higher number of right-of-way violations. At both intersection types 'a first come, first served' tendency in yielding behaviour was revealed, since the probability for a violation was significantly higher when the no-priority vehicle arrived first. Furthermore, approach behaviour was also a significant predictor of right-of-way violations. At both intersections, the priority rule was more often violated when the no-priority driver accelerated or drove at a constant speed than when he or she decelerated/stopped. To conclude, looking behaviour also played a role in the occurrence of right-of-way violations. At the right-hand priority intersection, the probability to violate the priority rule was higher when the driver did not look to the side(s). At the priority-controlled intersection, the probability to violate the priority rule was higher when the driver on the main road looked to his or her right side.

Chapter 6 draws upon the entire dissertation. Based on the identified patterns of behaviour, conflicts and accidents, several policy recommendations are proposed aimed at improving intersection safety. Furthermore, several important insights regarding the use of accident data and techniques for observing empirical non-crash data are described. In their own way, each of the applied techniques definitely has a merit in conducting road safety research. For instance, accident data analysis are very useful for problem identification purposes whereas on-site traffic conflict and behavioural observation techniques and driving simulator studies are more useful for road safety problem analysis purposes and to evaluate road safety measures. Moreover, the results of all the techniques can also be applied for policy and monitoring purposes.

Additionally, the potential of combining road safety techniques to develop an integrated approach to road safety diagnosis and evaluation is described. It is concluded that a definite merit lies in combining different road safety techniques to enrich the results from one technique with the complementary results from other technique(s) or to verify study results. Furthermore, the most important merit of the empirical non-crash data techniques lies in the possibility to study road safety from a systems’ perspective. Therefore, it can be recommended that countries that pursue a system-based road safety vision should adopt an integrated approach. This integrated approach should combine road safety techniques based on crash and empirical non-crash data in order to be able to investigate road safety from a system’s perspective, get an overview of the policy results and formulate future policy priorities to pursue an inherently safe road traffic system.

Nederlandstalige samenvatting

De focus van dit doctoraatsonderzoek ligt op het uitvoeren van een diepgaande analyse van de verkeersveiligheid op kruispunten door gedrags-, conflict- en ongevalspatronen te identificeren.

Kruispunten vervullen een belangrijke functie in het wegennet. Het zijn locaties in het wegennet waarbij weggebruikers uit verschillende conflicterende rijrichtingen elkaar ontmoeten en van rijrichting kunnen veranderen. Omwille van deze eigenschap, zijn kruispunten een discontinuïteit en worden ze beschouwd als één van de meest gevaarlijke en complexe locaties in het wegennet. Voor weggebruikers zijn kruispunten een complexe situatie die extra aandacht vergt. Terwijl weggebruikers deelnemen aan een interactie met andere weggebruikers, hun voertuig en de kruispuntomgeving dienen ze meerdere beslissingen te nemen onder tijdsdruk (en soms aan hoge rijsnelheden). Het complexe karakter van deze locaties wordt verder nog versterkt door de verschillende kruispunttypen (rotondes, verkeerslichtengeregelde kruispunten, voorrangskruispunten, kruispunten met voorrang van rechts, enz.) die aanwezig zijn in het wegennetwerk.

De verkeersveiligheid op kruispunten blijft ook een significant probleem. Door de jaren heen is het aantal ongevallen en gewonden in Europa globaal gedaald terwijl het aantal ongevallen, dodelijk en ernstig gewonde weggebruikers op kruispunten relatief constant gebleven is. Dit is ook de situatie in Vlaanderen (België). Het is daarom belangrijk om de verkeersveiligheid op kruispunten te verbeteren.

Traditioneel wordt de verkeersveiligheid op kruispunten onderzocht aan de hand van analyses van verkeersongevallendata. Ongevallendata worden echter gekenmerkt door een aantal belangrijke beperkingen. Verkeersveiligheidsonderzoekstechnieken die gebruikmaken van geobserveerde data van niet-ongevallengebeurtenissen kunnen daarom een belangrijke bijdrage leveren. De term 'niet-ongevallengebeurtenis' houdt in dat deze data niet afkomstig zijn van ongevallen, maar eerder gebaseerd zijn op andere gebeurtenissen in het verkeer die gerelateerd zijn aan ongevallen (i.e. bijna-ongevallen, risicogedrag, enz.).

In tegenstelling tot ongevallendata, laten deze technieken toe om het interactieproces tussen de verschillende componenten van het verkeerssysteem te onderzoeken en inzicht te verwerven in de gedrags- en situationele aspecten die voorafgaan aan ongevallen. In dat opzicht resulteren deze proactieve onderzoekstechnieken in een diepgaandere analyse van de verkeersveiligheidssituatie op kruispunten. Deze onderzoekstechnieken laten immers niet enkel toe om te identificeren welke verkeersveiligheidsproblemen plaatsvinden maar geven ook weer hoe deze problemen tot stand komen. Binnen dit doctoraatsonderzoek worden de volgende proactieve verkeersveiligheidstechnieken toegepast om de verkeersveiligheid op kruispunten te onderzoeken: locatiegebaseerde conflictobservaties, locatiegebaseerde gedragsobservaties en een rijsimulatoronderzoek. Naast deze proactieve onderzoekstechnieken zal de traditionele onderzoekstechniek gebaseerd op ongevallendata ook toegepast worden om inzicht te krijgen in de verkeersveiligheidssituatie op kruispunten.

De volgende vier case studies die in het kader van dit doctoraatsonderzoek zijn uitgevoerd, hebben hierdoor niet enkel bijgedragen tot een verbeterd inzicht in de verkeersveiligheid op kruispunten. Ze hebben ook geleid tot gedetailleerde inzichten in de toepassingsmogelijkheden van ongevallendata en verkeersveiligheidsonderzoekstechnieken die gebruikmaken van geobserveerde data van niet-ongevallengebeurtenissen.

Hoofdstuk 2 beschrijft de resultaten van een verkennende studie, nl. een gedetailleerde analyse van verkeersongevallenpatronen op rotondes. Het doel van deze studie was om meer inzicht te krijgen in de dominante verkeersongevallenpatronen door de locatie van het ongeval in de analyse op te nemen. Hiertoe werd een analyse van 399 letselongevallen en ongevallen met materiële schade uitgevoerd. De ongevallenpatronen van 28 rotondes in Vlaanderen (België) werden geanalyseerd door gebruik te maken van gedetailleerde ongevallendata, bestaande uit ongevallendata aangevuld met de exacte ongevalslocatie en informatie afkomstig uit manoeuvrediagrammen. Deze ongevallengegevens werden door de politie verzameld in de periode 2005-2010.

Dankzij deze verrijkte ongevallendata werd de ongevalsproblematiek op rotondes geanalyseerd op een gedetailleerder niveau door de rotondes verder op te delen in 11 gedetailleerde en specifieke locatiesegmenten. Aan de hand van manoeuvrediagrammen werden de ongevallen ingedeeld in 8 verschillende ongevalstypes. Vervolgens werden de ongevallen toegewezen aan een locatiesegment waarna de ongevallen werden geanalyseerd volgens ernst, betrokken weggebruikers, locatie en rotonde-ontwerp (type fietspad, aantal rijstroken).

De resultaten toonden aan dat vier dominante ongevalstypes plaatsvinden op rotondes: kop-staartongevallen, eenzijdige aanrijdingen met het middeneiland, ongevallen met zwakke weggebruikers en voorrangsongevallen bij het oprijden van de rotonde. De ongevalsernst bleek ook gerelateerd te zijn aan het ongevalstype aangezien ongevallen met zwakke weggebruikers en eenzijdige aanrijdingen met het middeneiland significant vaker resulteerden in ernstige letselongevallen. Kop-staartongevallen vonden hoofdzakelijk plaats op de toerit (segment 1-2) terwijl bijna alle eenzijdige ongevallen gebeurden in de omgeving van het middeneiland (segment 4). De ongevallen met zwakke weggebruikers vonden plaats op de afrit (segment 6-7) waar het gemotoriseerde verkeer de rotonde verlaat en in contact komt met zwakke weggebruikers. Segment 3 op de toerit werd voornamelijk gekenmerkt door voorrangsongevallen bij het oprijden van de rotonde. Verder werd ook vastgesteld dat bepaalde ontwerpkarakteristieken van een rotonde een rol speelden bij het voorkomen van een specifiek ongevalstype.

In hoofdstuk 3 ligt de nadruk op het identificeren van verkeersongevallenpatronen op verkeerlichtengeregelde kruispunten. In deze studie werden gedetailleerde ongevallendata (ongevallendata aangevuld met de exacte ongevalslocatie en manoeuvrediagrammen) van 1295 letselongevallen en ongevallen met materiële schade op 87 kruispunten met verkeerslichten in Vlaanderen (België) geanalyseerd. Deze ongevallengegevens werden door de politie verzameld in de periode 2007-2011. De manoeuvrediagrammen werden gebruikt om de ongevallen in zes verschillende ongevalstypes in te delen. Daarnaast werd de informatie afkomstig uit de manoeuvrediagrammen ook gebruikt om een ongevalslocatietypologie te ontwikkelen waarbij het verkeerslichtengeregelde kruispunt wordt opgedeeld in 13 typische en gedetailleerde kruispuntsegmenten. Vervolgens werden logistische regressieanalyses gebruikt om de relaties tussen de ongevalstypes, hun locatie op bepaalde kruispuntsegmenten, de ongevalsernst en de specifieke ontwerpeigenschappen van een verkeerslichtengeregeld kruispunt te identificeren.

De resultaten toonden aan dat verkeerslichtengeregelde kruispunten gekenmerkt worden door 4 dominante ongevalstypes: kop-staartongevallen, zijdelingse ongevallen, frontale ongevallen en ongevallen met ten minste één zwakke weggebruiker. Met uitzondering van de kop-staartongevallen, resulteerden deze ongevalstypes ook vaker in ernstige letselongevallen. Daarnaast bleek ook dat de ongevalslocatie van deze dominante ongevalstypes gerelateerd is aan bepaalde kruispuntsegmenten. Zo vonden kop-staartongevallen vaker plaats voor het kruispuntvlak (segment 1-3) en op de bypass (segment 12-13) terwijl zijdelingse en frontale ongevallen frequenter voorkwamen op het kruispuntvlak (segment 4-6). Het merendeel van de ongevallen met zwakke weggebruikers vond plaats op de oversteekvoorzieningen na het kruispuntvlak (segment 7-8) en op de bypass (segment 12). Verder werd ook vastgesteld dat bepaalde ontwerpkarakteristieken van een verkeerslichtengeregeld kruispunt een rol speelden bij het voorkomen van een specifiek ongevalstype.

In hoofdstuk 4 wordt beschreven op welke manier bestuurders hun gedrag aanpassen wanneer ze geconfronteerd worden met snelheids- en roodlichtcamera's (SRLC's). Overdreven snelheid en roodlichtnegatie zijn belangrijke oorzaken van ongevallen op verkeerslichtengeregelde kruispunten. Om dit gedrag te ontmoedigen worden verkeerslichtengeregelde kruispunten uitgerust met snelheids- en roodlichtcamera's. Verschillende effect-evaluatiestudies toonden echter aan dat de installatie van snelheids- en roodlichtcamera's het aantal kop-staartongevallen significant doet toenemen (tot 44%). Deze studie had als doel om een verbeterd inzicht te krijgen in welke factoren de gevonden stijging in kop-staartongevallen kunnen verklaren. Hiertoe werd het rijgedrag van bestuurders op twee kruispunten met SRLC’s geanalyseerd.

De effecten op het rijgedrag van naderende bestuurders werden geanalyseerd door locatiegebaseerde conflict- en gedragsobservaties te combineren met een rijsimulatoronderzoek. Video-opnames op twee verkeerslichtengeregelde kruispunten werden gebruikt om het bestuurdersgedrag voor de plaatsing van de SRLC te vergelijken met het bestuurdersgedrag na de plaatsing. Daarnaast werd één van deze twee kruispunten nagebouwd in de rijsimulator van het Instituut voor Mobiliteit (Universiteit Hasselt) met als doel om het rij- en kijkgedrag van bestuurders te evalueren. 63 deelnemers naderden het kruispunt in verschillende condities: controle conditie (geen SRLC), conditie met snelheids- en roodlichtcamera (SRLC) en de conditie met snelheids- en roodlichtcamera gecombineerd met een waarschuwingsbord (SRLCWS). De data van de 63 deelnemers werden vervolgens gebruikt om de kans op kop-staartbotsingen te voorspellen via een Monte Carlo simulatie.

De resultaten van de conflict- en gedragsobservaties toonden aan dat SRLC’s zorgen voor een daling in het aantal bestuurders die het oranje en rode verkeerslicht schenden, een verandering in het keuzegedrag in de dilemmazone en een kortere volgafstand. De resultaten van het rijsimulatoronderzoek geven ook aan dat de kans op een kop-staartbotsing hoger is in de SRLC- (6.42) en de SRLCWS-conditie (4.01) in vergelijking met de controle conditie (1.00). Daarnaast bleek uit het rijsimulatoronderzoek ook dat bestuurders bruusker remmen wanneer ze geconfronteerd worden met een SRLC. Samengevat, geven de resultaten van beide onderzoeken aan dat het risico op kop-staartongevallen stijgt wanneer SRLC’s worden geïnstalleerd. Aangezien waarschuwingsborden de neveneffecten lijken te nuanceren wordt aanbevolen om bestuurders goed te informeren wanneer ze een SRLC-kruispunt naderen.

Hoofdstuk 5 beschrijft de resultaten van een studie waarin voertuiginteracties op voorrangskruispunten en kruispunten met voorrang van rechts werden geanalyseerd. In deze studie lag de nadruk op het onderzoeken of het verschil in voorrangsregeling een invloed heeft op de verkeersveiligheid. Aan de hand van locatiegebaseerde gedragsobservaties op twee kruispunten (één voorrangskruispunt en één kruispunt met voorrang van rechts) in Vlaanderen (België, periode november-december 2012) werden verschillende gegevens verzameld: het voorrangsgedrag, het kijkgedrag, de leeftijd en het geslacht van de bestuurder, het naderingsgedrag, het manoeuvretype, de aankomstvolgorde (wie komt eerst aan) en de manier waarop weggebruikers met elkaar communiceren. Vervolgens werden logistische regressieanalyses gebruikt om het kijkgedrag en het overtreden van de voorrangsregels te analyseren.

De resultaten van deze gedragsobservatiestudie toonden aan dat de voorrangsregels vaker overtreden worden op het kruispunt met voorrang van rechts (27% van alle interacties) dan op het voorrangskruispunt (8%). Vervolgens bleek uit de resultaten ook dat het ontstaan van een informele voorrangsregel op het kruispunt met voorrang van rechts aan de basis lag van het hogere aantal overtredingen van de voorrangsregel. Op beide kruispunttypen bleek ook dat het verlenen van voorrang een gevolg was van ‘wie eerst komt, eerst maalt’. Het risico op het overtreden van de voorrangsregels nam immers significant toe wanneer de bestuurder die voorrang moest verlenen eerst aankwam op het kruispunt. Het naderingsgedrag van de bestuurders bleek ook een significante invloed uit te oefenen op het overtreden van de voorrangsregels. De voorrangsregels werden vaker overtreden wanneer de bestuurder die voorrang moest verlenen versnelde of een constante rijsnelheid aanhield. Tot slot, had het kijkgedrag van de bestuurders ook een invloed op het overtreden van de voorrangsregels. Op beide kruispunten werden de voorrangsregels vaker overtreden wanneer de bestuurders die voorrang moesten verlenen niet in de richting keken van de bestuurder die voorrang had.

Ten slotte, wordt in hoofdstuk 6 een overzicht gegeven van de belangrijkste conclusies van dit doctoraatsonderzoek. Op basis van de geïdentificeerde gedragspatronen, conflict- en ongevalspatronen worden verschillende beleidsaanbevelingen voorgesteld ter verbetering van de verkeersveiligheid op kruispunten. Vervolgens worden enkele belangrijke inzichten met betrekking tot het toepassen van ongevallendata en verkeersveiligheidsonderzoekstechnieken die gebruikmaken van geobserveerde data van niet-ongevallengebeurtenissen besproken. Er kan geconcludeerd worden dat elke gebruikte onderzoekstechniek een meerwaarde heeft bij het uitvoeren van verkeersveiligheidsonderzoek. Het analyseren van ongevallendata is zeer geschikt om verkeersveiligheidsproblemen te identificeren, terwijl locatiegebaseerde conflictobservaties, locatiegebaseerde gedragsobservaties en de rijsimulator nuttiger zijn voor het analyseren van verkeersveiligheidsproblemen en het evalueren van verkeersveiligheidsmaatregelen. Bovendien kunnen de resultaten van alle technieken ook gebruikt worden om het verkeersveiligheidsbeleid te monitoren.

Verder wordt ook beschreven welke opportuniteiten er liggen in het combineren van de verkeersveiligheidstechnieken om zo te komen tot een geïntegreerde aanpak voor het uitvoeren van verkeersveiligheidsevaluatie en -analyse. Door deze aanpak worden rijkere onderzoeksresultaten bekomen en kunnen de gevonden resultaten geverifieerd worden. De belangrijkste meerwaarde van de verkeersveiligheidsonderzoekstechnieken die gebruikmaken van geobserveerde data van niet-ongevallengebeurtenissen, is dat deze technieken toelaten om verkeersveiligheid te bestuderen vanuit een systeemperspectief. Daarom wordt aanbevolen dat landen die een systeemgebaseerde visie op verkeersveiligheid nastreven, een geïntegreerde aanpak dienen toe te passen om hun verkeersveiligheidsbeleid te evalueren. Het combineren van verschillende verkeersveiligheidstechnieken die gebruikmaken van ongevallendata en geobserveerde data van niet-ongevallengebeurtenissen is alvast een goede manier om verkeersveiligheid te bestuderen vanuit een systeemperspectief, beleidsdoelstellingen te formuleren en uiteindelijk te evolueren naar een inherent veilig wegverkeerssysteem.

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List of abbreviations

AADT	Annual average daily traffic
ADAS	Advanced driver assistance systems
AIC	Akaike information criterion
ANPR	Automatic number plate recognition
CI	Confidence interval
DAS	Data acquisition system
DOCTOR	Dutch Objective Conflict Technique for Operation and Research
DR	Deceleration rate
EEG	Electroencephalography
euroFOT	European field operational test
FL	Flanders
FOTs	Field operational tests
FWO	Flemish research foundation
GDP	Gross domestic product
HEP	Human Error Probability
IMOB	Instituut voor Mobiliteit / Transportation Research Institute
InDeV	In-depth understanding of accident causation for vulnerable road users
ITS	Intelligent transport system
OECD	Organisation for Economic Co-operation and Development
OR	Odds ratio
PCEs	Passenger car equivalents
PET	Post encroachment time
Prim	Primary
PROSPECT	Proactive safety for pedestrian and cyclists
RLC	Red-light camera
ROI	Regions of interest
SD	Standard deviation
Sec	Secondary
SHRP2	Strategic Highway Research Program 2

SLDP	Standard deviation of lateral position
SRLC	Speed and red-light camera
SRLCW	Speed and red-light camera warning sign
SSM	Surrogate safety measure
STCT	Swedish traffic conflict technique
SWOV	Institute for road safety research
TA	Time-to-accident
TLC	Time-to-line-crossing
TTC	Time-to-collision
TTCmin	Minimal time-to-collision
UDrive	European naturalistic driving study
USTCT	United States’ traffic conflict technique
VIF	Variance inflation factor
VNP	No-priority vehicle
VP	In-priority vehicle
VRU	Vulnerable road user
WHO	World health organization

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CHAPTER 1: GENERAL INTRODUCTION

1.1 About this doctoral dissertation

The road traffic system plays a vital role in our mobility behaviour and society. Ever since cars were first introduced, the number of vehicles has increased dramatically. In 1970, approximately 29.35 billion kilometres were driven on Belgian roads. By 2015 this number had risen to more than 100.31 billion vehicle kilometres (Statistics Belgium, 2017). The growing number of vehicle kilometres has gone hand in hand with a corresponding increase in the number of road user interactions. Besides this increase in our mobility, the issues involved with road traffic have also changed accordingly. The fact that road traffic injuries still remain a leading cause of preventable death in countries all over the world (World Health Organization, 2015), emphasises that road safety continues to be a growing issue of concern. Especially, since road accidents and their related consequences have a tremendous impact on our society in terms of physical, emotional, material and economic costs.

In order to increase road safety and achieve inherently safe road traffic, it is necessary to adopt an integral approach focusing on the three components of the road traffic system: the road environment, the vehicle and the road user (Salmon, Lenné, Stanton, Jenkins, & Walker, 2010; Salmon, McClure, & Stanton, 2012; Wegman, Aarts, & Bax, 2008). According to this principle, accidents are the result of a "disturbance" in the interaction process between the road environment, the vehicle and the road user. Within this process, the road user is a dynamic component who constantly makes decisions and acts according to feedback he/she receives from other road users, the vehicle and the road environment. Furthermore, the vehicle needs to support the performance of traffic tasks and protect the road user in case of an accident while the road environment needs to be designed in such a way to meet the road users' capacities and limitations (Wegman et al., 2008). Road safety is also strongly influenced by the quality of the interaction process and the communication that takes place between road users (Svensson, 1998). The quality of the interaction process is also closely related to the complexity of the road environment. For instance, specific sites within the road network are more often characterised by a higher level of unsafety than others (Weller & Schlag, 2007).

Intersections are a prime example of such a complex road environment. The complex nature of intersections stems from two aspects. Firstly, intersections are locations of the road network where roads and vehicle streams from different directions converge. Secondly, the various intersection types (i.e. roundabouts, signalized intersections, non-signalized intersections, etc.) that can be applied further enhance the complexity. In Belgium, approximately 34% of all traffic accidents with injuries in 2015 occurred at intersections (Statistics Belgium, 2016). This figure remained relatively constant over the years. Hence, intersections are considered as one of the most dangerous parts of the road network and are awaiting a solution to improve road safety. It is therefore at these locations that the quality of the interaction process is an important condition for road safety. New insights in the interaction process at intersections may be a first step to further improve road safety.

Consequently, the aim of this dissertation is to identify and provide an in-depth analysis of patterns of behaviour, conflicts and accidents on intersections in urban environments. Within this dissertation, special focus is on the interaction between the environmental and behavioural component and its relationship to road safety. In general, most studies on road safety at intersections do not examine road safety in concurrence with both environmental and behavioural aspects. On the one hand, studies are focusing on the relationship between the environmental component (infrastructure) and road safety, see for example the studies of Abdel-Aty & Keller (2005); Alarifia, Abdel-Aty, Lee & Park (2017); Daniels, Brijs, Nuyts & Wets (2011) or Montella (2011). On the other hand, research is focussing on the behavioural aspect related to road safety, see for instance the studies of Rosenbloom (2009) Björklund & Åberg (2005) and Marisamynathan & Perumal (2014). Only quite recently, studies have started to focus on studying both infrastructural characteristics and behavioural aspects, see for example Madsen & Lahrmann (2017) and Sakshaug, Laureshyn, Svensson, & Hydén (2010). Therefore, this dissertation will elaborate further on this path by focusing both on the environmental component as well as on the behavioural aspects in relation to intersection safety.

Traditionally, accident[1] data are used to identify which locations, target groups or risk increasing behaviours require attention (Svensson & Hydén, 2006) while a significant number of collisions need to occur before action is taken (de Leur & Sayed, 2003). However, this reactive approach has many disadvantages such as underreporting, random variation related to the rare nature of crashes and the impossibility to capture behavioural and situational aspects that precede the accident (Laureshyn, 2010). Because of these limitations, accident data alone are insufficient to capture the road safety situation at intersections as this research focuses on the interaction between the environmental and behavioural component and its relationship to road safety.

Based on the continuum of safety-related events (Hydén, 1987) (section 1.5.1), both reactive and proactive road safety techniques are used to study the road safety situation at intersections. Proactive techniques or road safety techniques based on empirical data of non-crash events allow to examine the interaction process between the different components of the road traffic system and provide insights in the situational aspects that precede accidents (sections 1.5 & 1.6). In that respect, these proactive techniques allow to apply a system approach to study road safety. Consequently, they also provide a more comprehensive analysis of

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[1] The terms 'accident' and 'crash' are used synonymously in this dissertation. The author does not differentiate between both terms in relation to the context.

the road safety situation at intersections, as they are able to capture how safety problems arise and unfold.

Within this research, these techniques are based on the direct observation of events resulting from processes similar to accidents (traffic conflicts), on the observation of driving behaviour and performance in different events in a controlled environment (driving simulator) or on the observation of particular characteristics of traffic behaviour and analysis of their determinants (behavioural observations) (OECD, 1998). Besides these proactive techniques, the reactive road safety technique based on accident data will also be used to gain insights in the road safety situation at intersections. As both types of road safety techniques are applied, this dissertation also explores which opportunities lie in applying and combining these techniques to draw road safety inferences for policy-relevant research purposes.

For this purpose, four studies were performed in order to get a more comprehensive picture of the road safety situation at intersections. Accident patterns on roundabouts (chapter 2) and signalized intersections (chapter 3) were investigated by analysing accident characteristics, location characteristics and the exact position of the accident for a subset of these two intersection types in Flanders. In addition, drivers' behavioural responses to combined speed and red-light cameras (SRLCs) at signalized intersections were investigated by applying a combination of proactive research techniques consisting of behavioural observations, traffic conflict observations and a driving simulator experiment (chapter 4). The final case study focuses on studying road safety differences between right-hand priority intersections and priority-controlled intersections by means of a behavioural analysis of vehicle-vehicle interactions (chapter 5).

The remainder of this general introduction provides background information on the main topics of this doctoral dissertation. First, the scope of the road safety problem is discussed. Besides a general overview, this first section also provides a generic overview of the road safety situation at different types of intersections. The second section addresses the complexity of the road safety problem. The third section highlights the need for empirical based road safety research. The fourth section describes the rationale and added value of using non-crash events as surrogates for accident analysis in road safety studies. The fifth part provides more information about the various techniques to collect data about non-crash events or observe particular characteristics of road user behaviour. The general introduction concludes with a short presentation of the dissertation's aims and outline of the performed studies.

1.2 The scope of the road safety problem

In general, road safety is defined by its negative outcome and the related consequences: crashes and casualties. Road crashes have a tremendous impact on our society in terms of physical, emotional, material and economic costs. During the past decades, countries worldwide have made significant advances in curtailing crashes and their impact on society. However, road traffic injuries still remain a leading cause of preventable death in countries all over the world (World Health Organization, 2015). Every year, more than 1.2 million people die in road crashes and 3% of the global gross domestic product (GDP) is lost to road crashes and injuries (World Health Organization, 2015). In 2015, more than 26.000 Europeans lost their lives in road crashes and more than 130.000 people were seriously injured, accounting for a 2% loss in European GDP (Directorate-General for Mobility and Transport, 2016).

A closer look at the Belgian road safety situation reveals that in 2015, 732 people died in road crashes and almost 52.000 people were injured (Statistics Belgium, 2016). In Europe, the average fatality rate was equal to 51.5 road fatalities per million inhabitants in 2015 (Directorate-General for Mobility and Transport, 2016). Compared to other European countries, Belgium (65 fatalities per million inhabitants) ends up in the lower middle in the list of 28 countries between Luxembourg and Hungary (Directorate-General for Mobility and Transport, 2016). In Figure 1, the number of road fatalities per million inhabitants in 2015 is presented for 28 European countries (Directorate-General for Mobility and Transport, 2016) and Flanders (FL) (Statistics Belgium, 2016).

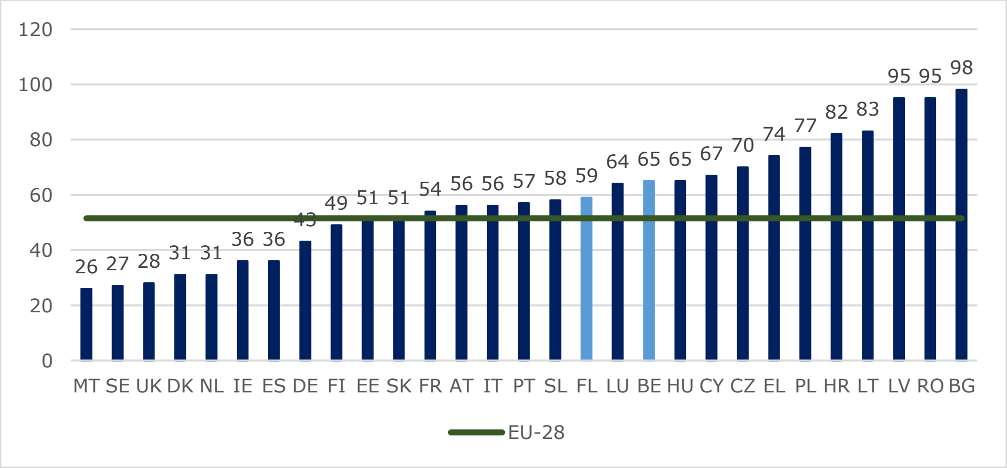

Figure 1: Road fatalities per million inhabitants in 28 European countries and Flanders in 2015 (Directorate-General for Mobility and Transport, 2016; Statistics Belgium, 2016).

Since 2001, the number of road fatalities has dropped significantly in Europe. However, progress has levelled off in recent years: the change in fatality figures was close to zero from 2013 to 2014, and in 2015 there was even a slight increase (as illustrated in Figure 2) (Directorate-General for Mobility and Transport, 2016). The WHO (2014) also indicated that road traffic injuries are currently estimated to be the ninth leading cause of death across all countries and age groups. By 2030, it is expected that road traffic injuries will become the seventh leading cause of death (World Health Organization, 2014). This forecast indicates that road traffic systems are one of the most dangerous systems with which people are confronted every day.

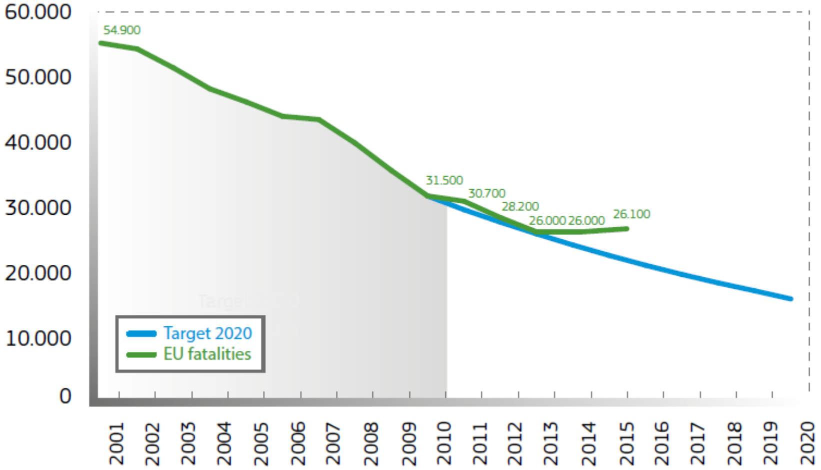

Figure 2: EU fatalities (2001-2015) and EU targets 2010-2020 (Directorate-General for Mobility and Transport, 2016).

In light of this prediction, the European Union has set the ambitious goal to reduce the number of road traffic fatalities between 2010 and 2020 by half (European Commission, 2010). The road safety goal of Flanders is even more ambitious with maximum 200 road traffic fatalities in 2020 (Vlaamse Overheid, 2010), 133 by 2030 and zero road traffic fatalities by 2050 (Vlaamse Overheid, 2013). In order to successfully achieve these ambitious road safety goals, additional efforts to further improve road safety are highly recommended. This requires a comprehensive picture of the road safety situation. In order to achieve this, it is necessary to understand and identify the processes that create or lead up to accidents.

1.2.1 Road safety at intersections

Intersections are an integral part of the road traffic system due to their role in facilitating movement of different road users in conflicting directions, and change of travel direction (Candappa, Logan, Van Nes, & Corben, 2015; Young, Salmon, & Lenné, 2013). Because of this distinguished characteristic, intersections present a discontinuity and are considered as one of the most dangerous parts of the road network. The fact that these sites are regarded as high-risk locations stems from the complex nature of intersections. Due to the convergence of multiple vehicle streams, road users are required to make multiple decisions in a limited amount of time and often at high speeds. Furthermore, the numerous intersection types (i.e. roundabouts, signalized intersections, non-signalized intersections, etc.) that are present within the road network further enhance their complex nature.

Road safety at intersections also seems to be a persistent problem. The number of accidents, fatally and severely injured road users at intersections remains relatively constant over the years whereas the overall number of accidents and injured road users has decreased over the past years (European Commission, 2017). In Belgium, approximately 34% of all traffic accidents with fatal or serious injuries in 2015 occurred at intersections (Statistics Belgium, 2016). Furthermore, in Europe the proportion of fatalities in road accidents at intersections of all fatalities was around 20% throughout the last years (European Commission, 2017). Regarding the type of involved road users, accident statistics also revealed that mainly pedestrians (15%), cyclists (25%) and car occupants (35%) were involved in fatal accidents at intersections in Belgium in 2015 (Statistics Belgium, 2016). For car occupants this is in line with the European average indicating that they are involved in 34% of the fatal accidents at intersections (European Commission, 2017). The situation is different for pedestrians and cyclists. Compared to the Belgian situation, the European average indicates that the share of pedestrians involved in fatal intersection accidents is higher (23%), while the share of involved cyclists is lower (12%) (European Commission, 2017).

Additionally, the road safety performance is strongly related to the type of intersection control. Different types of right-of way rules are in place at intersections in order to facilitate road user interactions. However, in order to create a safe road environment, the proper level of intersection control needs to be in accordance with the traffic volumes, the surrounding environment and the intended use of the intersection. In general, the level of intersection control ranges from light controlled (e.g. right-hand priority intersections) and strongly controlled (e.g. signalized intersections) to a circular type of intersection control (e.g. roundabouts).

1.2.1.1 Non-signalized intersections

In urban areas, the most common types of intersections are right-hand priority and priority-controlled intersections. At right-hand priority intersections all intersecting roads are considered to be of an equivalent importance, and all approaching road users need to give way to traffic coming from the right. At priority-controlled intersections, a designated main road (priority road) is identified at the intersection and road users approaching from the minor road need to yield to approaching road users on the main road. Both types of intersection control are often emphasised by means of markings or yield signs at each intersection approach.

Priority-controlled intersections are often assumed to be safer than right-hand priority intersections because the higher level of control is less ambiguous for road users, leading to more consistent yielding behaviour compared with right-hand priority intersections (Elvik, Høye, Vaa, & Sørensen, 2009). However, several studies investigated the safety effects of priority-control and right-hand priority control and concluded that a higher level of control does not necessarily result in safety benefits (Elvik et al., 2009; Janssen, 2004; Polus, 1985). Earlier studies mentioned that the absolute number of accidents at intersections increases with an increase in control levels, including converting the right-hand priority rule to priority-control and that the most frequent accident types are rear-end and angle collisions (Polus, 1985). These results were confirmed by a meta-analysis of 14 studies which concluded that the number of injury crashes is generally reduced only by 3% when right-hand priority intersections are converted to priority-controlled intersections (Elvik et al., 2009). A Dutch study, focusing on intersections in built-up areas, also concluded that the accident number is 50% higher at priority-controlled intersections compared to right-hand priority intersections while the accident risk is 34% lower on intersections with the right-hand priority rule (Janssen, 2004).

According to Elvik et al. (2009), the higher accident number at priority-controlled intersections is due to the higher driving speeds on the main road. More specifically, at right-hand priority intersections, all road users are required to approach the intersection more cautiously because they may need to yield to other road users. Road users on the main road of a priority-controlled intersection, however, do not need to yield to other road users, leading to higher approach speeds. Because of these higher speeds, the accident severity is generally higher at priority-controlled intersections (Elvik et al., 2009; Janssen, 2004). Two recent studies confirm these results (Hoekstra & Houtenbos, 2013). For instance, the absence of an explicit right-of-way (e.g. right-hand priority) at intersections results in in-priority road users yielding more often to no-priority road users and in slower driving speeds (Hoekstra & Houtenbos, 2013).

Moreover, several studies indicated that failure to yield and disobeying a traffic sign are one of the main accident contributory factors at non-signalized intersections (Gstalter & Fastenmeier, 2010; Lee et al., 2004; Parker, West, Stradling, & Manstead, 1995; Young et al., 2013). In general, formal priority rules are quite well respected at priority-controlled intersections, but not at right-hand priority intersections (Elvik et al., 2009; Helmers & Åberg, 1978). This right-of-way compliance at right-hand priority intersections depends on the road design, driving speeds and looking behaviour of the road users. For instance, the right-hand priority rule is more often violated when the road user coming from the right approaches from a narrower road (Björklund & Aberg, 2005; Helmers & Åberg, 1978). Although both roads are equally important, this aspect indicates the existence of an "implicit main road" at right-hand priority intersections (Björklund & Aberg, 2005; Helmers & Åberg, 1978). At both intersections, drivers also tend to yield more often when the driver who has priority maintains his or her speed than when he or she decelerates (Björklund & Aberg, 2005). In addition, drivers who do not look to the right when approaching a right-hand priority intersection appear to be convinced that they have priority (Kulmala, 1990).

1.2.1.2 Signalized intersections

Traffic signals are often implemented at intersections in order to minimise conflicts and improve road safety (CROW, 2008; McShane & Roess, 1990). Furthermore, traffic signals separate different traffic streams in space and time, and improve capacity and traffic flow at intersections. Despite these benefits, accidents still occur at signalized intersections. Elvik et al. (2009) indicated that the introduction of traffic signal control reduces the number of property-damage-only and injury accidents by around 15% at T-junctions and around 30% at crossroads. However, the implementation of traffic signals also induces side effects. For instance, traffic signals change the accident pattern at intersections by decreasing head-on and angle accidents while also increasing rear-end accidents (Abdel-Aty et al., 2006; CROW, 2008; Elvik et al., 2009; Ogden, 1996). Additionally, Abdel-Aty et al. (2006) mention that the increase in rear-end accidents strongly depends on the number of lanes and traffic volumes. Subsequently, traffic signals also give rise to red-light running accidents. Collisions caused by red-light running are typically associated with side impacts (Garber, Miller, Abel, Eslambolchi, & Korukonda, 2007) and tend to be more severe as these accidents typically occur at high speeds (CROW, 2008; Elvik et al., 2009; Ogden, 1996; Shin & Washington, 2007). Therefore, signalized intersections are often equipped with red-light cameras (RLCs) to prevent red-light running and improve road safety (De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Llau & Ahmed, 2014; Martinez & Porter, 2006). The results of a Flemish effect evaluation study (De Pauw et al., 2014) indicated that the installation of red-light cameras has a favourable effect on the number of fatal and serious injury accidents (-14%) whereas the number of rear-end accidents has significantly increased by 44%. The same study also reported that the introduction of red-light cameras has a beneficial effect on accidents with vulnerable road users. Other studies have shown similar results (Erke, 2009; Høye, 2013; Retting, Ulmer, & Williams, 1999; Retting, Williams, Farmer, & Feldman, 1999; Vanlaar, Robertson, & Marcoux, 2014).

Furthermore, signalized intersection speed limits play an important role in the severity of accidents with higher speed limits resulting in more severe injuries (Abdel-Aty & Keller, 2005; Keller, Abdel-Aty, & Brady, 2006). The type of traffic signal phasing also contributes to accidents at intersections. Generally, three types of left-turn phasing can be distinguished (De Pauw, Daniels, Van Herck, & Wets, 2015): permitted (left-turns are not controlled), protected-only (left-turns are fully controlled) and protected-permitted signal phasing (left-turns are only partially controlled). Protected-only and protected-permitted left-turn signal phasing lead to substantial decreases in the number of injury and severe injury accidents at signalized intersections (De Pauw et al., 2015). These types of signal phasing also have a favourable effect on left-turn accidents (De Pauw et al., 2015; Srinivasan et al., 2012). Research also indicated that driver errors are more likely to occur at intersections with permitted and protected-permitted left-turn signal phasing (Gstalter & Fastenmeier, 2010; Young et al., 2013). 'Misjudgement', 'violation' and 'action mistimed' errors appeared to be more pronounced when turning left at intersections with permitted and protected-permitted left-turn signal phasing (Gstalter & Fastenmeier, 2010; Young et al., 2013). Finally, several studies (Land & Nilsson, 2002; Lee et al., 2004; Najm, Koopmann, & Smith, 2001; Sandin, 2009) also concluded that failure to yield, running a traffic light and missed observation due to distraction and sight obstructions, are frequent signalized intersection accident contributing factors.

1.2.1.3 Roundabouts

From an intersection safety point of view, roundabouts already have quite a safe design as this type of circular intersection control reduces or eliminates conflict types (i.e. right-angle, left-turn and head-on conflicts), lowers vehicle speeds, and reduces accident severity (Flannery & Elefteriadou, 1999; Persaud, Retting, Garder, & Lord, 2000; Robinson et al., 2000; SWOV, 2012a). Several international studies demonstrated that converting intersections to roundabouts results in favourable road safety effects, particularly for accidents with fatal or serious injuries (Brüde & Larsson, 2000; Elvik, 2003; Elvik, Høye, Vaa, & Sørensen, 2009; Persaud et al., 2000; Robinson et al., 2000; Rodegerdts et al., 2010). A recent meta-analysis by Elvik (2017) concluded that converting intersections to roundabouts is associated with a reduction in injury accidents of about 40% and with a large reduction in fatal accidents of about 65%. Flemish road safety research focusing on the effects of roundabouts yields similar results (De Brabander & Vereeck, 2007).

However, the safety effects of roundabouts are not equally distributed across the different types of road users. Earlier research already indicated that the road safety effects of roundabouts are less favourable for cyclists (Dijkstra, 2004; Schoon & van Minnen, 1993). A Flemish study concluded that compared to motorised vehicles, vulnerable road users[2] are far more present in the roundabout accident statistics and have a higher probability of getting seriously injured in case of an accident (Daniels, Brijs, Nuyts, & Wets, 2010b). In the same study, bicyclists even represented almost half of the total number of killed or seriously injured victims in multiple-vehicle collisions at roundabouts (Daniels et al., 2010b). A more recent study also indicated that the conversion of intersections to roundabouts leads to a significant increase in the number of fatally and seriously injured bicyclists (Jensen, 2013). Bicyclist accidents at roundabouts are often characterised by a circulating cyclist and a car that enters or exits the roundabout (Herslund & Jørgensen, 2003; Møller & Hels, 2008). 'Looked-but-failed-to-see' plays an important role in these accidents (Herslund & Jørgensen, 2003; Räsänen & Summala, 1998).

Furthermore, the roundabout design also influences the safety effects for bicyclists and other road users. Jensen (2017) states that the diameter and height of central islands and the type of bicycle facilities at single-lane roundabouts have considerable impacts on bicyclists' safety. Other studies also confirm that roundabouts with separate cycle paths are safer for bicyclists than roundabouts with cycle lanes close to the roadway (Daniels, Brijs, Nuyts, & Wets, 2009, 2010a, 2011; Jensen, 2013; Sakshaug, Laureshyn, Svensson, & Hydén, 2010). Additionally, roundabouts with bypasses seem to be more prone to passenger car and multiple-vehicle accidents, whereas a large central island results in more single-vehicle accidents (Daniels et al., 2011). Moreover, the radius of deflection, deviation angle, and missing or ineffective yield signs/markings at the entry also play a role in the occurrence of rear-end and angle accidents (Montella, 2011). Single-lane roundabouts result in larger accident reductions for all road users than double or multiple-lane roundabouts, since the number of conflict points increases with the number of lanes (Brüde & Larsson, 2000; Persaud et al., 2000). Finally, failure to give way is identified as a main accident contributory factor at roundabouts (Gstalter & Fastenmeier, 2010; Montella, 2011).

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[2] Pedestrians, bicyclists, moped riders and motorcyclists.

1.3 The complexity of the road safety problem

In general, factors contributing to road safety and thus road accidents consist of three elements or components: the road environment, the vehicle and the road user (Figure 3). Research indicated that the behaviour of road users is the most important contributing factor in nearly all accidents (94%), while the road environment and the vehicle only play a role in 28 and 8% of the accidents respectively (Rumar, 1985; Sabey & Taylor, 1980; Treat et al., 1979). This is in line with Stanton and Salmon (2009) who confirmed the significance of human or road user error in accident occurrence.

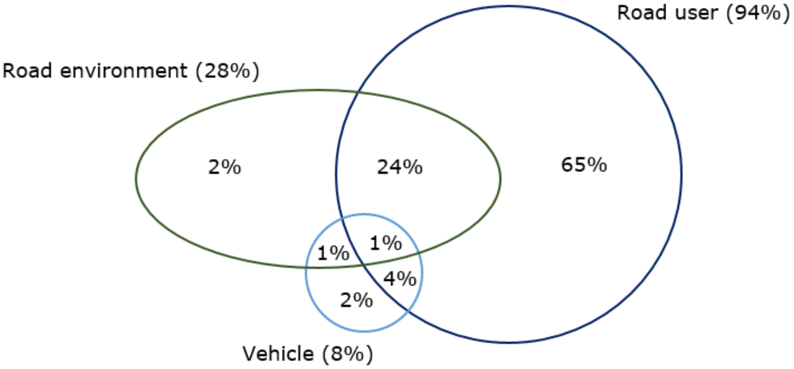

Figure 3: Overview of factors contributing to road accidents (Sabey & Taylor, 1980).

However, road accidents can rarely be attributed to one causal factor but are often the result of the interaction process between at least two elements. For example, Figure 3 shows that around one quarter of the road accidents originates from a combination of road user behaviour and environmental factors. This illustrates that road accidents are often the result of the interaction process between (improper) road user behaviour and other road traffic system components such as the road infrastructure, the environment and the vehicle. Therefore, instead of looking at the different accident contributing elements individually, it is necessary to study and analyse the road traffic system as a whole (Ottino, 2003). This approach is essential to understand it and capture the interaction between the different components and the overall behaviour that emerges from these interactions (Ottino, 2003).

The interaction process within the road traffic system is illustrated in Figure 4. Fastenmeier and Gstalter (1993, p.160 in Gstalter & Fastenmeier, 2010) have based this interaction model on the existence of a safety continuum. According to Hydén (1987), traffic events such as safe encounters, erroneous manoeuvers and near-accidents/conflicts can be located on the continuum and are assumed to precede accidents. In this assumption, the level of road safety varies between the extremes of safe encounters (i.e. correct behaviour) and accidents (Fastenmeier

& Gstalter, 1993). Within this rationale, the frequency of an event is inversely related to the severity (i.e. accidents and events closely situated to accidents are more dangerous but occur less frequently). Figure 4 shows that an accident is the consequence of an event sequence, preceded by erroneous behaviours and dangerous situations (i.e. disturbances in the road traffic system). Therefore, the fewer system disturbances occur, the more reliable and safer the road traffic system will be. "Human Error Probability" (HEP) presents the reliability of the road user within the system and indicates the probability of unsafe road user behaviour/action depending on the error occurrence and disturbances present in the road traffic system (Gstalter & Fastenmeier, 2010).

According to the model, the situations preceding accidents can be of different degrees of dangerousness - depending on safety margins provided by road infrastructure elements, the possibility of error compensation by other road users and the necessity and time available for compensatory action (Gstalter & Fastenmeier, 2010). Subsequently, these system disturbances can be reduced by hazard avoidance or reduction strategies. From this it can be inferred that an accident cannot occur without a road traffic system disturbance (Gstalter & Fastenmeier, 2010). Consequently, this interaction model clearly illustrates that accidents need to be perceived as the result of the integral road traffic system.

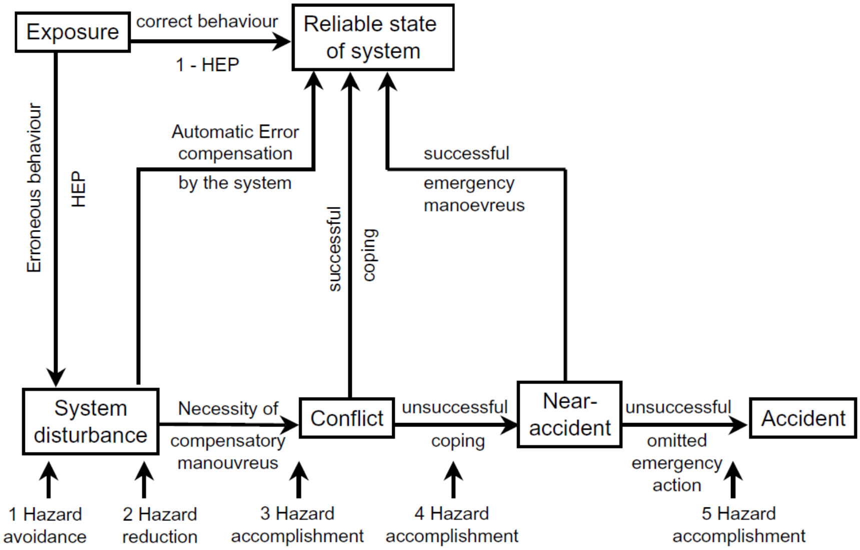

Figure 4: Interaction model of the road traffic system (adopted from Fastenmeier and Gstalter, 1993, p.160 in Gstalter & Fastenmeier, 2010).

1.3.1 Reason’s “Swiss Cheese Model”

The “Swiss Cheese Model” of Reason is a well-known system description of accident causation which illustrates how accidents occur by considering the interaction between latent conditions and errors in complex systems (Reason, 1990).

The origin of this model lies in the domain of industrial safety, and more specifically in the aetiology, investigation or prevention of industrial or organisational accidents (Reason, 1990). Since its development, the Swiss Cheese Model has made significant contributions to safety in a range of domains such as health care, risk management, aviation, and engineering (Salmon et al., 2010; Stanton & Salmon, 2009). However, the model’s principles are also highly applicable in a road transport context (Salmon et al., 2010; Wegman & Aarts, 2006). This is illustrated by the fact that prominent road safety strategies such as the Swedish Vision Zero strategy (Johansson, 2009), the Dutch Sustainable Safety approach (Wegman, Aarts, & Bax, 2008) and Australia’s Safe System Approach consider the road traffic system to be characterised by latent errors and to be inherently dangerous. For instance, these system-based road safety visions all acknowledge the fallibility of road users, and are developed from the notion that safety is the responsibility of actors at all levels of the system (Salmon et al., 2010). In that respect, these safe system approaches state that the infrastructure and vehicles should be designed in such a way that human errors are taken into account and that the impact forces are minimalised when collisions occur so that road users are able to avoid serious injuries or death when using the road system (Wundersitz, Baldock, & Raftery, 2014). In that respect, both the WHO and the OECD recommend all countries, irrespective of their road safety level, to apply this proactive Safe System Approach in their road safety policy (OECD, 2008; World Health Organization, 2010).

When the Swiss Cheese Model is transferred to road safety, the road traffic system is represented as consisting of different defence layers. As follows, an accident occurs when a specific chain of latent conditions (or errors) and dangerous actions, pass each of the different defence layers of the system without any resistance (Reason, 1990). In most situations, accident occurrence is prematurely terminated because of defences or barriers that are inherently present in each of the system’s defence layers.

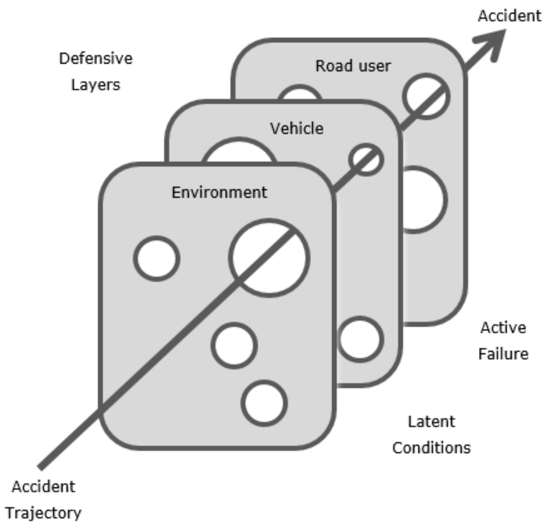

Figure 5: Combination of Reason's Swiss Cheese model (1990) and the road user – vehicle – road environment approach of Sabey and Taylor (1980).

The multi-causal and complex nature of the road safety problem is especially emphasised when Reason's Swiss Cheese Model is combined with the aforementioned road user – vehicle – road environment approach (Sabey & Taylor, 1980) (Figure 5). Correspondingly, accidents are the outcome of a failure in one or more components (road user, vehicle, and environment) of the road traffic system.

In that respect, road safety research needs to approach the road safety problem from a 'holistic' point of view in order to understand and identify the processes that create accidents. This is not a straightforward procedure as research indicated that behaviours implicated in accidents often represent normal, everyday behaviour and in themselves offer little indication of impending accidents; it is rather the interaction between behaviours and the ensuing emergent properties of the road traffic system that create accidents as opposed to the behaviours themselves (Salmon et al., 2012 p.1830).

To conclude, this complexity expresses the need for road safety techniques that are able to capture the interactions between the various elements of the road environment, the road users and the vehicle that make up the road traffic system. Therefore, there is enormous potential for proactive road safety techniques (section 1.6). These techniques not only allow to study the various elements of the road environment, the road users and the vehicle but also the way in which these elements interact. It is the latter, which is an important prerequisite for creating a road traffic system with inherent safety features.

1.4 The need for empirical based road safety research

Almost a century ago, the practical necessity to bring an end to the increasing number of road traffic crashes and casualties led to the development and implementation of road safety research. During this century, road safety thinking and road safety research - focusing on accident causes and the role of road user behaviour - has undergone a remarkable evolution as the emphasis has shifted from bad luck and accident prone drivers towards a system's approach in which accidents are perceived as the result of the integral road system (Hagenzieker, Commandeur, & Bijleveld, 2014).

Over the past few decades, this evolution in road safety research has contributed in selecting effective measures to improve road safety. However, selecting effective measures is not straightforward as road traffic accidents can rarely be attributed to one causal factor. As a consequence, large road safety investments can bring little or no positive results and may even result in negative effects (Hasson, Kauppila, Assing, Yannis, & Lassarre, 2012). This is the case when the implemented road safety measure or policy is not suited to intervene in the causal factors that contribute to severe road crashes. Therefore, the implementation of road safety management systems and policies needs to be evidence-based in order to guarantee that road safety investments contribute in achieving beneficial road safety outcomes (Papadimitriou & Yannis, 2013).

The notion of evidence-based policy has only recently come into use more often, indicating that any new measure should have been proven to be effective before implementation (Sanderson, 2004; Wegman & Hagenzieker, 2010). Schulze and Koßmann (2010) also mention that the stronger road safety policies are evidence-based, the more efficient they will be in reducing fatalities and the severity of road accidents.

The purpose of evidence-based road safety research is to gain a better understanding of the accident development process and contributory factors by analysing the number of road accidents and their related consequences, expressed as casualties of varying severity. This traditional and reactive approach has established the use of accident data as the main data source for road safety analysis making accidents and their consequences a well-accepted road safety indicator. As a consequence, most road safety research has relied on accident data to address multiple road safety-related concerns, such as (Chin & Quek, 1997; Muhlrad, 1993; Oppe, 1993; Svensson & Hydén, 2006):

- the identification of which hazardous locations, target groups or risk-increasing behaviours require attention;
- the detection of positive or negative road safety developments;
- the evaluation of road safety measures.

Although accident data provide interesting and useful information for road safety evaluation purposes, they are characterised by widely acknowledged availability and quality limitations. Some of the main concerns about accident data are:

- Accidents are exceptional, compared to other events in traffic. Therefore, accident data are characterised by the random variation inherent in small numbers (Hauer, 1997). Additionally, it takes quite some time to collect enough accident data to produce reliable estimates of traffic safety. For longer periods it is difficult to associate the change in accident number with a specific factor as the other factors might also change during this period (Chin & Quek, 1997; Laureshyn, 2010; OECD, 1998). Consequently, it is insufficient to only rely on accident data for everyday road safety purposes.
- Not all accidents are reported and the level of reporting is unevenly distributed depending on the accident severity and type of road users involved (Laureshyn, 2010; OECD, 1998; Svensson, 1998). For instance, vulnerable road users in particular are heavily underrepresented in police accident statistics compared to accident information in hospital records (Alsop & Langley, 2001; Amoros, Martin, & Laumon, 2006; Elvik et al., 2009).
- Accidents are the consequence of a dynamic process in which a certain combination of factors related to the road user, the vehicle and the environment leads to a collision. However, accident data are not capable to capture the interaction between these factors and the behavioural and situational aspects that precede the accident, and thus play a role in accident occurrence (Laureshyn, 2010; OECD, 1998). Because of this, the accident development process remains unclear since the information in accident databases only describes the final outcome for each registered accident. Without knowing and understanding the accident development process, it is difficult to identify the contributing factors and propose effective measures to reduce accident occurrence (Laureshyn, 2010).
- Road safety analysis based on accident data is a reactive approach since a large number of accidents have to take place before a particular road safety problem is identified and remedied using appropriate safety countermeasures (Archer, 2005; Lord & Persaud, 2004). This also raises ethical concerns with the use of accident data since one has to wait for accidents to occur and thus for people to suffer before the road safety situation can be evaluated (Chin & Quek, 1997; Laureshyn, 2010). In that respect, indicators that provide faster feedback about the road safety situation are more preferable (Chin & Quek, 1997).

From this point of view, there is a distinct need and enormous potential for swifter, more informative and more resource effective road safety techniques that are able to provide a more comprehensive analysis of the road safety situation (Archer, 2005). Road safety techniques based on indirect road safety indicators are a type of such methods. The term 'indirect' in this context means that these indicators are not based on accidents, but rather on other occurrences in traffic that are causally related to accidents or injuries (ETSC, 2001; Laureshyn, 2010; Tarko, Davis, Saunier, Sayed, & Washington, 2009).

1.5 Road safety diagnosis by means of empirical non-crash data

In road safety literature, the terms non-crash data or surrogate safety measures (SSM) tend to be used to refer to indirect road safety indicators. The term "surrogate" describes that these measures or indicators do not rely on accident data (Tarko et al., 2009). Instead, non-crash data are a means to facilitate proactive road safety diagnosis and evaluation from field observations by addressing the fundamental issues with accident data (St-Aubin, 2016). According to Tarko et al. (2009) non-crash data or SSM provide more context-appropriate information, particularly with regards to providing an understanding of the relevant underlying collision and failure mechanisms of accidents.

Additionally, Laureshyn et al. (2010, p.1637) also argue for the use of indirect safety indicators based on the following motivations:

- to increase the possibility of evaluating road safety changes more efficiently and in a shorter time;
- to elaborate the relation between design elements and risk;
- to gain a more thoroughly understanding of the relationships between behaviour and risk;
- to gain a better understanding of the processes characterising normal traffic and critical situations including accidents.

1.5.1 The safety continuum of traffic events

The rationale behind the use of non-crash data for road safety purposes is that the interactions between road users can be described as a continuum of safety-related events in which the frequency of the events is inversely related to the severity of the event (Svensson, 1998; Svensson & Hydén, 2006). According to this rationale, non-crash data can be used for road safety diagnosis and evaluation purposes if there is an adequate understanding of the relationships between these safety-related events and of how these events are related to differences in road safety.

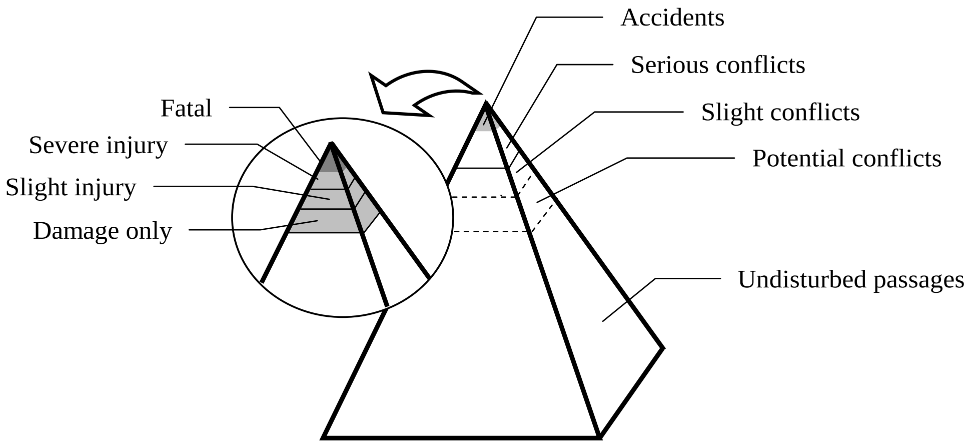

Figure 6: The 'safety pyramid' – the interaction between road users as a continuum of events (Adopted from Laureshyn (2010), based on Hydén (1987)).

This continuum of safety-related events, describing the relationship between the severity and frequency of road user interactions, is usually illustrated by a pyramid (Hydén, 1987). This '*safety pyramid*' describes the relationship between normal events in traffic, traffic conflicts and accidents, as shown in Figure 6. The top of the pyramid represents the most severe and most exceptional events in traffic, the *accidents*. Accidents can be further distinguished in fatal, injury and material-damage-only accidents, and the accident frequency increases with a decreasing accident severity (Hydén, 1987; Svensson, 1998). *Traffic conflicts* or "near-accidents" are traffic events that are characterised by very small margins in time and space that almost end up as accidents. In these events, the collision is avoided because (at least one of) the involved road users detect(s) each other and are able to avoid the imminent risk of colliding by successfully taking an evasive action (Svensson, 1998). Equivalent to the accidents, traffic conflicts can also be classified in serious, slight or potential conflicts according to their severity. The base of the 'safety pyramid' is formed by the majority of the events that characterise the normal traffic process; the *undisturbed passages* (Laureshyn, 2010).

According to Svensson and Hydén (2006), accidents are also exceptional in the sense that they are a collection of events where all alternatives to handle the situation safely, have vanished one by one. This is indeed exceptional compared to most other events in the safety pyramid, which are handled safely by the involved road users. The 'safety pyramid' also illustrates that traditional road safety diagnosis and evaluation based on accidents only encompasses an insignificant fraction of the traffic events that take place as there is a total disregard of the much more frequent traffic events which describe safe or unsafe interactions between road users. This can result in overlooking important insights in road safety. In order to gain a more in-depth picture of the road safety situation, it is necessary to get a more comprehensive understanding of the connection between road user behaviour and safety within the whole continuum of safety-related events. Therefore, it seems reasonable to also analyse normal or successful interactive situations instead of only serious traffic conflicts or accidents.

1.5.2 A severity hierarchy of road user interactions

Moving within the road traffic system requires interaction. Put differently, all events in the road traffic system contain some kind of interaction. This view has also been confirmed by Larsson et al. (2010) who emphasised that road traffic includes numerous elements (e.g. road users, vehicles, road components) characterised by millions of random interactions on a daily basis.

From a theoretical point of view, every encounter between two or more road users may eventually result in an accident during this interaction process. However, not every encounter leads to a collision because the relationship between the factors contributing to an accident (interactions between road user, vehicle and road environment) and road safety is of a probabilistic instead of a deterministic nature. As defined by Svensson (1998, p. 2), an accident is the result of an unhappy realisation of many small probabilities. In other words, accidents are stochastic events. Each accident is the result of a number of factors, that all have contributed to this event. If some of the contributing factors had not been present or if the contributing factors coincided with other circumstances, the accident might have been avoided (Laureshyn, Svensson, & Hydén, 2010). As a consequence, it can be considered as an unlucky coincidence that all these factors happened to be present at the same time to result in an accident. Furthermore, this ‘accident potential’ implies that every interaction can result in a collision when new factors arise or if the circumstances differ.

The more problematic the interaction between road users is, the higher the probability that this event could develop into an accident and the more severe the consequences of this event are. So, the more likely this event would be situated near or at the top of the ‘safety pyramid’. Therefore, the ‘safety pyramid’ illustrates that there is some severity dimension common to all the elementary events, defined in general terms as the closeness to an accident and severity of its consequences (Laureshyn, 2010).

By assigning severity to the interaction process, all encounters can be placed in a distribution comparable with Hydén’s pyramid (Laureshyn, Svensson, & Hydén, 2010). Svensson (1998) used the term ‘*severity hierarchy*’ to refer to such a distribution. According to Svensson (1998), the shape of the hierarchy is strongly affected by the approach that is used to define the ‘severity concept’. To illustrate, the pyramid of Hydén encloses all events (with and without a collision course). When only events or interactions with a collision course are studied it can be assumed that the shape of the hierarchy will be different. In such a situation, Svensson (1998) concluded that a diamond shape is more appropriate than a pyramid shape to operationalise the severity hierarchy. Moreover, the shape of the hierarchy is also influenced by various factors such as geometrical design, type of intersectional control, type of manoeuvre and involved road users, etc. (Svensson, 1998). The shape of the hierarchy can be used to describe differences in road user behaviour, predict the frequency of more severe events (based on the observation of less severe events in the hierarchy) and to formulate road safety measures (Svensson, 1998).

In that respect, the severity hierarchy gives a better understanding of the situation from a safety point of view compared to accidents that only represent the top of the distribution (Laureshyn et al., 2010). What remains crucial is how the frequency of events, with a varying severity, need to be interpreted.

Serious traffic conflicts, i.e. safety-critical events in which an accident is barely avoided, are often used as a surrogate measure for accident data (Ismail, 2010; Tarko et al., 2009). Hydén (1987) has identified a robust relationship between the frequency of serious conflicts and the actual number of police-reported accidents. This relationship provides proof that serious conflicts are closely related to accidents. Several researchers have argued that the processes that result in accidents are similar to the processes that lead to less severe events (near-accidents, serious conflicts, etc.); with the major difference being the outcome of the situation (Hydén, 1987; Perkins & Harris, 1968; Svensson 1998; Van der Horst, 1990). Serious conflicts can therefore be used to understand how accidents develop as the development process of both events appears to be highly comparable; making serious conflicts a logical precursor of accidents within the safety continuum. Evidence suggests that the events, located just below the serious conflicts, i.e. non-serious or slight conflicts with still fairly high severities, bear different information depending on how close they are located to the serious conflicts in the severity hierarchy (Svensson, 1998). As these events are also characterised by some critical closeness in time and space between road users, it can be assumed that they still have a strong relation to road safety. Several studies also advocate that the observation of behaviour in normal interactions between road users, provides valuable information in order to understand how the relations between events of different severity lead to road safety differences (Davis, Hourdos, Xiong, & Chatterjee, 2011; Laureshyn et al., 2010; Svensson, 1998; Svensson & Hydén, 2006; van Haperen, 2016; Zheng, Ismail, & Meng, 2014a).

1.6 Methods for the observation of non-crash events

Reliable accident data will remain an important source for road safety assessments. Nevertheless, data from non-crash events merit their place and can be supportive in the following situations (Svensson, Daniels, & Risser, 2017, p.261-262):

- To collect information on preconditions or circumstances that in a chain of events affect the occurrence or outcome of accidents. Such information can hardly be included in accident data.
- To complement accident data in case of poor registration or poor availability of accident information.
- To assess safety in gradually improving road systems at aggregation levels with such low accident frequencies that no longer allow to analyse accident data in a systematic way.

The fact that data from non-crash events have the potential to shed light on major issues that are still poorly understood, indicates that these data can serve as a vital supplement to accident data (Svensson et al., 2017). To date various data collection techniques have been developed and applied in scientific road safety literature to collect qualitative and quantitative empirical data from non-crash events:

- Driving simulator studies
- Behavioural observation studies
- Traffic conflict observation studies
- Instrumented vehicle studies

Each technique has its particular characteristics, advantages and drawbacks (Table 1). For instance, the latter three data collection techniques study or observe road users' behaviour and interactions in the real-world, while the former technique makes use of a controlled environment in which researchers can manipulate and repeat road user interactions. Subsequently, behavioural and traffic conflict observation studies are a form of site-based observations which only reflect road user interactions at a particular site, while instrumented vehicle studies such as naturalistic driving studies continuously collect road user behaviour as the road user moves within the road traffic environment. Nevertheless, these four data collection techniques fit well in a proactive approach since the road safety situation can be diagnosed or evaluated before serious accidents occur. Although instrumented vehicle studies are not applied in this dissertation, they are briefly introduced and discussed for reasons of completeness.

1.6.1 Driving simulator studies

A driving simulator consists of a mock-up of a vehicle, surrounded by screens on which a virtual road environment is projected. Participants of driving simulator studies navigate through the simulated road environment by controlling the vehicle actuators (steering wheel, brake pedal, throttle, and gears). Driving simulators are commonly classified based on three levels: high-level, mid-level and low-level simulators (Kaptein, Theeuwes, & Van Der Horst, 1996). Simulators consisting of full vehicle cabs mounted on a moving base platform and providing almost 360-degree fields of view are in the high-level category, static simulators based around large projection screens and full cars are in the mid-level, while low-level simulators are characterised by a fixed mock-up and use one or more computer monitors for scenario visualization (Auberlet et al., 2014; Carsten & Jamson, 2011; Fisher, Rizzo, Caird, & Lee, 2011). Driving simulators log detailed information about a vast range of driving behaviour and performance parameters (e.g. speed, acceleration, deceleration, steering data, engine data) as well as data about the precise position of the vehicle within the virtual road environment (i.e. variation of lateral position, lane position, position relative to other objects, time headway, time-to-collision, friction and lateral g). Additionally, driving simulators can be combined with an eye-tracking system to monitor driver head and eye movements, while physiological information can be recorded by means of electroencephalography (EEG). These objective data can be supplemented with subjective data on workload, acceptance, trust, behavioural intention, etc. (Carsten & Jamson, 2011).

Driving simulators allow for a more proactive and detailed modelling of driving performance. These studies provide insights into how driver, vehicle and roadway characteristics influence driving safety and also monitor how road safety improvements or measures influence driver performance (Boyle & Lee, 2010). Driver awareness and response to risky situations, near-crashes and even real crashes can be monitored in a simulator (McGehee & Carsten, 2010). Thereby, simulator studies also provide insights into the underlying mechanisms of safety-critical events (Boyle & Lee, 2010). Additionally, driving simulators have the potential to identify road design problems, explore effective infrastructural countermeasures, test advanced vehicle technologies and investigate a variety of driver impairments (Carsten & Jamson, 2011).

One of the major motivations of conducting a driving simulator study is related to health and safety. Studies that would be very difficult or impossible to conduct in the real-world because they are considered unsafe can be performed in the risk-free environment of a simulator (Carsten & Jamson, 2011; Godley, Triggs, & Fildes, 2002). Besides the road safety aspect, other important advantages are the optimal experimental control over the road environment and the behaviour of other (virtual) road users, efficiency and the fact that effectiveness of new road designs can be tested before they are implemented in the real-world (Auberlet et al., 2014; Godley et al., 2002).

However, driving simulators also have some disadvantages, including simulator sickness and the fact that the driving task in a simulator cannot be completely realistic (Auberlet et al., 2014; Godley et al., 2002). Furthermore, the most important drawback is the extent to which behaviour in the simulated road environment corresponds to drivers' actual driving behaviour in real life (Fisher et al., 2011). Therefore, every driving simulator needs to be validated in order to establish whether the simulator is sufficiently valid for the experiment that will be conducted (Auberlet et al., 2014; Bella, 2008; Kaptein et al., 1996). Two types of driving simulator validity can be distinguished: physical validity and behavioural validity. *Physical validity* or the simulator's fidelity indicates the degree to which the simulator dynamics and visual system corresponds with its real-world counterpart (Godley et al., 2002; Kaptein et al., 1996). On the other hand, *behavioural or predictive validity* refers to the simulator's ability to induce the same response from a driver as would be performed in the same situation in real-life (Jameson, 1999). This type of validity can either be relative (when differences found between experimental conditions are in the same direction, and have a similar or identical magnitude on both systems) or absolute (when the numerical values between the two systems are the same) (Auberlet et al., 2014; Bella, 2005, 2008; Carsten & Jamson, 2011; Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008). Törnos (1998) concluded that relative validity is necessary in a driving simulator study, but absolute validity is not essential since the focus usually lies on the effects of independent variables instead of determining absolute numerical measurements of driver behaviour.

Nevertheless, several studies show that driving simulators in general reach high relative validity (Bella, 2005, 2008, 2009; Godley et al., 2002; Kaptein et al., 1996; Törnros, 1998; Yan et al., 2008). For instance, Yan et al. (2008) compared differences between behaviour in the driving simulator and at real-world signalized intersections. The results indicated a high relative validity, indicating that driving simulators are a valid tool to assess road safety at signalized intersections.

1.6.1.1 Driving simulator of the Transportation Research Institute – Hasselt University

The driving simulator of the Transportation Research Institute – Hasselt University was used to perform the driving simulator study experiment in the study on *Drivers' behavioural responses to combined speed and red-light cameras* (chapter 4). The medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated) is a fixed-based (i.e., drivers do not get kinaesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual/auditory (e.g. sound of traffic in the environment and of the participant's car) feedback and a performance measurement system. The visual virtual environment was presented on a large 180-degree field of view seamless curved screen, with rear view and side-view mirror images (Figure 7). Three projectors offer a resolution of 1024 x 768 pixels at a 60 Hz frame rate. The eye movements of the participants can also be recorded through a camera-based eye tracking system (faceLAB 5 Seeing Machines).

Figure 7: Medium-fidelity driving simulator at the Transportation Research Institute – Hasselt University.

1.6.2 Behavioural observation studies

Behavioural observations are a type of traffic observation techniques, which are used to study road user behaviour. In these studies, the emphasis lies on analysing the objective actions of road users in their natural setting by means of observable (mostly qualitative) variables (e.g. gender, age, interaction type, approach behaviour, looking behaviour, priority behaviour, distraction, communication behaviour) while they interact with other road users and the road environment (Laureshyn, 2010). The road user behaviour can be observed by a researcher or by installing a video camera on-site. This type of naturalistic study can be divided into two categories: unstructured and structured behavioural observation studies. In *unstructured observation studies*, researchers look with an “open mind” at road user behaviour and record any observable action or behaviour that seems interesting or conspicuous. In that respect, these studies help researchers to “get acquainted” with the research site. These studies are often combined with traffic conflict observation studies (section 1.6.3.) as they provide very rich qualitative information about the road safety situation at a certain location. *Structured behavioural observation* studies can originate from unstructured observation studies. Unlike unstructured observation studies, the focus lies on the explicit and detailed observation of a specific safety-related behaviour such as for instance crossing and looking behaviour or traffic rule compliance at a certain location. Such studies are essential to gain a better understanding of complex road safety problems; especially when they are combined with other techniques.

The aim is usually to observe the frequency of road user behaviour and to identify particular characteristics of road user behaviour in different situations, rather than to quantify road safety levels (OECD, 1998; van Haperen, 2016). Hence, behavioural observation studies can be used to observe all types of traffic events ranging from undisturbed passages to serious conflicts. It is therefore possible to gain knowledge about the behavioural and situational aspects which play a role in encounters with a low safety risk as well as the aspects that precede serious conflicts (Muhlrad, 1993). In that respect, these studies provide the opportunity to better understand the different contributory factors that play a role in accident development. In the context of road safety evaluation and diagnosis, behavioural observation studies are used to monitor the frequency of road user behaviour, to check findings of accidents and traffic conflict studies regarding possible accident factors and to evaluate the effects of road safety countermeasures or strategies (OECD, 1998).

Important advantages of behavioural observation studies are the direct observation of road user behaviour in a natural setting which results in strong face and construct validity, the non-intrusive nature of the data collection, the practice-readiness of the technique, the large sample size and the fact that the road safety situation can be diagnosed very quickly (Eby, 2011). The main shortcoming of these studies is that only variables describing the revealed behaviour of road users can be observed and collected, while the underlying causes of the behaviour remain undetected (Eby, 2011). Another disadvantage is the generalisability of the results (Eby, 2011). Because these studies are a type of site-based observation studies, it is difficult to conclude that the observed behaviours would also occur at other locations at which no behavioural study has been performed. Other drawbacks are the labour-intensive data collection and observer bias. This observer bias can be mitigated through training or by using a video camera to register road user interactions. In the latter case, the use of a video camera can cause problems since it is not always easy to find a good location to install the camera. In addition, privacy rules may also restrict the use of a video camera.

A structured behavioural observation study with human observers and video camera observations was used to perform a *behavioural analysis of vehicle-vehicle interactions at priority-controlled and right-hand priority intersections* (chapter 5).

1.6.3 Traffic conflict studies

Traffic conflicts are the most well-known category of surrogate safety measures to describe individual road user behaviour and the interaction process between road users. The rationale behind the introduction of traffic conflicts for road safety analysis and diagnosis purposes is the assumption of a safety continuum of traffic events (section 1.5.1) in which traffic conflicts occur more frequently and precede accidents (Shbeeb, 2000; Svensson 1998). Because at least one of the road users undertakes an evasive action, the majority of the conflicts have no chance to develop into accidents. Studies have shown that conflicts do not always precede accidents because accidents often occur without the presence of an evasive action (Chin & Quek, 1997; Zheng, Ismail, & Meng, 2014b). However, conflicts can still reveal a lot about accidents because the underlying processes are assumed to be similar (Laureshyn, 2010). Consequently, studying conflicts would provide the opportunity to examine road safety conditions at any location before accidents occur.

Similar to behavioural observations, traffic conflict observations are a site-based naturalistic traffic observation technique used to study road user behaviour. However, the main difference between these two methodologies is that traffic conflict studies aim to quantify road safety levels by measuring road safety in terms of the expected number of (injury) accidents instead of merely focusing on what happens (van Haperen, 2016). Indeed, applied to road user interactions, a traffic conflict study includes the examination of measurable parameters such as speed, position, distance and observable signals and actions, etc. and their relation to conditions and factors in the road environment and actions of other road users (Laureshyn, 2010). In that respect, traffic conflict studies rely on continuous parameters whereas behavioural observation studies generally use single value or “yes/no” indicators to describe road users’ behaviour in interactions.

Over the past 50 years, various versions of traffic conflict techniques have been developed and applied. These techniques have some basic elements in common but also vary on certain aspects such as the inclusion of events with or without a collision course (STCT versus DOCTOR), the appearance of evasive actions (USTCT and STCT) or the incorporation of driver error (German TCT) (Zheng et al., 2014b). In traffic conflict techniques the severity of an event is defined as its proximity to develop into an actual collision and the severity of the consequences if this occurs (Laureshyn, 2010). Time-proximity indicators reflect both speed and distance proximity, which are two measures with a very high relevance to expressing road safety. Therefore, many traffic conflict techniques use some type of time-proximity indicators as a basis for conflict detection and indicating conflict severity. These time-based surrogate safety measures include for example Time-To-Collision (TTC), Post-Encroachment-Time (PET), Time-To-Accident (TA), time/distance headway, etc. Within conflict situations, these measures can also be combined with other SSM describing the safety of certain behaviours such as Time-to-Line-Crossing (TLC), Deceleration Rate (DR) and Standard Deviation of Lateral Position (SDLP). Combined these measures provide a comprehensive overview of the safety of a certain interaction or situation between road users, without necessarily needing accident data as a safety measure (Schaap, 2012).

Traffic conflict techniques are very effective for road safety evaluation and diagnosis purposes. These studies can be used to identify the behavioural aspects of road users that are important for road safety, to add relevant information to existing accident data or replacing missing accident data, to determine unsafe locations and to evaluate the effects of road safety countermeasures or strategies (de Jong, Gysen, Petermans, & Daniels, 2007; de Jong et al., 2007; Kraay, van der Horst, & Oppe, 1986; Laureshyn, 2010; OECD, 1998). Traditionally, traffic conflict data were collected by means of trained human observers. Lately, this procedure has been replaced by observations from video footage, which can be processed manually, or with the help from advanced video analysis tools.

The direct observation of road user behaviour in traffic conflict studies enables to capture and explain the underlying contributory behavioural and situational factors that play a role in the development of near-accidents and even accidents. Other advantages are the non-intrusive nature of the data collection, the practice-readiness of the technique, the large sample size, a swift assessment of the road safety situation and the fact that traffic conflict data can be a possible supplement/replacement for accident data (e.g. potential on low-volume locations, developing countries,…) (de Jong et al., 2007). The most important shortcoming is the validity of the technique. The validity is not yet fully established since the relationship between traffic conflicts (as an indirect measure for accidents) and accidents is not entirely understood (De Ceunynck, 2017). Past validation studies show mixed results; several studies indicate a poor relationship between conflicts and accidents (Tiwari, Mohan, & Fazio, 1998; Williams, 1981) whereas others came to more favourable results (El-Basyouny & Sayed, 2013;

Hydén, 1987; Songchitruksa & Tarko, 2006; Zheng et al., 2014b, 2014a). However, there is consensus that some of these validity issues originate from the inaccurate, unreliable and underreporting of accidents (Chin & Quek, 1997). Collecting traffic conflict data by means of field observation is also quite labour-intensive and expensive. Another disadvantage is the generalisability of the results (Eby, 2011). Because these studies are a type of site-based observation studies, it is difficult to conclude that the observed conflicts would also occur at other locations at which no conflict study has been performed. Furthermore, even trained observers register conflicts in a subjective way which leads to the reliability problem caused by inter- and intra-observer variability (Zheng et al., 2014b). The use of more advanced video analysis techniques ensures a more cost-effective, efficient and reliable detection and analysis of traffic conflicts but these techniques are currently still under development (Auberlet et al., 2014; Zheng et al., 2014b).

1.6.3.1 The Swedish traffic conflict technique

The Swedish traffic conflict technique was used to analyse the traffic conflict data collected in the study on *Drivers' behavioural responses to combined speed and red-light cameras* (chapter 4).

In the Swedish Traffic Conflict Technique (STCT) a conflict is defined as follows: an event in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged (Amundsen & Hydén, 1977, cited in Hydén, 1987). The collision is avoided because one or more road users take an evasive action. Evasive actions are actions like braking, accelerating or decelerating and evasive manoeuvres. In this technique, two parameters are used to define the severity of an event (Laureshyn, 2010):

- the speed of the road user who performs an evasive action at the moment of the evasive action, and
- the distance from the road user who performs an evasive action to the imaginary point of collision.

Both parameters are used to calculate the following time-based surrogate safety measures: Time-To-Collision (TTC) and Time-To-Accident (TA). *TTC* is the time until two road users would have collided had they continued with unchanged speeds and directions (Shbeeb, 2000). TA is used in order to determine whether a conflict can be defined as a serious conflict or not. *TA* is a special value of the TTC and is defined as the time that remains to an accident at the moment the evasive action is initiated, presupposed that the road users had continued with unchanged speeds and directions (Hydén, 1987; Svensson, 1998). The TA-value is calculated for the road user who takes the evasive action. When both road users take evasive actions, the TA-value is calculated for each of them (Hydén, 1987; Svensson, 1998). When this is the case, the seriousness of the conflict is determined by the least serious TA-value. These two indicators can only be calculated if there is a collision course. However, road users can just avoid a collision although they do not follow the same course. More specifically, in the absence of a collision course a small change in course or speed could lead to a collision (e.g. crossing traffic). An indicator for such near-miss situations is the Post-Encroachment-Time (PET). The *PET* is defined as the time between the first road user leaving the conflict zone and the second one entering it (Laureshyn, 2010). The PET-value represents the risk for an accident, namely the way in which an accident did not happen.

These indicators can be calculated by means of speed and distance estimates of trained observers or can be derived from video-based road user trajectories. In this dissertation the latter option was preferred. The video data were processed using T-analyst (2014), i.e. a semi-automated video analysis system developed at Lund University. The system transforms the image coordinates of each individual pixel to road section coordinates, which allows the software to accurately determine the position of an object in the image and to calculate its trajectory. This allows the calculation of road users' speeds and positions, distances to fixed objects and traffic conflict indicators in an accurate and objective way.

1.6.4 Instrumented vehicle studies

Indirect safety measures can also be collected by means of instrumented vehicle studies. In these studies, a large number of vehicles is equipped with a host of sensors which discretely record the actions undertaken by the driver in its natural setting (Carsten, Kircher, & Jamson, 2013). These sensors can also record characteristics of the driving situation, so that location on the road, steering wheel angle, speed, (time and distance) headway, performance on secondary tasks, video recordings of participants' expressions, eye movement data, vehicle environment and many other variables can be recorded simultaneously (Schaap, 2012). This instrumentation is installed as unobtrusively as possible in order to ensure that the driver forgets that he/she is being constantly observed and to prevent that other road users alter their behaviour when they interact with the instrumented vehicle.

Instrumented vehicle studies on the road can be grouped into two categories: Field Operational Tests (FOTs) and naturalistic driving studies. *FOTs* focus on testing and evaluating the safety aspects of advanced driver assistance systems (ADAS) or other Intelligent Transport Systems (ITS) (Carsten et al., 2013; Klauer, Perez, & McClafferty, 2011). Typically, participants are handed special test vehicles equipped with several ADAS and additional instrumentation to record how the driver responds to these in-vehicle systems. An example of a very recent large-scale FOT in Europe is euroFOT (2012). In euroFOT (2012) 1.000 passenger cars and trucks were equipped with eight different ADAS for an entire year.

Naturalistic driving studies aim to enhance the understanding of how safety problems arise and unfold (Carsten et al., 2013). In these studies, the everyday behaviour of road users is observed unobtrusively in a natural setting for a long period of time (Dingus et al., 2006). The observations take place during ordinary trips in the drivers’ own car or other means of transport (in the case of instrumented bicycles, motorcycles or mopeds). The first large-scale naturalistic driving study was the 100-car study in the United States (Dingus et al., 2006). This study has paved the path for the SHRP2 naturalistic driving study in which approximately 3400 drivers drove more than 3300 vehicles over a period of 1-2 years in six States, they made ± 5 million vehicle trips and were involved in 1549 crashes and 2705 near-crashes (Virginia Tech Transportation Institute, 2016). The data were collected by using four video views, vehicle network information (e.g., speed, brake, accelerator position), and information from additional sensors included within the data acquisition system (DAS) (e.g., forward radar, accelerometers) (Virginia Tech Transportation Institute, 2016). In Europe, UDRIVE was the first large-scale naturalistic driving study in which 87871 hours of data were collected in six European countries with 48 trucks, 186 passengers cars and 47 powered two-wheelers (UDRIVE, 2016).

Because of their diagnostic nature, naturalistic driving studies provide insights into the frequency and context of safety critical events (Boyle & Lee, 2010). They are often used as an instrument to collect data about road users’ behaviour and interactions in normal traffic situations, traffic conflicts and sometimes even accidents in order to find out how safety problems arise and unfold. Because these studies collect data on a continuous basis, not only the last movements and constellations leading up to the accident can be evaluated, but also the underlying factors that may have led that the road user(s) ended up in a certain safety-critical situation (Carsten et al., 2013; Zheng et al., 2014b). Furthermore, because these data are collected over longer time periods (e.g. months, years) it is also possible to capture behavioural changes over time as well as reactions to external influences (Carsten et al., 2013).

The largest advantage of naturalistic driving studies is that the collected data are more detailed and provide a fuller idea of behaviour, which in turn offers the opportunity to gain in-depth understanding into the natural behaviour of road users (van Nes, Christoph, Hoedemaeker, & van der Horst, 2013). Other important advantages are the high external validity, the possibility to study behaviour over extended time periods, the opportunity to obtain prevalence data for different types of behaviour, and the possibility to improve the understanding of the safety continuum from the perspectives of road user behaviour and accident causation (Carsten et al., 2013; Zheng et al., 2014b).

A major issue is the fact that it can be difficult to determine the exact cause of certain road user behaviours and the experimenter cannot control for outside variables (van Nes et al., 2013). As a consequence, there are limited possibilities to compare the behaviour of different road users on a specific location (intersection, curve) and in similar situations (weather, traffic density) (van Nes et al., 2013). Additionally, naturalistic driving studies also have some practical disadvantages such as the large logistic effort to conduct these studies, the very high set-up costs and the time-consuming data analysis process caused by the richness and large amount of collected data (Carsten et al., 2013; Zheng et al., 2014b). In addition, there is the problem of selection bias because, very likely, the most exemplary road users will be more eager to participate in a study in which their behaviour is monitored in detail for a longer period of time. Finally, data about the behaviour and interactions of varying severity are only collected from the viewpoint of one of the involved road users. Since the collected information about the opposing road user is very limited, it is possible that the evasive action or behaviour of this road user remains undetected by the sensors. This complicates the objective to obtain a complete understanding of the factors leading to safety-critical events.

Table 1: Overview of four data collection techniques for (non-)crash events and their characteristics (based on Auberlet et al., 2014; Schaap, 2012; Zheng et al., 2014b).

Data collection techniques for non-crash events	***Driving simulator study***	***Behavioural observation study***	***Traffic conflict observation study***	***Naturalistic driving study***
Variables	Detailed logging of driving behaviour and performance parameters (i.e. speed, acceleration, position, etc.), EEG-data, eye-tracking data, in normal safety-critical events	Qualitative indicators of road user behaviour (i.e. looking behaviour, priority behaviour, communication, etc.) and road user characteristics (gender, age) in normal and safety-critical events	Measurable (continuous in case of video based observation) parameters of road user behaviour in traffic conflict situations	Detailed and continuous logging of vehicle data (i.e. speed, acceleration, position, etc.), driver behaviour data and characteristics of the driving situation in normal and safety-critical events
Data collection techniques	Mock-up of a vehicle	Human observers or video-based behavioural data	Human observers or video-based trajectory data	Instrumented vehicle
Study area	Simulated road environments, often replicated from existing road environments or road plans	Site-based	Site-based	Real-world road environments
Data processing efforts	Moderate	Low	Low to moderate depending on the use of (semi) automated video analysis techniques	High
Deployment costs	Moderate to high depending on the type of driving simulator	Low	Low	High

Table 1: Overview of four data collection techniques for (non-)crash events and their characteristics (based on Auberlet et al., 2014; Schaap, 2012; Zheng et al., 2014b) (continued).

Data collection techniques for non-crash events	***Driving Simulator study***	***Behavioural observation study***	***Traffic conflict observation study***	***Naturalistic driving study***
External validity	Low-moderate: virtual environment, participants know they are being observed, no actual safety-critical situations, but simulation of these situations can have high validity	Low-moderate: natural setting, unobtrusive data collection, actual safety-critical situations and behaviours, but study results are only valid for the location under study	Low-moderate: natural setting, unobtrusive data collection, actual safety-critical situations and behaviours, but study results are only valid for the location under study	Very high: natural setting, unobtrusive data collection, actual safety-critical situations and behaviour
Experimental control	Very high control over scenario, e.g. route, weather, sight, timing, events	No control over road users interactions or road environment	No control over road users interactions or road environment	No control over road users interactions or road environment
Participant safety	No safety-critical issues, other than possible simulator sickness	Participants responsible for their own safety, no precautions necessary	Participants responsible for their own safety, no precautions necessary	Participants responsible for their own safety, no precautions necessary
Average time duration of study	Several minutes to several hours	Several days to weeks	Several days to weeks	Several months; up to one year or longer

Table 1: Overview of four data collection techniques for (non-)crash events and their characteristics (based on Auberlet et al., 2014; Schaap, 2012; Zheng et al., 2014b) (continued).

Data collection techniques for non-crash events	***Driving simulator study***	***Behavioural observation study***	***Traffic conflict observation study***	***Naturalistic driving study***
Specific advantages	Controlled environment; same experiment can be repeated; experimental vehicle equipment and safety-critical situations can be investigated	Direct observation of road user behaviour in normal and safety-critical events; strong face and construct validity; non-intrusive data collection practice-ready; large sample size; swift road safety diagnosis	Direct observation of road user behaviour in safety-critical events; non-intrusive data collection; practice-ready; large sample size, swift road safety diagnosis; possible supplement/replacement for crash data	In-depth understanding of natural behaviour of road users; high external validity; allows to study normal, conflict and accident situations; possibility to study behaviour over extended time periods
Potential disadvantages	Doubt about whether this “virtual trip” represents real driving behaviour	Generalisability; only revealed road user behaviour; observer bias, labour-intensive data collection (observers)	Labour intensive data collection (observers), generalisability; validity; inter- and intra-observer variability; advanced video analysis techniques are still under development	No control for outside variables; high set-up costs, time-consuming data–analysis process; selection bias; data from only one of the involved road users

1.7 Overview of aims and studies

This doctoral dissertation was carried out within the framework of the multi-annual programme of the Policy Research Centre on Traffic Safety, authorised by the Flemish Government. The activities of the Policy Research Centre are to provide scientific support and to perform both policy-relevant and fundamental scientific road safety research to improve the Flemish road safety policy. For this purpose, the Flemish Government has set several road safety priorities, which have been translated into five different work packages within the Policy Research Centre (SPRINT, 2012). The studies within this dissertation were carried out within the framework of WP 2 'Risk analysis' focusing on the analysis of detailed accident data, and WP 3 'Human behaviour' aimed at adopting a system's perspective to study road safety by describing and analysing road user behaviour as a component of the road traffic system.

The main purpose of this dissertation is to identify and provide an in-depth analysis of patterns of behaviour, conflicts and accidents on intersections in urban environments. More specifically, the objective of this dissertation is twofold:

- to gain deeper insight in accident causation factors, based on the observation and analysis of crash and non-crash events on intersections;
- to establish the merits of combining multiple road safety techniques, based on empirical non-crash data in order to study policy-relevant road safety issues for which accident data appear to be less suitable.

1.7.1 Research questions and scope

In order to achieve these objectives four studies were performed of which the scope is determined in consultation with the Flemish Government. All these studies emphasise on studying interactions of varying severity at intersections in urban areas by means of reactive and proactive road safety techniques. The following research questions are studied throughout this dissertation in order to accomplish these aims:

1) Which patterns of behaviour, conflicts and accidents occur at intersections?
2) What are the strengths and limitations of road safety techniques based on crash and non-crash data?
3) To what extent can the observation of non-crash events be used to draw road safety inferences, complement or even replace traditional road safety techniques based on crash data?
4) What are the merits of combining road safety techniques to conduct policy-relevant road safety research?

The safety continuum of traffic events or "safety pyramid" of Hydén (1987) is used as a guide to structure the four studies in this dissertation (Figure 8).

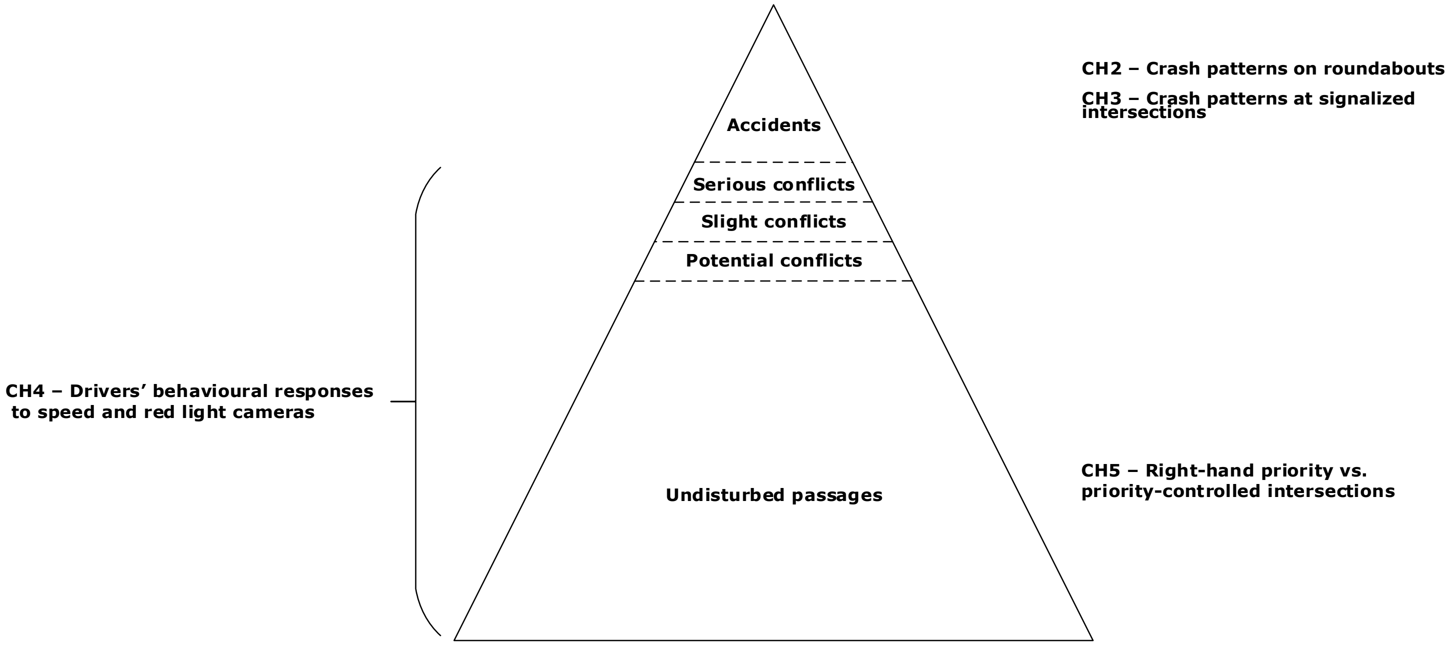

Figure 8: Overview of the link between the studies in the doctoral dissertation based on Hydén's safety pyramid (1987).

The first study described in chapter 2 focusses on accident patterns at roundabouts and is related to WP 2 of the research programme of the Policy Research Centre on Traffic Safety. Even though roundabouts have been implemented for several years in Flanders, there is still much diversity in roundabout construction and design. Additionally, former studies (Daniels, Brijs, Nuyts, & Wets, 2009, 2010a, 2010b, 2011; Daniels, Nuyts, & Wets, 2008) have already provided valuable insights into safety impact of roundabout design. However, one of these studies (Daniels, et al. 2010b) also highlighted that future research, concerning the safety effects and accident proneness of roundabouts, would strongly benefit from more detailed analysis based on the exact accident location (entry, exit lane, roundabout itself) at roundabouts and collision diagram information. Therefore, this study focuses on investigating accident patterns on roundabouts, by means of the exact location of accidents and collision diagrams. More specifically, accident characteristics, location characteristics and the exact position of the accident are determined for a subset of roundabout locations. For this purpose, a protocol is developed to divide the roundabout location into different roundabout sections or segments in order to gain better insights in the accident patterns, accident propensity and contributing factors at different sections or segments on roundabouts.

Chapter 3 is concerned with accident patterns on signalized intersections and is related to WP 2 of the research programme of the Policy Research Centre on Traffic Safety. Traffic signals result in safety benefits but also lead to increases in the number of rear-end accidents (Abdel-Aty et al., 2006; CROW, 2008; Elvik et al., 2009; Ogden, 1996) and to the occurrence of red-light running accidents (De Pauw et al., 2014; Garber et al., 2007). Several national (De Pauw, 2015; De Pauw, Daniels, Van Herck, & Wets, 2015; De Pauw et al., 2014) and international (Abdel-Aty et al., 2006; Mohamed Abdel-Aty & Keller, 2005; Elvik et al., 2009; Gstalter & Fastenmeier, 2010; Keller, Abdel-Aty, & Brady, 2006) studies have focused on the road safety performance of signalized intersections. However, little is known about the exact location of the accidents. Therefore, this study focuses on identifying and analysing the accident patterns at signalized intersections by using detailed information about the accident location. Similar to the study presented in chapter 2, this study divides a signalized intersection location into different segments in order to identify the dominant accident type inside each segment and to link the accident occurrence with design characteristics of the signalized intersection. As a result, the findings of this study result in a detailed description of the accident patterns at signalized intersections, which provide insights into the safety impact and possible safety issues of this intersection design.

In chapter 4, the focus lies on the interaction between the environmental and behavioural component in the road traffic system. This study is related to WP 3 of the research programme of the Policy Research Centre on Traffic Safety. Traffic signals result in safety benefits but also give rise to red-light running accidents

(De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Garber, Miller, Abel, Eslambolchi, & Korukonda, 2007). Therefore, signalized intersections are often equipped with red-light cameras (RLCs) to prevent red-light running and improve road safety (De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Llau & Ahmed, 2014; Martinez & Porter, 2006). However, the results of a Flemish effect evaluation study (De Pauw et al., 2014) indicated that the installation of speed and red-light cameras has a favourable effect on the number of fatal and serious injury accidents (-14%) but also leads to a significant increase of 44% in the number of rear-end accidents. Moreover, the implementation of speed and red-light cameras has also been the subject of considerable debate. Citizens do not perceive speed and red-light cameras as beneficial to road safety but merely as a means to increase government revenue. The Flemish Government also aims to further increase automated enforcement solutions (Vlaamse Overheid, 2017a) such as speed and red-light running enforcement. Therefore, they have commissioned to further investigate the safety effects of speed and red-light cameras (SRLCs) in order to gain insights in the possible explaining factors for the increase in rear-end collisions. For this purpose, drivers' behavioural responses to SRLCs are studied in a before and after study at two signalized intersections where SRLCs were about to be installed. The implementation of SRLCs is evaluated on-site by observing and analysing driver behaviour in traffic conflict situations and in normal encounters. One signalized intersection is also rebuilt in the driving simulator of Hasselt University. Therefore, this study also examines how the results from site-based observations and driving simulator experiments can complement each other.

The final case study is presented in chapter 5 and concentrates on observing normal interactive behaviour by means of human observers. This study is related to WP 3 of the research programme of the Policy Research Centre on Traffic Safety. Intersections with right-hand priority and priority-controlled intersections are predominantly applied in urban areas. However, the scientific literature is inconclusive about which of the two intersection types should be preferred from a safety point of view. No significant difference in the number of accidents is found when right-hand priority intersections are converted to priority-controlled intersections (Elvik et al., 2009). Both types of intersection control are also the subject of considerable debate in Flanders. Several municipalities consider to replace the right-hand priority rule by priority-controlled intersections. Therefore, this study aims to investigate road safety differences between right-hand priority intersections and priority-controlled intersections by means of a behavioural analysis of vehicle-vehicle interactions.

Chapter 6 draws upon the entire dissertation by discussing the main findings, strengths and limitations of the conducted studies and formulating policy recommendations. The chapter concludes with an outlook for future research possibilities.

CHAPTER 2: IDENTIFYING CRASH PATTERNS ON ROUNDABOUTS

In the following chapter, I was involved in the design, methodological execution, development of the accident location typology, performing the literature review, data collection, analyses and writing the paper.

This chapter is based on:

Polders, E., Daniels, S., Casters, W. & Brijs, T., (2015). *Identifying crash patterns at roundabouts: an exploratory study*. Traffic Injury Prevention, 16 (2), p. 202-207. (Web of Sience: 5-year impact factor 1.451).

Research report:

Polders, E., Daniels, S., Casters, W., & Brijs, T. (2013). *Het identificeren van verkeersongevallenpatronen op rotondes: een exploratieve studie*. Steunpunt Verkeersveiligheid 2012-2015, RA-2013-004, Diepenbeek, Belgium.

ABSTRACT

Objectives: Roundabouts are a type of circular intersection control generally associated with a favourable influence on traffic safety. International studies of intersections converted to roundabouts indicate a strong reduction in injury crashes, particularly for crashes with fatal or serious injuries. Nevertheless, some crashes still occur at roundabouts. The present study aims to improve the understanding of roundabout safety by identifying crash types, locations, and factors that are associated with roundabout crashes.

Methods: An analysis of 399 injury and property damage–only crashes on 28 roundabouts in Flanders, Belgium, was carried out based on detailed crash descriptions; that is, crash data and collision diagrams. The crashes are sampled from police-reported crashes at roundabouts in the region of Flanders, Belgium (period 2005–2010). Collision diagrams of the registered crashes were used to distinguish 8 different crash types. The roundabout itself is divided into 11 detailed and different typical segments, according to previously established knowledge on the occurrence of crashes at roundabouts. The 8 roundabout crash types are examined by injury severity, crash location within the roundabout, type of roundabout, type of cycle facility, and type of involved road user.

Results: Four dominant crash types are identified: rear-end crashes, collisions with vulnerable road users, entering–circulating crashes, and single-vehicle collisions with the central island. Crashes with vulnerable road users and collisions with the central island are characterised by significantly higher proportions of injury crashes. About 80% of the crashes occurred on the entry lanes and the circulatory road (segments 1–4). Road users who are the most at risk to be involved in serious injury crashes at roundabouts are cyclists and moped riders.

Conclusions: The main goal of this study was to identify and analyse dominant crash types at roundabouts by taking into account detailed information on the crash location. Some connections between certain roundabout crash types, their crash location, and roundabout design characteristics have been found.

Keywords: roundabout, design, crash, collision diagram

2.1 Introduction

Roundabouts are a type of circular intersection control generally associated with a favourable influence on traffic safety. International studies of intersections converted to roundabouts indicate a strong reduction in injury crashes, particularly for crashes with fatal or serious injuries (Brüde & Larsson, 2000; De Brabander, Nuyts, & Vereeck, 2005; Elvik, 2003; Elvik et al., 2009; Persaud, Retting, Garder, & Lord, 2000; Robinson et al., 2000; Rodegerdts et al., 2007). However, the safety effects of roundabouts are not equally distributed across the different types of road users because they seem to induce a higher number of bicyclist-involved accidents (Daniels et al., 2009; Daniels, Nuyts, & Wets, 2008; Maycock & Hall, 1984). Roundabouts improve road safety by reducing or eliminating conflict types, lowering vehicle speeds, and reducing crash severity (Flannery & Elefteriadou, 1999; Persaud et al., 2000; Robinson et al., 2000). Previous studies identified 3 dominant crash types: crashes between entering and circulating vehicles, run-off-road crashes, and rear-end crashes (Mandavilli, McCartt, & Retting, 2009; Maycock & Hall, 1984; Montella, 2011; Robinson et al., 2000; Rodegerdts et al., 2007).

Many studies have already focused on the road safety performance of roundabouts, but little is known about the exact location of the crashes. Therefore, this study focuses on identifying and analysing the crash patterns at roundabouts by taking into account detailed information about the location of the crash. Mandavilli et al. (2009) and Montella (2011) analysed crash patterns at roundabouts by taking the crash location into account. We elaborated on this approach and tried to delineate the crash location on the roundabout itself in more detail. Because this study uses more detailed roundabout segmentations than previous studies, a better insight is gained into the crash patterns and their exact location on the roundabout. This method identifies the dominant crash type inside each segment and enables us to link the crash occurrence with the roundabout infrastructural design characteristics. As a result, the findings of this study lead to a detailed description of the crash patterns at roundabouts that provides insights into the safety impact of the roundabout design. Other studies have also applied this method to other locations, including intersections (Gstalter & Fastenmeier, 2010; Retting, Weinstein, & Solomon, 2003), freeway ramps (McCartt, Northrup, & Retting, 2004), and work zone crashes (Khattak & Targa, 2004).

2.2 Method

The crashes are sampled from police-reported crashes at 28 roundabouts in the region of Flanders, Belgium. The national crash database could not be used to sample the crashes because it does not contain detailed information about the crash location at the roundabout. Therefore, several police zones were selected that registered detailed information about the crash location. The data collection process revealed that designing a collision diagram of a crash is a post-processing step that is not a mandatory standard procedure. Ultimately, 7 police zones met the research demands and provided the crash data. This approach resulted in a convenience sample of roundabout locations.

The crashes occurred in the period 2005–2010. In total, 399 crash reports containing injury and property damage–only crashes were obtained, including 290 crashes at 25 single-lane roundabouts and 109 crashes at 3 double-lane roundabouts. The police reports provided basic (such as time, place of occurrence, weather/light conditions) and detailed (such as crash type and location) information about the registered crashes. The detailed crash location is included by dividing the roundabouts into different typical segments, according to previously established knowledge on the occurrence of crashes at roundabouts (Mandavilli et al., 2009; Maycock & Hall, 1984; Montella, 2011; Robinson et al., 2000; Rodegerdts et al., 2007). Figure 9 depicts the selected 11 segments and Table 2 provides a detailed description.

Table 2: Roundabout segments.

Roundabout segment	Description
Entry lane	
Segment 1	20-100 meters off the roundabout. Oncoming traffic, queues associated with congestion.
Segment 2	20 meters before the roundabout until the yield markings. Includes pedestrian and cyclist crossings, if present.
Circulatory road	
Segment 3	Location on the entry path of the circulatory road situated beyond the yield markings of the entrance lane.
Segment 4	Continuation of segment 3. Location on the circular part of the roundabout near the central island. Includes the (truck) apron, if present.
Segment 5	Location on the circulatory road situated 10 meters beyond the entry lane and 10 meters before exit lane of the roundabout.
Segment 6	Location on the circular part perpendicular to the exit lane and before the curved exit path of the roundabout.
Exit lane	
Segment 7	20 meters beyond the circulating part of the roundabout. Includes pedestrian and cyclist crossings, if present.
Segment 8	20-100 meters off the roundabout. Leaving traffic.
Bypass	
Segment 9*	The beginning of the bypass, if present.
Segment 10*	The middle section of the bypass which includes pedestrian and cyclist crossings, if present.
Segment 11*	The end section of the bypass, if present.

*These segments are optional and are only relevant when the roundabout is characterised by a bypass. The definitions of the segments are based on the geometric design features of roundabouts discussed in Rodegerdts et al. (2010).

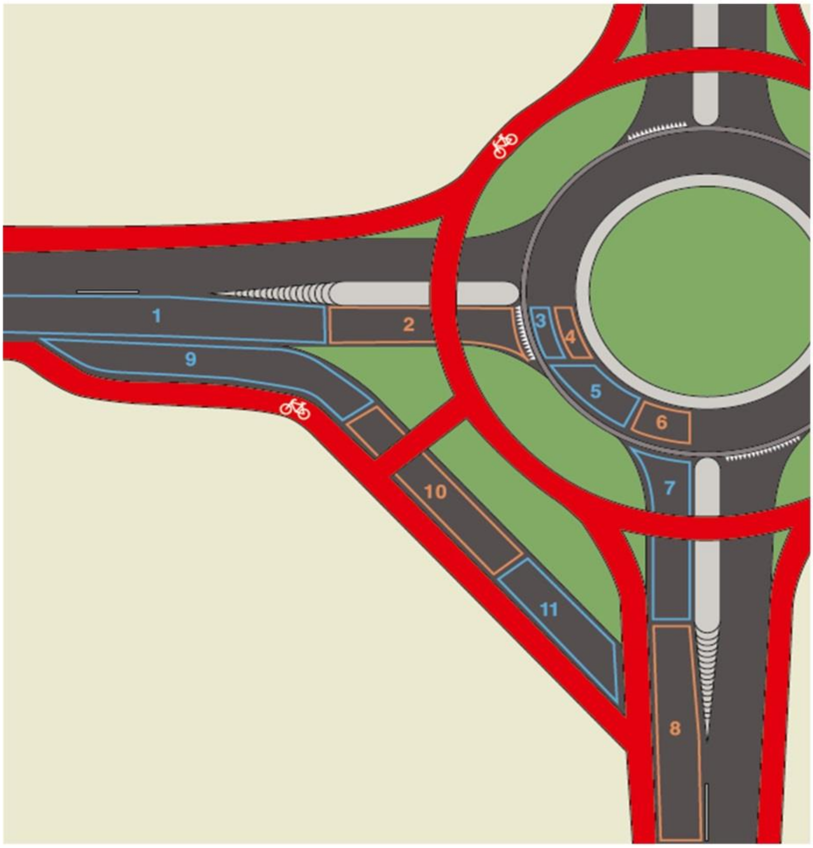

Figure 9: Roundabout segments.[3]

Figure 9 is a representation of a typical roundabout quadrant. The segments are defined in such a way that the variety of real-world designs is represented by the figure and meaningful analyses based on the defined standard segments are possible. To capture all possible designs, a sort of maximal design is used, representing a typical roundabout layout with some extra features that are not necessarily present. For example, a bypass lane is added in order to include crashes that occur on bypass lanes at certain roundabouts. Nevertheless, bypass lanes are in reality rather infrequent at roundabout locations. This means that only crashes at segments 9, 10, or 11 must be registered in case of a roundabout with such a bypass lane. The same goes for the cycle facilities (cycle paths and cycle crossings): pedestrian or bicyclist crossings at real-world roundabouts occur in different varieties (Daniels et al., 2009). This means that, whereas the figure is representing a cycle path on some distance of the circulatory roadway, the real distance between the cycle facility and the roadway may vary between 0 and

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[3] The alternate colour coding of the roundabout segments has no specific purpose and is applied to make a clear distinction between the defined roundabout segments.

about 10m. This principle also applies to the number of lanes at the circulatory roadway and/or the entries and exits: both one-lane and 2-lane roundabouts are represented by Figure 9.

Collision diagrams (Ogden, 1996) of the registered crashes were used to develop the crash types and to assign them to a roundabout segment. This method was also used by other roundabout studies (Mandavilli et al., 2009; Montella, 2011) and intersection studies (Retting et al., 2003) to determine crash patterns. The collision diagram indicates the dominant crash types at a roundabout and the manoeuvres that lead to these crashes while providing detailed information about the crash location at the roundabout. Figure 10 represents the collision diagram of a roundabout location. Every crash is depicted as a group of arrows, one for every involved road user, representing the crash type and travel directions. These arrows are labelled with codes for day/night, weather, road user type, and injury severity.

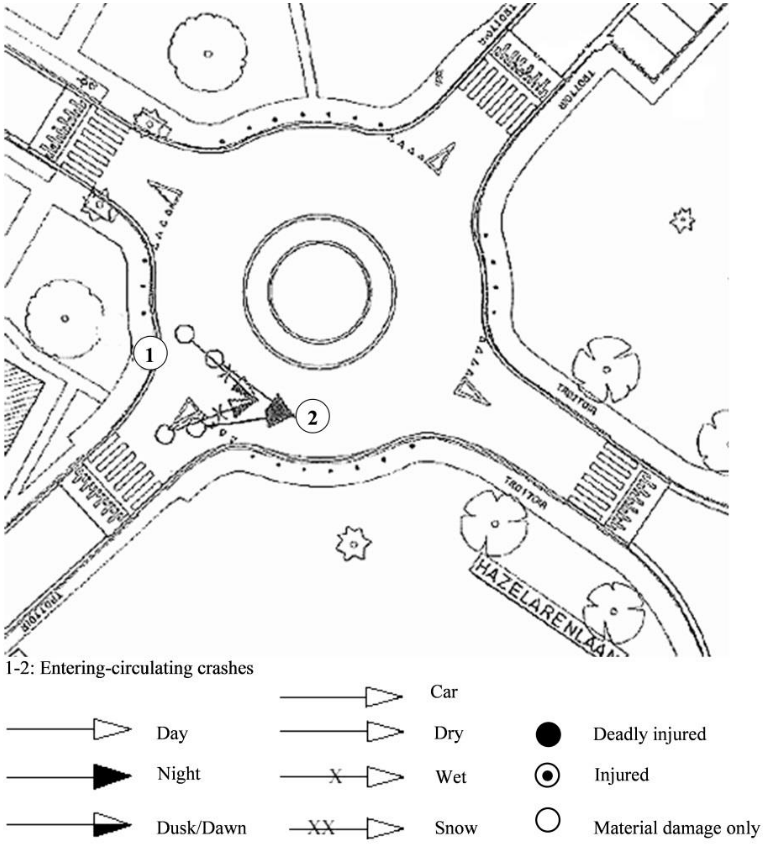

Figure 10: Collision diagram of a roundabout location (Local police department of Hasselt, 2013).

2.2.1 Analysis of the crash data

2.2.1.1 Pearson's Chi-square Tests

Pearson's chi-square tests and descriptive statistics are used to identify the characteristics of roundabout crashes. Chi-square tests are used to measure the presence of a statistical significant relation between 2 categorical variables (Field, 2009). The null hypothesis of the chi-square test always assumes that both variables are statically independent of each other, implying that no relation exists between both variables. Because chi-square tests are not reliable if the number of cases is less than 5, Fisher's exact test is used to compute the exact probability of the chi-square statistic that is still accurate when sample sizes are small (Field, 2009). This study uses a confidence interval of 95%.

2.2.1.2 Logistic regression models

Logistic regression models are built to predict the probability of being injured in a roundabout crash and to predict the probability of being involved in a roundabout crash by type of road user. These models can be used to predict the probability of a certain event when the dependent variable is a categorical variable and the predictor variables are continuous or categorical (Allison, 1999; Field, 2009). The functional form of the chosen logistic regression models was the following (Allison, 1999):

$$\mathrm{logit} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \qquad (1)$$

where logit is the predicted natural logarithm of the odds ratio: ln (P/1-P); β_0 is the intercept (constant); β_n are the partial logistic regression coefficients and β_1 expresses the influence of x_1 on the logit. Every x_n (independent variable) has its own partial logistic regression coefficient β_n.

Odds ratios (OR = Exp(B)) were calculated to determine the rate of decrease ($0 \leq OR < 1$) or increase ($OR > 1$) of the probability of the outcome when the value of the independent variables increases with one unit (Field 2009). Firth's penalised maximum likelihood is applied to overcome the most common convergence failure in logistic regression, namely the problem of quasi-complete separation (Allison, 1999; Heinze & Schemper, 2002). The models are assessed with the Akaike Information Criterion Eq. (2). This measure indicates the relative goodness-of-fit of the model and corrects for model complexity by taking the number of estimated parameters into account (Akaike, 1987). The AIC is defined as:

$$\mathrm{AIC} = -2\,(\ln(\text{likelihood})) + 2\,K \qquad (2)$$

where likelihood is the maximised value of the likelihood function for the model and *K* is the number of free parameters in the model (Burnham & Anderson, 2002). The variance inflation factor (VIF) is used to identify multicollinearity between the predictor variables. O' Brien (2007) suggests that VIF's higher than 4 indicate a high correlation. Since, all variables in the end models have VIF's lower than or near 1, there are no multicollinearity issues in the presented models.

2.3 Results

2.3.1 Crash distribution over segments

The registered crashes at the study locations were mostly property damage–only (64%). Most crashes occurred before and on the entering lanes of the roundabouts (Table 3). The exiting lanes seem to be less prone to crashes. No crashes were registered for segments 9 and 11. This may be due to the low number of crashes on the bypass and to the small share of roundabouts with bypass (*N=3*) in the police data.

Table 3: Distribution of roundabout crashes by roundabout segment and crash severity.

Roundabout segment	**Total crashes**	**Property damage only crashes**	**Injury crashes**	**Slightly injured***	**Severely injured***	**Fatally injured***
All segments	399 (100)					
Segment 1	65 (16)	48	17	17	0	0
Segment 2	52 (13)	31	21	19	2	0
Segment 3	75 (19)	48	27	25	2	0
Segment 4	83 (21)	45	38	32	5	1
Segment 5	32 (8)	28	4	4	0	0
Segment 6	53 (13)	33	20	18	1	1
Segment 7	27 (7)	14	13	13	0	0
Segment 8	8 (2)	7	1	1	0	0
Segment 9	0	0	0	0	0	0
Segment 10	4 (1)	3	1	1	0	0
Segment 11	0	0	0	0	0	0

Values between parentheses represent percent values of the column total.

* The severity of the injury crashes is determined by the injury severity of the road user who endured the most serious injury during the crash (Carpentier & Nuyttens, 2013):

- Fatally injured: every person involved in a crash and died at the scene or before hospitalization or within 30 days after the crash;
- Severely injured: every person involved in a crash and whose condition is so severe that hospitalization for more than 24 hours is required;
- Slightly injured: every person who is injured in a crash and for whom the definitions of fatally and severely injured is not applicable.

2.3.2 Crash types

The crashes were categorised into eight different crash types. These crash types are described in Table 4. Four main crash types – rear-end, collision with central island, entering-circulating and vulnerable road user – accounted for 75% of roundabout crashes.

Table 4: Roundabout crash types.

Crash Type	Description
Run-off-road	Single-vehicle crash in which a vehicle leaves the road and collides with an off-road object such as a traffic sign or splitter island
Collision with central island[1]	Single-vehicle crash in which a vehicle leaves the circulatory road and collides with the central island
Wrong-way	Road user enters the roundabout in the non-permitted direction
Rear-end	Second vehicle collides with the rear of the lead vehicle
Loss-of-control	Collision between two road users due to loss of control
Vulnerable road user	Collisions between a vehicle and vulnerable road users such as pedestrians, bicyclists, motorcycles or mopeds
Entering-circulating	Collisions between two road users in which the entering vehicle fails to yield and collides with the circulating vehicle
Sideswipe	Collisions caused by lane-changing on the circulatory road and by exiting the roundabout

[1] Collisions with the central island can be regarded as a form of loss-of-control crashes or run-off-road crashes. Due to the high number of collisions with the central island it was decided to define it as a separate crash type.

2.3.3 Relation between crash type and location

The crash types were allocated to the roundabout segments according to their crash location (Table 5). The results in Table 5 indicate that significantly more run-off-road crashes took place in segments 7 and 8. In segment 4, significantly more collisions occurred with the central island. Significantly, more wrong-way crashes took place in segment 5. However, the sample size of this crash type in segment 5 is very small ($N = 2$). Rear-end crashes were the dominant crash type for segments 1, 2, and 5. Significantly, more loss-of-control crashes occurred in segments 5 and 6. Entering–circulating crashes were the dominant crash type for segment 3. Segments 6 and 7 are characterised by significantly more vulnerable road user crashes. Sideswipe crashes were the dominant crash type for segment 6. Significantly more collisions with the central island occurred during night-time, $\chi2$ (1, $N = 372$) = 52.911, $P < .001$, whereas significantly more loss-of-control crashes took place at dusk/dawn. Daytime crashes were more likely than night-time crashes to be rear-end crashes, $\chi2$ (1, $N = 372$) = 11.881, $P = .001$, vulnerable road user crashes, $\chi2$ (1, $N = 372$) = 6.301, $P = .012$, and entering–circulating crashes, $\chi2$ (1, $N = 372$) = 6.528, $P = .011$.

Table 5: Roundabout crash types by crash location.

Crash type^a	**Crashes**	**X^{2b}**	**P^***
All crash types	**399 (100)**		
Run-off-road	**43 (11)**		
Segment 2	10 (23)	1.836	.175
Segment 3	1 (2)	8.556	.003
Segment 4	5 (12)	2.576	.109
Segment 5	5 (12)	0.850	.369
Segment 6	5 (12)	0.115	.735
Segment 7	10 (23)	20.769	**<.001**
Segment 8	6 (14)	35.018	**<.001**
Segment 10	1 (2)	1.599	.290
Collision with central island	**79 (20)**		
Segment 4	78 (99)	357.636	**<.001**
Segment 5	1 (1)	6.092	.014
Wrong-way	**4 (1)**		
Segment 2	1 (25)	0.511	.429
Segment 5	2 (50)	9.653	**.034**
Segment 7	1 (25)	2.129	.245
Rear-end	**115 (29)**		
Segment 1	61 (53)	160.036	**<.001**
Segment 2	27 (23)	15.554	**<.001**
Segment 3	3 (3)	27.739	<.001
Segment 5	15 (13)	5.527	**.019**
Segment 6	5 (4)	11.199	.001
Segment 8	2 (2)	0.058	1.000
Segment 10	2 (2)	2.110	.201

Table 5: Roundabout crash types by crash location (continued).

Crash type^a	Crashes	X^{2b}	P^*
Loss-of-control	**41 (10)**		
Segment 1	3 (7)	2.881	.090
Segment 2	3 (7)	1.437	.231
Segment 3	6 (14)	0.626	.429
Segment 4	1 (2)	9.846	.002
Segment 5	9 (21)	11.441	**.003**
Segment 6	14 (33)	16.383	**<.001**
Segment 7	6 (14)	4.206	0.052
Entering-circulating	**54 (13)**		
Segment 3	51 (96)	240.062	**<.001**
Segment 6	2 (4)	4.798	.028
Vulnerable road user	**50 (13)**		
Segment 2	9 (18)	1.244	.368
Segment 3	14 (28)	3.172	.075
Segment 6	17 (34)	21.299	**.000**
Segment 7	10 (20)	15.866	**.001**
Sideswipe	**13 (3)**		
Segment 1	1 (8)	0.729	.703
Segment 2	2 (15)	0.066	.681
Segment 6	10 (77)	47.248	**.000**

Values in bold in parentheses represent percentage values of the column total.
Values between parentheses represent percentage values of the column total regarding the segment distribution within each crash type.
^{a} Not every crash type occurred in each segment.
^{b} X^2 test: each crash type is per segment compared to the combined average of all other segments
* $P \leq .05$ (significant at 95% confidence interval).The *P* value of the overrepresented crash types is highlighted in bold.

2.3.4 Relation between crash type, crash location and crash severity

The results of the logistic regression models are presented in Table 6. The models in Table 6 indicate the variables that influence the probability of being injured (injured versus uninjured) in a roundabout crash. The models are fit on the subject level; that is, on the level of the involved road users in the crashes. The results for model 1 show that the probability of being injured in a roundabout crash is more likely when the road user is involved in collisions with the central island (OR = 5.91) and crashes on double-lane roundabouts (OR = 1.52). The injury severity appears to depend on the road user type. Moped riders (OR = 3.49) and cyclists (OR = 10.36) seem to be more likely to be injured in roundabout crashes than car (OR = 0.12) and truck drivers (OR = 0.02). Subsequently, the second model also shows that the probability of being injured in a roundabout crash is more likely when road users are involved in crashes in segment 4 (OR = 6.24) and crashes on double-lane roundabouts (OR = 1.60). Again, the injury severity appears to be affected by the road user type. The probability to get injured is significantly lower when the road users are involved in crashes in segment 5 (OR = 0.20).

Table 6: Logistic regression results for crash severity on subject level[a].

	Model 1			**Model 2**		
	Parameter	Odds ratio	Significance	Parameter	Odds ratio	Significance
Intercept	0.3844		.3683°	0.0732		.9850°
Crash type (ref. sideswipe)						
Run-off-road	0.3125	1.37	.5146°			
Collision with central island	1.7761	**5.91**	<.0001***			
Wrong-way	-0.0727	0.93	.9605°			
Rear-end	0.4517	1.57	.1299°			
Loss-of-control	-0.3726	0.69	.3870°			
Entering-circulating	-0.3095	0.73	.4230°			
Vulnerable road user	0.9282	2.53	.0877*			
Road user (ref. pedestrian)						
Car	-2.0880	**0.12**	<.0001***	-1.6908	**0.18**	<.0001***
Moped rider	1.2506	**3.49**	.0352**	1.3799	**3.98**	.0216**
Cyclist	2.3382	**10.36**	<.0001***	2.2573	**9.56**	<.0001***
Motorcyclist	0.4044	1.50	.6372°	0.3356	1.40	.6854°
Truck	-3.7178	**0.02**	<.0001***	-3.2773	**0.04**	<.0001***

Table 6: Logistic regression results for crash severity on subject level[a] (continued).

	Model 1			**Model 2**		
	Parameter	Odds ratio	Significance	Parameter	Odds ratio	Significance
Roundabout (ref. single-lane)						
Double-lane	0.4209	**1.52**	.0009***	0.4712	**1.60**	.0007***
Segment (ref. segment 10)						
Segment 1				0.5726	1.77	.0838*
Segment 2				0.4855	1.63	.1546°
Segment 3				-0.3671	0.69	.3065°
Segment 4				1.8308	**6.24**	<.0001***
Segment 5				-1.5987	**0.20**	.0273**
Segment 6				-0.6332	0.53	.0996*
Segment 7				0.1404	1.15	.7717°
Segment 8				-0.1871	0.83	.8309°
Summary statistics						
Observations	636			636		
Observed nr. of injured	156			156		
Proportion of injured	0.25			0.25		
Hosmer and Lemeshow[b]	X^2 = 7.57 (df= 6, P =.27)			X^2 =1.67 (df=6, P =.94)		

[a] Due to convergence problems the variables ‘crash type’ and ‘segment’ could not be inserted in one model.

[b] The Hosmer and Lemeshow goodness-of-fit test indicates a good fit for both models.

Odds ratio values that are significant at $P \leq .05$ are highlighted in bold.

*** $P \leq .01$ (significant at 99% confidence interval), ** $P \leq .05$ (significant at 95% confidence interval), * $P \leq .10$ (significant at 90% confidence interval), ° $P > .10$ (not significant at 90% confidence interval).

2.3.5 Single-lane and double-lane roundabouts

One roundabout design characteristic which is studied is the impact of the number of lanes on the crash type and the location of the crashes. Table 7 shows a distribution of the crashes by crash type according to number of roundabout lanes. Five of the eight crash types seem to be related with the number of roundabout lanes. At single-lane roundabouts significantly more rear-end and vulnerable road user crashes occurred than at roundabouts with 2 lanes. Double-lane or 2-lane roundabouts are characterised by significantly more loss-of-control, collision with the central island and sideswipe crashes compared to single-lane roundabouts. These three crash types are possibly related to the larger size of double-lane roundabouts. Furthermore, two lanes make weaving manoeuvres possible, which can lead to sideswipe crashes.

Table 7: Distribution of crashes at single-lane and double-lane roundabouts by crash type[a].

Crash types	Total number of crashes	Single-lane roundabout	Double-lane roundabout	X^2	P^*
All crashes	399 (100)	290 *(73)*	109 *(27)*		
Run-off-road	43 (11)	34 *(79)*	*9 (21)*	0.990	.320
Collision with central island	79 (20)	47 *(59)*	32 *(41)*	8.105	**.004**
Wrong-way	4 (1)	3 *(75)*	1 *(25)*	0.011	.917
Rear-end	115 (29)	93 *(81)*	22 *(19)*	5.455	**.020**
Loss-of-control	41 (10)	22 *(54)*	19 *(46)*	8.328	**.004**
Entering-circulating	54 (13)	40 *(74)*	14 *(26)*	0.061	.805
Vulnerable road user	50 (13)	50 *(100)*	0	21.486	**<.001**
Sideswipe	13 (3)	1 *(8)*	12 *(92)*	32.917	**<.001**

[a] Values in italics between parentheses represent percentage values of the row total.
Values between parentheses represent percentage values of the column total.
$^*P \leq .05$ (significant at 95% confidence interval). The *P* value of the overrepresented crash types is highlighted in bold.

The crashes were distributed over the segments and assigned to the number of roundabout lanes according to their location (Table 8). Segments 1 and 7 on single-lane roundabouts are characterised by significantly more crashes than double-lane roundabouts. On double-lane roundabouts significantly more crashes took place in segments 4 and 6 compared to single-lane roundabouts. A separate chi-square test revealed that the crash severity was also higher in segment 4 on double-lane roundabouts X^2 (1, N = 145) = 18.834; P = .000, because more injury crashes occurred in this segment at roundabouts with two lanes. Although more crashes occurred in segment 6 on double-lane roundabouts, significantly more injury crashes took place in this segment on single-lane roundabouts X^2 (1, N = 145) = 6.951, P = .008. These two results are consistent with the results from Table 5 indicating that segment 4 is characterised by crashes resulting from collisions with the central island, whereas vulnerable road user crashes are the dominant crash type for segment 6.

Table 8: Distribution of crashes at single-lane and double-lane roundabouts by segment[a].

Segments	**Total number of crashes**	**Single-lane roundabout**	**Double-lane roundabout**	X^{2b}	P^*
All segments	399 (100)	290 *(73)*	109 *(27)*		
Segment 1	65 (16)	63 *(97)*	2 *(3)*	22.981	**<.001**
Segment 2	52 (13)	34 *(65)*	18 *(35)*	1.603	0.205
Segment 3	75 (19)	59 *(79)*	16 *(21)*	1.666	0.197
Segment 4	83 (21)	53 *(64)*	30 *(36)*	4.112	**.043**
Segment 5	32 (8)	24 *(75)*	*8 (25)*	0.094	0.759
Segment 6	53 (13)	26 *(49)*	27 *(51)*	17.181	**<.001**
Segment 7	27 (7)	24 *(89)*	*3 (11)*	3.831	**.050**
Segment 8	8 (2)	3 *(37)*	*5 (63)*	5.089	**.024**
Segment 10	4 (1)	4 *(100)*	0	1.519	.218

[a] Values in italics between parentheses represent percentage values of the row total.
Values between parentheses represent percentage values of the column total.

[b] X^2 test: the crash number for each segment is per roundabout type compared to the combined average crash number of all other segments.

[*] $P \leq .05$ (significant at 95% confidence interval). The P value of the overrepresented crash types is highlighted in bold.

2.3.6 Cycle facilities at roundabouts

The second design characteristic that is studied is the effect of the type of cycle facility at the roundabout on crashes with vulnerable road users (cyclists and mopeds). Four different types of cycle paths are distinguished: mixed traffic, cycle lanes within the roundabout, separate cycle paths, and grade separated cycle paths (see Daniels et al. (2009) for a more detailed explanation). The sample of crashes with cyclists and mopeds is rather small for all of the different cycle facilities; hence, it is not possible to draw hard conclusions. The results presented in this section can only be regarded as indicative. Table 9 compares the crashes with cyclists and mopeds for the four types of cycle facilities.

Table 9: Distribution of cyclists' and mopeds' crashes according to type of cycle facility.

Cycle facilities	Total number of crashes	Crashes (only cyclists and mopeds)	X^{2a}	P^*
All cycle facilities	399 (100)	46 (100)		
Mixed traffic	21 (5)			
Cyclists and mopeds		3 (6)	2.572	.109
Cycle lanes within roundabout	131 (33)		36.913	**<.001**
Cyclists and mopeds		36 (79)		
Separated cycle paths	138 (35)		12.585	<.001
Cyclists and mopeds		6 (13)		
Grade separated cycle paths	109 (27)		23.103	<.001
Cyclists and mopeds		1 (2)		

Values between parentheses represent percentage values of the column total.

[a] X^2 test: the crash number for each cycle facility is compared to the combined average crash number of all types of cycle facilities.

[*] $P \leq .05$ (significant at 95% confidence interval).The P value of the overrepresented crash types is highlighted in bold.

Significantly more crashes with cyclists and mopeds occurred at roundabouts with cycle lanes. Significantly fewer crashes occurred at roundabouts with separate and grade separated cycle paths. However, these differences in crash susceptibility may also be related to different cyclist volumes at the cycle facilities. Due to the lack of traffic volume data, we were unable to test this hypothesis. The design of the cycle facilities has an influence on the crash location of crashes with cyclists and mopeds because this location appears to be intertwined with the location where the cycle path interacts with the infrastructure for other (motorised) road users (Table 10).

Table 10: Distribution of cyclists' and mopeds' crashes according to type of cycle facility and roundabout segment.

Cycle facilities	Total number of crashes[a]	Crashes (only cyclists and mopeds)	X^{2b}	P^*
Mixed traffic	21 (100)	3 (100)		
Segment 2	3 (14)	0	0.010	1.000
Segment 3	9 (42)	2 (67)	0.397	.611
Segment 6	2 (9)	1 (33)	0.485	.650
Segment 7	0	0	0.000	1.000
Cycle lanes within roundabout	131 (100)	36 (100)		
Segment 2	7 (5)	5 (14)	1.427	.245
Segment 3	26 (20)	10 (28)	0.003	1.000
Segment 6	17 (13)	16 (44)	6.250	**.012**
Segment 7	7 (5)	5 (14)	3.001	.118
Separate cycle paths	138 (100)	6 (100)		
Segment 2	9 (7)	2 (33)	2.454	.144
Segment 3	2 (1)	1 (17)	1.135	.414
Segment 6	4 (3)	0	4.906	.039
Segment 7	4 (3)	3 (50)	5.375	**.041**
Grade separated cycle paths	109 (100)	1 (100)		
Segment 2	18 (17)	0	0.224	1.000
Segment 3	13 (12)	1 (100)	2.624	.280
Segment 6	27 (25)	0	0.526	1.000
Segment 7	2 (2)	0	0.255	1.000

Values between parentheses represent percentage values of the column total regarding the crash distribution within each type of cycle facility.

[a] Only the crashes that occurred in these 4 segments are mentioned in this column

[b] X^2 test: the crash number for each segment is per type of cycle facility compared to the combined average crash number of all other segments.

[*] $P \leq .05$ (significant at 95% confidence interval).The *P* value of the overrepresented crash types is highlighted in bold.

2.3.7 Involved road users

The results of the logistic regression models are presented in Table 11. The models in Table 11 indicate the variables that influence the probability of being involved in a roundabout crash according to the type of involved road user (motorised versus vulnerable road users). Model 1 shows that motorised road users are more likely to be involved in rear-end crashes (OR = 3.29) and in crashes on double-lane roundabouts (OR = 2.44), whereas they are underrepresented in crashes with vulnerable road users (OR = 0.06).

Model 2 also indicates that motorised road users are significantly more involved in crashes on double-lane roundabouts (OR = 3.09) and crashes occurring in segment 1 (OR = 6.84) and segment 4 (OR = 2.07). Furthermore, motorised road users are significantly less involved in crashes occurring in segment 6 (OR = 0.27) and segment 7 (OR = 0.28).

Table 11: Logistic regression results for type of involved road user on subject level[a].

	Model 1			**Model 2**		
	Parameter	Odds ratio	Significance	Parameter	Odds ratio	Significance
Intercept	2.7292		<.0001***	3.1485		<.0001***
Crash type (ref. sideswipe)						
Run-off-road	0.3466	1.41	.6658°			
Collision with central island	0.4309	1.54	.4541°			
Wrong-way	-0.5320	0.59	.7192°			
Rear-end	1.1895	**3.29**	.0236**			
Loss-of-control	0.4572	1.58	.4819°			
Entering-circulating	-0.3639	0.70	.4190°			
Vulnerable road user	-2.7696	**0.06**	<.0001***			
Roundabout (ref. single-lane)						
Double-lane	0.8899	**2.44**	.0003***	1.1289	**3.09**	<.0001***

Table 11: Logistic regression results for type of involved road user on subject level[a] (continued).

	Model 1			**Model 2**		
	Parameter	Odds ratio	Significance	Parameter	Odds ratio	Significance
Segment (ref. segment 10)						
Segment 1				1.9229	**6.84**	.0025***
Segment 2				-0.6826	0.51	.0955*
Segment 3				-0.6400	0.53	.0718*
Segment 4				0.7287	**2.07**	.0034***
Segment 5				0.6035	1.83	.3539°
Segment 6				-1.3129	**0.27**	.0008***
Segment 7				-1.2588	**0.28**	.0028***
Segment 8				0.2608	1.30	.8566°
Summary statistics						
Observations	636			636		
Observed nr. of motorised[b]	568			568		
Proportion of motorised	0.89			0.89		
Hosmer and Lemeshow[c]	X^2 = 2.59 (df= 6, *P* = .86)			X^2 =1.19 (df=6, *P* = .98)		

[a] Due to convergence problems the variables 'crash type' and 'segment' could not be inserted in one model.

[b] The motorised category contains cars and trucks while the vulnerable road user category consists of pedestrians, cyclists, motorcyclists and moped riders.

[c] The Hosmer and Lemeshow goodness-of-fit test indicates a good fit for both models.

Odds ratio values that are significant at p ≤ 0.05 are highlighted in bold.

*** *P* ≤.01 (significant at 99% confidence interval).

** *P* ≤.05 (significant at 95% confidence interval).

* *P* ≤.10 (significant at 90% confidence interval).

° *P* >.10 (not significant at 90% confidence interval).

2.4 Discussion

This study aimed to describe crash patterns at roundabouts. The number of roundabouts included was relatively low (*N* = 28) and could be a somewhat biased representation of a larger (e.g., countrywide) roundabout population in the sense that only roundabouts were included where at least one crash was registered and for which detailed crash data were available. A possible bias associated herewith is a slight overrepresentation of roundabouts with higher numbers of crashes. However, the objective of the study was not to make inferences about the performance of roundabouts compared to each other but to identify crash types, locations, and factors that are associated with roundabout crashes. The collected sample of 399 crashes can be considered to be valid for that purpose.

We believe that detailed roundabout segments as a proxy for the crash location, in combination with the identification of dominant crash types and type of involved road user, provides valuable insights in the nature of roundabout crashes and the safety impact of roundabout design.

The present study reveals that the crash frequency is higher when entering than exiting the roundabout because about 80% of the crashes occurred on the entry lanes and the circulatory road (segments 1–4 and 6). Two earlier studies also pointed out that the crash frequency is very high in these 2 roundabout locations (Mandavilli et al., 2009; Montella, 2011). In addition, 4 dominant crash types are identified, of which the crash location is related to certain roundabout segments. Rear-end collisions mostly occurred on the entry lanes (segments 1 and 2), indicating differences in decelerations between drivers before entering the roundabout. Most of the collisions with the central island (segment 4) took place in the evening or at night. Possibly, roundabouts are less visible in dusky light conditions or at night and road users might also tend to adopt higher approach speeds due to the lower traffic volumes at night. Mandavilli et al. (2009) also found that night-time crashes are more likely crashes where vehicles leave the roadway and collide with the central island or other objects. Given this crash pattern, roundabouts should be designed to be sufficiently conspicuous at night. At night the entire roundabout and especially the central island should be well illuminated or clearly visible with the headlights of the vehicle. Ground-level lighting of the central island, reflective pavement markings, and reflective paint on curbs may increase visibility. From a safety point of view, it is also crucial that roundabouts are constructed in such a way that the speeds of the approaching road users are reduced. Therefore, entry lanes and entry deflection should be narrow and tight enough to promote slow speeds.

Entering–circulating crashes primarily dominated the location where the entry lane is connected to the circulatory road (segment 3). A plausible cause for most of these crashes was entering drivers who failed to yield to circulating drivers (Flannery & Elefteriadou, 1999; Robinson et al., 2000) or circulating drivers who used their direction indicators too early. Crossing the roundabout at the exit lane appeared to be more dangerous for vulnerable road users because they predominated the crashes at the exit lanes (segments 6–7). Most likely, the lower speeds when exiting roundabouts are offset by the higher degree of complexity that drivers of exiting vehicles experience after interacting with other vehicles in the roundabout (Sakshaug et al., 2010). This situation might lead to less alertness from drivers for vulnerable road users when exiting the roundabout, which in turn increases the probability of vulnerable road user crashes. Furthermore, roundabouts with integrated cycle lanes turned out to result in significantly more crashes with cyclists and moped riders. The phenomenon "looked-but-failed-to-see" (Jörgensen & Jörgensen, 1994) and unadjusted speeds between interacting vulnerable road users and motorists leads to less attentiveness toward each other and higher crash risks for cyclists (Sakshaug et al., 2010). For this reason, the type of cycle facility is critically important for the safety of vulnerable road users. It is preferable that future roundabouts should not be constructed with cycle lanes close to the roadway. This is already the standard policy in most European countries (Rodegerdts et al., 2010). However, this recommendation does not imply that already implemented roundabouts with integrated cycle lanes need to be redesigned to roundabouts with separate or grade-separated cycle paths. Merely converting the cycle facility to another one without adjusting the geometric variables will not improve the safety for vulnerable road users and drivers of motorised vehicles. For example, removing integrated cycle lanes by renovating the circulatory road makes the roadway wider, which results in higher vehicle speeds that could lead to an increased occurrence of other crash types such as single-vehicle collisions with the central island or other fixed objects.

The results of the logistic regression models show that the crash type, road user type, and number of roundabout lanes affect the outcome severity of a crash. Crashes in which vulnerable road users (especially cyclists and moped riders) are involved, collisions with the central island, and crashes occurring on double-lane roundabouts have a higher probability of resulting in injuries. Daniels et al. (2010b) found the crash severity at roundabouts to be strongly dependent on the involved road user type and a higher number of injured road users -compared to crashes with cars or trucks - for crashes with pedestrians, bicyclists, moped riders, and motorcyclists. However, the higher injury rate for vulnerable road users might be the result of underreporting rates, because it is commonly known that less severe crashes with these road users are underreported (Amoros et al., 2006). Nevertheless, vulnerable road users represent 33% of the injured road users at the studied roundabout locations, whereas they represent merely 8.3% of the total number of involved road users. The higher crash severity rate of collisions with the central island might be determined by the rigidness of the central island, making it incapable of softening the impact. Furthermore, the probability of being injured in a roundabout crash is higher for crashes on double-lane roundabouts because significantly more collisions with the central island occur at these roundabout locations. According to Robinson et al. (2000), double-lane roundabouts are more dangerous due to a lower speed reduction compared to single-lane roundabouts, which results in more single-vehicle crashes with the central island and a higher rate of injured road users. Other studies confirmed this finding (Mandavilli et al., 2009; Montella, 2011).

The results of this explorative study provide interesting topics for further research. Future studies of crashes occurring at roundabouts should further examine the relationship between dominant crash types, their crash location in terms of the defined segments, and roundabout characteristics such as the speed limit, location (urban or rural), geometric aspects, complex double-lane roundabouts, and roundabouts with bypasses. The main conclusions of this study can be summarised as follows:

- Four dominant crash types occur at roundabouts: rear-end crashes, single-vehicle collisions with the central island, entering–circulating crashes, and crashes with vulnerable road users.
- Crashes with motorised vehicles mostly take place on the entry lanes and the circulatory road (segments 1 and 4) and vulnerable road user crashes prevail at the exit lane (segments 6–7).
- Crashes in which vulnerable road users are involved and single-vehicle crashes with the central island generally lead to more severe injuries.
- Detailed roundabout segments as a proxy for the crash location provide valuable insights into the nature of roundabout crashes and the safety impact of roundabout design.

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CHAPTER 3: CRASH PATTERNS AT SIGNALIZED INTERSECTIONS

In the following chapter, I was involved in the design, methodological execution, development of the accident location typology, performing the literature review, data collection, analyses and writing the paper.

This chapter is based on:

Polders, E., Daniels, S., Hermans, E., Brijs, T. & Wets, G. (2015) *Crash patterns at signalized intersections.* Transportation Research Record: Journal of the Transportation Research Board, 2514, p. 105-116. (Web of Science 5-year impact factor 0.872).

Proceedings:

Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2015). Crash patterns at signalized intersections. In: *Proceedings of the 94th Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

Research report:

Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2015). *Ongevallenpatronen op verkeerslichtengeregelde kruispunten*. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-004, Diepenbeek, Belgium.

ABSTRACT

Objectives: Traffic signals are often implemented to provide for efficient movement and to improve traffic safety. Nevertheless, severe crashes still occur at signalized intersections. This study aims to improve the understanding of signalized intersection safety by identifying crash types, locations and factors associated with signalized intersections.

Methods: For this purpose, 1295 police-reported injury and property damage–only crashes at 87 signalized intersections in Flanders, Belgium (period 2007-2011) were analysed. The analysis was carried out based on detailed crash descriptions, that is, crash data and collision diagrams. The information from the collision diagrams was used to distinguish six different crash types and to create a crash location typology to divide the signalized intersection into 13 detailed typical segments. Logistic regression modelling techniques were used to identify relations between crash types, their crash location on certain signalized intersection segments, the crash severity and the different features that affected crash occurrence.

Results: Four dominant crash types were identified: rear-end, side (i.e. left-turn plus right-angle), head-on and vulnerable road user crashes. The results of the logistic regression models showed that the location of these crash types was related to specific signalized intersection segments. The results also revealed important signalized intersection features that affected crash occurrence.

Conclusions: As a result, connections between certain signalized intersection crash types, their crash location and signalized intersection design characteristics were found. The combination of intersection features with detailed signalized intersection segments provided valuable insights into the nature of signalized intersection crashes and the safety impact of signalized intersection design.

Keywords: crash types, crash location, collision diagram, signalized intersection, logistic regression

3.1 Introduction

Intersections are crash-prone locations since they are characterised by many conflicting movements, which result in complexity and large variations in interactions between road users. To minimise the number of conflicts at intersections and to increase traffic safety, intersections are often equipped with traffic signals (Roess, Prassas, & McShane, 2011). Despite the fact that traffic signals separate movements in space and time, crashes at these intersections still occur. In Flanders, Belgium, approximately 8% of all injury crashes occur at signalized intersections and represent 4% of all road deaths (Nuyttens, Carpentier, Declerq, & Hermans, 2014). However, equipping intersections with traffic lights can also induce side effects. Traffic signals can change the crash pattern at intersections by decreasing head-on and angle crashes while increasing rear-end crashes (Elvik et al., 2009; Ogden, 1996). Subsequently, traffic lights also give rise to red-light-running crashes, which tend to be more severe since they typically occur at high speeds (Ogden, 1996).

Previous studies identified four dominant crash types at signalized intersections: rear-end, angle, sideswipe, and vulnerable road user crashes (Abdel-Aty et al., 2006; Antonucci, Kennedy Hardy, Slack, Pfefer, & Neuman, 2004; Chandler et al., 2013; Ogden & Newstead, 1994). Crashes with vulnerable road users and angle crashes are of a more severe nature and result more often in dead or severely injured road users, whereas sideswipe and rear-end crashes have a less serious outcome and result in crashes with material damage or slight injuries (Abdel-Aty & Keller, 2005; Chandler et al., 2013; Ye, Pendyala, Al-Rukaibi, & Konduri, 2008).

Several studies have also researched the relation between signalized intersection design and crash occurrence. The presence or absence of several signalized intersection design characteristics appears to have a beneficial or adverse effect on the traffic safety of these locations. The total number of lanes is positively related to the number of crashes (Abdel-Aty et al., 2006). However, exclusive right-turn and left-turn lanes have a positive effect on traffic safety since they reduce the total number of crashes, whereas exclusive right-turn lanes (in countries with right-hand traffic) also lead to a decrease in rear-end crashes (Chandler et al., 2013; Wang, 2006). Medians lead to lower crash severity levels since they prevent more severe head-on crashes (Abdel-Aty & Keller, 2005). Signalized intersection speed limits play an important role in the total number of crashes, angle crashes, left-turn crashes, head-on crashes, rear-end collisions, and crashes with vulnerable road users (Abdel-Aty & Keller, 2005; Keller, Abdel-Aty, & Brady, 2006). In general, red-light cameras tend to increase the number of rear-end crashes and decrease the occurrence of side crashes (i.e., left-turn plus right-angle crashes) (De Pauw, Daniels, Brijs, Hermans, & Wets, 2014; Høye, 2013; Shin & Washington, 2007). Protected-only and protected-permitted left-turn signal phasing leads to substantial decreases in the number of injury and severe injury crashes at signalized intersections (De Pauw, Daniels, Brijs, Hermans, & Wets, 2013). These types of signal phasing also have a favourable effect on left-turn crashes (De Pauw et al., 2013; Srinivasan et al., 2012). Vulnerable road user facilities also influence traffic safety at signalized intersections. At signalized intersections with low vehicle speeds and volumes, mixing cyclists with motorised traffic at the intersection has been reported to be the safest solution (Gårder, Leden, & Thedéen, 1994). Pedestrian safety at signalized intersections has been found to depend on the number of lanes. The more lanes pedestrians must cross, the higher the number of pedestrian crashes (Torbic et al., 2010).

3.2 Study objective

Many studies have already focused on the road safety performance of signalized intersections. However, little is known about the exact location of the crashes. Therefore, this study focuses on identifying and analysing the crash patterns at signalized intersections by using detailed information about the location of the crash. Gstalter and Fastenmeier (2010) analysed driver error by dividing intersections into segments according to the tasks that drivers should perform in each segment. The current study elaborates on this approach and tries to delineate the crash location on the signalized intersection itself in more detail to gain better insight into the crash patterns and their exact location. This method identifies the dominant crash type inside each segment and endeavours to link the crash occurrence with design characteristics of the signalized intersection. As a result, the findings of this study result in a detailed description of the crash patterns at signalized intersections, which provide insights into the safety impact and possible safety issues of this intersection design. Other studies have also applied the same or similar methods to other locations including stop-sign-controlled intersections (Retting et al., 2003), roundabouts (Polders, Daniels, Casters, & Brijs, 2015), freeway ramps (McCartt et al., 2004), and work zone crashes (Khattak & Targa, 2004).

3.3 Methodology

3.3.1 Data

3.3.1.1 Crash data

In this study, the crashes were sampled from police-reported crashes at 87 signalized intersections in the region of Flanders, Belgium. The national crash database could not be used since it does not contain detailed information about the crash location at the signalized intersection. Therefore, several police districts were selected that systematically register more detailed crash location information. Ultimately, 12 police districts were able to provide the requested data. This approach resulted in a convenience sample of signalized intersection locations.

The crashes occurred in the period of 2007 to 2011. Crash data were available for each year and for every sampled signalized intersection in this entire period. In total, 1,344 crash reports containing injury and property-damage-only crashes were obtained. These police reports provided basic (such as time, place of occurrence, weather and light conditions) and detailed (such as crash type and location) information about the registered crashes. The detailed crash information, in the form of collision diagrams, was used to develop crash types. A collision diagram is a schematic representation of all crashes that occurred at a given signalized intersection or other location over a specific period (Ogden, 1996). This diagram indicates the dominant crash types at a signalized intersection and the manoeuvres that led to these crashes while providing detailed information about the crash location at the intersection.

3.3.1.2 Intersection design and usage data

Crash data alone are not sufficient to provide insights into the crash patterns at signalized intersections. It is also important to know the crash location in terms of roadway and traffic data in order to gain a full understanding of the traffic safety situation. These factors may affect the crash occurrence. Roadway data aid in detecting the physical and use characteristics of the location that may have contributed to the crash occurrence or severity, whereas traffic volume data are used to control for use intensity of the location (Kweon, 2011).

Based on a literature review, the most relevant signalized intersection characteristics were selected as they appear from previous crash prediction model studies (Abdel-Aty et al., 2006; Nambuusi, Brijs, & Hermans, 2008; Reurings et al., 2006). They include number of arms, presence of exclusive turn lanes, number of lanes, location in a built-up area, type of bicycle infrastructure, presence of a median, speed limit, signal phasing, crossings for vulnerable road users, and presence of a bypass and red-light camera. Traffic volume data were available for 54 of 87 sampled signalized intersections. The traffic volumes in the data are expressed as annual average daily traffic (AADT). No data were available for exposure by type of road user and the actual driving speeds at the signalized intersection. A detailed description of intersection characteristics is provided in Table 12 and Table 13.

Table 12: Descriptive statistics – crash variables.

Variable	**Description**	**Signalized Intersection ($N_{\text{locations}}$= 87, N_{crashes} = 1295)**
Injury crash	Crash type with regard to the crash outcome.	Property damage only = 596, Injury crash = 699
Crash severity	Determined by the most severe casualty.	No injuries = 596, Dead = 7, Severely injured = 64, Slightly injured = 628
Road user	Type of involved road user; frequencies expressed at subject level.	Car = 2098, Truck = 105, Bus = 27, Motorcycle = 48, Moped = 100, Cyclist = 162, Pedestrian = 42, Other = 70
Crash	Crash type according to number of involved road users.	Single = 130, Multiple = 1165
Crash type	Crash type according to collision angle (0°, 90°, 180°).	Single vehicle = 130, Head-on (180°) = 181, Rear-end (0°) = 471, Pedestrian = 41, Sideswipe (45°) = 121, Side crash (90°) = 351
Segment	Location of crash expressed as one of the segments (seg.) of Figure 11.	Seg. 1 =103, Seg. 2 =301, Seg. 3 = 97, Seg. 4 = 214, Seg.5 = 71, Seg. 6 = 187, Seg. 7 = 79, Seg. 8 = 62, Seg. 9 = 66, Seg. 10 = 36, Seg. 11 = 8, Seg. 12 = 33, Seg. 13 = 38
Vulnerable road user (VRU)	Crash in which at least one VRU is involved.	Yes = 268, No = 1027

Note: VRUs are pedestrians, cyclists, mopeds, and motorcyclists.

Table 13: Descriptive statistics – intersection design variables.

Variable	**Description**	**Signalized Intersections ($N_{locations}$= 87, $N_{crashes}$ = 1295)**
Arms	Number of intersection arms	3 = 22 (201), 4 = 65 (1094)
Lanes	Total number of lanes at intersection[a]	1 = 12 (90), 2 = 39 (434), 3 = 26 (379), 4 = 10 (392)
Exclusive right turn	Presence of exclusive right-turn lane at intersection (at least on one intersection arm)	Yes = 63 (455), No = 24 (840)
Exclusive left turn	Presence of exclusive left-turn lane at intersection (at least on one intersection arm)	Yes = 72 (1186), No = 15 (109)
Built-up area	Location of intersection in terms of inside or outside built-up area	Yes = 50 (581), No = 37 (714)
Median	Presence of median at intersection[b]	Yes = 50 (930), No = 37 (365)
Speed limit	Speed limit at intersection	50 km/h = 42 (442), 70 km/h = 31 (414), 90 km/h = 14 (439)
Cycle facility	Type of cycle facility at intersection[c]	Mixed = 4 (30), Cycle lanes = 39 (507), Separated = 40 (554), Grade-separated = 4 (204)
Pedestrian crossing	Presence of pedestrian crossing at intersection[b]	Yes = 81 (1092), No = 6 (203)
Cyclist crossing	Presence of cyclist crossing at intersection[b]	Yes = 52 (833), No = 35 (462)
Signal phasing	The type of signal phasing at intersection (for left turns)	Protected-only = 12 (301) , Protected-permitted = 13 (236), Permitted = 62 (758)

Table 13: Descriptive statistics – intersection design variables (continued).

Variable	**Description**	**Signalized Intersections ($N_{\text{locations}}$= 87, N_{crashes} = 1295)**
Bypass	Presence of a bypass at the intersection[b]	Yes = 29 (712), No = 58 (583)
Red-light camera (RLC)	Presence of a red-light camera at the intersection (at least in one direction)	Yes = 31 (657), No = 56 (638)
Traffic volume	The traffic volume at the intersection (AADT)	Mean = 30959.66 S.D. = 11960.80 Min. = 14561.73 Max. = 67497.13

Note: Values in parentheses = number of crashes that occurred in entire sample with a certain characteristic.

[a] In case of different situations at intersection arms, highest number in lane is applied.

[b] In case of different situations at intersection arms = yes.

[c] In case of different situations at intersection arms, highest cycle facility type is applied.

3.3.2 Signalized intersection segments

The detailed crash location was determined by dividing the signalized intersection into different typical segments according to previously established knowledge on the crash occurrence and road user behaviour at signalized intersections (Abdel-Aty et al., 2006; Chandler et al., 2013; De Pauw et al., 2014; Gstalter & Fastenmeier, 2010; Ogden & Newstead, 1994). Figure 11 shows the selected 13 segments, which are described as follows:

- Segment 1. 20 to 100 m from the signalized intersection; oncoming traffic and queues associated with congestion;
- Segment 2. 20 m before the intersection plane until the stop line; Segment 3. Exclusive left-turn lane, if present;
- Segment 4. First half of the intersection plane; pedestrian and cyclist crossings;
- Segment 5. Second half of the intersection plane for traffic going straight ahead;
- Segment 6. Second half of the intersection plane for traffic turning left;
- Segment 7. 20 m after the junction plane for right-turning traffic leaving the intersection; pedestrian and cyclist crossings;
- Segment 8. Identical to Segment 7 but for traffic going straight ahead;
- Segment 9. Identical to Segment 7 but for left-turning, leaving traffic;
- Segment 10. 20 to 100 m after the intersection plane; leaving traffic;
- Segment 11. Beginning of the bypass, if present;
- Segment 12. Middle section of the bypass, including pedestrian and cyclist crossings, if present; and
- Segment 13. End section of the bypass until the yield markings.

Segments 11 to 13 are optional and are only relevant when the signalized intersection is characterised by a bypass. Figure 11 is a representation of a typical signalized intersection. The segments were defined in such a way that the variety of real-world designs is represented and meaningful analyses based on the defined standard segments are possible. To capture all possible designs, a “maximal design” was used; this design represents a typical signalized intersection layout with some extra features that are not necessarily always present. For example, a bypass lane was added in order to include crashes that happen on bypass lanes at certain intersections. This layout means that only crashes at Segments 11 to 13 must be registered in case of a signalized intersection with such a bypass lane. The same applies for the cycle facilities (cycle paths and cycle crossings): pedestrian or bicyclist crossings at real-world intersections occur in different varieties. Therefore, although Figure 11 represents an adjacent cycle path, the real distance between the cycle facility and the roadway may vary between 0 and 10 m and be grade-separated. This principle also applies to the number of lanes and the number of intersection arms.

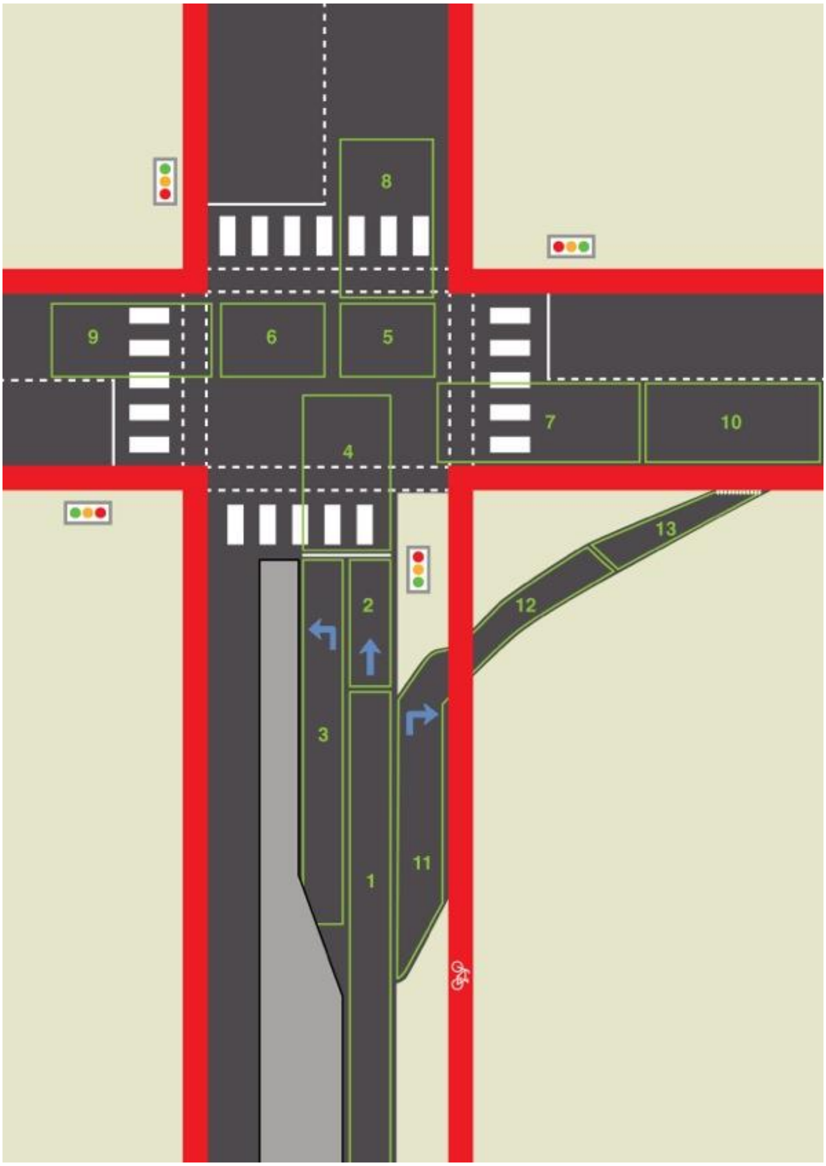

Figure 11: Signalized intersection segments.

3.3.3 Crash location typology

A crash typology was created to assign the crashes to the segments shown in Figure 11. This typology is based on the crash typology of Massie et al., who identified different crash scenarios between motorised vehicles based on crash data and collision diagrams (Massie, Campbell, & Blower, 1993). The first step involved revising the crash data and collision diagrams to select the variables that seemed most useful to the development of a crash location typology. The main focus of this review was on the pre-crash movements of the involved road users. The selected variables of the initial review were used to build a preliminary crash location typology, which was modified by adding and deleting variables until the final crash location typology scheme, as shown in Figure 12, was produced. This typology is applicable for crashes between motorised road users, between motorised and vulnerable road users, and between vulnerable road users. The southern intersection approach in Figure 11 was used as the analysis unit. Each crash was located by starting from this intersection approach. The road user who makes the pre-crash manoeuvre or movement always approaches the intersection from this side. The manoeuvring road user is based on the schematic representation of the crash in the collision diagrams.

The final crash location typology includes the number of road users involved in the crash, the location of the impact point, the relative pre-crash orientation of the road users, and the movement of the road user who makes the manoeuvre. Figure 12 provides an overview of the typology.

The crashes were first split according to whether the road user was involved in a crash with only one or with multiple road users (Step 1). These two groups were then divided on the basis of whether the crash took place before, after, at the intersection plane, or at the bypass (Step 2). Multiple road user crashes were split into three categories: road users approaching each other from the same direction before the crash, road users approaching from opposite directions, and road users approaching on crossing paths (Step 3). Subsequently, the single and multiple road user crashes were further split according to whether the manoeuvring road user was moving straight ahead or attempting to make a left, right, or U-turn (Step 4). Finally, the resulting subgroups were assigned to the crash location expressed as Segments 1 to 13 in Figure 11 (Step 5). Steps 4 and 5 are combined in Figure 12 for visualization purposes.

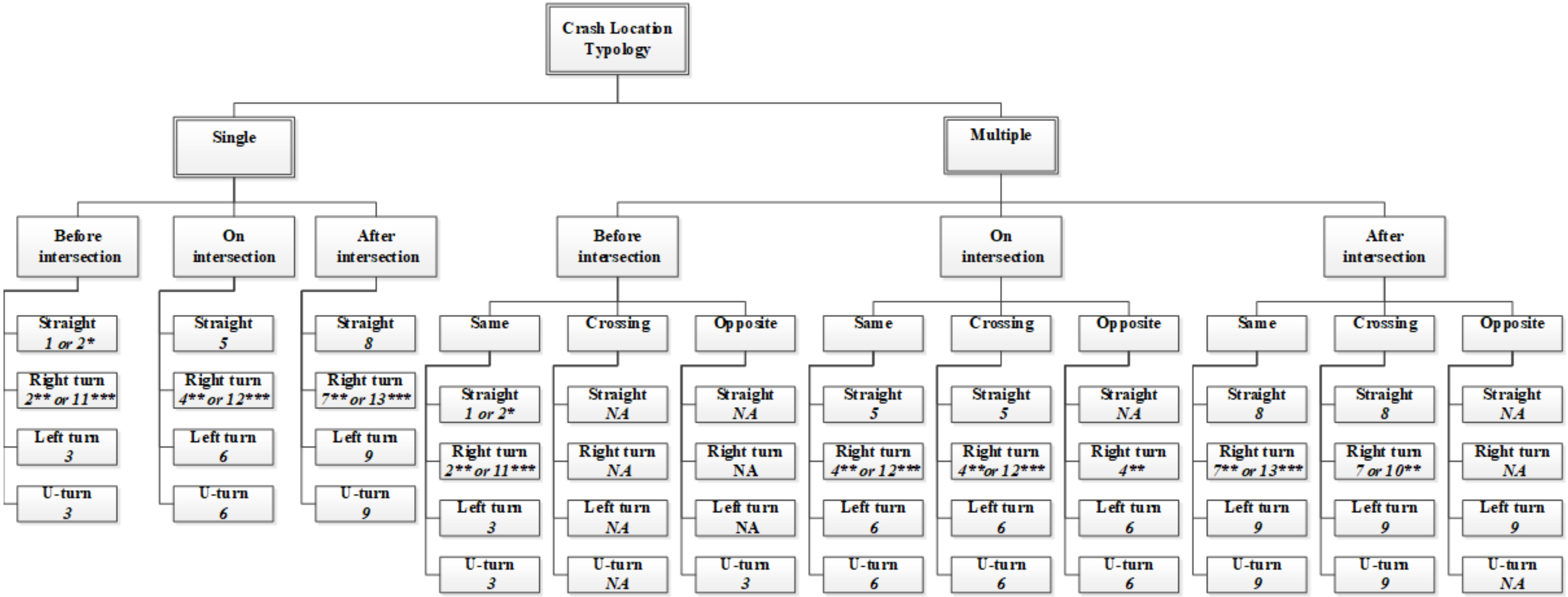

Figure 12: Crash location typology [numbers indicate intersection segment; NA = no segment available (not every manoeuvre can occur on each segment); *depends on distance to intersection; **intersection without bypass; ***intersection with bypass].

3.3.4 Crash data analysis

Several studies previously applied logistic regression analysis to test the influence of traffic crash risk factors (Al-Ghamdi, 2002; Chen, Cao, & Logan, 2012; Yan, Radwan, & Abdel-Aty, 2005; Yau, 2004; Zhang, Lindsay, Clarke, Robbins, & Mao, 2000). In this study the occurrence of certain dominant crash types at signalized intersections can be considered as a binary response variable. Therefore, logistic regression analysis was used to predict the probability of a certain event. This analysis also allows the testing of the relation between the dominant crash types and their crash location on the signalized intersection. The structure of the fitted logistic regression models was the following (Allison, 1999):

$$\mathrm{logit}\ (\mathrm{P}) = \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \ + \cdots + \beta_n x_n \tag{1}$$

where

P = probability of dominant crash types,

x_n = independent variable, and

β_n = partial logistic regression coefficient.

The odds of each dominant crash type were defined as the probability of the occurrence of this specific dominant crash type divided by the probability of the occurrence of all other signalized intersection crash types. Odds ratios [$OR = \exp(\beta_n)$] were calculated to determine the rate of decrease ($0 \leq OR < 1$) or increase ($OR > 1$) of the probability of the outcome when the value of the independent variables increases by one unit (Field, 2009). Firth's penalised maximum likelihood was applied to overcome the most common convergence failure in logistic regression, namely, the problem of quasi-complete separation (Allison, 1999; Heinze & Schemper, 2002). The logistic regression models were developed with the LOGISTIC procedure in SAS 9.3, and the variables identified in the literature as having a significant impact on signalized intersection crashes were added first.

Crash reports with missing data were omitted from the models, resulting in 1,295 complete crash records. The model fit was assessed with the Hosmer–Lemeshow test, which indicates if the final model provides a better fit than the null model. If the chi-square goodness of fit is not significant at a confidence interval of 95%, the model has an adequate fit. Since this statistic gives no indication of the error reduction of the final model, Nagelkerke's R^2 was also used. The variance inflation factor was used to identify multicollinearity between the predictor variables. According to O'Brien (2007), variance inflation factors higher than 4 indicate a high correlation between variables. Since all variables in the end models had variance inflation factors below this threshold, there are no multicollinearity issues in the presented models.

3.4 Results

3.4.1 Descriptive statistics

All crashes within 100 m from the centre of the intersection were included in the analysis to ensure that all crashes related to the signalized intersection were incorporated into the data set. Descriptive statistics of the crash data are presented in Table 12 and Table 13. The registered crashes at the study locations were mostly injury crashes (53%, 699 out of 1,295). The variable "segment" indicates that most crashes occur in Segments 1, 2, and 4 before the intersection plane and on Segment 6 of the intersection plane, where left-turning traffic conflicts with oncoming vehicle streams. Segments 11 to 13 on the bypass seem to be less prone to crashes. This finding may be due to the small share of signalized intersections with a bypass ($N = 29$) in the police data.

The crashes were categorised into six different crash types: rear-end, head-on, sideswipe, single-vehicle, pedestrian, and side crashes. Three main crash types can be considered as the dominant crash types - rear-end, side (left-turn plus right-angle crashes), and head-on crashes - since they accounted for 77% of the signalized intersection crashes. In general, these three crash types typically take place between motorised road users. This characteristic is also the case in this study since 96%, 74%, and 85% of the involved road users in rear-end, side, and head-on crashes, respectively, were motorised road users. No separate crash type was developed for cyclists, as was done for pedestrians, because the action radius of cyclists is larger than that for pedestrians. Therefore, the 150 registered cyclist crashes were divided among the six defined crash types. The majority of cyclist crashes were side (71%) and head-on collisions (14%). The other crash types - single-cyclist (5%), rear-end (8%), pedestrian (1%), and sideswipe crashes (1%) - occurred less frequently.

3.4.2 Logistic regression results

Table 14 presents the factors that influence the dominant signalized intersection crash types and the factors that affect the probability that one of these dominant crash types will occur. The dependent variable was the probability that a specific dominant crash type occurred over the entire 5-year period from 2007 to 2011.

The results show that the probability of an injury increases in the case of side crashes, head-on crashes, and crashes with vulnerable road users, whereas single-vehicle crashes result significantly less in injuries. The injuries are also more severe in crashes involving vulnerable road users.

The crash types seem to be related to certain signalized intersection segments. Injury crashes are more likely on Segments 4, 5, and 6, which are the segments on the intersection plane, than on Segments 3, 10, and 13. Crashes before the intersection plane (Segments 1 to 3) and on the bypass (Segments 11 to 13) are more likely rear-end crashes than crashes on and after the intersection plane (respectively, Segments 5 and 6 and Segments 7 and 10). Side crashes are more likely on the intersection plane (Segments 4 to 8) than before (Segments 1 to 3) and after the intersection plane (Segment 10). Crashes on the intersection plane (Segments 4 to 6) are also more likely head-on crashes than crashes before the intersection plane (Segments 1 and 2). The probability of crashes with vulnerable road users is higher on the crossing facilities after the intersection plane (Segments 7 and 8) and on the bypass (Segment 12) than before (Segments 1 to 3) and on the intersection plane (Segments 5 and 6).

The type of left-turn signal phasing also influences the probability of certain dominant crash types. Injury crashes are less likely at intersections with protected-only and protected-permitted signal phasing (compared with the standard permitted signal phasing). Rear-end, head-on, and vulnerable road user crashes are less likely at signalized intersections with protected-only signal phasing. Vulnerable road user crashes are also less likely at signalized intersections with protected-permitted signal phasing whereas the probability of rear-end crashes increases. The odds of head-on crashes seem to decrease non-significantly at signalized intersections with protected-permitted signal phasing.

Moreover, the signalized intersection layout affects the odds of certain dominant crash types. The probability of an injury crash decreases at signalized intersections with an exclusive lane for right-turning traffic, and rear-end crashes appear to be more likely at signalized intersections with three arms. Furthermore, rear-end and vulnerable road user crashes appear to be less likely at signalized intersections with two lanes, whereas vulnerable road user crashes also are significantly more likely at signalized intersections with three lanes. Rear-end and head-on crashes are less likely at signalized intersections with medians.

Side crashes are more likely at signalized intersections located inside built-up areas, whereas the probability of head-on crashes decreases. Furthermore, injury crashes are less likely at 50-km/h intersections (compared with 70- and 90-km/h intersections), and vulnerable road user crashes are more likely at 50-km/h intersections and less likely at 70-km/h intersections (compared with 90-km/h intersections). Crashes with vulnerable road users also appear to be more likely at signalized intersections where cycle traffic is mixed with motorised traffic.

Enforcement cameras at signalized intersections also appear to affect certain crash types since the presence of a red-light camera decreases the probability of side, head-on and vulnerable road user crashes.

Table 14: Factors influencing probability of signalized intersection crash types.

Variables[1]	**Logistic regression results at crash level (N=1295)**					
	Injury crashes[a] according to crash type (Y=699)	Injury crashes[a] according to crash location (Y=699)	Rear-end crashes (Y=471)	Side crashes[b] (Y=351)	Head-on crashes (Y=181)	VRU crashes[c] (Y=268)
Intercept	0.6719 ***	0.8753 ***	-1.2603 ***	-1.5545 ***	-3.2815***	-0.3506°
Crash type (ref = sideswipe)						
Single vehicle	-0.9745 (**0.38**)***					
Head-on	0.8965 (**2.45**)***					
Rear-end	-0.0396 (0.96)°					
Side	0.6679 (**1.95**)***					
Pedestrian	0.6527 (1.92)°					
Segment (ref = segment 9)						
Segment 1		0.00209 (1.00)°	1.7636 (**5.83**)***	-0.6957 (**0.50**)**	-1.3791 (0.25)*	-0.7382 (**0.48**)**
Segment 2		-0.091 (0.91)°	2.7385 (**15.46**)***	-3.7433 (**0.02**)***	-2.4178 (**0.09**)***	-2.1688 (**0.11**)***
Segment 3		-0.7963 (**0.45**)***	1.4328 (**4.19**)***	-2.5073 (**0.08**)***	-0.7805 (0.46)°	-1.3573 (**0.26**)***
Segment 4		0.5328 (**1.70**)***	-0.1245 (0.88)°	1.545 (**4.68**)***	1.4759 (**4.37**)***	0.1931 (1.21)°
Segment 5		0.9915 (**2.70**)***	-2.1494 (**0.12**)***	2.799 (**16.42**)***	1.0755 (**2.93**)***	-1.0304 (**0.36**)***
Segment 6		0.7509 (**2.12**)***	-3.6358 (**0.03**)***	0.9333 (**2.54**)***	3.3968 (**29.87**)***	-1.1661 (**0.31**)***
Segment 7		-0.092 (0.91)°	-1.6861 (**0.19**)***	1.9607 (**7.10**)***	0.1590 (1.17)°	2.3335 (**10.31**)***
Segment 8		-0.0188 (0.98)°	-0.3096 (0.73)°	1.1573 (**3.18**)***	0.1479 (1.16)°	1.3144 (**3.72**)***
Segment 10		-0.8600 (**0.42**)*	-1.6962 (**0.18**)***	-2.6337 (**0.07**)**	-1.3188(0.27)°	0.00919 (1.01)°
Segment 11		0.9540 (2.60)°	1.5628 (**4.77**)**	0.7828 (2.19)°	-0.1309 (0.88)°	0.2505 (1.28)°
Segment 12		-0.5459 (0.58)°	1.1263 (**3.08**)***	0.2856 (1.33)°	-1.3473 (0.26)°	1.1215 (**3.07**)**
Segment 13		-0.6863 (**0.50**)**	2.7873 (**16.24**)***	-0.9771 (0.38)°	0.8286 (2.29)°	-0.2283 (0.80)°
VRU (ref= no)						
Yes	1.0217 (**2.78**)***	1.2739 (**3.57**)***	-0.6937 (**0.50**)***			
Exclusive right (ref = no)						
Yes	-0.1518 (**0.86**)**					
Speed limit (ref = 90)						
50	-0.6209 (**0.54**)***	-0.6153 (0.54)***				1.1511 (**3.16**)***
70	0.1664 (1.18)°	0.1513 (1.16)°				-0.5889 (**0.55**)***
Cycle facility (ref = grade-separated)						
Mixed traffic						1.4599 (**4.31**)***
Adjacent						-0.3425 (0.71)°
Separated						-0.1700 (0.84)°

Table 14: Factors influencing probability of signalized intersection crash types (continued).

Variables[1]	**Logistic regression results at crash level (N=1295)**					
	Injury crashes[a] according to crash type (Y=699)	Injury crashes[a] according to crash location (Y=699)	Rear-end crashes (Y=471)	Side crashes[b] (Y=351)	Head-on crashes (Y=181)	VRU crashes[c] (Y=268)
Signal phasing (ref = permitted)						
Protected-only and Protected-permitted	-0.2325 (**0.79**)**	-0.2232 (**0.80**)**				
Protected-only			-0.2677 (0.77)*		-0.7673 (**0.46**)***	-0.5139 (**0.60**)**
Protected-permitted			0.514 (**1.67**)***		-0.0103 (1.00)°	-0.3845 (**0.68**)**
Arms (ref = 4)						
3			0.3497 (**1.42**)***			
Lanes (ref = 4)						
1			0.015 (1.02)°			0.1538 (1.17)°
2			-0.7966 (**0.45**)***			-0.3603 (**0.70**)**
3			0.0113 (1.01)°			0.6654 (**1.95**)***
Median (ref = no)						
Yes			-0.4030 (**0.67**)***		-0.1582 (**0.85**)**	
Built-up area (ref = no)						
Yes				0.2423 (**1.27**)***	-0.3889 (**0.68**)***	
RLC (ref = no)						
Yes				-0.1814 (**0.83**)**	-0.4832 (**0.62**)***	-0.4089 (**0.66**)***
Crash severity (ref = slightly injured)						
Unharmed						-2.8083 (**0.07**)***
Dead						1.6745 (**5.34**)**
Severely injured						1.0825 (**2.95**)***
Hosmer and Lemeshow test[2]	$\chi^2 = 8.9597$ (df = 8, *p* =.3457)	$\chi^2 = 6.8137$ (df = 8, *p* =.5569)	$\chi^2 = 3.5617$ (df = 8, *p* =.8943)	$\chi^2 = 7.7375$ (df = 8, *p* =.4595)	$\chi^2 = 10.4146$ (df = 8, p =.2371)	$\chi^2 = 14.9971$ (df = 8, *p* =.0592)
Nagelkerke R^2	.3087	.2747	.6332	.4602	.5005	.5950

Note: Values present parameter estimates of logistic regression model. For categorical variables with more than two categories, the category is indicated. Homer–Lemeshow goodness-of-fit test indicates good fit for all models. Nagelkerke statistic indicates error reduction of model in percentage (0.3087 is equal to error reduction of 30.87%). Odds ratios are shown in parentheses; odds ratios that are significant at $p \leq .05$ are in bold type. VRU = vulnerable road user; RLC = red-light camera; *Y* = number of "Yes" cases in logistic model; df = degrees of freedom.

[a] Because of convergence problems, the variables "crash type" and "segment" could not be inserted in one model,

[b] Side crashes consist of left-turn and right-angle crashes.

[c] VRU crashes = crashes in which at least one cyclist, motorcyclist, moped rider, or pedestrian is involved.

*$p > .10$ [not significant at 90% confidence interval (CI)]; **$p \leq .10$ (significant at 90% CI); ***$p \leq .05$ (significant at 95% CI); ****$p \leq .01$ (significant at 99% CI).

The results of the logistic regression models were not able to reveal all the characteristics of the dominant crash types. No meaningful models could be fit for sideswipe (N = 121) and single-vehicle (N = 130) crashes. However, occurrence of sideswipe crashes is significantly more likely on the left-turn lane in Segment 3 [($\chi^2(1, N = 1{,}295) = 62.734$, $p < .0001$] and on Segment 10 where the vehicles from the bypass merge with oncoming traffic [$\chi^2(1, N = 1{,}295) = 18.729$, $p < .0001$], whereas Segment 1 before the intersection [$\chi^2(1, N = 1{,}295) = 8.846$, $p = .0003$], Segment 8 after the intersection [$\chi^2(1, N = 1{,}295) = 30.747$, $p < .0001$], Segment 9 after the intersection [$\chi^2(1, N = 1{,}295) = 31.801$, $p < .0001$], and Segment 12 on the bypass [$\chi^2(1, N = 1{,}295) = 7.088$, $p = .016$] are characterised by significantly more single-vehicle crashes. The results of the descriptive statistics also revealed that occurrence of rear-end and sideswipe crashes is significantly more likely at red-light-camera signalized intersections, whereas single-vehicle, pedestrian, head-on, and side crashes dominate signalized intersections without a red-light camera [$\chi^2(5, N = 1{,}295) = 66.986$, $p < .0001$]. Significantly more crashes occur before the intersection (Segments 2 and 3) and on or near the bypass (Segments 10 to 13) for signalized intersections with a red-light camera, whereas signalized intersections without a red- light camera are characterised by significantly more crashes at Segment 1 before the intersection and Segments 4 to 9 on and after the intersection [$\chi^2(12, N = 1{,}295) = 57.940$, $p < .0001$].

3.5 Discussion of results

The current study used an in-depth crash location approach based on crash data and collision diagrams to analyse crash patterns at signalized intersections. The collision diagram information has proved to be essential and valuable for this purpose since these diagrams not only allow the definition of dominant crash types but also show the pre-crash manoeuvres and provide detailed information about the crash location on the signalized intersection. This crash location information was used to define 13 detailed signalized intersection segments that enabled categorization of the crash locations. This crash location approach in combination with the identification of dominant crash types and causal crash factors provide valuable insights into the nature of signalized intersection crashes and the safety impact of signalized intersection design.

Six crash types are identified of which four can be regarded as dominant signalized intersection crash types: rear-end, side, vulnerable road user, and head-on crashes. These results are more or less in line with the existing literature (Abdel-Aty et al., 2006; Antonucci et al., 2004; Chandler et al., 2013; Ogden & Newstead, 1994), but the earlier studies identified sideswipe instead of head-on crashes as the fourth dominant crash type. Except for rear-end crashes, these crash types are also characterised by higher-than-average crash severity levels. Single-vehicle crashes also appear to result in fewer injury crashes. Since more trucks are involved in this crash type [χ^2 (1, $N = 2{,}652) = 4.338$, $p = .037$], the lower crash severity levels can be accounted for by the higher mass of the truck, which protects the truck driver from serious injuries.

In addition, the results show that the crash location is related to certain signalized intersection segments. Rear-end collisions mostly occur on the entry lanes (Segments 1 to 3), possibly indicating differences in braking behaviour between road users because of conflicting decisions in the dilemma zone. This relation between crash type and crash location on the intersection is supported by the results of another study (Yan et al., 2005), which indicated that rear-end crashes are the most common crash type at signalized intersections since the diversity of actions taken increases because of the signal change. Inattentive driving by following drivers, differences between vehicles in braking performance, and following too closely at the time of a signal change are identified as specific causes of rear-end crashes (Abdel-Aty & Abdelwahab, 2004; Sayer, Mefford, & Huang, 2000; Strandberg, 1998).

Since rear-end crash occurrence is related to a signal change, the presented crash pattern on the entry lanes is plausible because drivers need to be confronted with the traffic signals in order to make a conflicting decision that can result in a rear-end crash. The bypass is also prone to more rear-end crashes, which can be caused by drivers yielding to vulnerable road users on the crossing facility (Segment 12) or stopping to find a gap to merge with the oncoming traffic (Segment 13). Since both situations result in braking movements, differences between drivers' braking performance and inattentiveness also result in more rear-end crashes at these locations.

Given this crash pattern, signalized intersections should be designed to be sufficiently conspicuous. The visibility of the intersection, traffic signals, or both should be improved for approaching drivers to increase their awareness. Improvements in signal coordination and optimisation of change intervals also lead to a decrease in rear-end crashes (Antonucci et al., 2004). Segments 4 to 6 are dominated by side and head-on crashes. Possibly, these crashes are the result of red-light-running drivers approaching the intersection from opposite directions, loss of control, or left-turning vehicles that are not yielding to oncoming vehicles during the permitted phase. In their observational study, Gstalter and Fastenmeier (2010) found that drivers make most errors when turning left at a signalized intersection. Therefore, driver errors can be related to the crashes in Segment 6. This finding emphasises the importance of clear road design concepts that are easily understandable for road users, the so-called self-explaining roads. Since these crashes take place between crossing road users or road users approaching each other from opposite directions, it is expected that they occur on the intersection plane. It is well known that these crashes are above all the result of red-light running or unprotected left-turn phasing. As a result, possible countermeasures include the implementation of protected left-turn phasing and red-light cameras even though the latter measure gives rise to increases in rear-end crashes.

Additional measures such as improvements in sight distance, signal coordination, and change intervals also result in fewer head-on and side crashes (Antonucci et al., 2004). Side crashes between vehicles and crossing cyclists and mopeds also characterise Segments 7 and 8. Crossing the signalized intersection after the intersection plane and on the bypass seems to be more dangerous for vulnerable road users since they prevail in crashes at Segments 7, 8, and 12. In general, motorists are more focused on other motorists than on vulnerable road users. Most likely, this aspect played a role in these crashes. Furthermore, conflicts between vulnerable road users and motorised vehicles still occur frequently at signalized intersections when they are not fully protected by the signal phasing (i.e., vulnerable road users have the same green phase as the turning traffic). As such, potential countermeasures for vulnerable road user crashes include the implementation of protected phasing for vulnerable road users at the crossing facilities and improved visibility for drivers approaching the crossing facilities. The type of signal phasing influences the proportion of certain crash types. Similar to findings by De Pauw et al. (2013) and Srinivasan et al. (2012), protected-only and protected-permitted left-turn signal phasing decrease the proportion of injury and vulnerable road user crashes. Srinivasan et al. (2012) found that protected-only phasing decreases rear-end crashes whereas protected-permitted left-turn signal phasing increases rear-end crashes; this finding is similar to the results presented here. Possibly, protected-permitted left-turn signal phasing still results in braking or stopping manoeuvres from left-turning vehicles waiting to select gaps in the opposing traffic. Protected-only signal phasing also decreases the occurrence of head-on crashes since this signal phasing type prevents possible conflicts between road users.

In line with previous studies (De Pauw et al., 2014; Høye, 2013), red-light cameras at signalized intersections are associated with lower proportions of side and vulnerable road user crashes. The presence of red-light cameras also gives rise to fewer head-on crashes since these cameras prevent red-light running. However, χ^2-tests also indicated that red-light cameras result in adverse effects since they lead to increases in the number of rear-end crashes. Probably, red-light cameras cause drivers to brake more abruptly in the dilemma zone since these cameras lead to higher stopping propensities (Lum & Wong, 2003). As a result, conflicting decisions in the dilemma zone have a higher chance to result in rear-end crashes.

The presence of a median results in a lower proportion of head-on crashes. Another study indicated that a median prevents vehicles from crossing into the path of oncoming traffic leading to fewer head-on crashes (Keller et al., 2006). Speed limits are significant for the proportion of injury crashes with an indication that higher speeds lead to higher crash severity. Similar to a study by Steinman and Hines (2004), the proportion of vulnerable road user crashes is also affected by the speed limit at the signalized intersection.

At signalized intersections where cycle traffic is mixed with motorised traffic, the proportion of vulnerable road user crashes is higher. However, these differences in crash susceptibility may also be related to different cyclist volumes at the cycle facilities. Because of the lack of traffic volume data for cyclists, this hypothesis could not be tested. Elvik et al. (2009) support this hypothesis; they found that the reduction of bicycle crashes is smaller at signalized intersections with cycle lanes since cycle lanes attract more cyclists and may give rise to increased speeds among cyclists. In line with research by Torbic et al. (2010), the proportion of vulnerable road user crashes increases with the number of lanes.

One limitation of the current study concerns the sample. The sample of signalized intersections used (N = 87) could be a somewhat biased representation of a larger (i.e., countrywide) signalized intersection population in the sense that only intersections where at least one crash was registered for each year and where detailed crash data were available were included. A possible bias associated here is a slight overrepresentation of intersections with higher numbers of crashes. However, the objective of the study was not to make inferences about the performance of signalized intersections compared with each other but to identify crash types, locations, and factors that are associated with signalized intersection crashes. The collected sample of 1,295 complete crash records can be considered valid for that purpose.

The next issue is the accuracy of the crash allocation. The crash location typology used to allocate the crashes to the different segments is based on simplified rules. By following this typology, the allocation of the crashes to the different segments does not fully correspond to the actual location of the crash. Despite this inconsistency, the allocation is still quite accurate since the typology is based on the impact point, the pre-crash orientation of the road users, and the manoeuvre that the road users make (i.e., the most important characteristics to reconstruct a crash). The objective of the study was not to duplicate an exact replica of each crash location but to provide insights into the crash patterns of dominant signalized intersection crashes. The developed crash location typology is assumed to be valid for this purpose since the reported crash location in the collision diagrams may also slightly deviate from the actual crash location. To ensure a consistency of 100% in both crash locations, advanced in-depth crash research such as crash reconstruction techniques is required. Since most police districts in Belgium are not familiar with these techniques, the results are not greatly affected by this variation.

Another point of discussion is the cross-section design of the study. According to Hauer (2010), causality cannot be reliably inferred from cross-section designs since cross-section studies compare intersections with a certain characteristic with other intersections with another characteristic. Therefore, this study design lacks the continuity in which the intersection remains the same. The possibility of confounding factors between the different intersections is not eliminated since this requires information about why a certain characteristic is present at one intersection and is absent at another (Hauer, 2010). Since this information is often not available and is difficult to account for but is required to draw cause-and-effect conclusions from cross-section data (Hauer, 2010), the presence of a correlation between the proportion of crashes (the dependent variable) and certain intersection characteristics (the independent variables) is not sufficient to conclude that there is a causal relationship between both variables. Finally, traffic flow count data were only available for 54 of 87 signalized intersections. Previous studies indicated that AADT (Chin & Quddus, 2003; Lui & Young, 2004; Reurings et al., 2006) is a critical variable for crash analysis. However, this requirement only applies to studies that aim to explain the variation in road safety performance of a sample of locations by identifying the influence of design characteristics on the level of safety. The focus of the current study is to explore the crash location of dominant crash types at a typical signalized intersection. To fulfil this objective, crash data of intersections with missing AADT values can be used since AADT as such is not a crucial variable to define the crash location. Because this study does not predict crashes but explores available crash data by delineating the crash location on the signalized intersection itself, the lack of an AADT value does not present any analysis issues.

An important advantage of the crash location approach is the generalisability. The presented approach is based on a sort of "maximal design" representing a typical signalized intersection layout with some extra features that are not necessarily always present but are quite common. Since the intersection layout and characteristics may vary, the approach can easily be adjusted to different designs and locations by tailoring the segments to the specific intersection or location layout in question and by adding the inherent characteristics that play a role in the crashes to the typology. For example, if researchers want to study the safety difference between signalized intersections and signed intersections (i.e., controlled with stop or yield signs), they can simply add this feature to the typology.

This approach is also a useful context for exploring intersection safety since it combines crash data with collision diagram information. As such, this method combines basic in-depth crash analysis with the benefits of aggregated crash analysis, leading to more reliable quantitative analysis. As a result, a more detailed insight is gained in the development and occurrence of crash types by relating crash occurrence with design characteristics of the signalized intersection. This insight is needed to assess the safety impact and possible safety issues of this intersection design, which is necessary to select the appropriate countermeasures to decrease crashes.

3.6 Conclusions

The main goal of this study was to identify and analyse dominant crash types at signalized intersections by taking detailed information on the crash location into account. Some connections between certain signalized intersection crash types, their crash location, and signalized intersection design characteristics have been found:

- Four dominant crash types occur at signalized intersections: Rear-end, side, vulnerable road user, and head-on crashes. Except for rear-end crashes, these crash types are also characterised by higher-than-expected crash severity levels.
- The crash location of these dominant crash types is related to specific signalized intersection segments: Rear-end crashes occur mostly before the intersection or on the bypass, side and head-on crashes mostly take place on and near the intersection plane, and vulnerable road user crashes occur predominantly at the crossing facilities after the intersection plane or on the bypass.
- Protected-only and protected-permitted left-turn signal phasing, exclusive turn lanes and 50-km/h speed limits are associated with lower proportions of injury crashes.
- Characteristics associated with higher proportions of rear-end crash types are protected-permitted left-turn signal phasing and red-light cameras.
- Lower proportions of head-on crashes are associated with red-light cameras, protected-only left-turn signal phasing, and medians.
- Red-light cameras are associated with lower proportions of side crashes.
- Lower proportions of vulnerable road user crashes are associated with red-light cameras and protected-only and protected-permitted left-turn signal phasing.
- Intersection features combined with detailed signalized intersection segments as a proxy for the crash location features provide valuable insights into the nature of signalized intersection crashes and the safety impact of signalized intersection design.

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CHAPTER 4: DRIVERS' BEHAVIOURAL RESPONSES TO SPEED AND RED LIGHT CAMERAS

In the following chapter, I was involved in the development of the study design, methodological execution, literature review, data collection, analyses of the on-site behavioural observation study and writing the vast majority of the paper. The second author performed the study design, methodological execution, literature review, data collection and analyses of the driving simulator experiment and also reported the results of this experiment in the paper.

This chapter is based on:

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., Wets, G. (2015). *Drivers' behavioural responses to speed and red light cameras.* Accident Analysis and Prevention, 81, p.153-166. (Web of Science 5-year impact factor 3.244).

Proceedings:

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., Wets, G. (2015). Schrik niet, u wordt gefotografeerd. In*: Geeraerd, Ingrid; Dergent, Stijn (Ed.). Jaarboek Verkeersveiligheid 2015*.

Daniels, S., **Polders, E.**, Cornu, J., De Ceunynck, T., Brijs, K., Brijs, T., Hermans, E., & Wets, G. (2014). Drivers' behavioural responses to red-light-cameras. In: *Proceedings of the 8th Fit to drive Congress*. Warsaw, Poland.

Polders, E., De Ceunynck, T., Daniels, S., Hermans, E., Brijs, T., & Wets, G., (2013). Rear-end conflicts at intersections with red light cameras: a before and after study. In: *Proceedings of the 26th ICTCT-workshop*. Maribor, Slovenia.

Research report:

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., & Wets, G. (2015). *Gedragsaanpassingen van bestuurders aan snelheids- en roodlichtcamera's. Vervolgonderzoek: effectiviteit van roodlichtca*mera's. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-002, Diepenbeek, Belgium.

ABSTRACT

Background: Numerous signalized intersections worldwide have been equipped with enforcement cameras in order to tackle red-light running and often also to enforce speed limits. However, various impact evaluation studies of red-light cameras (RLCs) showed an increase of rear-end collisions (up to 44%).

Objective: The principal objective of this study is to provide a better insight in possible explaining factors for the increase in rear-end collisions that is caused by placing combined speed and red-light cameras (SRLCs).

Method: Real-world observations and driving simulator-based observations are combined. Video recordings (period 2012-2013) at two signalized intersections where SRLCs were about to be installed are used to analyse rear-end conflicts, interactions and driver behaviour in two conditions (i.e., with and without SRLC). Furthermore, one of these intersections was rebuilt in a driving simulator equipped with an eye tracking system. At this location, two test conditions (i.e., SRLC and SRLC with a warning sign) and one control condition (i.e., no SRLC) are examined. The data of 63 participants were used to estimate the risk of rear-end collisions by means of a Monte Carlo Simulation.

Results: The results of the on-site observation study reveal decreases in the number of red and yellow light violations, a shift (i.e., closer to the stop line) in the dilemma zone and a time headway reduction after the installation of the SRLC. Based on the driving simulator data, the odds of rear-end collisions (compared to the control condition) for the conditions with SRLC and SRLC + warning sign is 6.42 and 4.01, respectively.

Conclusion: The real-world and driving simulator observations indicate that the risk of rear-end collisions increases when SRLCs are installed. However, this risk might decrease when a warning sign is placed upstream.

Keywords: conflict observation, driving simulator, combined speed and red-light cameras (SRLCs), enforcement, behaviour

4.1 Introduction

Numerous signalized intersections worldwide have been equipped with enforcement cameras in order to tackle red-light running and often also to enforce speed limits. Both red-light running and speeding are considered substantive problems, frequently leading to collisions. Collisions caused by red-light running are typically associated with side impacts (Polders, Daniels, Hermans, Brijs, & Wets, 2015). Red-light running at signalized intersections has a significant impact on road safety since this leads to more serious collisions, being side collisions or collisions with vulnerable road users (Kloeden, Ponte, & McLean, 2001; Retting, Ulmer, et al., 1999; Retting, Williams, et al., 1999; Shin & Washington, 2007). Urban areas are at greater risk for red-light running collisions (De Pauw et al., 2014; Retting, Williams, Preusser, & Weinstein, 1995) since 22% of the collisions in these areas are caused by red-light running (Retting et al., 1995). Therefore, road authorities most of the time place red-light cameras (RLCs) at signalized intersections to prevent red-light running and improve road safety (De Pauw et al., 2014; Llau & Ahmed, 2014; Martinez & Porter, 2006). Studies have shown that RLCs lead to a reduction of up to 44% in red-light running (Retting, Ulmer, et al., 1999; Retting, Williams, et al., 1999). However, rear-end collisions tend to occur more frequently at these intersections. This is often the result of a sudden braking manoeuvre of the leading vehicle, resulting in the fact that the following vehicle cannot stop in time (Shin & Washington, 2007). The effects of RLCs on the number of collisions are discussed in more detail below.

4.1.1 Effectiveness of red-light cameras

In general, the effectiveness of RLCs appears to be studied less extensively than the effectiveness of speed cameras. The studies which have been carried out primarily focus on the effects of RLCs on red-light running and collisions (i.e., rear-end and side) at intersections. Høye (2013) investigated the effects of RLCs in a meta-analysis, which replicated the results from a previous meta-analysis by the same author (Erke, 2009). Based on a total of 28 before-after studies, Høye (2013) found a non-significant decrease of all injury collisions by 13%. The number of right-angle collisions decreased by 13%, but the rear-end collisions increased by 39%. Furthermore, the effectiveness of RLCs tended to be higher when warning signs for the RLCs were set up at main entrances to areas with RLC enforcement than when each intersection with a RLC was signposted separately.

The aforementioned meta-analyses only examined the effect of cameras that detect red-light running. Some recent studies also investigated the effects of combined speed and red-light cameras (SRLCs). De Pauw et al. (2014) found an increase of 5–9% of the total injury collisions after the installation of SRLCs at intersections. However, the fatal and serious injury collisions showed a significant decrease of 14–18%. The increase in the number of injury collisions can be mainly attributed to the increased number of rear-end collisions (+44%). This number of rear-end collisions had a stronger rise at intersections in urban areas (+70%) than intersections outside built-up areas (+33%). A time series analysis showed that right angle collisions decreased by 46% at SRLCs intersections, but rear-end collisions also increased by 42% (Vanlaar et al., 2014). Results indicated that there were significantly fewer red-light running violations after installing a SRLC. Furthermore, SRLCs had a protective effect on speeding behaviour (also during green phases) at the intersections. In conclusion, it can be said that all available studies have found a decrease in the number of side collisions after the SRLC was installed. On the other hand, the existing literature also consistently observed an increase in the number of rear-end collisions.

4.1.2 Dilemma zone

One of the main problems with signalized intersections is that drivers have to make a decision whether or not to stop at the yellow onset (Wilson, 2006; Yan, Radwan, Guo, & Richards, 2009; Zaal, 1994). This decision can be difficult and depends on the current speed and position of the vehicle, the vehicle type (Gates, Noyce, Laracuente, & Nordheim, 2007), the time-to-stop-line, the time-to-cross intersection, the presence of an (S)RLC (Huang, Chin, & Heng, 2006) and whether the driver is a leading or following vehicle (Elmitiny, Yan, Radwan, Russo, & Nashar, 2010; Huang et al., 2006).

When the length of the yellow period is insufficient for the driver to stop comfortably, or to pass the stop line before the red phase has started, the driver is considered to be in the dilemma zone. The dilemma zone is a theoretical area of an intersection approach (2.0–5.5 s from the stop line) where a driver must take a decision (i.e., stop or go) when the traffic light has switched from green to yellow (Bonneson et al., 2002; Federal Highway Administration, 2005; McGee et al., 2012; Wilson, 2006; Yan et al., 2009). Especially when drivers approach a signalized intersection with a high speed, the dilemma zone problem may result in some drivers stopping abruptly while others decide not to stop (or even accelerate). Such variation in driving behaviour can lead to collisions (mainly rear-end collisions) on the intersection approach (Institute of Transportation Engineers (ITE), 2009; Yan et al., 2009).

4.1.3 Warning signs

SRLC warning signs (SRLCWSs) can be used to announce that the next intersection is equipped with a SRLC. Such warnings may have the potential to reduce the probabilities of collisions nearby intersections (Yan et al., 2009; Zaal, 1994). These warning signs can either be placed at all SRLC-intersections or at the start of an area with multiple SRLC-intersections. If SRLCWSs are only installed nearby the main entrances of an area, spillover effects are more likely to occur because most drivers will not be aware of the exact locations of the SRLCs (Høye, 2013). Zaal (1994) concluded that drivers will have more respect for red lights when not all SRLC-intersections are signposted, which increases the favourable (i.e., prevention of red-light running) and decreases the unfavourable (i.e., sharp braking manoeuvres) effects of SRLCs. However, Zaal (1994) also indicated that generalised signposting (e.g., only at the boundaries of a certain area) can have a disadvantage. Generalised signposting may reduce the deterrent effect of site-specific signposting, which possibly results in an increase of the number of collisions at potentially dangerous intersections.

4.2 Objectives

A lot of studies have already focused on the road safety performance of red-light cameras. However, little is known about the mechanisms contributing to the increase in rear-end collisions. The present study is designed to investigate the behavioural responses of drivers approaching signalized intersections with combined speed and red-light cameras (SRLCs) in urban areas. The principal objective of this study is to provide a better insight in possible explaining factors for the increase in rear-end collisions that is caused by placing SRLCs. For this purpose, real-world observations and driving simulator-based observations are combined.

4.3 Methodology

Two signalized intersections where SRLCs were about to be installed were selected for an on-field behavioural observation study in a before-and-after design. The intersections are both located in urbanised areas but differ in characteristics (Table 15). Both intersections are situated in the province of Antwerp, Belgium (Figure 13 a and b). The intersection in Kapellen is also recreated in a driving simulator.

Table 15: Site characteristics.

Characteristics	**Study Sites**	
	Kapellen	**Mechelen**
Approach lanes	2x1	2x1
Intersection arms	4	3
Speed limit (kph)	50	70
Cycle lane	Adjacent to roadway	Adjacent to roadway
Separate lane for left turn	35m long	84m long
Number of signal cycles per hour	Day: 52 Night: 76	Day: 36 Night: 36
Area	Urbanised	Urbanised
Function	Functional and recreational activities (home, work, shopping, etc.)	Functional and recreational activities (home, work, shopping, etc.)

(a) (b)

Figure 13: Study site (a) Kapellen and (b) Mechelen.

4.3.1 Behavioural observation

Video-based data collection system was used to record the road user behaviour before and after the installation of SRLCs. The cameras captured the vehicles as they approached the intersection from one intersection leg and aimed downstream at the intersection so that the rear of the vehicles was visible. From this angle, the cameras could capture all the required intersection and vehicle characteristics, such as brake light indications, traffic signal colour, vehicle location regarding the stop line, distance between vehicles in a car following situation and the decision of the driver during the yellow phase.

4.3.1.1 Data

Table 16 provides an overview of the data collection and analysis specifics. The video observations for the after period started six weeks after the installation of the SRLCs to reduce the novelty effect. Furthermore, the drivers were not informed about the installation of the cameras and no warning signs were present at the intersections to inform the drivers that they were approaching a SRLC-intersection. Afterwards, two observers went through the video recordings and selected 24 h of video data for both intersections in the two conditions for detailed analyses. The video data were selected according to predefined criteria to limit any differences between the before and after period to a minimum:

1. Only periods with dry road surface conditions were selected.
2. The duration of the selected time periods in the before and the after period should be the same. These should be selected from at least three different days to reduce the risk of introducing day-specific influences.
3. Weekdays are preferred over weekends.
4. Preferably the weekdays of the after period should be consistent with the selected weekdays in the before period.

Table 16: Data characteristics.

	Study sites	
	Kapellen	**Mechelen**
Data characteristics		
Before period	December 2012	June 2013
Total days recorded	14	14
After period	May 2013	October 2013
Total days recorded	14	14
Data analysis characteristics		
Before period	Dry pavement	Dry pavement
Hours[a]	24	24
Weekdays	Tuesday Wednesday Thursday Friday	Tuesday Wednesday Thursday Friday
Number of signal cycles	Day: 832 Night: 608	Day: 576 Night: 288
After period	Dry pavement	Dry pavement
Hours[a]	24	24
Weekdays	Tuesday Thursday Friday	Monday Tuesday Thursday Friday
Number of signal cycles	Day: 832 Night: 608	Day: 576 Night: 288

[a] Total analysed time period consisted of a full day (e.g. 24 hours) spread over several weekdays to avoid biased data resulting from day-specific random factors.

The selected video data were processed using T-Analyst (2014), i.e., a semi-automated video analysis system developed at Lund University. The system transforms the image coordinates of each individual pixel to road plane coordinates, which allows the software to accurately determine the position of an object in the image and to calculate its trajectory. This allows the calculation of road users' speeds and positions, distances to fixed objects and traffic conflict indicators in an accurate and objective way. Data were extracted from the video according to three different encoding procedures:

1. *Red/yellow/green light running*: for every vehicle approaching the intersection, vehicle type, exit movement (left/right/straight through) and the phase of the traffic light at the moment the vehicle crosses the stop line are registered. In this study, a vehicle runs the red, respectively, the yellow signal when the vehicle crosses the stop line one second after the onset of the red/yellow phase. According to the Belgian traffic law, it is

forbidden to run the red lights in any circumstance and drivers risk severe penalties if they are caught. Yellow light running is allowed by the traffic regulations but drivers should stop if they are able to. As such, time gains are the only benefits drivers have when running the red/yellow signal.

2. *Dilemma zone behaviour*: the decision process of the drivers confronted with a yellow traffic light is examined for every vehicle that is captured by the camera during the yellow phase. In this study, the dilemma zone is defined as the area in which more than 10% but less than 90% of the drivers decide to stop at the onset of the yellow phase (Zegeer, 1977).
3. *Rear-end conflicts*: potential rear-end conflict situations are identified by selecting every situation where the first vehicle in a car following process brakes for the yellow light. Subsequently, the camera captures the second vehicle at the moment the first vehicle applies the braking manoeuvre. When these situations are identified, the conflict severity and characteristics are analysed by means of the minimal time to collision indicator (TTC_{min}). TTC_{min} is the lowest TTC-value that is reached during an encounter process and is calculated by means of the relative distance between two vehicles and their relative speed. TTC_{min} is an indicator for the maximum chance of a conflict. The lower the TTC_{min}, the larger the chance of a collision.

A detailed overview of the collected variables for each encoding procedure is presented in Table 17.

Table 17: Variable summary on-field behavioural observation study.

Variables	**Kapellen**		**Mechelen**	
	Before	After	Before	After
Red/yellow/green light crossing	N = 4478	N =4571	N =12538	N =12137
Vehicle				
Car	3747	3811	9331	9149
SUV	131	134	453	531
Truck	207	212	1362	1339
Bus	59	42	71	76
Van	293	257	1142	927
Motorcycle	17	75	146	87
Moped	19	32	19	15
Other	8	8	14	13
Manoeuvre				
Left turn	916	916	1077	1107
Right turn	449	384	0	0
U-turn	0	0	1	1
Going straight	3109	3275	11460	11029
Traffic light phase				
Red	9	4	3	3
Yellow	143	123	156	123
Green	4326	4444	12379	12137

Table 17: Variable summary on-field behavioural observation study (continued).

Variables	**Kapellen**		**Mechelen**	
	Before	After	Before	After
Dilemma zone behaviour	N = 316	N = 303	N = 239	N = 236
Free flow - car following situation at the onset of the yellow phase				
Yes	287	278	210	202
No	29	25	29	34
Speed (m/s) - at the onset of the yellow phase				
Mean	12.24	12.11	13.36	13.06
S.D.	3.10	2.73	3.18	2.88
Min.	3.00	2.00	2.90	1.90
Max.	21.00	20.00	22.00	20.40
Time headway[b] (in s) - the time between the front of the lead vehicle passing a point on the roadway and the front of the following vehicle passing the same point.				
Mean	1.90	1.72	1.88	1.65
S.D.	0.95	0.74	0.72	0.75
Min.	0.61	0.60	0.44	0.45
Max.	4.20	3.80	3.91	3.42
Distance headway (in m) - the distance between the two vehicles at the onset of the yellow phase				
Mean	20.88	16.97	21.19	20.04
S.D.	11.51	6.97	9.74	9.26
Min.	4.30	4.21	6.10	6.20
Max.	50.40	29.30	52.80	42.00
Time-to-stop-line[c] (in s) - the time that remains until a vehicle would reach the stop line at the onset of the yellow phase.				
Mean	2.69	2.09	2.67	2.63
S.D.	1.69	1.38	1.22	1.22
Min.	0.03	0.05	0.01	0.45
Max.	9.15	6.91	6.98	7.40
Decision – decision of the driver at the time of the yellow phase				
Stops	158	136	84	112
Drives through	158	147	155	124
Traffic light phase - the color of the traffic light phase at which the vehicle makes the decision to drive through				
Red	10	1	3	3
Yellow	148	146	152	121
Vehicle				
Car	254	218	165	156
SUV	15	18	10	9
Truck	18	11	32	33
Bus	5	4	1	5
Van	24	22	30	32
Motorcycle	0	10	1	1
Moped	0	0	0	0
Other	0	0	0	0
Manoeuvre - manoeuvre of the vehicle at the onset of the yellow phase				
Left turn	62	57	45	52
Right turn	34	11	0	0
U-turn	0	0	0	0
Going straight	220	215	194	184

Table 17: Variable summary on-field behavioural observation study (continued).

Variables	**Kapellen**		**Mechelen**	
	Before	After	Before	After
Rear-end conflicts	N =8	N =5	N =8	N =5
Speed V1^d (in m/s) - the speed of V1 at the onset of the yellow phase				
Mean				
S.D.	8.44	9.4	7.91	8.05
Min.	2.32	3.11	2.51	3.93
Max.	6.0	4.0	4.0	1.11
	12.0	12.0	12.50	11.3
Speed V2^e (in m/s) - the speed of V2 at the onset of the yellow phase				
Mean				
S.D.	8.75	11.0	8.55	8.07
Min.	2.56	3.40	2.17	4.91
Max.	6.0	5.0	5.4	2.11
	13.0	13.5	11.60	12.6
Speed evasive action V1^d (in m/s) - the speed of V1 at the onset of the evasive action of V2				
Mean	6.63	8.90	6.0	5.93
S.D.	2.57	3.63	1.74	3.97
Min.	4.0	2.5	3.3	1.0
Max.	11.0	11.0	8.2	10.8
Speed evasive action V2^e (in m/s) - the speed of V2 at the onset of its evasive action				
Mean	9.25	11.2	7.74	8.21
S.D.	2.74	3.78	2.22	4.12
Min.	6.0	4.5	4.0	2.2
Max.	14.0	13.5	11.50	12.4
Intermediate distance (in m) - the distance between the two vehicles at the onset of the evasive action				
Mean	18.15	11.94	13.26	14.42
S.D.	7.71	5.16	3.84	3.65
Min.	7.90	6.89	7.50	10.90
Max.	28.90	19.21	17.90	19.60
Distance-to-stop-line V1^d (in m) - the distance of the V1 to the stop line at the onset of the yellow phase [g]				
Mean	20.39	22.10	29.43	28.70
S.D.	9.91	4.78	10.30	9.23
Min.	1.32	17.24	12.90	12.70
Max.	33.66	28.47	43.50	36.40
Time-to-stop-line V1^d (in s) - the time that remains until V1 reaches the stop line at the onset of the yellow phase				
Mean	2.55	2.75	3.79	2.77
S.D.	1.57	1.68	1.06	0.83
Min.	0.22	1.68	1.93	1.55
Max.	4.81	5.59	5.24	3.87
Minimum Time-to-Collision (TTC_{min}) (in s) - minimum value of the time until two road users would have collided had they continued with unchanged speeds and directions				
Mean	2.34	1.66	2.71	2.07
S.D.	0.75	0.89	0.69	0.94
Min.	0.90	0.90	2.03	1.01
Max.	3.80	2.90	3.83	3.67

Table 17: Variable summary on-field behavioural observation study (continued).

Variables	**Kapellen**		**Mechelen**	
	Before	After	Before	After
Rear-end conflicts	N =8	N =5	N =8	N =5
Time-to-Accident (TA) (in s) - the time that remains to an accident at the moment the evasive action is initiated, presupposed that the road users had continued with unchanged speeds and directions				
Mean	7.96	6.95	8.44	5.73
S.D.	3.96	2.66	4.40	5.19
Min.	3.80	3.00	4.20	1.71
Max.	15.40	9.50	16.02	11.59
Time headway[f] (in s) - the elapsed time (in s) between the front of V1 passing a point on the roadway and the front of V2 passing the same point.				
Mean	2.00	1.54	1.81	1.63
S.D.	0.66	0.89	0.66	0.23
Min.	1.30	0.70	1.10	1.50
Max.	3.00	2.90	3.20	2.00
Distance headway (in m) - the distance between the two vehicles at the onset of the yellow phase				
Mean	17.73	15.04	14.65	17.66
S.D.	8.45	6.26	3.52	2.70
Min.	7.61	8.48	8.80	14.70
Max.	34.94	24.21	17.90	21.70
Vehicle V1				
Car	7	5	7	4
SUV	0	0	0	0
Truck	0	0	0	1
Bus	0	0	0	0
Van	1	0	1	0
Motorcycle	0	0	0	0
Moped	0	0	0	0
Other	0	0	0	0
Vehicle V2				
Car	6	3	4	4
SUV	2	0	0	0
Truck	0	1	1	0
Bus	0	0	0	0
Van	0	1	1	1
Motorcycle	0	0	2	0
Moped	0	0	0	0
Other	0	0	0	0
Manoeuvre V1 [d] - manoeuvre of V1 involved in the conflict				
Left turn	2	1	1	0
Right turn	3	0	0	0
U-turn	0	0	0	0
Going straight	3	4	7	5
Manoeuvre V2 [e] - manoeuvre of V2 involved in the conflict				
Left turn	2	1	1	0
Right turn	3	0	0	0
U-turn	0	0	0	0
Going straight	3	4	7	5

[a] Vehicle has not passed the stop line

[b] Calculated at the onset of the yellow phase as a function of distance headway and relative speeds

[c] Calculated as a function of the instantaneous distance to the stop line and speed

[d] V1 = first vehicle or leader in the car following process, [e] V2 = second vehicle or follower in the car following process

[f] Measured at the onset of the yellow phase

[g] Vehicle has not passed the stop line

4.3.1.2 Data analysis

Descriptive statistics. Pearson's chi-square tests and independent T-tests are used to identify the characteristics of drivers' behaviour.

Logistic regression models. Logistic regression models are built to predict the probability of a stop/go decision when a driver is confronted with the yellow signal. The functional form of the chosen logistic regression models is the following (Allison, 1999):

$$\text{logit} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{1}$$

Where logit is the predicted natural logarithm of the odds ratio: ln ($P/1\text{-}P$); β_0 is the intercept (constant); β_n are the partial logistic regression coefficients. β_1 expresses the influence of x_1 on the logit; every x_n (independent variable) has its own partial logistic regression coefficient β_n.

Odds ratios (OR = Exp(B)) are calculated to determine the rate of decrease ($0 \leq OR < 1$) or increase ($OR > 1$) of the probability of the outcome when the value of the independent variables increases with one unit (Hilbe, 2009). The model fit was assessed using the Hosmer and Lemeshow test which indicates if the final model provides a better fit than the null model. If the chi-square goodness-of-fit is not significant at CI 95%, the model has an adequate fit. Since this statistic gives no indication of the error reduction of the final model, Nagelkerke's R^2 was also used. Variance Inflation Factors (VIF) are used to identify multicollinearity between the independent variables. Since all variables in the end models have VIFs lower than or near 1, there are no multicollinearity issues in the presented models.

4.3.2 Driving simulator experiment

4.3.2.1 Participants

Sixty-three volunteers (all gave informed consent) participated in the study. No outliers were identified based on the three interquartile distance criterion. Thus the sample contained 63 participants (39 men), approximately equally divided over four age categories from 20 to 75 years old (mean age 46.2; SD age 18.1). All participants had at least two years of driving experience.

4.3.2.2 Driving simulator and eye tracker

The experiment was conducted on a medium-fidelity driving simulator (STISIM M400; Systems Technology Incorporated). It is a fixed-based (i.e., drivers do not get kinaesthetic feedback) driving simulator with a force-feedback steering wheel, brake pedal, and accelerator. The simulation includes vehicle dynamics, visual/ auditory (e.g., sound of traffic in the environment and of the participant's car) feedback and a performance measurement system. The visual virtual environment was presented on a large 180-degree field of view seamless curved screen, with rear view and sideview mirror images (Figure 14). Three projectors offer a resolution of 1024 x 768 pixels and a 60 Hz frame rate. Data were collected at frame rate.

The eye movements of the participants were recorded while driving through the scenario, making use of a camera-based eye tracking system (faceLAB 5 Seeing Machines) (Figure 14). The recorded eye tracking data were analysed with the EyeWorks software package.

Figure 14: Driving simulator and eye tracking equipment.

4.3.2.3 Scenario

Road segment development. To rebuild the selected location in the driving simulator environment, a procedure called geo-specific database modelling (Yan et al., 2008) was adopted. In order to reproduce the existing situation as realistic and detailed as possible, we made use of photographs, videos, detailed field measurements, AutoCAD drawings, and Google Street View. A picture of the real-world environment and the simulated replica can be found in Figure 15.

Figure 15: Real-world vs. simulator image at intersection.

Scenario design. The overall scenario is a systematic combination of the real life replicated section with a set of 2–4 km long filler pieces, differing from the analysis sections with respect to design, speed limit, and surrounding environment and meant to provide some variation throughout the scenario. Figure 17 gives an overview of the intersection, including the positioning of the SRLC and SRLCWS. The analysis zone has a length of 500 m, where the stop line at the intersection is set at the relative distance of 0 m (cf. Figure 17).

Figure 16: Red-light camera warning sign (SRLCWS).

The traffic lights are placed 5 m beyond the stop line (i.e., down the road). Participants were always confronted with a leading vehicle (at 65 m) and a following vehicle (at 25 m) when approaching the intersection. These vehicles did not influence the stop/go decision of the participants, since the distance headway was sufficiently large and the leading vehicle always drove through the green phase. The signal light turned from green to yellow when participants were 2.5 s removed from the stop line (i.e., time-to-stop-line of 2.5 s). All participants were exposed to three conditions (i.e., passed the intersection three times):

- Control condition: no SRLC was installed,
- SRLC condition: a SRLC was installed 15 m before the stop line,
- SRLCWS condition: a SRLC was installed 15 m before the stop line and a red-light camera warning sign (SRLCWS) (cf. Figure 16) was placed 50 m before the stop line.

Procedure and design. Participants were asked for their voluntary cooperation and requested to fill out a form with some personal data (e.g., gender, driving experience, date of birth, etc.). After a general introduction, drivers acquainted themselves with the driving simulator by handling various traffic situations (e.g., highway, curves, traffic lights, urban and rural areas) during two practice trips of 4 km each. Subsequently, the eye tracking equipment was calibrated. Then participants completed the experimental trip of 14.8 km, resulting in a randomised within (three conditions: control, SRLC, SRLCWS) subjects design. Subjects were asked to drive as they normally would do with their own car and apply the traffic laws as they would do (or would not do) in reality. A GPS voice instructed them during the trip.

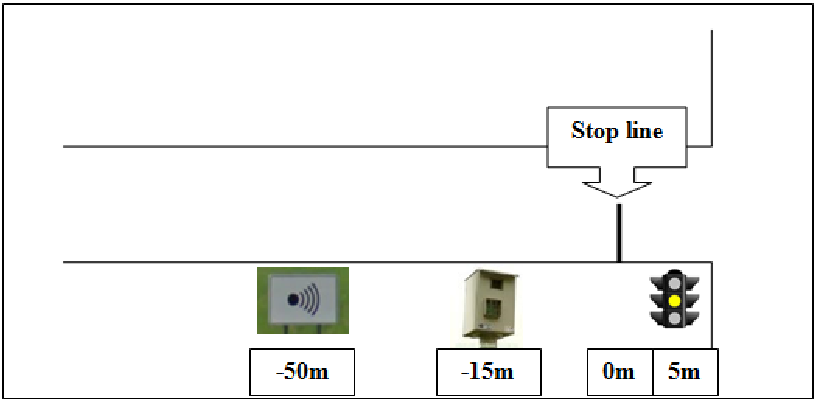


Figure 17: Scenario overview.

4.3.2.4 Data collection and analysis

Dependent measures. The simulator recorded driving performance measures for both longitudinal and lateral control. For this study, measures for longitudinal control are particularly of interest. The speed (in m/s) of the participants at the yellow onset is used in the Monte Carlo Simulation below. Furthermore, mean acceleration/deceleration (acc. /dec.) [in m/s^2] is also an important measure regarding the probability of rear-end collisions. Another dependent measure (i.e., distance headway) needed for the Monte Carlo Simulation was gathered at the real-world location by means of observations.

Concerning the eye tracking data, the percentage of participants that fixated on the regions of interest (ROI) and the mean fixation duration are analysed when the participants approached the intersections. Here we make a distinction between the participants who stopped for the yellow light (i.e., 'stop') and drove through (i.e., 'go').

Data analysis. The odds of rear-end collisions for each condition are estimated by means of a Monte Carlo Simulation using a normal distribution. The distance headway data observed at the real-world location (i.e., field observations) are gathered from the behavioural observations described above. Since no setting with a SRLCWS has been implemented on field, the data could only be collected for the control (*n* = 18) and SRLC (*n* = 9) conditions. Therefore, the data from the SRLC-condition are also used for the SRLCWS-condition. To calculate the risk of rear-end collisions for each condition, the following parameters are used:

Following vehicle

- V_0: mean speed (in m/s) at the yellow onset (based on simulator data). Since the participants are the leading vehicle and we have no speed data for the following vehicle, the speed of the following vehicle is assumed to be comparable to the speed of the leading vehicle.
- a: maximum deceleration value (in m/s^2) based on simulator data, assuming that the driver in the following vehicle can adjust his/her behaviour based on the leading vehicle and even can make an emergency stop when necessary. Since the highest overall value is selected, the maximum deceleration rate is constant for all conditions.
- t_{reaction}: reaction time (in s.) based on the literature (Caird, Chisholm, Edwards, & Creaser, 2007; Liu, Bonsall, & Young, 2003; Yan et al., 2008), calculated with respect to the decision of the leading vehicle to stop.
- Distance headway: distance (in m) between the rear of the leading vehicle and the front of the following vehicle (observed at real-world location).

Leading vehicle

- V_0: mean speed (in m/s) at the yellow onset (based on simulator data).
- a: mean deceleration value (in m/s^2) based on simulator data.

For the leading vehicle, no reaction time was included in the Monte Carlo Simulation because the reaction time of the following vehicle was selected with respect to the stopping manoeuvre of the leading vehicle. The Monte Carlo Simulation was performed using Microsoft Excel with 100,000 iterations for each condition. The stopping distance is calculated for both the following and leading vehicle. A rear-end collision will occur when the sum of the stopping distance of the following vehicle and the distance headway is larger than the stopping distance of the leading vehicle.

Concerning the looking behaviour, several regions of interest (ROI) are selected: leading vehicle, traffic light, rear view mirror, speedometer (on screen, below the rear view mirror), SRLC, and SRLCWS. The mean fixation duration for these ROI are analysed using the EyeWorks software package. Fixation durations of less than 0.05 s are not taken into account. Subsequently, paired samples t-tests at a 5% confidence level were conducted using SPSS.

4.4 Results

4.4.1 Decision behaviour

4.4.1.1 Red/yellow/green light running

As displayed in Table 18, there are significant associations between red and yellow light running and the presence of a SRLC. Results show a significant decrease in red and yellow light running for both intersections combined, indicating that the odds of drivers obeying the red and yellow phase are 1.20 times higher in the presence of a SRLC.

Table 18: Overview of red/yellow/green light running.

Location	Before SRLC			After SRLC			χ^2	Odds	df
	Red + Yellow	Green	*N*	Red + Yellow	Green	*N*			
Kapellen	152	4326	4478	127	4444	4571	2.872^{**}	1.06^{**}	1
Mechelen	159	12379	12538	128	12009	12137	2.446	1.18	1
Both intersections	311	16705	17016	255	16453	16708	4.634^{*}	1.20^{*}	1

$^{*}p < .05$
$^{**}p < .10$

The presence of a SRLC seems to influence the violation behaviour of drivers in certain vehicle types more strongly. For both intersections, the effect of a SRLC was very favourable for the violation behaviour of truck drivers (X^2; (1, N = 3120) = 3.671, p = 0.055). This seems to represent the fact that, based on the odds ratio, the odds of truck drivers obeying the red and yellow phase were 1.71 times higher in the presence of a SRLC.

4.4.1.2 Dilemma zone behaviour

The results of the logistic regression show that the drivers' decision to stop or go at the onset of the yellow phase is influenced by several factors (Table 19). The dependent variable is the probability that a driver decides to run the yellow phase. The results indicate that the time-to-stop-line significantly influences the decision to run the yellow phase. If the time-to-stop-line increases (i.e., if the car is still further away from the stop line), the probability that drivers decide to run the yellow phase will decrease and vice versa. Drivers are also more likely to run yellow when they drive straight through. The presence of a SRLC at the intersections is found to influence the decision to stop or go at the onset of yellow since significantly less drivers decide to drive through the yellow phase if a SRLC is present. Finally, the results also indicate that the decision to run yellow depends on the location. Significantly less drivers decide to run yellow at the intersection in Kapellen compared to the intersection in Mechelen. This difference might be related to the difference in speed limits at both locations (i.e., 50 km/h at Kapellen and 70 km/h at Mechelen).

Since the presence of a SRLC influences the decision whether to stop or not at yellow, the SRLC also influences the location of the dilemma zone at both signalized intersections. Figure 18 a and b illustrates this shift of the dilemma zone. The length of the zone remained the same at the intersections (Kapellen ± 2.5 s; Mechelen ± 2.0 s) after the installation of the SRLCs compared to the situation with no SRLC.

However, the installation of a SRLC appears to shift the dilemma zone more closely towards the stop line:

- Kapellen: 10% of the drivers decides to stop at 1.3 s and 90% stops at 3.8 s of the stop line before the installation of the SRLC compared to 0.9 s (10%) and 3.3 s (90%) after the installation of the SRLC.
- Mechelen: 10% of the drivers decides to stop at 2.2 s and 90% stops at 4.2 s of the stop line before the SRLC compared to 1.7 s (10%) and 3.7 s (90%) after the SRLC.

These results suggest that drivers' stopping behaviour is influenced by SRLCs. In case a SRLC is present, drivers tend to stop earlier and even tend to stop at the onset of yellow when they are very close to the stop line.

Table 19: Logistic regression results for decision behaviour at the onset of yellow.

Variables [a]	**Logistic regression results: odds of driving through at the onset of yellow**		
	Kapellen (N = 598; Y = 305)	Mechelen (N = 475; Y= 279)	Combined model (N = 1043; Y=584)
Intercept	3.1784***	6.4521***	4.7309***
Time-to-stop-line	-1.7447 (**0.18**)***	-2.3059 (**0.10**)***	-1.9845 (**0.14**)***
Movement			
Going straight	0.6702 (**3.13**)***	0.4871 (**2.65**)***	0.6913 (**3.50**)***
Left turn	-0.1998 (1.31)$^{\circ}$	Reference	-0.1296 (**1.54**)$^{\circ}$
Right turn	Reference	-	Reference
Red-light camera			
Yes	-0.4488 (**0.41**)***	-0.5108 (**0.36**)***	-0.4838 (**0.38**)***
No	Reference	Reference	Reference
Free flow			
Yes	0.5348 (**2.91**)**		
No	Reference		
Intersection			
Kapellen			-0.5450 **(0.34)*****
Mechelen			Reference
Hosmer and Lemeshow test[b]	χ^2= 8.7222 (df=8, *p*= 0.3663)	χ^2= 7.9695 (df=8, *p*= 0.4365)	χ^2= 10.9686 (df=8, *p*= 0.2035)
Nagelkerke R^2 [c]	0.6558	0.6232	0.6385

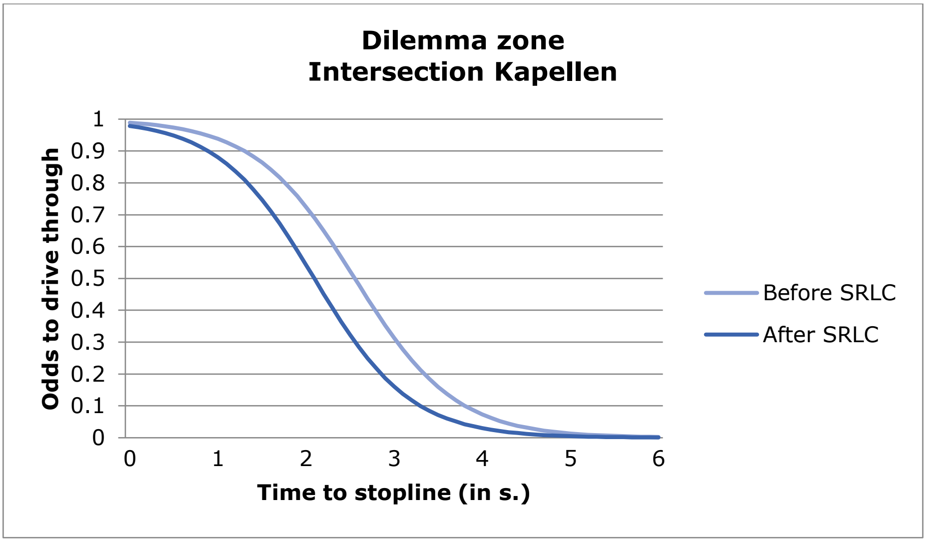
Note: Odds ratios between ().Odds ratio values that are significant at $p \leq 0.05$ are highlighted in bold.

[a] Values present the parameter estimates of the logistic regression model. For categorical variables with more than 2 categories, the category is indicated.

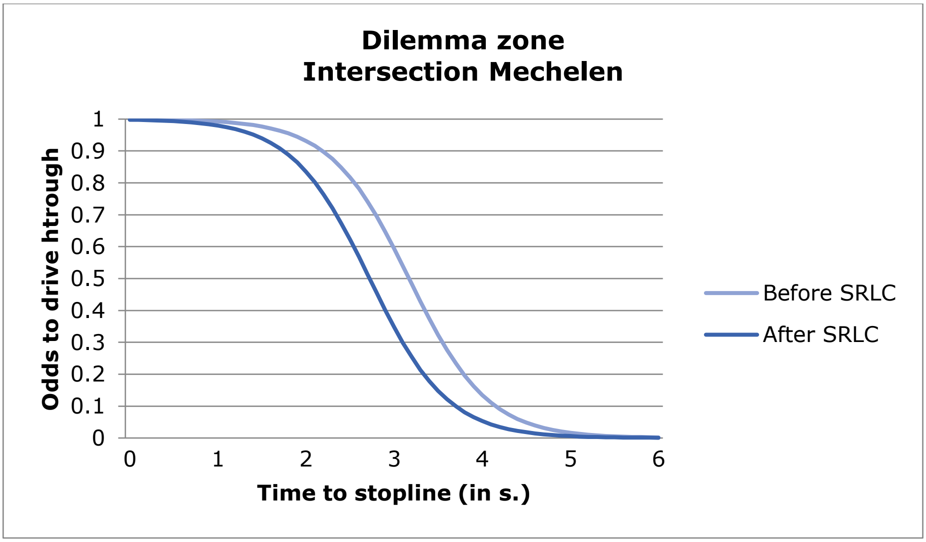
[b] The Hosmer and Lemeshow goodness-of-fit test indicates a good fit for all models.

[c] The statistic indicates the error reduction of the model in percentages; e.g. 0.3087 is equal to an error reduction of 30.87%.

$^{***}p \leq 0.01$ (significant at 99% CI); $^{**}p \leq 0.05$ (significant at 95% CI); $^{*}p \leq 0.10$ (significant at 90% CI); $^{\circ}p > 0.10$ (not significant at 90% CI)



(a)



(b)

Figure 18: Change in dilemma zone at (a) Kapellen and (b) Mechelen.

4.4.2 Following behaviour

Multiple studies (Brackstone, Sultan, & McDonald, 2002; Michael, Leeming, & Dwyer, 2000; Rajalin, Hassel, & Summala, 1997) state that a time headway of 2 s (e.g., "two seconds rule") is the minimum time gap to follow a vehicle safely on a dry road surface. Table 20 compares the time headways of vehicles in a car following situation at the onset of the yellow phase before and after the SRLC installation.

As Table 20 shows, there is a significant difference between the time headways before and after the SRLC. The time headway decreases after the installation of the SRLC. As such, it indicates that the installation of SRLCs has a significant, but small effect on drivers' car following behaviour.

4.4.3 Driving simulator

In the control condition 7 participants (i.e., 11%) stopped for the yellow sign. For the SRLC and SRLCWS conditions the number of participants who did not drive through was 8 (i.e., 13%) and 19 (i.e., 30%), respectively. This means that most drivers drove through the yellow phase in the control condition (*n* = 56), followed by the conditions SRLC (*n* = 55) and SRLCWS (*n* = 44). The results of the chi-square analysis indicate that the proportion of drivers that decided to stop is significantly higher (X^2 (2, *N* = 189) = 9.540, *p* = 0.008) in the SRLCWS-condition compared to the control- and SRLC-condition.

4.4.4 Occurrence of rear-end conflicts

Table 21 provides the summary statistics (mean values) for the observed rear-end conflict situations at the onset of yellow. The speed at the moment of evasive action is measured at the time that the following vehicle brakes since this is a prerequisite for the occurrence of a rear-end conflict. The Minimum Time-to-Collision (TTC_{min}) indicator is used to assess the conflict severity. All rear-end conflicts with a TTC_{min} less than or equal to 2 s are considered to be serious conflicts (Kraay & van der Horst, 1988). The time headway between both vehicles also has a significant influence on the occurrence of rear-end collisions (Huang et al., 2006). As such, the time headway is also an important indicator for rear-end conflicts. In accordance with the "two-seconds-rule", potential rear-end conflict situations are characterised by a time headway <2 s.

Table 20: Comparison of time headways (in s.) before and after SRLCs.

Location	**Before SRLC**			**After SRLC**			**95% CI for Mean Difference**	**r**[a]	**t**	**df**
	M	SD	*N*	M	SD	*N*				
Kapellen	1.92	0.88	37	1.69	0.75	29	-0.18, 0.64	0.14	1.12	64
Mechelen	2.06	0.79	37	1.64	0.70	39	0.71, 0.75	0.15*	2.41*	74
Both intersections	1.99	0.83	74	1.67	0.72	68	0.64, 0.58	0.20*	2.47*	140

[a] effect size.

*$p < 0.05$.

Table 21: Characteristics of rear-end conflict situations.

	Before SRLC				**After SRLC**				**90% CI for Mean Difference**	**r**[c]	**t**	**df**
	M[a]	SD	#serious conflicts[b]	*N*	M[a]	SD	#serious conflicts[b]	*N*				
TTC_{min}												
Kapellen	2.34	0.98	3	8	1.66	0.89	3	5	-0.29, 1.65	0.36	1.266	11
Mechelen	2.71	0.69	0	8	2.08	0.94	3	7	-0.11, 1.38	0.39	1.516	13
Both intersections	2.53	0.84	3	16	1.90	0.90	6	12	0.62; 1.19	0.35*	1.893*	26
Time headway												
Kapellen	2.00	0.66	4	8	1.54	0.89	4	5	-1.40, 0,48	031	-1.08	11
Mechelen	1.81	0.66	6	8	1.60	0.19	4	7	-0.77, 0.36	0.21	-0.78	13
Both intersections	1.90	0.65	10	16	1.45	0.64	8	12	-0.87, -0.03	0.34*	-1.85*	26

[a] average TTC_{min}/time headway (in s).

[b] conflicts with TTC_{min}/time headway < 2s.

[c] effect size.

*$p < 0.10$.

The results in Table 21 reveal significant differences in rear-end conflict severity. The rear-end conflicts tend to be more severe in the presence of a SRLC. The time headway in rear-end conflicts situations also appears to be significantly lower after the installation of the SRLC. Overall, these results indicate that SRLCs have a moderate effect on rear-end conflicts.

4.4.5 Risk of rear-end collisions

Table 22 presents the parameter values (including SD) that were used for the Monte Carlo Simulation. The stopping distances for both the following and the leading vehicle were calculated. For the following vehicle, this calculation was based on the reaction time and the braking distance while the stopping distance of the leading vehicle was only based on the braking distance. A simulated rear-end collision occurred when the sum of the stopping distance of the following vehicle plus the distance headway was larger than the stopping distance of the leading vehicle. Given the fact that there were 100.000 iterations for each condition, the number of simulated rear-end collisions was 1973; 12646; and 7984 for the control-, SRLC-, and SRLCWS-condition respectively. As the resulting odds of a rear-end collision in the SRLC- (6.42) and the SRLCWS-condition (4.01) compared with the control condition were clearly above 1, the revealed probability of a rear-end collision in those conditions is higher than in the control condition.

Table 22: Parameter values (mean and SD) used for the Monte Carlo Simulation.

	Control condition	**SRLC condition**	**SRLCWS condition**
Following vehicle			
V_0 (in m/s)	12.69 (1.42)	12.29 (1.95)	11.03 (1.84)
a (in m/s²)	-7.14	-7.14	-7.14
$t_{reaction}$ (in s)	0.75 (0.25)	0.75 (0.25)	0.75 (0.25)
Distance headway (in m)	19.81 (8.56; n = 18)	14.01 (5.51; n = 9)	14.01 (5.51; n = 9)
Leading vehicle			
V_0 (in m/s)	12.69 (1.42)	12.29 (1.95)	11.03 (1.84)
a (in m/s²)	-2.83 (1.42)	-4.28 (2.15)	-3.45 (2.36)

4.4.6 Looking behaviour

4.4.6.1 Number of participants that fixated on ROI

Figure 19 depicts the looking behaviour of the participants who stopped. In this case, 100% of the participants fixated on the traffic light in the control- and SRLC-condition, compared to 72% in the SRLCWS-condition. Furthermore, more participants fixated on the SRLC in the SRLC-condition than in the SRLCWS-condition. In the SRLCWS-condition almost 70% of the participants fixated on the warning sign.

The number of participants that fixated on the ROI is approximately equal for the 3 conditions when participants drove through (i.e., 'go'). However, in the SRLCWS-condition participants fixated more on the SRLC compared to the SRLC-condition. Remarkable is that 50% of the participants who did not stop at the intersection fixated on the SRLCWS and that approximately 70% fixated on the traffic light (in each condition).

4.4.6.2 Mean fixation duration

The mean fixation duration for the participants who stopped for the yellow light is visualised in Figure 20. For the participants who stopped there seems to be a difference in mean fixation time for the traffic light, rear view mirror and speedometer between the control and SRLC-condition. These differences are however not statistically significant at a 5% confidence level. Between the conditions SRLC and SRLCWS no statistically significant differences appear at a 5% confidence level either. However, a significant difference in mean fixation time for the SRLC exists between the SRLC- and SRLCWS-condition at a 10% confidence level (t (4) = 2.46; p = 0.070).

For the 'go' situation, no significant differences for the ROI between the conditions exist. The mean fixation duration for the SRLC tends to differ between the SRLC- and SRLCWS-condition, but this difference is not significant (t (13) = 1.47; p = 0.167).

Figure 19: Number of participants that fixated on ROI for ‘stop’.

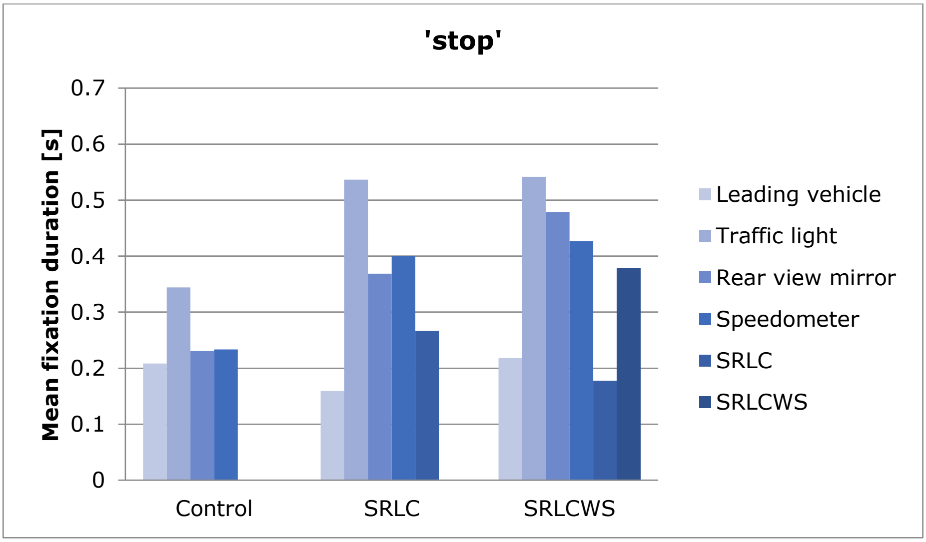


Figure 20: Mean fixation duration for ‘stop’.

4.5 Discussion

4.5.1 Drivers' behaviour

4.5.1.1 Decision behaviour

The analyses show a clear impact of SRLCs on drivers' decision whether or not to enter the intersection on yellow/red signal. Firstly, for the full population of motorised road users in the on-site observations, there is a significant reduction in the number of drivers passing through the yellow and red signal. For drivers facing a signal switch to yellow, there is a clear shift in the dilemma zone. The shift is consistent for both observed locations. The dilemma zone moves approximately 0.5 s closer towards the stop line. This indicates that also drivers who are closer to the stop line are more inclined to stop when a SRLC is installed at a signalized intersection. Analyses also indicated that, the time-to-stop-line (in line with Huang et al., 2006 and Lum & Wong, 2003) and the driving direction of the vehicle influence the likelihood of stopping for the yellow light. While a higher compliance with the traffic light may generally be considered as a favourable effect, this higher compliance may also partly be responsible for the increase in rear-end collisions. Huang et al. (2006) suggest that the risk for rear-end collisions at intersections with RLCs will decrease for vehicles with a longer estimated time-to-stop-line, but that the risk may increase for vehicles with a shorter time-to-stop-line, especially at higher driving speeds. The simulator experiment showed a strong increase in stopping propensity in case the SRLC is accompanied by an SRLCWS: when a warning sign is installed, 30% of the drivers stop for the yellow light. This is in line with Yan et al. (2009).

4.5.1.2 Following behaviour

The on-site observations show a reduction in the time headway between road users after installation of SRLCs. Shorter gap times, especially gap times lower than 2 s, are considered to constitute a safety risk (Brackstone et al., 2002; Huang et al., 2006; Michael et al., 2000; Rajalin et al., 1997). If SRLCs lead to shorter gap times between vehicles this is likely to cause more collisions, especially rear-end collisions. Although this result is based on a relatively low number of situations, it may indicate a behavioural effect that could (partly) explain the increase in rear-end collisions at intersections with SRLCs.

4.5.1.3 Looking behaviour

To our knowledge, no study has investigated the looking behaviour of drivers nearby intersections equipped with SRLCs and SRLCWSs to date. Concerning the looking behaviour, no statistically significant differences were found between the 3 conditions. However, some interesting conclusions can be listed up:

- Only 70% of the drivers who did not stop fixated on the traffic light. However, this does not necessarily mean that the other 30% of the drivers did not notice the traffic light (cf. peripheral vision; (Dewar & Olson, 2007)).
- A higher percentage of the participants who stopped observed the SRLC (62% vs. 28%) and the SRLCWS (68% vs. 51%) compared to the participants who did not stop. This finding emphasises that people are more inclined to stop when they see a SRLC, or when they know that they are approaching one. It is therefore important that the SRLC is sufficiently conspicuous to drivers.
- Mean fixation duration for both rear view mirror and speedometer is longer in the SRLCWS-condition compared to the SRLC-condition. Different from that, mean fixation duration for the SRLC was longer in the SRLC-condition than in the SRLCWS-condition. This can possibly be explained by the fact that participants who have already noticed the SRLCWS, do not look at the SRLC anymore. The longer fixation duration for the rear view mirror in the SRLCWS-condition may indicate that drivers check whether they have other road users closely behind them, in order to evaluate the risk of a rear-end collision in case they would stop if a signal change would take place. Such anticipation may help to reduce the number of rear-end collisions at signalized intersections with SRLCs.
- Mean fixation duration for both rear view mirror and speedometer was longer for the participants who stopped in comparison with the participants who did not stop.
- Participants who stopped had a longer mean fixation duration for the SRLCWS compared to drivers who did not stop (0.38 s vs. 0.23 s).

4.5.2 Risk of rear-end conflicts & collisions

The results of the observation study indicate that SRLCs have a moderate effect on the occurrence of rear-end conflicts. Despite the small number of observed rear-end conflicts these results provide an indication that SRLCs increase the rear-end collisions risk. This is confirmed by the driving simulator experiment since the odds of a rear-end collision equals 1.00, 6.42 and 4.01 in the control, SRLC, and SRLCWS-condition respectively. This indicates that the presence of a SRLC increases the risk of a rear-end collision. Several studies support this increase (up to 44%) in rear-end collisions (De Pauw et al., 2014; Erke, 2009; Høye, 2013; Bhagwant Persaud, Council, Lyon, Eccles, & Griffith, 2005; Pulugurtha & Otturu, 2014; Shin & Washington, 2007; Vanlaar et al., 2014). Interestingly, when a warning sign is positioned on the approaching segment towards the intersection, this risk decreases even though it remains higher compared to situations where no SRLC is present (i.e., control condition). Other studies (Høye, 2013; Ni & Li, 2014; Zaal, 1994) also found a lower risk of rear-end collisions when a warning sign was installed before (i.e., upstream) (S)RLCs. In general, such (S)RLCWS seem to reduce the unfavourable effects (such as hard braking manoeuvres) of (S)RLCs.

Concerning the parameter values used for the Monte Carlo Simulation, we draw the following conclusions. Firstly, the mean driving speed at the yellow onset is highest in the control condition (12.69 m/s), and lowest in the SRLCWS-condition (11.03 m/s). Both values lie below the speed limit of 50 kph (i.e., 13.89 m/s). The stimulus provided by either the presence of a SRLC or the combination SRLC and SRLCWS is probably responsible for this difference in speed. Subsequently, mean deceleration values of -2.83 m/s^2, -4.28 m/s^2, and -3.45 m/s^2 were found for the control-, SRLC-, and SRLCWS-condition, respectively. We can conclude that the deceleration value is highest for the SRLC-condition, but decreases to a more ‘normal’ value in the SRLCWS-condition. A normal, comfortable braking deceleration value that is recommended is -3 m/s^2 (Koppa, 2003; Liu et al., 2003; McGee et al., 2012; Yang, Han, & Cherry, 2013). Høye (2013) also found a smaller deceleration value when a warning sign was installed. Finally, the average distance headway (observed at the real-world location) for the control (19.81 m) and SRLC (14.01 m) condition differs slightly, albeit these values are based on a limited dataset and are both lower than the average distance headway (25–35 m) found in the literature (Liu et al., 2003; Yan et al., 2008).

4.5.3 Strengths, limitations and further research

One of the main assets of this study is the integrated approach of on-site behavioural observations with a driving simulator experiment. To the best of our knowledge, this research design is a unique approach to gain more insight in the effects of SRLCs. Both techniques strengthen each other by showing a number of results that are in line, and complement each other by resulting in different types of data. This has led to a more holistic insight in the behavioural effects of SRLCs.

The use of the semi-automated video analysis software was also important in this study. While this is still a rather time consuming way to analyse road user behaviour, it allows for highly accurate, reliable, objective and flexible analyses of revealed micro-level road user behaviour. More conventional techniques for field observations such as inductive loops, radars or human observers do not allow the level of detail in the analyses that has been achieved in this study.

Sometimes, the validity of driving simulator research is questioned. One may wonder how realistic the driving behaviour of participants is in a simulated road environment compared to their actual driving behaviour in a real-world environment (Fisher et al., 2011). It must be said however that there is enough research showing that driving simulators generally reach high relative validity (i.e., comparing different scenarios in an experimental design) (Bella, 2009; Godley et al., 2002; Törnros, 1998; Yan et al., 2008). However, the geo-specific database modelling technique increases the reliability and validity of the experiment and the results (Yan et al., 2008). In addition, the simulator used in this study is equipped with a 180° field of view, which satisfies the prescribed minimum of 120° field of view for the correct estimation of longitudinal parameters (Kemeny & Panerai, 2003). Therefore, we believe that the validity of the driving simulator experiment is ensured.

A limitation of the study is that the before/after design cannot observe the changes in driver behaviour over time. Vanlaar et al. (2014) used a time-series analysis approach to evaluate the impact of a photo enforcement program on speeding and red-light running, and found a first indication that the side effects of such an enforcement program decreases over time as drivers become more accustomed to the intervention. Given the limited number of locations included in the study, it is difficult to infer effect estimations for other intersections. It can reasonably be assumed that the effects (change in dilemma zone, decision behaviour, braking manoeuvres, etc.) will evolve in the same direction. However, the absolute values or the magnitude of the SRLC(WS) effects on drivers' behaviour may differ according to specific intersection characteristics such as speed/geometric and operational conditions.

Furthermore, due to the low number of traffic conflicts in the observation period, the conclusions about the impact of SRLCs on serious conflicts should be treated with caution. Future research should aim at analysing longer time periods in order to collect more traffic conflict data for more robust conclusions. Also, the robustness of some of the input parameters for the Monte Carlo simulation that were based on the video analyses could possibly be improved by further increasing the observation periods. This integrated approach shows some clear benefits of combining on-site behavioural observations with driving simulator experiments. Future research about road users' behavioural adaptations to road safety measures or to different infrastructural designs may therefore consider the use of such an integrated study design. Furthermore, the positive impact of the SRLCWS in the driving simulator experiment justifies a field experiment to assess its impact in a real-world setting.

4.6 Conclusions

This study investigated the behavioural responses of road users approaching speed and red-light camera sites to gain a better understanding of possible explaining factors for the revealed effects on collisions, in particular the observed increase in the number of rear-end collisions. The actual behaviour of drivers approaching a SRLC-intersection was observed by means of an on-site before and after study and a driving simulator study.

The results show that combined speed and red-light cameras do influence road user behaviour. The results of the on-site observation study reveal decreases in the number of red and yellow light violations and a shift (i.e., closer to the stop line) in the dilemma zone after the installation of the SRLC. The findings of the driving simulator study also reveal possible adverse effects of the presence of SRLCs on road user behaviour such as stronger decelerations and a possible increase in the number of rear-end collisions. However, in case the presence of SRLCs is announced with warning signs, these adverse effects are somewhat reduced. Although, this latter effect is still unsure.

To conclude, the results reveal behavioural effects after the implementation of the combined speed and red-light camera. The observed behavioural effects such as the shift in dilemma zone and the higher deceleration values are responsible for the increase in rear-end collisions mentioned in the international literature.

Acknowledgements

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CHAPTER 5: ROAD SAFETY DIFFERENCES BETWEEN PRIORITY-CONTROLLED INTERSECTIONS AND RIGHT-HAND PRIORITY INTERSECTIONS: BEHAVIOURAL ANALYSIS OF VEHICLE-VEHICLE INTERACTIONS

The study presented in the following chapter was carried out in the context of my master dissertation. As a result, I was involved in selecting the locations under study, designing the observation protocol under the guidance of the first author, performing the literature review, performing the data collection and analyses and writing the first draft version of the paper.

This chapter is based on:

De Ceunynck, T., **Polders, E**., Daniels, S., Hermans, E., Brijs, T., & Wets, G., (2013). *Road safety differences between priority-controlled intersections and right-hand priority intersections: a behavioural analysis of vehicle-vehicle interactions*. Transportation Research Record: Journal of the Transportation Research Board, 2365, p. 39-48. (Web of Science 5-year impact factor 0.872).

Proceedings:

De Ceunynck, T., **Polders, E.**, Daniels, S., Hermans, E., Brijs, T., & Wets, G., (2013). Road safety differences between priority-controlled intersections and right-hand priority intersections: a behavioural analysis of vehicle-vehicle interactions. In*: Proceedings of the 92nd Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

De Ceunynck, T., **Polders, E.**, Daniels, S., Laureshyn, A., Hermans, E., Brijs, T., & Wets, G. (2012). Behavioural analysis of vehicle interactions at priority-controlled and right-hand priority intersections. In: *Proceedings of the 25th ICTCT-workshop*. Hasselt, Belgium.

Master dissertation:

Polders, E. (2012). *Road safety differences between priority intersections and intersections with priority to the right: a behavioural analysis of road user interactions* (master dissertation). Retrieved from:
https://uhdspace.uhasselt.be/dspace/handle/1942/14183

ABSTRACT

Objectives: This study analyses interactions between two vehicles at right-hand priority intersections and priority-controlled intersections and will help to gain a better insight into safety differences between both types of intersections.

Methods: Data about yielding, looking behaviour, drivers' age and gender, approaching behaviour, type of manoeuvre, order of arrival, and communication between road users are collected by on-site observations at one priority-controlled intersection and one right-hand priority intersection in Flanders, Belgium (period November to December 2011). Logistic regression models are built to identify variables that affect the probability that a violation against the priority rules will occur and the probability that a driver will look to the side when entering the intersection.

Results: The number of right-of-way violations is significantly higher at the observed right-hand priority intersection (27% of all interactions) than at the priority-controlled intersection (8%). Furthermore, at the right-hand priority intersection, the behaviour of drivers on the lower volume road is more cautious than the behaviour of drivers on the higher volume road, and violations are more likely when the driver from the lower-volume road has priority. This situation indicates that the higher-volume road is considered as an implicit main road. At both intersection types, there is a higher probability of a right-of-way violation when the no-priority vehicle arrives first: this condition indicates that yielding is partly a matter of first come, first served. For both intersections, the way a driver approaches the intersection (i.e., stopping, decelerating, or holding the same speed) is highly relevant for the occurrence of a right-of-way violation and the probability that the driver will look to the sides on his or her approach to the intersection.

Conclusions: The results suggest a general first come, first served tendency in yielding behaviour, a higher number of violations at the right-hand priority intersection, and an informal right-of-way at the right-hand priority intersection that leads to a higher number of violations against drivers on the secondary road.

Keywords: safety continuum, driver interactions, right-of-way violations, looking behaviour, priority-controlled intersections, right-hand priority intersections

5.1 Introduction

Intersections are complex locations with many different movements, resulting in a wide range of possible interactions between road users. To facilitate these interactions, different types of right-of way rules are in place. The level of control these types of right-of-way rules exert on interactions ranges from strongly controlled (e.g., signalized intersections) to little controlled (e.g., right-hand priority intersections).

The proper level of control for non-signalized intersections in urban areas is often the subject of debate because various factors may be taken into account, such as traffic volumes, surrounding environment, and safety considerations (Polus, 1985). In urban areas, priority-controlled intersections and right-hand priority intersections are the most common types. These intersection types exert the lowest level of control over road user interactions. At priority-controlled intersections, drivers arriving from the secondary road have to yield to drivers coming from the primary road. At right-hand priority intersections, all arriving roads are considered equivalent, and all arriving drivers need to yield to drivers coming from their right-hand side.

Unfortunately, the scientific literature is inconclusive about which of the two intersection types should be preferred in which situations, from a safety point of view. Generally, no significant difference in the number of crashes is found when right-hand priority intersections are transformed into priority-controlled intersections, which indicates that a higher level of control does not guarantee an improvement in safety (Elvik et al., 2009). Since the low level of control at both intersection types necessitates a lot of interaction between road users, a better insight into these interactions can lead to a better understanding of the safety issues at these types of locations.

Therefore, this study analyses road users' interactions at a micro level by using structured on-site behavioural observations to explore the way these interactions take place and how they differ in the two types of intersections.

5.2 Background

5.2.1 Overall traffic safety at priority-controlled and right-hand priority intersections

Priority-controlled intersections are often assumed to have an important safety advantage over right-hand priority intersections. The higher level of control at these intersections is less ambiguous for road users and leads to more consistent yielding behaviour compared with right-hand priority intersections (Elvik et al., 2009).

However, an overview based on 14 studies concludes that the number of injury crashes is generally reduced only by 3% (95% CI [-9; +3]) when right-hand priority intersections are converted to priority-controlled intersections (Elvik et al., 2009). Elvik et al. (2009) mention that some studies even indicate an increase in the number of crashes, for instance, in the case of low traffic volumes on the secondary road (Vaa & Johannessen, 1978; Vodahl & Giæver, 1986a, 1986b). This may seem surprising, but the counterbalancing factor is that driving speeds on the primary road of priority-controlled intersections tend to be higher (Elvik et al., 2009). At right-hand priority intersections, all vehicles are required to approach the intersection with greater caution because they may need to yield to another vehicle, while vehicles on the primary road of a priority-controlled intersection do not need to yield to other vehicles, leading to higher approach speeds. Therefore, the crash severity is generally higher at priority-controlled intersections (Casteels & Nuyttens, 2009).

5.2.2 Road user behaviour

Drivers' behaviour in intersections is influenced by the right-of-way rules that apply, the intersection design, and other road users' expected and actual behaviour (Björklund & Åberg, 2005; Helmers & Åberg, 1978; Johannessen, 1984; Kulmala, 1990). Interacting with other road users would be impractical without formal rules. These rules describe how a driver should behave in different traffic situations and provide information about the intentions and behaviours that can be expected from other road users (Björklund & Åberg, 2005). However, violations of the formal rules are common in practice.

Violations can be committed deliberately (e.g., to reduce driving time) or because of driver errors (lack of knowledge about the rules, misjudgement, etc.) (Lawton, Parker, Manstead, & Stradling, 1997). Behavioural, personal, and environmental elements can have an influence on the occurrence of violations. Behaviour that is in contradiction to formal rules but has become common in particular situations indicates that an informal rule has developed (Björklund & Åberg, 2005). In the case of an interaction between two road users, a dangerous situation can occur when one of the road users complies with formal priority rules while the other road user applies an informal rule.

5.2.3 Yielding behaviour

Research indicates that failure to yield is one of the primary factors leading to crashes at non-signalized intersections (Lee et al., 2004; Parker et al., 1995).

Formal priority rules are respected quite well at priority-controlled intersections, but not at right-hand priority intersections (Elvik et al., 2009; Helmers & Åberg, 1978). Helmers and Åberg (1978), cited by Björklund and Åberg (2005), indicate that the right-hand priority rule is violated most often when the vehicle coming from the right is on a connector road, which can be considered as an "implicit minor road", although the two approaching roads are technically equally important. This is the result of a combination of drivers on the main road behaving as if they have priority, and drivers on the minor road behaving as if they do not have priority (Helmers & Åberg, 1978). The study indicates lower compliance with the right-hand priority rule at three-leg intersections compared with four-leg intersections. Johannessen (1984), cited in Björklund and Åberg (2005), indicates that on average 75% of all drivers comply with the right-hand priority rule at four-leg intersections, and 56% of the drivers at three-leg intersections.

5.2.4 Communication

Communication between interacting road users is an aspect of behaviour that may help to make one's own intentions clear to other road users and to predict the behaviour that the other road user will execute. In that way, it can benefit road safety. Communication may include using direction indicators, which is an official form of communication, or hand gestures, flashing the headlights, sounding the horn, or other forms of nonofficial communication. However, most communication signals can be ambiguous and may therefore also lead to dangerous situations when misinterpreted (Risser, 1985).

5.2.5 Approach behaviour

The speed of another approaching vehicle is an important factor in a driver's decision to give way or not (Janssen, Van Der Horst, Bakker, & Ten Broeke, 1988). The approach speed can implicitly indicate the driver's intentions in the interaction. Slowing down or stopping can indicate an intention to yield, while holding the same speed or accelerating can indicate an intention not to yield. Drivers state that they yield more often when another driver maintains his or her speed than when the other driver slows down (Björklund & Åberg, 2005).

5.2.6 Looking behaviour

Detection errors (i.e., not seeing another road user) are an important cause of collisions, and failure-to-look errors are the most common detection error (Parker et al., 1995; Rumar, 1990). When drivers expect that drivers coming from the side roads will yield to them, they tend not to look to the sides (Helmers & Åberg, 1978; Kulmala, 1990). Kulmala (1990) indicates that 80% of drivers who enter right-hand priority intersections look to the right by turning their heads. Drivers who look to the right do this at lower approach speeds than other drivers. Looking behaviour can also be a form of communication, for instance not looking toward a driver coming from a side road may express that one has no intention to yield.

5.2.7 Influence of driver age and gender

For all age groups, failure to yield is one of the strongest primary contributing circumstances in crashes (McGwin & Brown, 1999). However, the relative fraction of failure-to-yield crashes increases with age (Braitman, Kirley, McCartt, & Chaudhary, 2008; McGwin & Brown, 1999). Search and detection errors and evaluation errors are the highest contributors to intersection crashes for all age groups (Braitman et al., 2008). Keskinen et al. (1998) indicate that there are no differences in looking behaviour between different ages.

Young drivers have a general crash rate that exceeds the risk of any other age group (McKnight & McKnight, 2003). In failure-to-yield crashes, younger drivers are especially overrepresented in “passive” crashes (i.e., someone violates the young driver’s right-of-way), most likely the result of a combination of speeding, slow hazard perception, and a firmness to enforce their right-of-way (Braitman et al., 2008). Middle-aged drivers are less likely to be at fault in failure-to-yield crashes (Mayhew, Simpson, & Ferguson, 2006).

Older drivers are overrepresented in most types of intersection crashes (Keskinen et al., 1998). At non-signalized intersections, failure-to-yield crashes are most common (Braitman et al., 2008; Oxley, Fildes, Corben, & Langford, 2006). The main issue is that the complexity of the driving task conflicts with age-related impairments such as declining vision, perception, cognitive functioning, and physical abilities (Oxley et al., 2006). Older drivers have difficulty in selecting safe gaps in conflicting traffic, mainly because they are less able to correctly estimate the speed of approaching vehicles (Oxley et al., 2006). They overestimate the speed of vehicles driving at slow speeds and underestimate the speed of vehicles driving at higher speeds (Scialfa, Guzy, Leibowitz, Garvey, & Tyrrell, 1991). Older drivers tend to drive and accelerate more slowly than other drivers, which might lead to dangerous situations when they are interacting at non-signalized intersections because other drivers might incorrectly interpret the slower speeds as an intention to give way (Keskinen et al., 1998).

Gender differences in driving behaviour also influence interactions between road users. Generally, women have more cautious driving habits than men, resulting in a lower overall crash involvement, even when corrected for exposure (Al-Balbissi, 2003). Men are significantly more often involved in crashes involving right-of-way violations than are women (Al-Balbissi, 2003). Kulmala (1990) indicates that women enter right-hand priority intersections on average 3 to 4 km/h slower than men.

5.2.8 Status

A number of elements affecting interactions between road users have been explored in previous research, but the number of studies is limited. Moreover, variables that are potentially important have sometimes not been explored in an integrated way, and most studies date from a long time ago. Furthermore, priority-controlled and right-hand priority intersections have rarely been compared on the basis of elements other than the number of right-of-way violations. Therefore, the understanding of interactions between drivers at these intersections is limited. More precisely, elements that have an influence on yielding behaviour and elements that influence drivers' looking behaviour seem to be important aspects to investigate more profoundly. This study collects these behavioural elements in an integrated way and focuses on examining which elements have an influence on yielding behaviour and drivers' looking behaviour.

5.3 Methodology

5.3.1 Study design

This study aims to further explore the way drivers interact with each other at priority-controlled and right-hand priority intersections. The design of the study is cross sectional, indicating that two intersections have been selected that are as comparable as possible, except for the difference in the right-of-way rules. The study focuses on side interactions between two vehicles. Observable elements of interactions that are potentially relevant to road safety were collected, including yielding, looking and approaching behaviour, communication, gender, and age of the involved drivers.

5.3.2 Selection of study locations

One priority-controlled intersection and one right-hand priority intersection were selected in the province of Limburg (Belgium) for extensive observation. At the priority-controlled intersection, yield signs and pavement markings indicate the right-of-way. When no yield signs or pavement markings are present, the right-hand priority rule applies by default. That is the case for the selected right-hand priority intersection.

The intention of this study is to investigate the influence of the type of priority control on vehicle–vehicle interactions. Therefore, interactions should be as unguided as possible by specific intersection characteristics, other than the type of priority control. For that reason, two "basic" intersections are chosen that have no geometrical particularities such as bicycle paths, crossings, or speed-reducing measures that may influence the way interactions between drivers take place. The road widths are the same for both intersections and for all approaching branches to avoid an influence from the fact that drivers tend to yield less to drivers coming from a narrower road (Björklund & Åberg, 2005). Four-leg intersections have been chosen because three-leg intersections influence yielding behaviour. The intersections are located in a residential area and have a speed limit of 50 km/h on all branches. The intersections have relatively low traffic volumes because intersections with higher volumes tend to be equipped with additional geometric properties such as bicycle paths. Both intersections have similar traffic volumes, with a higher volume on one of the roads. The priority-controlled intersection has an approaching traffic volume (7 a.m. to 6 p.m. period) of 2,441 passenger car equivalents (PCEs) on the primary (in-priority) road and 278 PCEs on the secondary road; the right-hand priority intersection has traffic volumes of 2,648 PCEs and 289 PCEs, respectively. For reasons of brevity, the higher-volume road at the right-hand priority intersection is also referred to as the "primary road" and the lower-volume road as the "secondary road." The terms, however, do not indicate a hierarchy here.

5.3.3 Definition and application of the concept of "interaction"

A first crucial element is what is to be considered an "interaction." An interaction is defined as a situation in which two road users arrive at the intersection with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other. An interaction between two road users is an elementary event in the traffic process that has the potential to end in a collision (Laureshyn et al., 2010). Interactions are the lowest (least severe) level of a safety hierarchy in which relationships exist between the lower severity levels and the highest severity level, that is, a crash (Hydén, 1987; Saunier, Mourji, & Agard, 2011; Svensson & Hydén, 2006).

To facilitate and objectify the observations, this definition is applied in a geographic space around the intersection. At both types of intersections the limits of this space are 50 m away from the intersection plane on both sides of the primary road and 25 m on both sides of the secondary road. The choice for two distances is based on speed measurements that indicate a significantly higher driving speed for vehicles approaching the intersection from the primary road. The average approach speeds on the secondary roads are similar for both intersection types, while the approach speeds on the primary roads are on average slightly higher (± 3 km/h) at the priority-controlled intersection compared with the right-hand priority intersection. The distances are chosen on the basis of pilot tests that have indicated that this is in most situations a good cut-off value to distinguish between vehicles that have an influence on each other and vehicles that do not.

5.3.4 Observation protocol

Each intersection was observed for 30 h during the November 24 through December 5, 2011, period. All observations took place in dry weather conditions during the daytime because of the need to look inside the vehicles to collect information about the drivers' gender, age, and looking behaviour. Twilight, night, and rainy conditions did not allow this. The observations were done in blocks of 2 to 3 h, spread evenly throughout the hours of the day and days of the week (including weekends) for both intersections, to avoid possible biases. All observations were executed by one observer using a standardised observation form. All variables were objectified and standardised as binary or categorical variables to allow quantitative analyses of the interactions.

5.3.5 Ensuring and assessing the reliability of the data collection

A second observer examined the same interactions for part of the observation period to perform an intercoder reliability assessment. Intercoder reliability is the extent to which independent observers reach the same conclusion when evaluating the same situation using the same method (Lombard, Snyder-Duch, & Bracken, 2002). A high level of agreement between coders is considered to be a sign of theoretical solidity of the applied method and the good training of the observers, while large differences among coders suggest weaknesses in the research methods, such as poor operational definitions or poor training of the observers (De Ceunynck, Kusumastuti, Hannes, Janssens, & Wets, 2013; Hak & Bernts, 1996; Lombard et al., 2002).

Furthermore, all interactions were recorded, which allowed validation of most of the variables. Therefore, the data about these variables should be virtually 100% correct, irrespective of their intercoder reliability. Drivers' gender, age, and looking behaviour could not be verified this way.

5.3.6 Analysis of the collected behavioural data

The data are analysed with logistic regression models, which can be used to predict the probability of a certain event when the dependent variable is dichotomous (Allison, 1999). Firth's penalised maximum likelihood is applied because it avoids the problem of quasi-complete separation, which is the most common convergence failure in logistic regression (Allison, 1999; Heinze & Schemper, 2002).

Models are built with a stepwise procedure. The Akaike information criterion is used to assess the models. The measure indicates the model's relative goodness-of-fit, but penalises larger numbers of parameters, providing a trade-off between accuracy and complexity of the model (Akaike, 1987). Variance inflation factors (VIFs) are used to check for multicollinearity (i.e., a high correlation between two or more independent variables). VIFs higher than 4 indicate a high correlation (O'Brien, 2007). All variables in the end models have VIFs lower than 2, so there are no multicollinearity issues in the presented models.

5.4 Results and discussion

5.4.1 Intercoder reliability

An extensive intercoder reliability assessment based on 113 of the 483 interactions (23% of all data) was performed. The intercoder reliability was assessed by two measures: Cohen's κ and percent agreement. Percent agreement is the simplest intercoder reliability measure and expresses the percentage of cases for which the observers agree. Cohen's κ is a measure that corrects percent agreement for agreement by chance and is therefore generally considered to be a more favourable intercoder reliability measure than percent agreement (Lombard et al., 2002). However, percent agreement was calculated as well because some of the calculations suffered from the so-called "κ paradox". These are situations in which Cohen's κ incorrectly yields a low reliability estimate because the distribution over the data categories is strongly skewed (Cicchetti & Feinstein, 1990; Krippendorff, 2004). In these situations, the use of percent agreement is recommended because this measure is not susceptible to the κ paradox (Krippendorff, 2004).

A κ-value of 0.70 is considered satisfactory for exploratory studies; a value of 0.80 is acceptable in most studies (Lombard et al., 2002). All variables that had a reliable κ-value exceeded the 0.70 threshold for Cohen's κ, and all but one (i.e., gender of the driver on the primary road) exceeded even the stricter criterion of 0.80. All variables (including those with an unreliable κ-value) had a percent agreement of 0.85 or higher. Most important, the agreement on which situations are considered interactions and which ones are not was 100%. The differences in reliability between both intersection types were minimal. In conclusion, the intercoder reliability values were high and quite stable across all variables and intersections.

5.4.2 Descriptive statistics

Descriptive statistics are presented in Table 23. At the priority-controlled intersection, the vehicle on the primary road is always the vehicle that has priority. However, the situation at the right-hand priority intersection is not as clear. Vehicles entering the intersection from each intersection leg may be either the in-priority vehicle or the no-priority vehicle, depending on which leg the other interacting vehicle is coming from.

The variables "Approach prim" and "Approach sec" indicate that drivers on the secondary road of the right-hand priority intersection stop and decelerate more often when they are approaching the intersection, while drivers on the primary road often hold their speed. Also, the looking behaviour variables indicate that drivers on the secondary road nearly always look to the sides, while drivers on the primary road do not. Therefore, drivers on the secondary road seem to approach the intersection more cautiously than drivers on the primary road, which indicates that road users may consider the primary road as an implicit main road. The high number of right-of-way violations is another element that stresses the presence of an informal priority rule (Björklund & Åberg, 2005). The higher traffic volume on the primary road is likely to contribute to the occurrence of this informal priority rule. Driver interactions are influenced by expectations based on previous experience (Sivak & Schoettle, 2011). Therefore, drivers who are familiar with the intersection may be especially likely not to expect drivers arriving from the secondary road, and therefore they approach the intersection incautiously, leading to violations of the priority rule.

Therefore, there are two possibilities of coding the data from the right-hand priority intersection: either distinguishing between in-priority vehicles and no-priority vehicles or distinguishing between vehicles on the primary road and vehicles on the secondary road. It was decided that the data would be analysed according to both possibilities to check whether the results differ. The variables recoded according to the distinction in-priority and no-priority are indicated in italics.

Drivers comply with the right-hand rule in only 73% of the interactions (147 out of 201), this is similar to the finding of Johannessen (1984), which indicates 75% compliance. The compliance at the priority-controlled intersection (92%) is significantly higher than at the right-hand priority intersection ($X^2(1, N = 483) = 22.46, p < .001$), which is in line with Helmers and Åberg (1978).

Table 23: Descriptive statistics.

		Right-hand priority intersection (N=201)	
Variable name and description	**Priority-controlled intersection (N=182)**	**Distinction = primary or secondary road**	**Distinction = driver in-priority vs. no-priority**
Data about yielding			
ViolationPriority – right-of-way rule is violated	Yes = 15, No = 167	Yes = 54, No = 147	Yes = 54, No = 147
HasPriority prim – vehicle on primary road has priority	Yes = 182, No = 0	Yes = 86, No = 115	-
HasPriority VP – in-priority vehicle has priority	-	-	*Yes = 201, No = 0*
HasPriority sec – vehicle of secondary road has priority	Yes = 0, No = 182	Yes = 115, No = 86	-
HasPriority VNP – no-priority vehicle has priority	-	-	*Yes = 0, No = 201*
GetPriority prim – vehicle on primary road gets priority	Yes = 167, No = 15	Yes = 124, No = 77	-
GetPriority VP – in-priority vehicle gets priority	-	-	*Yes = 147, No = 54*
GetPriority sec – vehicle of secondary road gets priority	Yes = 15, No = 167	Yes = 77, No = 124	-
GetPriority VNP – no-priority vehicle gets priority	-	-	*Yes = 54, No = 147*
Demographic variables			
Gender prim – gender of driver on primary road	M= 125 , F= 57	M = 138, F = 63	-
Gender VP – gender of in-priority driver	-	-	*M = 121, F = 80*
Gender sec – gender of driver on secondary road	M= 104 , F = 78	M = 108, F = 93	-
Gender VNP – gender of no-priority driver	-	-	*M = 125, F = 76*
Age prim – age of driver on primary road	Y = 5, M=159, O = 18	Y = 5, M = 186, O = 10	-
Age VP – age of in-priority driver	-	-	*Y = 4, M = 17 , O = 23*
Age sec – age of driver on secondary road	Y = 3, M = 150, O = 29	Y = 6, M = 166, O = 29	-
Age VNP – age of no-priority driver	-	-	*Y = 7, M = 178, O = 16*

Table 23: Descriptive statistics (continued).

Variable name and description	**Priority-controlled intersection (N=182)**	**Right-hand priority intersection (N=201)**	
		Distinction = primary or secondary road	**Distinction = driver in-priority vs. no-priority**
Approaching behaviour			
Prim arrives first – vehicle on primary road reaches junction plane first	Yes = 15, No = 167	Yes = 58, No = 143	-
VP arrives first – in-priority vehicle reaches junction plane first	-	-	*Yes = 77, No = 124*
Sec arrives first – vehicle on secondary road reaches junction plane first	Yes = 112, No = 70	Yes = 90, No = 111	-
VNP arrives first – no-priority vehicle reaches junction plane first	-	-	*Yes = 71, No = 130*
Arrive same time – vehicle on primary and secondary road reach junction plane at the same time	Yes = 55, No = 127	Yes = 53, No = 148	Yes = 53, No = 148
Same time –in-priority and no-priority vehicle reach junction plane at the same time	-	-	-
Approach prim – approach behaviour of vehicle on primary road at junction plane	Stop = 1, Dec.= 24, Hold = 157, Acc.= 0	Stop = 40, Dec.= 53, Hold = 106, Acc.= 2	-
Approach VP – approach behaviour of in-priority vehicle at junction plane	-	-	*Stop = 52, Dec.= 64, Hold=84, Acc.= 1*
Approach sec – approach behaviour of vehicle on secondary road at junction plane	Stop = 179, Dec.= 1 , Hold = 2, Acc.= 0	Stop = 110, Dec.= 69, Hold = 22, Acc.= 0	-
Approach VNP – approach behaviour of no-priority vehicle at junction plane	-	-	*Stop = 98, Dec.= 58, Hold = 44, Acc.= 1*

Table 23: Descriptive statistics (continued).

Variable name and description	**Priority-controlled intersection (N=182)**	**Right-hand priority intersection (N=201)**	
		Distinction = primary or secondary road	**Distinction = driver in-priority vs. no-priority**
Drivers' looking behaviour			
LookLeft prim – driver on primary road looks left	Yes = 21, No = 161	Yes = 22, No = 179	-
LookLeft VP – in-priority driver looks left	-	-	*Yes = 123, No = 78*
LookRight prim – driver on primary road looks right	Yes = 10, No = 172	Yes = 90, No = 111	-
LookRight VP – in-priority driver looks right	-	-	*Yes = 128, No = 73*
DontLook prim – driver on primary road does not look right or left	Yes = 155, No = 27	Yes = 107, No = 94	-
DontLook VP – in-priority driver does not look right or left	-	-	*Yes = 160, No = 41*
LookLeft sec – driver on secondary road looks left	Yes = 182, No = 0	Yes = 198, No = 3	-
LookLeft VNP – no-priority driver looks left	-	-	*Yes = 97, No = 104*
LookRight sec – driver on secondary road looks right	Yes = 181, No = 1	Yes = 198, No = 3	-
LookLeft VNP – no-priority driver looks right	-	-	*Yes = 66, No = 135*
DontLook sec – driver on secondary road does not look right or left	Yes= 0, No = 182	Yes = 0, No = 201	-
DontLook VNP – no-priority driver does not look right or left	-	-	*Yes = 41, No = 160*
Manoeuvre			
TurnLeft prim – vehicle on primary road turns left	Yes = 14, No = 168	Yes = 9, No = 192	-
TurnLeft VP – in-priority vehicle turns left	-	-	*Yes = 85, No = 116*
TurnRight prim – vehicle on primary road turns right	Yes = 0, No = 182	Yes = 2, No = 199	-
TurnRight VP – in-priority vehicle turns right	-	-	*Yes = 28, No = 173*
DontTurn prim – vehicle on primary road does not turn	Yes = 168, No = 14	Yes = 190, No = 11	-
DontTurn VP – in-priority vehicle does not turn	-	-	*Yes = 88, No = 113*
TurnLeft sec – vehicle on secondary road turns left	Yes = 83, No = 99	Yes = 144, No = 57	-
TurnLeft VNP – no-priority vehicle turns left	-	-	*Yes = 68, No = 133*
TurnRight sec – vehicle on secondary road turns right	Yes = 58, No = 124	Yes = 29, No = 172	-
TurnRight VNP – no-priority vehicle turns right	-	-	*Yes = 3, No = 198*
DontTurn sec – vehicle on secondary road does not turn	Yes = 41, No = 141	Yes = 28, No = 173	-
DontTurn VNP – no-priority vehicle does not turn	-	-	*Yes = 130, No = 71*

Table 23: Descriptive statistics (continued).

Variable name and description	**Priority-controlled intersection (N=182)**	**Right-hand priority intersection (N=201)**	
		Distinction = primary or secondary road	**Distinction = driver in-priority vs. no-priority**
Communication data			
Direction prim – driver on primary road uses directional lights	Yes = 168, No = 14	Yes = 11, No = 190	-
Direction VP – in-priority driver uses directional lights	-	-	*Yes = 99, No = 102*
Direction sec – driver on secondary road uses directional lights	Yes = 116, No = 66	Yes = 153, No = 48	-
Direction VNP – no-priority driver uses directional lights	-	-	*Yes = 65, No = 136*
Gesture prim – driver on primary road uses horn, hand gesture or flash of headlights to communicate	Yes = 1, No = 181	Yes = 1, No = 200	-
Gesture VP – in-priority driver uses horn, hand gesture or flash of headlights to communicate	-	-	*Yes = 8, No = 193*
Gesture sec – driver on secondary road uses horn, hand gesture or lights to communicate	Yes = 0 No = 182	Yes = 8, No = 193	-
Gesture VNP – no-priority driver uses horn, hand gesture or flash of headlights to communicate	-	-	*Yes = 1, No = 200*

Note: Variables coded for distinction between vehicles on primary (prim) road and those on secondary (sec) road are in roman. Variables coded for distinction between in-priority vehicles and no-priority vehicles are in italic. - = not applicable; M = male; F = female; Y = young driver; MA = middle-aged driver; O = older driver; stop = stops completely; dec. = decelerates; hold = holds same speed; acc. = accelerates.

5.4.3 Priority violation models

The models in Table 24 show the variables that influence the probability that the right-of-way rule is violated. Since the logistic regression models the logistic transformation of the dependent variable (i.e., the natural logarithm of the odds of the dependent variable), *e* should be raised to the power of the variable estimate to obtain the influence of the variable on the probability that a priority violation takes place. For example, in the priority-controlled intersection model, the estimate of "Sec arrives first" is 1.5265, which implies that the odds of a priority violation are $e^{1.5265} = 4.6$ times higher when the vehicle on the secondary road arrives first at the intersection than when the vehicle on the secondary road does not arrive first.

The priority-controlled intersection model shows three significant variables. "Sec arrives first" indicates that a violation is significantly more likely when the vehicle on the secondary road (i.e., the vehicle that should give way) arrives first at the intersection. "Approach sec" indicates that a violation is less likely when the vehicle on the secondary road comes to a full stop compared with when it only slows down. Perhaps the most remarkable finding is that the probability of a right-of-way violation is significantly (99% CI) higher when the driver on the primary road looks to the right. There are a number of possible explanations. The most likely explanation is that drivers who look to the right while entering an intersection do this at a lower speed than other drivers. This explanation would be in line with Kulmala's findings (1990), although his observations apply only to right-hand priority intersections. This way, looking to the right could be a proxy for a cautious driving style of the driver on the primary road, with the side effect that the vehicle on the secondary road sees this either as implicit communication indicating that the driver on the primary road may give way or as an opportunity to infringe on the primary road driver's right-of-way with a low perceived personal risk (Risser, 1985). Another possibility is that the driver on the secondary road directly observes that the driver on the primary road is looking to the right, with the same possible side effects (i.e., implicit communication or opportunity to infringe).

Right-Hand Priority Intersection Model A includes "HasPriority sec," "Sec arrives first," and "DontLook prim." The first two variables indicate a higher probability of a right-of-way violation when the secondary road has priority and a lower probability of a violation when the vehicle on the secondary road arrives first. Both variables seem to confirm that the primary road is indeed considered to be a higher-order road, resulting in a higher number of right-of-way violations committed by the drivers on this road. "DontLook prim" indicates a higher probability of a violation when the driver on the primary road does not look to either side. As in the priority intersection model, this situation can indicate that these drivers approach the intersection at higher speeds [in line with Kulmala, 1990], in that way discouraging the driver on the secondary road from enforcing his or her right-of-way for safety reasons, or it can indicate an implicit way of communicating a lack of intention to give way.

Right-Hand Priority Intersection Model B includes “VNP arrives first,” “approach VP,” and “approach VNP.” “VNP arrives first” indicates a higher chance of a right-of-way violation when the no-priority vehicle arrives first at the intersection. “Approach VP” indicates the highest chance of a priority violation in the case in which the in-priority vehicle comes to a full stop. “Approach VNP” indicates a significantly higher chance of violation when the no-priority vehicle maintains its speed and a significantly lower chance when the no-priority vehicle comes to a stop.

Two general patterns are observed for both intersections. The presence of “Sec arrives first–VNP arrives first” in the model of the priority-controlled intersection and Model B of the right-hand priority intersection indicates that the chance of a right-of-way violation is significantly higher when the no-priority vehicle arrives first at the intersection. This finding indicates that the priority behaviour of road users is partly a matter of first come, first served. Another possibility is that the no-priority drivers are more likely to make mistakes in estimating the approaching vehicles’ time, speed, or both when they arrive first at the intersection. When the in-priority vehicle arrives at the same time or even before the no-priority vehicle, these mistakes are much less likely. “Approach sec–Approach VNP” is also present in the priority-controlled intersection model and Right-Hand Priority Model B. The variable indicates that the probability of a violation is significantly reduced when the no-priority vehicle stops, compared with the reference category of only decelerating. This finding indicates that once road users have completely stopped, they are much less likely to commit a right-of-way violation than in other situations. Furthermore, at the right-hand priority intersection, the chance of a violation is higher when the no-priority vehicle holds its speed. This finding is also confirmed by “Approach VP,” which shows the reverse pattern for the in-priority vehicle, that is, a significantly higher probability of a violation when the in-priority vehicle stops and a lower (although not significant) probability in the case in which the in-priority vehicle maintains its speed.

Table 24: Factors influencing probability of right-of-way violation.

Variables	**Priority-controlled intersection**	**Right-hand priority intersection (distinction prim/sec) ("model A")**	**Right-hand priority intersection – (distinction VP/VNP)[1] ("model B")**
Intercept	0.027 (*p* =.980)$^{\circ}$	-1.591 (*p* <.001)***	_-0.765 (p =.365)_$^{\circ}$
HasPriority sec		1.281 (*p* <.001)	
Sec arrives first	1.5265 (*p* =.034)**	-0.473 (*p* =.013)**	
VNP arrives first			_1.198 (p <.001)*_**
Approach VP			_Stop: 2.153 (p =.004)*_** _Dec.: 0_ _Hold: -1.009 (p =.150)_$^{\circ}$ _Acc.: -1.134 (p =.526)_$^{\circ}$ _(p <.001)_***
Approach sec	Stop: -2.653 (*p* =.017)** Dec.: 0 Hold: 1.154 (*p* =.451)$^{\circ}$ (*p* =.050)**		
Approach VNP			_Stop: -1.823 (p =.007)_*** _Dec.: 0_ _Hold: 1.544 (p =.023)_** _Acc.: 0.677 (p =.702)_$^{\circ}$ _(p<.001)_***
LookRight prim	1.098 (*p* =.009)***		
DontLook prim		0.771 (*p* <.001)***	

Note: VP = in-priority vehicle; VNP = no-priority vehicle.
$^{\circ}p$ > .10 (not significant at 90% CI); $^{*}p$ ≤ .10 (significant at 90% CI); $^{**}p$ ≤ .05 (significant at 95% CI); and $^{***}p$ ≤ .01 (significant at 99% CI).

5.4.4 Looking behaviour models

Table 25 presents the factors that influence drivers' looking behaviour. Only the looking behaviour of drivers on the primary roads could be modelled, since virtually all drivers from the secondary roads look to the sides. For Right-Hand Priority Intersection Model B, the looking behaviour of in-priority and no-priority drivers could be modelled. The models present variables that influence the chance that the driver looks to at least one of the sides.

The priority-controlled intersection model includes only "Prim arrives first" and "Turn prim." "Prim arrives first" indicates a higher probability that the driver on the primary road looks to the sides in the case in which the driver arrives first, but the result is not significant. There is a significantly higher probability that the driver looks to the sides in the case in which the driver makes a turn, which is expected, making a turning manoeuvre without looking to the side is quite difficult.

Right-Hand Priority Model A indicates that "GetsPriority sec," "Approach prim," and "Turn prim" influence the looking behaviour of the driver on the primary road. "GetsPriority sec" indicates a higher chance that drivers on the primary road look to the sides when the vehicle on the secondary road gets priority. "Approach prim" indicates that drivers have a significantly higher probability of looking to the sides when they come to a full stop and a lower probability when they hold their speed. "Turn prim" indicates a (non-significant) higher probability of looking to the sides in the case in which a turning manoeuvre is executed.

Right-Hand Priority Intersection Model B1 indicates that "GetsPriority VNP," "VP arrives first," "gender VP," and "age VP" have an influence on the looking behaviour of the in-priority driver. "GetsPriority VNP" indicates a higher probability that the in-priority driver looks to the sides when the no-priority vehicle gets priority. The in-priority driver is also more likely to look to the sides when he or she arrives at the intersection first. Furthermore, in-priority male drivers tend to look less to the sides than female drivers, although the difference is not significant. "Age VP" indicates that older in-priority drivers look to the sides more often than other age categories.

Right-Hand Priority Intersection Model B2 indicates a significant influence of "GetsPriority VP" and "Approach VNP" on the no-priority drivers' looking behaviour. "GetsPriority VP" indicates that the no-priority drivers are more likely to look to the sides when they yield to the in-priority drivers. "Approach VNP" indicates that no-priority drivers are more likely to look to the sides when they come to a full stop and less likely when they hold their approach speed.

Table 25: Factors influencing likelihood that driver will look to sides on approach to intersection.

Variables	**Priority-controlled intersection – Driver primary road**	**Right-hand priority (distinction prim/sec) model A – Driver primary road**	**Right-hand priority intersection (distinction VP/VNP) – model B1 – in-priority driver**	**Right-hand priority intersection (distinction VP/VNP) – model B2 – no-priority driver**
Intercept	0.0292 (*p* =.951)$^{\circ}$	1.368 (*p* =.028)**	2.260 (*p* <.001)***	1.570 (*p* =.013)**
GetsPriority sec		0.5124 (*p* =.036)**		
GetsPriority VNP			*1.262 (p <.001)****	
GetsPriority VP				*0.561 (p =.052)**
Prim arrives first	0.502 (*p* =.171)$^{\circ}$			
VP arrives first			*0.4649 (p =.008)****	
Approach prim		Stop: 2.056 (*p* =.006)*** Dec.: 0 Hold: -2.218 (*p* <.001)*** Acc.: -0.200 (*p* =.856)$^{\circ}$ (*p* <.001)***		
Approach VNP				Stop: 2.173 (*p* =.013)** Dec.: 0 Hold: -2.472 (*p* <.001)*** Acc.: 0.090 (*p* =.960)$^{\circ}$ (*p* <.001)***
Turn prim	1.904 (*p* <.001)***	0.655 (*p* =.185)$^{\circ}$		
Gender VP			F: 0 M: -0.287 (*p* =.101)$^{\circ}$	
Age VP			Y: -0.529 (*p* =.528)$^{\circ}$ M: 0 O: 1.248 (*p* =.081)* (*p* =.095)*	

Note: VP = in-priority vehicle; VNP = no-priority vehicle.
$^{\circ}p > .10$ (not significant at 90% CI); $^{*}p \le .10$ (significant at 90% CI); $^{**}p \le .05$ (significant at 95% CI); and $^{***}p \le .01$ (significant at 99% CI).

However, the causality in this relationship is likely to be the other way around, because road users look to the sides, they are more likely to yield to the other road user. This is the case for both in-priority and no-priority drivers. In-priority drivers are also more likely to look to the sides when they arrive first at the intersection. Furthermore, two right-hand priority intersection models indicate a significantly higher probability of the driver looking to the sides when the driver comes to a full stop, while this probability is significantly lower when the driver holds his or her speed.

5.5 Study limitations and further research

Because this study is based on observations on two intersections, the possibilities to draw generalised conclusions are limited. This is a common limitation of studies focusing on the lower severity levels of the traffic safety hierarchy (i.e., interactions or conflicts) (Lange, Haiduk, Schwarze, & Eggert, 2011; Rosenbloom, 2009; Saunier et al., 2011; St-Aubin, Miranda-Moreno, & Saunier, 2012; Svensson & Hydén, 2006). Nevertheless, the study can be considered as a pilot project that tests a standardised observation protocol and reveals some interesting hypotheses and topics for further research. Research should investigate the generalisability of the study results and the influence of particular design elements (e.g., bicycle paths, crossing facilities) on interactions. This study can be a good base case to compare against since the chosen intersections do not have such specific characteristics. Furthermore, the link between road user interactions and the higher levels of the safety hierarchy, that is, conflicts and crashes, should be further investigated. That investigation should reveal to what extent the lower levels of the safety hierarchy can be used to make predictions about the safety level of particular locations, at this point these links are still insufficiently clear.

Another limitation is that the study does not analyse all types of interactions. Observations in reduced visibility conditions, such as rain, twilight, or night, were not possible. Data about interactions between vehicles approaching each other from opposite roads have been collected, but they were too sparse to analyse quantitatively. Interactions between more than two road users were too complex to handle within the scope of this study.

The actual driving speed of the interacting vehicles would be a useful additional variable to collect since it might help to interpret the influence of the looking behaviour on the occurrence of right-of-way violations. At this point, it was often unclear whether looking to the side is a proxy for a lower approach speed, as suggested by the literature, or a directly influencing factor (Kulmala, 1990).

5.6 Conclusions

The number of priority violations appears to be significantly higher at the right-hand priority intersection compared with the priority-controlled intersection.

Concerning right-of-way violations, it appears that at both intersections the chance for a violation is significantly higher when the no-priority vehicle arrives at the intersection first, indicating a first come, first served tendency. Furthermore, approach behaviour is significantly predictive of right-of-way violations. The lowest chance of a violation is when the no-priority driver comes to a full stop, while the chance of a violation is highest when the no-priority driver holds his speed. Explicit communication, gender, and age do not significantly influence drivers' yielding behaviour at either intersection.

At the priority-controlled intersection, there is also a higher probability of a violation in the case in which the driver on the primary road looks to his or her right side when entering the intersection.

At the right-hand priority intersection, there is a lower probability of a right-of-way violation when the secondary road vehicle arrives first, despite the general first come, first served tendency. Combined with the finding that there is a significantly higher chance of a right-of-way violation when the secondary road driver has priority, the indication is that drivers on the secondary road are much less likely to enforce their right-of-way or to infringe on the right-of-way of a vehicle on the primary road, indicating that the primary road is implicitly considered to be a main road by drivers. The probability of a violation of the right-hand priority rule is higher when the driver on the primary road does not look to the sides.

Concerning looking behaviour, few conclusions can be drawn for the priority-controlled intersection. At the right-hand priority intersection, drivers who look to the sides are more likely to give way to other road users. In-priority drivers are more likely to look to the sides when they arrive first at the intersection. The probability of looking to the sides is highest when drivers come to a full stop and lowest when drivers hold their approach speed. The latter combination (holding speed and not looking to the sides) can be considered dangerous behaviour as both factors increase the probability of a right-of-way violation and therefore may increase the probability of getting involved in a crash. Since right-of-way violations are identified as one of the main factors that contribute to crashes, further research is merited.

In summary, the results suggest a general first come, first served tendency in yielding behaviour, a higher number of violations at the right-hand priority intersection, and an informal right-of-way at the right-hand priority intersection that leads to a higher number of violations against drivers on the secondary road.

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CHAPTER 6: FINAL CONCLUSIONS

The performed studies in this doctoral dissertation lead to more insights in patterns of behaviour, conflicts and accidents that occur on intersections in urban areas. Furthermore, they also provide an overview of the strengths, weaknesses and opportunities of applying different road safety techniques in conducting policy-relevant road safety research.

This final chapter summarises the main findings, strengths and limitations of the conducted studies, formulates policy recommendations and provides an outlook on further research possibilities. In the first section, the main findings and characteristics regarding the road safety situation at intersections are summarised. Based on the main findings, the second section describes several policy recommendations to increase intersection safety. The third section discusses the strengths and limitations of road safety techniques based on crash data and empirical non-crash data. Additionally, this section also describes whether the observation of non-crash events can be used to draw road safety inferences compared to road safety techniques based on crash data. The fourth section provides an outlook for future research possibilities, and the final section provides an overview of the final conclusions.

6.1 Overview of the main findings and characteristics of the studies

Two studies investigated accident patterns at roundabouts and signalized intersections by including the exact location of the accident in the analysis. Additionally, the effects of implementing SRLCs at signalized intersections have also been assessed by examining driver behaviour in traffic conflict situations and in normal encounters, by means of a driving simulator and video-based observations. Finally, a behavioural analysis of vehicle-vehicle interactions has been applied to investigate road safety differences between right-hand priority and priority-controlled intersections. The main findings and characteristics of these studies are summarised in Table 26 and are discussed below.

Table 26: Overview of the main findings and key characteristics of the studies.

Intersection type	Objectives	Outcome	Method	Study design	Main results
Roundabouts (chapter 2)	Identification of crash types; relation crash occurrence and roundabout design	Crash patterns (crash types; location; severity; characteristics of roundabout)	Accident analysis (accident data and collision diagrams)	Cross section	- Dominant crash types: rear-end, collision with central island, entering-circulating, VRU - Link between crash type and crash location -Single-lane roundabouts: ↑ rear-end and VRU crashes -Double-lane roundabouts: ↑ collisions with central island - Cycle lanes within the roundabout: ↑ crashes with cyclists and mopeds
Signalized Intersections (chapter 3)	Identification of crash types; relation crash occurrence and intersection design	Crash patterns (crash types; location; severity; characteristics of intersection)	Accident analysis (accident data and collision diagrams)	Cross section	- Dominant crash types: rear-end, side, VRU, head-on crashes - Link between crash type and crash location - Exclusive turn lanes ↓ injury crashes - Protected–permitted left-turn signal phasing: ↑ rear-end crashes - Protected-only left-turn signal phasing: ↓ head-on crashes, ↓ rear-end crashes - Protected-only and protected-permitted left-turn signal phasing: ↓ VRU and injury crashes - 50-km/h speed limits: ↓ injury crashes - Medians: ↓ head-on crashes - RLCs: ↓ VRU, ↓ head-on, ↓ side, ↑ rear-end crashes - Cycle facility – mixed traffic: ↑ VRU crashes

Table 26: Overview of the main findings and key characteristics of the studies (continued).

Intersection type	Objectives	Outcome	Method	Study design	Main results
Signalized Intersections (chapter 4)	Identification of contributing factors for increase in rear-end collisions at SRLC-locations	Decision, following and looking behaviour; Risk of rear-conflicts and collisions	Video based behavioural observation & traffic conflict study; driving simulator study	Before and after	- Reduction in red and yellow light running - Shift in dilemma zone - Shorter following distance - Stronger deceleration values - SRLCs increase risk of rear-end collisions but risk is lower in SRLCWS-situation
Priority-controlled and right-hand priority intersection (chapter 5)	Identification of road safety differences between both intersection types	Yielding and looking behaviour	On-site behavioural observation with human observers	Cross section	- First come, first served tendency in yielding behaviour - Approach behaviour significant predictor of right-of-way violations - Looking behaviour plays a role in right-of-way violations - Higher number of violations at right-hand priority intersection - Informal right-of-way at right-hand priority intersection

6.1.1 Accident patterns on roundabouts

The study focusing on identifying accident patterns on roundabouts has shown that four dominant accident types occur at roundabouts: rear-end, collisions with the central island, entering-circulating and accidents with vulnerable road users. Another interesting finding is the fact that the accident occurrence of these dominant accident types is related to certain locations on the roundabout. Rear-end accidents predominantly occurred in the zones before entering the roundabout while nearly all accidents in the zones close to the central island were single-vehicle collisions with this island. Vulnerable road user accidents mostly took place in the zone where drivers leave the roundabout and cross the path of circulating cyclists. Entering–circulating accidents primarily dominated the location where the entry lane is connected to the circulatory road.

Furthermore, it was also found that certain roundabout design characteristics are related to accident occurrence. Significantly more accidents with vulnerable road users and rear-end accidents occurred at single-lane roundabouts while double-lane roundabouts led to more collisions with the central island, especially in the evening or at night. Moreover, cycle lanes within the roundabout were found to be more dangerous for vulnerable road users. Compared to the roundabouts with other types of cycle facilities (i.e. mixed traffic, separate cycle paths, and grade separated cycle paths), significantly more accidents with vulnerable road users occurred on the exit lanes of roundabouts with cycle lanes.

Finally, accidents in which vulnerable road users are involved, collisions with the central island and accidents occurring on double-lane roundabouts appeared to have a higher probability of resulting in severe injuries.

6.1.2 Signalized intersections

6.1.2.1 Accident patterns

By investigating accident patterns on signalized intersections, it became clear that four dominant accident types characterised these intersections: rear-end, side (i.e. left-turn plus right-angle), head-on and vulnerable road user accidents. Additionally, side, head-on and vulnerable road user accidents had a higher probability of resulting in injury accidents, while the latter accident type also had a higher probability of resulting in severe injuries.

The findings also showed that there was a link between the occurrence of the dominant accident types and their location on the signalized intersection. Rear-end accidents predominantly occurred before the intersection and on the bypass. Side and head-on accidents mostly took place on and in the vicinity of the intersection plane. In line with the roundabout study, vulnerable road user accidents primarily occurred at the crossing facilities after the intersection plane (according to the perception of the motorised road users) or on the bypass.

Besides the accident location, it was also found that specific signalized intersection properties were associated with accident occurrence. Protected-only and protected-permitted left-turn signal phasing had a positive effect on accidents involving vulnerable road users and injury accidents in general. Additionally, protected-only signal phasing also had a positive effect on head-on and rear-end accidents. However, protected-permitted left-turn signal phasing was found to have a negative effect on rear-end accidents. Furthermore, the probability of an injury accident decreased at signalized intersections with exclusive turn lanes. Lower design speeds also appeared to have a favourable effect on injury accidents in general.

The presence of a red-light camera decreased the number of side, head-on and vulnerable road user accidents whereas this measure had an adverse effect on rear-end accidents. The occurrence of this adverse effect also accords with the findings of the SRLC-study (chapter 4). Signalized intersections equipped with medians were characterised by less head-on accidents. Vulnerable road user facilities also influenced signalized intersection safety. Mixing cyclists with motorised traffic had a negative effect on vulnerable road user accidents.

6.1.2.2 Patterns of road user behaviour and conflicts

The study investigating the behavioural responses of road users approaching signalized intersections with SRLCs showed that SRLCs influenced road user behaviour.

The results of the on-site observation study revealed that SRLCs appeared to influence drivers' stopping behaviour as the number of red and yellow light violations decreased significantly after the installation of the SRLC. Furthermore, in case a SRLC was present, drivers tended to stop earlier and even tended to stop at the onset of yellow when they were very close to the stop line. Because of this higher stopping propensity during the yellow phase, the location of the dilemma zone on the signalized intersection also changed after the SRLC introduction. The length of the dilemma zone remained the same but the zone shifted 0,5 s closer to the stop line. The results of the driving simulator experiment confirmed the idea of higher stopping propensities; in case the SRLC was combined with a warning sign, 30% of the drivers stopped for a yellow light. Moreover, the results also revealed that SRLCs led to shorter following distances (< 2 s) and had a moderate effect on the occurrence of rear-end conflicts at the onset of the yellow phase. While a higher stopping propensity and compliance with the traffic light may generally be considered as a favourable effect, this higher compliance in combination with a shorter following distance may also partly be responsible for the increase in rear-end collisions.

The findings of the driving simulator study also reveal possible adverse effects of the presence of SRLCs on road user behaviour such as stronger decelerations and a possible increase in the number of rear-end collisions. The odds of a rear-end collision was equal to 1.00, 6.42 and 4.01 in the control-, SRLC-, and SRLCWS-condition respectively. This indicates that the presence of a SRLC increases the risk of a rear-end collision. Furthermore, mean deceleration values of -2.83 m/s², -4.28 m/s² and -3.45 m/s² were found for the control-, SRLC- and SRLCWS-condition respectively. The decelerations appear to be much stronger in case of the SRLC-condition and are more or less mitigated by the introduction of a warning sign. In that case, the deceleration values approximated the more normal braking deceleration value of -3m/s². In general, SRLCWS seemed to reduce the unfavourable effects of SRLCs.

6.1.3 Road user behaviour at priority-controlled and right-hand priority intersections

The behavioural analysis of vehicle-vehicle interactions revealed that the number of right-of-way violations was significantly higher at the right-hand priority intersection (27% of all interactions) than at the priority-controlled intersection (8%).

Furthermore, the results revealed that the presence of an informal right-of-way at the right-hand priority intersection was responsible for this higher number of right-of-way violations. This intersection consisted out of two roads with different traffic volumes, i.e. a lower- and a higher-volume road. Drivers on the lower-volume road appeared to adopt a more cautious approaching behaviour compared to the drivers on the higher-volume road. As follows, the right-hand priority rule was more often violated when the driver on the lower-volume road of the intersection had priority. This behavioural pattern revealed that the higher-volume road is perceived as an implicit main road.

At both intersection types, ‘a first come, first served’ tendency in yielding behaviour was revealed since the probability for a violation was significantly higher when the no-priority vehicle arrived first. Furthermore, approach behaviour was also a significant predictor of right-of-way violations. At both intersections, the priority rule was more often violated when the no-priority driver accelerated or drove at a constant speed than when he or she decelerated/stopped.

To conclude, looking behaviour also played a role in the occurrence of right-of-way violations. At the right-hand priority intersection, the probability to violate the priority rule was higher when the driver did not look to the side(s). At the priority-controlled intersection, the probability to violate the priority rule was higher when the driver on the main road looked to his or her right side.

6.2 Policy recommendations with respect to intersection safety

The results of this dissertation extent the current knowledge regarding the safety performance of intersections. This insight can assist road authorities, road designers and decision makers engaged in road safety management in making well-based decisions. In this light, several policy recommendations can be proposed aimed at improving the safety performance of intersections.

6.2.1 Roundabout safety

The occurrence of rear-end accidents at the roundabout approach is an indication of heterogeneous speeds between drivers on the roundabout approach. Previous studies (Kennedy, Peirce, & Summersgil, 2005; Montella, 2011; SETRA, 1998; TNZ, 2000) also indicated that an excessive radius of deflection on the entry approach gives rise to high entry speeds. This may cause the following vehicle to rear-end the leading vehicle when the lead vehicle breaks suddenly to yield to circulating traffic or to vulnerable road users at the crossing facilities (Burdett, Alsghan, Chiu, Bill, & Noyce, 2016). In line with Montella (2011), Rodegerdts et al. (2010) and Mandavilli (2009), it is recommended to address rear-end collisions by keeping the approach deflection narrow and tight enough in order to promote slow speeds. Additionally, clear advance signs and markings can also assist in reducing rear-end collisions by mitigating heterogeneous driving speeds. These measures already inform drivers about the presence of a roundabout and (possible) vulnerable road user crossing ahead, which allows them to anticipate to the traffic situation by adjusting their driving speed to a more appropriate speed.

Another policy recommendation relates to the size of the central island. A higher number of single-vehicle collisions with the central island characterised double-lane roundabouts. These collisions predominantly occurred at night. Given this accident pattern, roundabouts should be designed to be sufficiently conspicuous at night. An increased conspicuity of the central island assists drivers to focus on the entry area and circulating traffic rather than on the area behind the central island, and reduces the risk that drivers fail to notice the central island and collide into it (Mandavilli et al., 2009). Therefore, it is recommended that the entire roundabout and especially the central island should be well illuminated at night. Ground-level lighting, reflective pavement markings and reflective paint on curbs also assist in increasing the visibility of the central island.

Comparable to reducing rear-end accidents, narrow and tight approach deflections are also recommended to reduce entering-circulating accidents. With respect to entering-circulating accidents, this measure encourages slow entry speeds which in turn may lead to less failure to yield to circulating traffic (Kennedy et al., 2005; Montella, 2011). Additionally, it is also advised to install clear and effective yield markings/signs at the entry.

Regarding the vulnerable road user accidents, a careful consideration should be made regarding the type of cycle facility at roundabouts. This is in in line with an earlier policy recommendation of Daniels (2010) who highly recommended that future roundabouts should not be constructed with cycle lanes close to the roadway, as they turned out to result in significantly more accidents with cyclists and moped riders. Grade-separated crossings for cyclists are probably the most desirable solution from a safety point of view because this infrastructural solution prevents interactions between motorised traffic and cyclists. However, grade-separated crossings are difficult to implement because of space and budget constraints. However, as Daniels (2010) also states this recommendation does not imply that already implemented roundabouts with cycle lanes close to the roadway need to be redesigned, as merely converting the cycle facility to another one without adjusting the geometric variables will not improve the overall roundabout safety.

6.2.2 Signalized intersection safety

Rear-end collisions mostly occurred at the entry lanes. Several studies indicated that these collisions are possibly caused by differences in braking performance at the onset of the yellow phase, inattentive driving and following too closely at the time of a signal change (Mohamed Abdel-Aty & Abdelwahab, 2004; Sayer et al., 2000; Strandberg, 1998). Given this accident pattern, it is recommended that signalized intersections should be designed to be sufficiently conspicuous. The visibility of the intersection, traffic signals, or both should be improved to increase the awareness of approaching drivers. Improvements in signal coordination and optimisation of change intervals can also be applied to reduce rear-end collisions (Antonucci et al., 2004).

It is widely acknowledged that side and head-on collisions are above all the result of red-light running or unprotected left-turn phasing. As a result, possible countermeasures include the implementation of protected-only left-turn phasing and red-light cameras even though the latter measure gives rise to increases in rear-end collisions. Additional measures such as improvements in sight distance, signal coordination, and change intervals also result in fewer head-on and side accidents (Antonucci et al., 2004).

Crossing the signalized intersection after the intersection plane appeared to be more dangerous for vulnerable road users. In general, motorists are more focused on other motorists than on vulnerable road users. Most likely, this aspect played a role in these accidents. Therefore, crossing facilities at signalized intersections should be designed to be clearly visible for approaching drivers. Furthermore, conflicts between vulnerable road users and motorised vehicles still occur frequently at signalized intersections when they are not fully protected by the signal phasing (i.e. vulnerable road users have the same green phase as turning traffic). From a safety perspective, protected-only phasing for vulnerable road users is recommended (De Pauw, Daniels, Van Herck, & Wets, 2015).

Finally, a recommendation can also be formulated regarding the unintended driver behaviour adaptation effects that are accompanied with the implementation of SRLCs. Several studies have previously shown that this form of automated enforcement leads to a significant decrease in the number of severe crashes (i.e. side, head-on, vulnerable road user crashes) (De Pauw et al., 2014; Erke, 2009; Høye, 2013; Vanlaar et al., 2014) but also gives rise to increases in the number of rear-end collisions. Since warning signs seem to nuance and even reduce the unintended effects of SRLCs to some extent, it is recommended that drivers are well-informed when they approach an intersection equipped with a SRLC. The driver can be informed in several ways: a warning sign at a considerable distance of the intersection (e.g. 50 m), road markings or by means of a warning embedded in navigation systems. The current guideline of the Flemish Road Agency already allows to announce automated speed enforcement on motorways by means of warning signs but forbids the announcement of red-light cameras (Vlaamse Overheid, 2009a). This prohibition is based on the following principles: red-light running is so dangerous that it can never be tolerated, the road user should never get the impression that the chance of being caught for red-light running on certain intersections is greater compared to other locations, and placing additional traffic signs before intersections is less appropriate (Vlaamse Overheid, 2009a). However, as the research results indicate that drivers brake less abruptly when they are aware that they approach a SRLC, it is recommended to revise the current guideline and allow the announcement of SRLCs. A starting point could be to allow warning signs at SRLC-intersections with a high number and/or share of rear-end collisions.

6.2.3 Non-signalized intersection safety

The results of the study focusing on road safety differences between priority-controlled and right-hand priority intersections revealed that the interactions between drivers are very heterogeneous in terms of yielding behaviour. Despite the difference in priority rule, yielding appeared to be mostly a matter of first come, first served. However, this heterogeneity in road user behaviour appeared to be more prevailing at the right-hand priority intersection as it resulted in creation of an informal right-of-way.

From a safety point of view, this heterogeneity is not desirable as it contributes to the unpredictability of the behaviour of road users. Therefore, this heterogeneity can give rise to unsafe situations when the road user’s intentions are misinterpreted during the interaction process. According to Björklund & Åberg, (2005), the development of an informal right-of-way occurs when the formal right-of-way does not correspond with the road design. Therefore, it is highly recommended to increase the predictability of the road environment at these intersections. As a starting point, clear and effective yield markings and signs should be implemented at each intersection approach. As a next step, the recognisability of these intersection types should also be improved by creating more uniformity across the different intersection types (section 6.2.4).

6.2.4 Uniformity in intersection types and design

During this research, it became apparent that there are numerous types of intersections (roundabouts, priority-controlled intersections, right-hand priority intersections and signalized intersections with different signal phases) in Flanders, Belgium. This large variation in intersection types and design is often the result of the traffic situation, space or budget constraints and of the fact that there are several road authorities in Flanders. For instance, intersections on (inter)regional roads are under the jurisdiction of the regional road authority (Flemish Road Agency) while intersections on local roads fall under the jurisdiction of the local road authority (municipalities). Moreover, the current intersection design guidelines (Vlaamse Overheid, 2009b) also leave much room to the road designer. All these aspects contribute to the lack of uniformity in intersection design.

It is generally acknowledged that a recognisable and uniform road design (cfr. self-explaining roads) increases the predictability of the road environment. This predictability principle prescribes that roads should be recognisable by their design in the sense that a distinction can be made between road categories and that there is uniformity within road categories (SWOV, 2012b). Uniformity between road categories and in this case, intersection types, is central to increase the recognisability and predictability of the road design for all road users in order to encourage the desired road user behaviour (CROW, 2008). In this light, a recognisable and uniform design is especially important for intersections as they are a discontinuity and thus a potential black spot in the road network. A key policy priority in the future should therefore be to increase uniformity in intersection types and design by limiting the number of intersections types between different road categories and aligning the intersection design within road categories. In that respect, uniformity in intersection design contributes to the creation of an inherently safe road traffic system which is one of the action points of the Road Safety Plan of Flanders (Vlaams Ministerie van Mobiliteit en Openbare Werken, 2017).

A first step to create more uniformity in intersection types should be to make an inventory of the current practice regarding the construction and design of intersections in Flanders. This should be realised by identifying the different characteristics of existing intersections. The data obtained from this inventory can be used for management purposes by the local and regional road administrations in order to determine the different intersection types and to establish what the basic characteristic of each intersection type should be. Additionally, this inventory will also reveal whether the current intersections are designed and constructed according to the formulated guidelines.

Subsequently, the current intersection design guidelines date from 2009 (Vlaamse Overheid, 2009b) and should be updated in order to keep pace with best practices and new design procedures. Furthermore, the opportunity should be grasped to establish formal design guidelines in order to create more uniformity in intersection design by narrowing down the number of intersection types and aligning the intersection type with the road category. This requires engagement from the road administrations at both local and regional levels. The different road administrations should work together and exchange their expertise and best practices regarding road and intersection design. The results from the inventory combined with the available knowledge in the different design guidelines could serve as a starting point to reduce the number of intersection types and establish a common acknowledged framework regarding the choice of intersection type. The type of intersecting road category, capacity, traffic composition, available space and road safety considerations are examples of aspects that should be taken into account while creating this formal framework (Dijkstra, 2014).

6.2.5 Improving the quality of road safety data

Evaluation, monitoring and policy-relevant research are essential components to achieve an improved understanding of road safety issues, to assess and manage the effects of implemented road safety measures and to identify best practices. Therefore, the definite need for a structural and high quality evaluation policy remains in the future. In order to be successful, the data used for evaluation purposes need to be available, complete and reliable.

The current evaluation policy of the Flemish Government still relies on accident data as the main data source for road safety analysis (Vlaams Ministerie van Mobiliteit en Openbare Werken, 2017). During this research, it became clear that availability, completeness and reliability issues undermine the quality of the accident data. For instance, accident data suffer from underreporting issues. Earlier studies found that the accident reporting rate strongly depends on the accident severity and type of road users involved (Davidse, 2003; Laureshyn, 2010; OECD, 1998; Svensson, 1998). To illustrate, a Belgian study found that the ratio of the hospital data and police-reported data was 2.5, indicating that the number of severely injured was 2.5 times higher according to the hospital data (Nuyttens, 2013). Furthermore, the meta-analysis of Elvik and Mysen (1999) revealed that the reporting of injuries in official accident statistics is incomplete at all levels of injury severity. The average reporting rate was 95% for fatal injuries according to the 30-day rule, 70% for serious injuries (individuals admitted to hospital), 25% for slight injuries (individuals treated as outpatients) and 10% for very slight injuries (defined as individuals treated outside hospital) (Elvik & Mysen, 1999). Furthermore, the highest reporting rate was found for car occupants whilst cyclists were heavily underrepresented in the reported accident statistics.

Additionally, it was also experienced that it takes quite some time before the registered accident data by the local police forces is processed and is made available for evaluation purposes. Moreover, collision diagrams offer rich information about the circumstances and possible causes of accidents but are often not available. In turn, all these issues have undesired effects on the quality of the evaluation policy. Therefore, it is recommended to improve the accident registration and data access process by encouraging local police forces to draw up collision diagrams of registered accidents and thus increasing the availability of collision diagram data. Furthermore, incomplete accident reporting issues can be mitigated by linking police registered accident data with hospital and insurance data, which is quite a common procedure to increase the quality of accident data (Amoros et al., 2006; Cooper & Henson, 1996; Polak, 1997).

Even if the quality of the accident registration process can be significantly improved, the issue still remains that accident data cannot be used to assess all road safety measures or provide insights in all road safety aspects. This is due to the fact that accident data are not capable of capturing the behavioural and situational aspects that preceded the accident and played a role in accident occurrence. Moreover, evaluation and monitoring based on accident data is a reactive approach, which implies that accidents first need to occur before the road safety situation can be assessed and appropriate action can be taken. Therefore, future research and evaluation initiatives should also focus on the use of empirical non-crash data, because these data provide detailed insights in the causal processes that lead to accidents. Additionally, as non-crash events are related to but do not rely on accident data, they are also a more proactive approach to assess road safety.

To summarise, there is a strong need for a structured research and evaluation policy; which combines road safety techniques based on (improved) crash and empirical non-crash data; in order to receive a comprehensive picture of the road safety situation, get an overview of the policy results and formulate future policy priorities.

6.3 Application of crash and empirical non-crash data in policy-relevant road safety research

Accident data are considered as the main data source for road safety assessment and evaluation making accidents and their consequences a well-accepted road safety indicator. However, the various drawbacks associated with the use of accident data (section 1.4) have fostered the development of various techniques for the observation of non-crash events. Additionally, research on these complementary safety indicators has also gained renewed interest as new data collection techniques (section 1.6) have become available which can serve as a vital supplement to accident data.

Several important insights regarding the use of accident data and data collection techniques for observing empirical non-crash data are described below (section 6.3.1). Additionally, the potential of combining road safety techniques to develop an integrated approach to road safety diagnosis and evaluation is elaborated (section 6.3.2). Based on these acquired insights, section 6.3.3 provides a brief overview of the road safety research application areas of the different road safety techniques.

6.3.1 Important insights in techniques based on crash and empirical non-crash data

First, the opportunities of accident data in conducting policy-relevant research are elaborated whereupon some advantages and disadvantages are discussed. This description is followed by an elaboration of the opportunities, strengths and limitations of the techniques using empirical non-crash data. These are traffic conflict observation studies, behavioural observation studies and driving simulator studies.

6.3.1.1 Accident data

Accident data analysis is useful to gain insights in the various aspects of the road safety situation and are an important tool for improving road safety (Elvik et al., 2009). Within accident data analysis, the phenomenon that one wants to avoid from a safety point of view, namely accidents and their related consequences, is examined directly. This direct assessment can be regarded as the main advantage of accident data analysis.

Based on the aggregation level of the available data, multiple approaches can be used to conduct these analyses ranging from a network or country level to a very detailed in-depth level focusing on a designated part of the road infrastructure. These aggregated analyses are particularly useful for problem identification purposes (Muhlrad, 1993; Oppe, 1993) such as:

- the description, monitoring and prognosis of accident development;
- the detection of positive or negative road safety developments;
- to define safety targets;

- to assess the size of the overall safety problem in terms of accident numbers and their related severity; and
- to identify main targets for action in terms of frequent accident types, at risk road users and hazardous locations.

Accidents statistics are often also analysed to get more insights in accident causation factors, in order to subsequently implement remedial measures to improve road safety. However, the available accident data are too restricted for these purposes. Accident statistics almost exclusively contain information about the outcome of accidents whereas information about the processes leading to accidents (i.e. the behaviours and circumstances which played a role in accident causation) is necessary to identify causal factors, establish causal links between these factors and select appropriate remedial measures (Laureshyn, 2010; Svensson & Hydén, 2006). The main reason why there is no in-depth registration of accident data is related to the purpose of the accident registration process. More specifically, the current accident registration procedure is intended for the juridical settlement (i.e. to determine the guilty party) and not for identifying causal factors in order to be able to design measures that prevent similar accidents in the future (Davidse, 2003).

Information about the processes leading to accidents can be collected by means of in-depth accident research. According to the OECD (1988, p.75), in-depth accident research can be described as "a detailed research that is executed primarily at the accident scene, including a reconstruction of all accident phases and events". In contrast to regular accident statistics, a multidisciplinary team collects and records several additional variables in order to gain insights in the accident causation process. These variables are related to characteristics of the involved road users, the vehicle and the road environment (Davidse, 2007). Unfortunately, data collection is laborious, requires a high level of expertise and is very costly (Hagstroem et al., 2010).

Consequently, this research has sought to take a step towards in-depth accident research by making an optimal use of the available detailed accident data. This was realised by combining collision diagrams, collected by the local police, with infrastructural characteristics. This approach was applied to identify crash patterns at roundabouts and signalized intersections (chapter 2 and 3) in order to obtain a more complete road safety picture. For this purpose, a protocol or crash location typology was developed to divide the intersection into different sections. The collision diagram information has proved to be vital for this purpose as these diagrams not only allow to define dominant accident types, but also show the pre-crash manoeuvres and provide detailed information about the accident location on the intersection. The approach of dividing a road location into different sections or segments has been already applied in naturalistic driving studies (Gstalter & Fastenmeier, 2010), but not in studies focusing on road infrastructure.

A methodological issue that occurred is related to the accuracy of the accident location when allocating the accidents to the different intersection sections by means of the crash location typology. Simplified rules were used to allocate the accidents. Therefore, the accident allocation to the different sections might not fully correspond to the actual accident location. Despite this inconsistency, the allocation is still quite accurate since the typology is based on the impact point, the pre-crash orientation of the road users and the manoeuvre that the road users made (i.e., the most important characteristics to reconstruct a crash). However, the objective of the roundabout (chapter 2) and signalized intersection (chapter 3) study was to provide insights into the accident patterns and accident propensity of roundabout and signalized intersection design features instead of producing an exact replica of the accident location. Additionally, the reported accident location in the collision diagram information might also slightly deviate from the actual accident location. A 100% consistency in both accident locations can only be guaranteed by means of advanced in-depth accident research. As most police districts in Belgium are not familiar with these techniques, the results are not greatly affected by this variation. In this light, it can be assumed that the developed crash location typology was valid for this purpose.

Another methodological problem is the absence of exposure data. In Flanders, there is only limited exposure data available and thus it was not possible to include this data in the crash pattern studies. By combining accident data with exposure data it becomes possible to estimate the relative safety risk at the various roundabout and signalized intersection locations. Previous studies regarding the analysis of accident data to gain insights in critical situations and factors at intersections (Chin & Quddus, 2003; Lui & Young, 2004; Reurings et al., 2006), indicated that exposure data are a critical variable for accident analysis. However, this requirement is more important for studies that aim to explain the variation in road safety performance of a sample of locations by identifying the influence of design characteristics on the level of safety. Because, both studies do not predict accidents but explore available detailed accident data by delineating the accident location on the roundabout and signalized intersection itself, it can be expected that the lack of exposure data had no substantial influence on the study results.

Incomplete accident reporting is a well-known limitation of accident data which can introduce uncertainty in the results (section 6.2.5). However, it can be assumed that the incomplete reporting of accident data had no considerable influence on the dominant accident types and patterns that were identified in the roundabout (chapter 2) and signalized intersection (chapter 3) study. Both the collision diagram information and the accident statistics originated from the same dataset, namely police records.

A strength of this accident location approach is the generalisability. Within this dissertation, the presented approach is applied on roundabouts and signalized intersections. However, this approach can also be applied at other road locations given the availability of the required accident statistics and collision diagram information. If this information is available, the approach can easily be adjusted to different designs and locations by tailoring the sections to the specific location layout in question. Furthermore, the approach to combine accident data with collision diagram information has shown to provide valuable insights into the nature of intersection accidents and in the safety impact of roundabout and signalized intersection design.

Compared to aggregated accident analysis, this basic in-depth approach not only identifies dominant accidents types and causal factors. By also taking the accident location into account, it became possible to analyse the accident data at the detailed level of intersection and roundabout location sections. Additionally, the approach also allows to explore specific differences between different types of road users at each intersection section in detail. By analysing accident data at such a detailed level of a signalized intersection or roundabout, more specific recommendations in terms of road infrastructure design become possible. This is especially valuable as accidents at different sections of a roundabout or signalized intersection can have different accident characteristics depending on the infrastructural design characteristics. Therefore, this approach assists in identifying crucial points of attention in roundabout and signalized intersection design. As a consequence, tailored design solutions can be selected and implemented for the dominant accident type within each intersection section.

6.3.1.2 Traffic conflict studies

Traffic conflicts or near-accidents can be regarded as “breakdowns” within the traffic interaction process, which have similar characteristics as the situations that lead to accidents. This similarity makes it possible to assess the accident potential of locations and the processes which result in accidents without the direct observation of accidents (Laureshyn, 2010).

The various advantages of traffic conflict studies (section 1.6.3) makes this site-based observation technique particularly useful to obtain a swift evaluation of the general road safety situation at a particular location. Furthermore, this technique can also be applied to assess the effectiveness of road safety measures, which are difficult to evaluate using traditional accident data. This is especially applicable for new measures that are not yet implemented on a large scale, and for which little accident data are available, and for measures for which accident data are available but are insufficiently detailed for a good evaluation.

This technique was used to evaluate the effectiveness of SRLCs in order to gain more insights in the accident causation factors that resulted in the increase in rear-end accidents at SRLC-locations (chapter 4). Within this study, the traffic conflict technique not only provided an outcome evaluation[4] of SRLCs, but also a process evaluation[5]. The results revealed that the increase in rear-end accidents was caused by drivers adapting their behaviour due to the presence of a SRLC. These insights would have never been obtained from accident analysis as these data cover little behavioural or situational characteristics of the event.

The reliability of traffic conflict studies has always played a very important role in their application. Until quite recently, human observers were predominantly used to make road safety assessments by measuring conflicts. This fostered the subjective perception of the technique. Recent advances in computer vision techniques have the opportunity to strongly improve the reliability and assist in a more objective and detailed analysis of the conflicts that are registered by means of video cameras installed at the location of interest (Ismail, Sayed, Saunier, & Lim, 2009; Kastrinaki, Zervakis, & Kalaitzakis, 2003; Laureshyn, 2010; Saunier & Sayed, 2007; Saunier, Sayed, & Ismail, 2010; Zheng et al., 2014b). Afterwards, the collected video data are analysed by means of a computer vision based traffic conflict detection system usually consisting of two components: a video-processing module, for detecting and tracking objects, and an interpretation module for extracting information and detecting traffic conflicts (Ismail et al., 2009; Saunier & Sayed, 2007). In an ideal situation, the traffic conflicts and conflict indicators in the recorded videos can be detected and calculated automatically to enable large-scale analysis (Saunier et al., 2010; Sayed, Ismail, Zaki, & Autey, 2012; Songchitruksa & Tarko, 2006). However, the classification and tracking accuracy of these systems remain a problem (low detection rate, high number of false detections, difficulties with detecting smaller objects such as vulnerable road users, etc.) as these fully automated tracking systems are still under ongoing development (Sayed, Zaki, & Autey, 2013; Zheng et al., 2014b).

Therefore, the semi-automated video analysis tool, T-analyst (2014), was used in the SRLC-study to assist in the traffic conflict detection and analysis. This tool requires the researcher to manually process the events of interest, calculate conflict indicators and to store them in a systematic way (Ušpalytė-Vitkūnienė & Laureshyn, 2017). This approach has shown to be a rather time consuming activity for analysing road user behaviour in traffic conflict and normal interactive events (i.e. for each day of video data approximately one day is necessary to perform the analysis). These high data analysis efforts also have implications for the generalisability of the study results. Compared to the evaluation studies using accident data, the number of locations that were included in the SRLC-study were quite limited (only 2). Even though, more useful data could be gathered from each individual location, it remains difficult to infer effect estimations for other intersections. It can reasonably be assumed that the effects (change in dilemma zone, decision behaviour, etc.) will evolve in the same direction. However, the

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[4] The extent to which the measure improves road safety or not.

[5] Why does the measure (not) improve road safety?

absolute values or the magnitude of the SRLC(WS) effects on drivers' behaviour may differ according to specific intersection characteristics such as speed/geometric and operational conditions. Furthermore, due to the low number of detected traffic conflicts in the observation period, the conclusions about the impact of SRLCs on serious conflicts should be treated with caution.

Despite this labour intensiveness, it was experienced that this tool allows for highly accurate, reliable, objective and flexible analysis of revealed micro-level road user behaviour. More conventional techniques for field observations such as inductive loops, radars or human observers do not allow the level of detail in the analyses that has been achieved in this study. This is because these point or single value measurements only provide a static description at certain moments instead of a continuous description of the traffic processes. It is the later that allows us to study the development of an encounter as a process evolving from normal encounters, to near-accidents and in some circumstances to accidents. Nonetheless, it appeared that not all information could be extracted from video data. Variables such as personal characteristics of road users (age and gender), certain gestures (head, eye, hand movements, eye contact) and the use of safety tools (helmets, seat belts, etc.) could not be clearly observed from video data and should therefore be collected through other techniques such as on-site behavioural observations by means of human observers (section 6.3.1.3).

Furthermore, the validity of the traffic conflict technique and indicators has been the subject of considerable debate within the scientific community (section 1.6.3). Within the context of traffic conflict studies there are two types of validity: product and process validity (Laureshyn et al., 2016; Zheng et al., 2014b). *Product validity* indicates the extent to which a conflict indicator is able to estimate the expected number of accidents (Hauer & Garder, 1986) whereas *process validity* indicates the extent to which safety indicators can be used for describing the processes that lead to accidents (Svensson, 1998). Product validity can be further divided into two types of validity, namely absolute and relative validity. *Absolute validity* is obtained when a traffic conflict study or indicator is able to reliably calculate the expected number of accidents while *relative validity* is obtained when the direction and magnitude regarding the expected number of accidents can be reliably inferred from traffic conflict data (Laureshyn et al., 2016). However, research has shown that the usefulness of traffic conflict techniques and indicators as a surrogate safety measure does not only depend on the extent to which expected accident numbers can be correctly estimated (Grayson, 1984). Moreover, the usefulness mainly depends on whether safety problems can be detected or not, and/or road safety treatments can be compared or evaluated (Chin & Quek, 1997; de Jong et al., 2007; Grayson & Hakkert, 1987; Hauer, 1978; van der Horst, 2007). In that respect, a sufficiently high level of relative validity suffices to perform road safety evaluation and diagnosis by means of traffic conflict studies. The objective of the study was to gain more insights in the possible explaining factors for the increase in rear-end collisions following SRLC implementation, rather than to predict accidents. Therefore, it can be assumed that the use of the traffic conflict technique was valid for this purpose.

Additionally, it should be added that establishing the validity of a technique requires large data samples representing different locations and conditions (Laureshyn, 2010). Most of the currently available validation studies are relatively old studies based on a limited data sample collected by human observers. In that respect, it is expected that the further development of fully automated video analysis tools in the future will further contribute in establishing the product and process validity of traffic conflict techniques and indicators.

6.3.1.3 Behavioural observation studies

Behavioural observation studies have a long history in studying road user behaviour and road safety, and can be regarded as a basic tool for research on human factors (Muhlrad, 1993).

In general, this technique is particularly useful for studying road user behaviour in order to diagnose road safety problems at specific locations or for specific target groups since the study design can be easily adapted to the specific requirements of a situation. Observing road user behaviour in a natural setting is a valuable approach as it provides greater knowledge of effective road user behaviour, as well as means to identify and describe some of its determining features (OECD, 1998). Such observation affords a better understanding of how a traffic system operates and thus contributes to the global safety diagnosis, as it not only provides an insight into the road safety process but also in the road safety outcome. In that respect, it represents a vital complement to accident analysis, and may even compensate for a shortage of available information on accident generating processes (Muhlrad, 1993). Furthermore, studying interactions between road users not only provides an indication about the usability of the road environment by all road users but is also regarded as a more proactive way to improve road designs compared to retrospective accident statistics (Mackie, Charlton, Baas, & Villasenor, 2013).

Despite the fact that on-site behavioural observations provide interesting insights in road users' behaviour, the main disadvantage is that often an indirect relationship exists between accident occurrence and the observed road user behaviour. Because of this indirect relationship, it is not always possible to draw road safety inferences solely based on behavioural observations. The results of the study focusing on vehicle interactions at priority-controlled and right-hand priority intersections (chapter 5), illustrate this point clearly. In this study, behavioural aspects in terms of road users' yielding and looking behaviour have been observed by means of human observers. While a higher number of yield violations between drivers at right-hand priority intersections than at priority-controlled intersections was found, these results are unable to provide strong conclusions regarding the safety performance of both types of yield rules. This inability is mostly linked to the fact that the results revealed indications of the existence of an informal yield rule influencing the interactions at the right-hand priority intersection. The prevalence of this informal rule, and thus violation of the formal yield rule, in itself does not necessarily result in undesirable road safety consequences (Björklund & Aberg, 2005). Right-hand priority intersections are mostly situated on local intersections used by local traffic (such as inhabitants). As these drivers are mostly familiar with the traffic situation and thus with the existence of an informal rule, it could be inferred from the study results that the majority of the interactions took place in a very controlled and anticipated manner. So despite the fact that earlier research identified failure to yield as a principal contributory factor in non-signalized intersection accidents (Lee et al., 2004; Parker et al., 1995), the results do not allow to conclude that a higher number of yield violations results in a higher accident risk. In that respect, the behavioural observation results did not allow to establish a direct relationship between road user behaviour and accident occurrence.

The indirect relationship between the results of behavioural observations and accident occurrence is closely related to the validity of the behavioural indicators. This was experienced during the development of the observation protocol of the aforementioned behavioural observation study. While selecting variables for the standardised observation form, it became apparent that a vast variety of indicators is used to describe road user behaviour and that the relation between these behaviours and safety is rarely validated and mostly based on assumptions. According to a recently completed systematic literature review of behavioural observation studies by van Haperen (2016), speed seems to be the only behavioural observation indicator for which a relationship between speed and road safety has been established (Elvik, Christensen, & Amundsen, 2004). It is widely acknowledged that higher driving speeds significantly increase the accident risk and severity (Elvik, Christensen, & Amundsen, 2004). As the selection of behavioural indicators has a direct influence on the road safety inferences that can be made, it is crucial to use behavioural indicators that have proven to be a valid proxy for road safety (Laureshyn, 2010). Compared to behavioural indicators, traffic conflict indicators can be considered to be such a valid proxy as these indicators aim to quantify road safety levels by measuring road safety in terms of the expected number of (injury) accidents instead of merely focusing on identifying relevant behaviours (van Haperen, 2016). Consequently, they provide a more direct relationship to accidents than behavioural indicators because the latter do not contain a direct risk assessment of the individual situation (Laureshyn, 2010). Therefore, behavioural observation studies are usually complemented with other road safety data collection techniques (such as accident data, traffic conflict observation studies, driving simulator research, etc.) to obtain a comprehensive picture of the road safety situation at a certain location.

The reliability of the study results is also often questioned because of inter- and intra-observer variability issues inherent to the use of human observers. However, due to observer training, high intercoder reliability values were obtained within the aforementioned behavioural study. Furthermore, the interactions at both intersections were also recorded by means of a video camera. Afterwards, every observed interaction was verified based on the video data. The ability to review the interactions multiple times had beneficial consequences for the data quality and reliability of the study results. Furthermore, the technological (r)evolution has already resulted in the availability of high-quality techniques - such as video, GPS, smart-phone tracking, naturalistic driving studies etc. – for collecting behavioural data. In that respect, the concern is no longer whether the behavioural data has been collected objectively, but how the necessary data can be extracted from these large datasets (CROW, 2008). The use of these techniques will also have a positive influence on the labour-intensive data collection efforts frequently associated with the use of human observers.

Another issue with behavioural studies is that only variables describing the revealed behaviour of road users can be observed and collected, while the underlying causes of the behaviour remain undetected (i.e. motivations, beliefs, attitudes) (Eby, 2011). For example, the behavioural study focusing on vehicle interactions at priority-controlled and right-hand priority intersections revealed a higher number of yield violations between drivers at right-hand priority intersections, but the results did not allow to identify the underlying motivation of the drivers to violate this yield rule. To establish this, techniques providing more insights into the psychological processes of behaviour - such as observing behaviour in a controlled setting, self-report measures, focus groups and in-depth interviews - should be applied.

Furthermore, the generalisability of the results of behavioural observation studies remains an issue. Because of the labour-intensive data collection, the vehicle-vehicle interactions could only be observed at two intersections. Therefore, it is difficult to conclude that the observed behaviours would also occur at other locations at which no behavioural study has been performed (Eby, 2011). This limited generalisability is a common limitation of studies focusing on the lower severity level of the road safety hierarchy (i.e. normal interactions) (Lange et al., 2011; Rosenbloom, 2009; Saunier et al., 2011; St-Aubin et al., 2012; Svensson & Hydén, 2006). It is expected that the use of more advanced data collection techniques will mitigate the generalisability problems, as these techniques allow to collect behavioural data at more locations. Nevertheless, the behavioural observation study revealed some interesting exploratory insights in driver behaviour at these types of intersections.

6.3.1.4 Driving simulator studies

The added value of using driving simulators for road safety research purposes are well documented (i.e. Bella, 2008; Boyle & Lee, 2010; Carsten & Jamson, 2011; Godley et al., 2002; McGehee & Carsten, 2010). Driving simulators can be used to gain insights in theoretical concepts such as workload (Backs, Lenneman, Wetzel, & Green, 2003) and situation awareness (Gugerty, Rakauskas, & Brooks, 2004). Furthermore, they can also be used for applied research purposes (Knodler, Noyce, Kacir, & Brehmer, 2006; Laurie et al., 2004) with the aim to provide road agencies and policy makers proactive insights in the effectiveness of new road designs or infrastructural countermeasures (Auberlet et al., 2014; Godley et al., 2002). A driving simulator study was performed within this dissertation for the latter case. More specifically, within the SRLC-study (chapter 4), a driving simulator experiment was performed to test an experimental condition, i.e. to establish the effects of the presence of an advance warning sign at SRLC-intersections on drivers' behavioural responses.

The advantage of experimental control has been pivotal for this study, as this provided the opportunity to make direct comparisons between different conditions (No SRLC, SRLC and SRLC + warning sign). This enabled a detailed analysis of drivers' behavioural responses in each condition, which provided the Flemish Road Agency a thorough and proactive insight in the effectiveness (including possible adverse effects) of the tested enforcement measures. The Flemish Road agency can use these results to inform their decisions regarding treatment implementation. Furthermore, the use of the driving simulator also allowed to study drivers' behaviour in all interaction types ranging from normal encounters to traffic conflicts and even accidents without exposing the participants to dangerous situations. Additionally, the driving simulator allowed to collect detailed deceleration values when drivers approached the intersection in each of the three conditions. Until recently, this parameter could not be accurately calculated by means of the semi-automated video analysis tool, which was used to analyse and detect traffic conflicts from video data. However, recent advances in the development of the extended Delta-V conflict indicator show promising results to also extract deceleration values from video data in the future (Laureshyn, De Ceunynck, Karlsson, Svensson, & Daniels, 2017). Nevertheless, the conclusion that higher deceleration values are associated with drivers approaching SRCLs and are responsible for the increase in rear-end collisions would not have been revealed without the use of a driver simulator.

The validity of driving simulator research is often questioned as one may wonder how realistic the driving behaviour of participants is in a simulated road environment, compared to their actual driving behaviour in a real-world environment (Fisher et al., 2011). As mentioned earlier, two types of driving simulator validity can be distinguished: physical validity and behavioural validity of which the latter can be further divided into absolute and relative validity (section 1.6.1). In general, most driving simulator studies only achieve relative validity. However, enough research has shown that driving simulators generally reach high relative validity (i.e., comparing different scenarios in an experimental design) and that only relative validity is necessary for a driving simulator to be a useful research tool (absolute validity is not essential) (Bella, 2008; Godley et al., 2002; Törnros, 1998; Yan et al., 2008). Furthermore, the geo-specific database modelling technique[6], which has been applied in the SRLC-study, increases the reliability and validity of the experiment and the results (Yan et al., 2008). In addition, the simulator used in this study is equipped with a 180° field of view, which meets the prescribed minimum of 120-degree field of view for the correct estimation of longitudinal parameters (Kemeny & Panerai, 2003). Moreover, the findings from the site-based observations confirm the results from the driving simulator experiment to a large extent. Taking all these aspects into account, it is believed that the validity of the driving simulator experiment is ensured.

Furthermore, the application of the geo-specific database modelling technique improved the realism of the simulator scenario. However, the creation of road environments based on this modelling technique is quite demanding (Yan et al., 2008) as photographs, videos, detailed field measurements, AutoCAD drawings and Google Street View images were used to replicated the real-world SRLC-intersection as best as possible in the simulated environment. Hopefully, advances in virtual reality applications might be able to transform real-life road environments more easily into a virtual driving simulator environment.

Additionally, the eye movements of the participants were recorded while driving through the scenario in order to gain more insights in drivers' looking behaviour when approaching SRLC-intersections. The data collected by means of the eye-tracker provided some interesting insights in drivers' looking behaviour, as it was possible to analyse which (road environment) objects were observed, for how long and in which order. According to Martens (2000), eye tracking is a direct and objective measure for object detection since eye movements are involuntary and thus can be regarded as relatively unbiased. However, even though it could be derived from the eye tracking data that drivers looked at the SRLC or SRLCWS, this data does not allow to determine whether participants internally processed the object at which they fixated (i.e. looked-but-failed-to-see error). This shortcoming is also confirmed by Castro & Horberry (2004) and Crundall & Underwoord (2012).

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[6] Technique used to replicate a real-world driving environment as realistic and detailed as possible into a simulated 3D virtual environment. Usually, photographs, videos, detailed field measurements, AutoCAD drawings, and Google Street View are used to make the simulated 3D virtual environment as realistic as possible.

Overall, the aspects discussed in this section suggest that driving simulators may not be able to be complete replicates of the real-world. Nevertheless, as Carsten & Jamson (2011, pp. 95–96) remind us: “The added value of driving simulators lies in the fact that they possess an advantage that real-world studies cannot match: the ability to control experimental conditions and create pre-scripted scenarios”.

6.3.2 The potential of combining road safety techniques – an integrated approach to road safety diagnosis and evaluation

Throughout this dissertation, the road safety techniques based on crash and empirical non-crash data have unquestionably proven to have an added value in performing evidence-based road safety research. In their own way, each technique has the opportunity to provide valuable road safety insights (sections 1.6 and 6.3.1). For instance, accident analyses are very useful to provide a generic overview of the road safety situation, by detecting positive or negative developments and for setting safety targets based on accident numbers and their related severity. Whereas empirical non-crash data are particularly useful to complement accident data as they allow to gain insights in the underlying contributory behavioural and situational aspects which play a role in accident occurrence. Furthermore, empirical non-crash data, as a proactive strategy, are extremely valuable to timely assess road safety measures for which little accident data are available or for which the available accident data are insufficiently detailed for a good evaluation, and in case of driving simulator studies even to assess the effects of road safety measures before they are implemented. Nevertheless, each technique also suffers from limitations, which makes it very difficult to gain a sound picture of the road safety situation based on one technique alone (sections 1.6 and 6.3.1). Consequently, a crucial opportunity lies in complementing the results from different the road safety techniques in order to overcome the limitations of each individual technique.

This view is not new, as it was already stated in the late 1980s and early 1990s that accident data alone will not suffice to get a good understanding of the risk increasing factors in traffic and that normal road user behaviour should also be included as a reference base (Hydén, 1987; Muhlrad, 1993; Oppe, 1993; Van der Horst, 1990). Currently, the US National Safety Council (2013, p. 58) supports this view of combining research methods by stating that: “There is no perfect study design for an issue as complex as traffic safety”. From this, it can be derived that it is necessary to tailor the research method to the research question or object under study in order to gain valuable results. But also that road safety problems exist for which no single technique is able to provide all the answers and that several techniques have to be used in a concerted fashion to approach a problem from different angles (Carsten et al., 2013). This vision is also shared in Europe. The objective of the Horizon 2020 project InDeV – in which Hasselt University participates – is to improve vulnerable road users’ safety in Europe by developing an integrated methodology based on a combined use of accident databases, in-depth accident investigations, surrogate safety indicators, self-reported accidents and naturalistic behavioural data (InDeV, 2017).

Within this dissertation, the merits of combining road safety techniques were indicated by the study focusing on drivers’ behavioural responses to speed and red-light cameras (chapter 4). Earlier studies based on accident analysis had already indicated that the implementation of SRLCs at signalized intersections goes hand in hand with a significant increase in rear-end collisions (De Pauw et al., 2014; Erke, 2009; Høye, 2013; Vanlaar et al., 2014). Therefore, this study combined a site-based traffic conflict and behavioural observation study with a driving simulator study in order to gain a better understanding of the possible explaining factors for the observed increase in the number of rear-end collisions. This integrated approach has shown clear benefits of combining on-site traffic conflict and behavioural observations with driving simulator experiments. Not only could the findings from the on-site observation study largely confirm the results from the driving simulator experiment, but the combination of both study results also provided additional insights, which could not have been achieved if both techniques would have studied the same problem separately. For instance, the on-site observations showed the revealed behaviour and provided more insights in drivers’ behavioural adaptations to SRLCs such as decreases in the number of red and yellow light violations and a shift in the dilemma zone (i.e. closer to the stop line when SRLCs are installed). On the other hand the driving simulator experiment provided a better insight into drivers’ deceleration and looking behaviour, and made it possible to test an experimental condition, i.e. to establish the effects of the presence of an advance warning sign on drivers’ behavioural responses.

Besides driving simulator experiments, on-site observations studies also appear to combine well with naturalistic driving observations. A study by van Nes, Christoph, Hoedemaeker and van der Horst (2013) combined site-based observations with naturalistic driving observations to study interactions between cyclists and right turning vehicles at urban signalized intersections. The study results revealed that each observation technique has unique characteristics and yields unique road safety insights. By combining both techniques, the researchers were able to establish what was going on both inside and outside the vehicle. For instance, in-vehicle data offered the possibility to observe drivers’ looking behaviour and to look into detail at the driving behaviour of the participants over time and in different situations (van Nes et al., 2013). While site-based observations created the opportunity to collect supplementary information about the position and speed of other road users surrounding the participant’s vehicle, including vulnerable road users such as cyclists and pedestrians (van Nes et al., 2013). According to the researchers the added values of combining both observation techniques are as follows: to obtain a more in-depth understanding and to relate the behaviour of participants of the naturalistic driving study to behaviour of the full population of drivers (non-participants) (van Nes et al., 2013).

The aforementioned studies both indicated the added value of combining road safety techniques based on empirical non-crash data. However, there also lies added value in combining road safety techniques based on crash and empirical non-crash data. This is illustrated by the Horizon 2020 project PROSPECT which pursues the integrated approach of combining in-depth accident analysis with naturalistic site-based observation studies to gain insights in accidents with vulnerable road users (PROSPECT, 2017). First, accident studies were applied to identify dominant accident types between vehicles and vulnerable road users. Subsequently, naturalistic site-based observations were used to collect information which could not be inferred from accident databases. These naturalistic site-based observations mainly focused on collecting data about near-accident situations between vehicles and vulnerable road users, in order to gain insights in contributory factors to accident occurrence, and in events characterised by normal interactive behaviour with the purpose of identifying situations that could provoke false alarms/activations in existing VRU-detection systems (Wisch et al., 2016). Consequently, this knowledge is used to tailor effective sensor processing, Human Machine Interface, driver warning and vehicle control strategies which can subsequently be integrated in simulators and vehicle demonstrators (PROSPECT, 2017).

Collectively, these studies outline a critical role for combining road safety techniques. As each technique has its unique values, the merit of combining different techniques lies in the opportunity to enrich the results from one technique with the complementary results from other technique(s). Although accident data provides valuable road safety insights and are an essential tool for road safety knowledge development, it is expected that an integrated research approach consisting of techniques based on empirical non-crash data or on a combination of crash and empirical non-crash data will be needed to evaluate road safety. This view is confirmed by Hakkert & Gitelman (2014) and Svensson, Daniels & Risser (2017) who state that transport systems have gradually evolved to higher road safety levels during the last few decades and that this positive evolution is likely to continue in the future. If this is the case, accidents will become even rarer and thus less suited to perform reliable road safety analyses. In this light, empirical non-crash data will fulfil an important role in future road safety evaluation policies. The need for techniques based on empirical non-crash data will be further fostered and promoted by the rapid technological improvements in the field of data collection and analysis (i.e. big data, video observation, vehicle instrumentation) (CROW, 2008; Hakkert & Gitelman, 2014; Svensson et al., 2017). From this, it can be concluded that combining various techniques based on empirical non-crash data as a complement for accident data will be a crucial approach to study road safety in order to evolve to an inherently safe road traffic system.

6.3.3 An overview of the road safety research application areas of the different road safety techniques

On an aggregated level, accident data analysis are very useful for problem identification purposes. However, accident data cannot be used to determine the frequency of road user behaviour as such information is generally not collected in the accident registration process. On-site traffic conflict and behavioural observation techniques are in general more suited to identify the frequency and particular characteristics of road user behaviour, as these techniques focus on identifying and analysing the objective actions of road users in their natural setting. Furthermore, as traffic conflicts are strongly related to accidents, these techniques can also be applied for problem identification purposes in case limited accident data are available. Additionally, behavioural observation techniques are less suited for most problem identification purposes because they merely focus on identifying relevant behaviours, and as a result do not contain a direct risk assessment of the road safety situation. However, if complemented with other road safety techniques, they can assist to define which risk increasing behaviours require attention. In a sense, driving simulators can be used for problem identification purposes. However, problem identification alone should not be the focus point of a driving simulator study since the detailed modelling of driving performance is more suited for other research purposes.

Accident analysis is strongly limited for problem analysis purposes. These data almost exclusively contain information about the outcome of accidents whereas information about the processes leading to accidents is required to conduct a meaningful problem analysis. However, accident data can assist in road safety problem analysis when these data are collected by means of in-depth accident research, or when these data are complemented with data from other road safety techniques (i.e. non-crash events). Data collected by means of a driving simulator and/or on-site traffic conflict and behavioural observation techniques do contain information about the accident development process. Therefore, these techniques are more useful to conduct a problem analysis. On-site traffic conflict and behavioural observation techniques can only observe revealed road user behaviour. Consequently, they are less suited to identify the underlying motivation of behaviour or test the influence of driver impairment or theoretical concepts. For this purpose, a driving simulator study should be used as driving simulators not only log a vast array of driving parameters but can also be used to collect physiological information. If combined with a self-report instrument (i.e. short questionnaire after the experiment), driving simulators can even be used to analyse the underlying motivation of behaviour.

With respect to research focusing on road safety evaluation, accident data can only be used to evaluate the outcome effects of road safety measures in the long term. This is related to the fact that accidents are a rare event, and therefore a large number of accidents need to take place before enough accident data are available to provide a reliable evaluation. As illustrated in section 6.3.2, accident data can also be used to develop/improve intelligent vehicle and/or infrastructure technologies if they are combined with other techniques such as naturalistic driving or driving simulator research. However, in such a case accident data should only be used as a complement to naturalistic driving or driving simulator research in order to gain additional insights. On-site traffic conflict and behavioural observation techniques can be used to evaluate the effects of road safety measures both in the long and short term, since traffic conflicts and normal interactive behaviour occur more frequently than accidents. Furthermore, these techniques provide an outcome and process evaluation of the road safety measure under evaluation, as they are able to capture the interaction process between the road user – vehicle – road environment within the road traffic system. Similar to accident data, these techniques can be used as a complement to naturalistic driving or driving simulator research in order to gain additional insights to develop/improve intelligent vehicle and/or infrastructure technologies. Subsequently, the high level of experimental control within driving simulator research not only allows to evaluate already implemented road safety measures but also allows to provide a proactive outcome and process evaluation of planned road safety measures. This technique is also very useful to develop/improve/evaluate intelligent vehicle and/or infrastructure technologies because of the high level of experimental control and the risk-free environment of a driving simulator. Driving simulator research can also be used to provide an outcome evaluation of implemented road safety measures on the long term. However, as driving simulators are not complete replicates of the real-world it is recommended to use other data (i.e. accident and conflicts) for this purpose.

Finally, the results of all the techniques can also be applied for road safety policy and monitoring purposes. As indicated in section 6.3.2, a definite merit lies in combining different road safety techniques to gain additional insights in various road safety aspects or to verify study results.

Table 27: Link between road safety techniques and road safety research application areas.

Road safety techniques/ Road safety research areas	***Accident analysis***	***Traffic conflict observation study***	***Behavioural observation study***	***Driving simulator study***
Problem identification				
Evolution of positive or negative road safety developments	+	+	-	-
Identification of hazardous locations, target groups or risk increasing that behaviours require attention	+	+	-/+	-
Assessing the size of the overall road safety problem	+	+	-	-
Frequency of road user behaviour	-	+	+	-/+
Problem analysis				
In-depth study of accident causation factors (road user, vehicle, environment)	-/+	+	+	+
Improved understanding of road user behaviour (identification of road user error and error recovery strategies)	-	+	+	+
Describe differences in road user behaviour	-	+	+	+
Micro-level road safety analysis with focus on specific target groups or locations	-/+	+	+	-/+
Underlying motivation of behaviour	-	-	-	-/+
Influence of driver impairment/neurological disorders	-	-	-	+
Testing influence of theoretical concepts (i.e. workload, situation awareness)	-	-	-	+

Note: - = Not applicable; -/+ = applicable if combined with other techniques; + = applicable.

Table 27: Link road safety techniques and road safety research application areas (continued).

Road safety techniques/ Road safety research areas	***Accident analysis***	***Traffic conflict observation study***	***Behavioural observation study***	***Driving simulator study***
Evaluation				
Outcome evaluation of implemented road safety measures (short term)	-	+	+	+
Process evaluation of implemented road safety measures (short term)	-	+	+	+
Outcome evaluation of implemented road safety measures (long term)	+	+	+	-
Outcome and process evaluation of road safety measures before implementation	-	-	-	+
Development and evaluation of intelligent vehicle and infrastructure technologies	-/+	-/+	-/+	+
Policy & monitoring				
Setting priorities in a road safety program	+	+	+	-/+
Formulation of road safety strategies	+	+	+	-/+
Verification of study results	+	+	+	+

Note: - = Not applicable; -/+ = applicable if combined with other techniques; + = applicable.

6.4 Suggestions for future research

Based on the present studies, several suggestions for future research can be defined.

This doctoral dissertation focused on investigating patterns of behaviour, conflicts and accidents on intersections. However, the different road safety techniques have not been applied to gain road safety insights at only one single intersection type. For instance, accident data have been used to identify accident patterns at roundabouts and signalized intersections, on-site behavioural and traffic conflict observations combined with a driving simulator experiment were used to investigate drivers' behavioural responses to SRLCs at signalized intersections whereas on-site behavioural observations were used to establish road safety differences between priority-controlled and right-hand priority intersections. This does not imply that the studies did not yield valuable results or that the techniques cannot be applied at other than the investigated intersection types. Therefore, future research should aim to apply the different techniques at each of the investigated intersection types in order to gain a more comprehensive understanding of the road safety situation and to establish how safe encounters between road users evolve to more safety-critical situations such as serious conflicts and accidents.

Related to the identification of accident patterns on roundabouts, future studies should further examine the relationship between dominant accident types and roundabout characteristics such as the speed limit, location (urban or rural) and geometric aspects (radius of deflection, entry angle, exit radius, entry radius,…). These studies should also include the study of more complex double-lane roundabouts and roundabouts with bypasses since these two roundabout types were under-represented in our sample.

The study focusing on the identification of accident patterns at signalized intersections investigated the influence of the type of traffic signal phasing on accident occurrence. The results revealed that the accident patterns differed according to the type of traffic signal phasing (i.e. protected-only, protected-permitted and permitted signal phasing). Protected-only signal phasing appeared to have a beneficial effect on vulnerable road user accidents. In the meanwhile, a new type of traffic signal phasing simultaneous green for cyclists has been developed. Within this traffic signal phase arrangement, all cyclists receive their own green phase during which they may travel in all directions at once at the intersection, while all motorised traffic is confronted with the red phase (CROW, 2006). The expected safety effects of simultaneous green for cyclists are unknown even though it appears to be very beneficial for vulnerable road user safety due to the absence of conflicts with motorised traffic. Therefore, future research should assess the effects of simultaneous green for cyclists in order to identify the benefits and implications for all road users and to establish how this new type of traffic signal phasing influences the current accident patterns at signalized intersections.

Given the limited number of locations in the study focusing on the behavioural responses of drivers to SRLCs, it is desirable to further research whether the found effects (change in dilemma zone, decision behaviour, braking manoeuvres, occurrence of rear-end conflicts etc.) can be generalised to other locations. Furthermore, further research using on-site behavioural and traffic observation techniques should also aim to extent the analysis period in order to collect more traffic conflict data for more robust conclusions. Fully automated video analysis tools could be a valuable asset to analyse longer observation periods, once the accuracy problems of these tools are resolved. The integrated approach of combining on-site behavioural and traffic conflict observations with a driving simulator experiment provided more comprehensive road safety insights. The application of such an integrated study design is therefore recommended in future studies focusing on road users' behavioural adaptations to road infrastructure measures.

The study on the road safety differences between priority-controlled and right-hand priority intersections was one of the first that investigated interactions between drivers at these intersection types. The generalisability of the study results remains an issue because of the limited number of locations included in the study. Therefore, future research should investigate the generalisability of the study results by including more locations and by exploring how the presence of certain intersection characteristics (e.g. bicycle paths, crossing facilities and raised intersections) influence road user interactions. Furthermore, this study only focused on vehicle-vehicle interactions. A further study, which also focuses on interactions between vulnerable road users and between vulnerable road users and motorised traffic, is therefore suggested.

To conclude, future research should explore the possibility to create more uniformity in intersection design by limiting the number of intersections types between different road categories and aligning the intersection design within road categories. Furthermore, as the creation of an inherently safe road traffic system is one of the action points of the Road Safety Plan of Flanders (Vlaams Ministerie van Mobiliteit en Openbare Werken, 2017), further research should also investigate whether the currently implemented intersection design features meet the Safe System and Vision Zero principles. The approach used by Candappa et al. (2015) can be applied for this purpose.

6.5 Conclusions

This doctoral dissertation focused on identifying and providing an in-depth analysis of patterns of behaviour, conflicts and accidents on intersections. For this purpose, a variety of road safety techniques was used: accident data analysis, on-site traffic conflict and behavioural observation techniques and driving simulator research. Therefore, the four studies conducted within the frame of this doctoral dissertation have not only provided improved insights into intersection safety but also led to detailed insights in the use of crash and empirical non-crash data to study policy-relevant road safety issues.

Traditional accident analysis is very useful to provide a generic overview of the road safety situation and to set road safety targets. However, the studies focusing on identifying accidents patterns on roundabouts and signalized intersections have shown that there lies merit in making optimal use of available accident data. The inclusion of collision diagram information made it possible to conduct a micro-level road safety analysis at the level of signalized intersection and roundabout location sections. This improved the knowledge about the safety impact of road infrastructure design. Consequently, these results contribute to the implementation of a safer road design as they indicated which typical roundabout and intersection locations require particular attention from road designers.

Despite the fact that accident data analyses have the advantage of a direct assessment of the object under study, accidents still remain rare events and only provide information concerning the road safety outcome (i.e. the number of accidents) and not about the behavioural and situational aspects which played a role in the accident development process. In that respect, road safety techniques based on empirical non-crash events definitely have merit to gain complementary road safety insights.

Within this dissertation empirical non-crash data, as a proactive strategy, have proved to be extremely valuable to timely assess road safety aspects for which little accident data are available, and in case of driving simulator studies even to assess the effects of road safety measures before they are implemented. This is illustrated by the study focusing on speed and red-light cameras which revealed that driver behavioural adaptation effects related to a higher stopping propensity (i.e. shift in dilemma zone) and higher deceleration values are responsible for the increase in rear-end collisions associated with SRLC implementation.

Subsequently, the case study of right-hand priority intersections versus priority-controlled intersections revealed interesting insights in the yielding behaviour of drivers by revealing the presence of an informal yield rule at the of right-hand priority intersection. However, the behavioural observation results did not allow to establish a direct relationship between road user behaviour and accident occurrence. Nevertheless, the study revealed some interesting exploratory insights in driver behaviour at intersections.

Even though the use of empirical non-crash data has provided valuable insights into policy-relevant road safety issues, it was experienced that these techniques also have their limitations. Future research should further aim to improve the validity and generalisability of on-site behavioural and traffic conflict observation studies. However, it is expected that the further development of fully automated video analysis tools will mitigate these issues in the future.

The findings of all these studies extended the current knowledge regarding the safety performance of intersections. Therefore, these results can assist decision makers in making well-based decisions in order to further improve intersection safety.

To conclude, the decision to apply techniques based on crash and empirical non-crash data not only contributed to assess intersection safety. In light of the Safe System and Vision Zero approach, a strong case has been made within the scientific community to adopt a system's approach when conducting road safety research. This research provides additional evidence with respect to that issue. The acquired insights regarding the strengths, limitations and applicability of the different road safety techniques revealed that the most important merit of the empirical non-crash data techniques lies in the possibility to study road safety from a systems' perspective. Additional merits also lie in combining road safety techniques. The added value of such an integrated approach lies in the opportunity to enrich the results from one technique with the complementary results from other technique(s) and to check whether the findings of the techniques are in line. This not only allows to overcome the limitations of each individual technique but also allows to draw very detailed and more sound road safety inferences which will ultimately result in a more comprehensive picture of the road safety situation. From this, it can be recommended that countries that pursue a system-based road safety vision should adopt an integrated approach. This integrated approach should combine road safety techniques based on crash and empirical non-crash data in order to be able to investigate road safety from a system's perspective, get an overview of the policy results and formulate future policy priorities to pursue an inherently safe road traffic system.

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ABOUT THE AUTHOR

Evelien Polders was born in Hasselt, Belgium, on December 5 1989. She graduated in Economics-Modern Languages at the Koninklijk Lyceum in Hasselt in 2007 (pre-university degree). Afterwards, she started her academic education in Transportation Sciences at Hasselt University. Evelien obtained her degree of bachelor in 2010, and subsequently her master degree with a specialization in Traffic Safety in 2012. Her master's dissertation focused on applying on-site behavioural observation and traffic conflict techniques in order to establish the impact of different priority rules (priority-controlled and right-hand priority intersections) on road safety and driving behaviour.

Later that year, Evelien joined the Transportation Research Institute (Hasselt University) as a PhD student. She is enrolled in the research group Traffic Safety. Her research task is primarily related to research concerning the relationship between crashes, near-crashes and normal interactive behaviour in which the focus lies on road user behaviour. While working on her Ph.D., she also followed a crash reconstruction and in-depth analysis course at the Local Police of Antwerp, Belgium.

Since January 2015, she is enrolled in business unit 'Applied Research' at IMOB. Within this unit, she is involved in practice-oriented research in the field of road safety, mobility and road design for several national and international applied research projects. Furthermore, Evelien is also enrolled in some educational activities of the bachelor-master programme in Transportation Sciences at Hasselt University.

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Journal publications

Publications in international peer-reviewed scientific journals (published)

De Ceunynck, T., De Pauw, E., Daniels, S., **Polders, E.**, Brijs, T., Hermans, E., & Wets, G. (2017). *The effect of wind turbines alongside motorways on drivers' behaviour*. European Journal of Transport and Infrastructure Research, 17 (3), p.477-494. (Web of Science 5-year impact factor 1.169).

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Tormans, H., Miermans, W., Cools, M., **Polders, E.**, Janssens, D., & Wets, G. (2013). *Performance assessment of local mobility policymaking using the principles of total quality management in Flanders, Belgium*. International Journal of Sustainable Transportation, 7 (4), p. 318-346. (Web of Science 5-year impact factor 2.451).

Publications in national journals

Polders, E., Tormans, H., & Miermans, W. (2011). Beleidsdomein mobiliteit vaak stiefmoederlijk behandeld. Verkeersspecialist, nr.174, p.18-21.

Polders, E., Tormans, H., & Miermans, W. (2011). Le domaine politique de la mobilité est souvent traité en parent pauvre – Une analyse qualitative de la politique de mobilité communale/ Beleidsdomein mobiliteit vaak stiefmoederlijk behandeld – Een kwalitatieve analyse van het gemeentelijk mobiliteitsbeleid. Moniteur de la mobilité et de la sécurité routière / Gids van de mobiliteit en de verkeersveiligheid, nr.31, p.15-19.

Conference publications/presentations

Vlahogianni, E., Papadimitriou, E., Yannis, G., Brijs, T., **Polders, E.**, Leopold, F., Durso, C., & Diamandouros, K. (2016). An in-depth analysis of road infrastructure interventions aiming to improve road safety of the elderly in Europe. In: *Proceedings of the 1st European Road Infrastructure Congress*. Leeds, United Kingdom.

De Ceunynck, T., De Pauw, E., Daniels, S., **Polders, E.**, Brijs, T., Hermans, E., & Wets, G. (2016). The effect of wind turbines alongside motorways on drivers' behaviour. In: *Proceedings of the 29th ICTCT-workshop*. Lund, Sweden.

Van Haperen, W., **Polders, E.**, De Ceunynck, T. & Daniels, S. (2015). Cyclists' safety at Channelized right turn lanes: a traffic conflict study comparing cases with cyclists in and out priority. In: *Proceedings of the 28th ICTCT-workshop*. Ashod, Israel.

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., Wets, G. (2015). Schrik niet, u wordt gefotografeerd. In*: Geeraerd, Ingrid; Dergent, Stijn (Ed.). Jaarboek Verkeersveiligheid 2015*.

Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2015). Crash patterns at signalized intersections. In: *Proceedings of the 94th Annual Meeting of the Transportation Research Board*. Washington D.C., USA.

Daniels, S., **Polders, E.**, Cornu, J., De Ceunynck, T., Brijs, K., Brijs, T., Hermans, E., & Wets, G. (2014). Drivers' behavioural responses to red-light-cameras. In: *Proceedings of the 8th Fit to drive Congress*. Warsaw, Poland.

Polders, E., De Ceunynck, T., Daniels, S., Hermans, E., Brijs, T., & Wets, G., (2013). Rear-end conflicts at intersections with red light cameras: a before and after study. In: *Proceedings of the 26th ICTCT-workshop*. Maribor, Slovenia.

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De Ceunynck, T., **Polders, E.**, Daniels, S., Laureshyn, A., Hermans, E., Brijs, T., & Wets, G. (2012). Behavioural analysis of vehicle interactions at priority-controlled and right-hand priority intersections. In: *Proceedings of the 25th ICTCT-workshop*. Hasselt, Belgium.

Research reports

Polders, E., Brijs, K., Brijs, T., Pavlou, D., Yannis, G., Winkelbauer, M., Salamon, B., Hausmann, M., Jost, G., & Calinescu, T. (2017). *The implementation of Directive 2006/126/EC on driving licences: Final report*. Commissioned by: European Commission – Directorate-General for mobility and transport (DG-MOVE).

Polders, E., Brijs, K., Brijs, T., Pavlou, D., Yannis, G., Winkelbauer, M., Salamon, B., Hausmann, M., Jost, G., & Calinescu, T. (2017). *The implementation of Directive 2006/126/EC on driving licences: Annex report*. Commissioned by: European Commission – Directorate-General for mobility and transport (DG-MOVE).

Declercq, K., Reumers, S., **Polders, E.**, Janssens, D., & Wets, G. (2017). *Onderzoek Verplaatsingsgedrag Vlaanderen 5.1 (2015-2016) Tabellenrapport*. Diepenbeek, Belgium.

Reumers, S., **Polders, E.**, Janssens, D., Declercq, K., & Wets, G. (2017). *Onderzoek Verplaatsingsgedrag Vlaanderen 5.1 (2015-2016) Analyserapport*. Diepenbeek, Belgium.

De Ceunynck, T., De Pauw, E., **Polders, E.**, & Daniels, S. (2016). *Onderzoek naar het effect van windturbines op het verkeersgedrag en –conflicten*. In opdracht van Rijkswaterstaat.

Polders, E., Cornu, J., Carpentier, A., Brijs, K., & Daniels, S. (2016). *Proefproject Langere en Zwaardere Vrachtwagencombinaties in Vlaanderen: Evaluatie van de effecten op verkeersveiligheid*. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-004, Diepenbeek, Belgium.

Polders, E., Brijs, T., Papadimitriou, E., Yannis, G., Leopold, F., Durso, C., Diamandouros, K., & Vlahogianni, E. (2016). *ElderSafe - Risks and countermeasures for road traffic of elderly in Europe*. Commissioned by: European Commission – Directorate-General for mobility and transport (DG-MOVE).

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., & Wets, G. (2015). *Gedragsaanpassingen van bestuurders aan snelheids- en roodlichtcamera's. Vervolgonderzoek: effectiviteit van roodlichtca*mera's. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-002, Diepenbeek, Belgium.

Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2015). *Ongevallenpatronen op verkeerslichtengeregelde kruispunten*. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-004, Diepenbeek, Belgium.

De Ceunynck, T., Daniels, S., **Polders, E.**, & Vernyns, L. (2015). *Geobserveerd voorrangsgedrag bij fietsoversteken op rotondes met vrijliggende fietspaden*. Steunpunt Verkeersveiligheid 2012-2015, RA-2015-007, Diepenbeek, Belgium.

Polders, E., Daniels, S., Casters, W., & Brijs, T. (2013). *Het identificeren van verkeersongevallenpatronen op rotondes: een exploratieve studie*. Steunpunt Verkeersveiligheid 2012-2015, RA-2013-004, Diepenbeek, Belgium.

Projects

- Flemish Mobility Plan: Explaining and optimising the financing of the sustainable transportation policy plan – 2018
  commissioned by: Vlaamse Overheid, departement MOW, afdeling Beleid Mobiliteit en Verkeersveiligheid (project assistant)

- The implementation of Directive 2006/126/EC on driving licences (2017)
  commissioned by: European Commission – Directorate-General for mobility and transport (DG-MOVE) (project assistant)

- Proactive commitment to increased road safety by Limburg transport companies – 2016-2017
  commissioned by: Vlaamse overheid (project assistant)

- InDeV - In-Depth understanding of accident causation for Vulnerable road users – 2015-2018
  commissioned by: EU Horizon 2020 (project assistant)

- ElderSafe - Risks and Countermeasures for Road Traffic of the Elderly in Europe (2015)
  commissioned by: European Commission – Directorate-General for mobility and transport (DG-MOVE) (project assistant)

- Smart Logistics Limburg - 2014-2017
  commissioned by: IWT (project assistant)

- Policy Research Centre Traffic Safety (Steunpunt Verkeersveiligheid) - 2012-2015
  commissioned by: Vlaamse Overheid, Departement MOW, Afdeling Beleid Mobiliteit en Verkeersveiligheid (project assistant)

Teaching activities

- Bachelor of Transportation Sciences, course Case Studie 1: work sessions (academic years 2012/2013 – 2013/2014 – 2014/2015)

- Bachelor Transportation Sciences, course Case Studie 2: work sessions (academic years 2012/2013 – 2013/2014)

- Bachelor of Transportation Sciences, course Road Safety: work sessions (academic year 2015/2016), lectures (academic year 2017/2018)

- Bachelor of Transportation Sciences, course Integrated Project: supervision of students (academic years 2012/2013 – 2013/2014 – 2017/2018)

- Master of Transportation Sciences, course Impact Infrastructure: work sessions of traffic conflict observation technique (academic years 2012/2013 - 2013/2014)

- Master of Transportation Sciences, course Road Safety Evaluation: methods and applications work sessions of traffic conflict observation technique (academic year 2014/2015)

- Master of Transportation Sciences, course Internship: supervision of students (academic years 2013/2014 – 2015/2016 – 2016/2017)

- Master of Transportation Sciences, course In-depth crash investigation: work sessions (academic years 2015/2016 – 2016/2017 – 2017/2018)

- Supervision of several bachelor dissertations:
    - Analyse van ongevallenpatronen op lichtengeregelde kruispunten (academic year 2012/2013)
    - Analyse van ongevalspatronen op voorrangsgeregelde kruispunten (academic year 2012/2013)
    - Implementatie van LZV's in Vlaanderen: Onderzoek naar de kennis en attitude van transportbedrijven ten opzichte van de implementatie van de LZV's in Vlaanderen (academic year 2013/2014)
    - Langere en Zwaardere Vrachtwagens in Vlaanderen: een pilootstudie over de standpunten van mobiliteitsambtenaren tegenover een mogelijke implementatie in Vlaanderen (academic year 2013/2014)
    - Fietsvoorzieningen tijdens wegenwerken (academic year 2017/2018)

    - Linksafbeweging voor fietsers op verkeerslichtengeregelde kruispunten met vrijliggende fietspaden (academic year 2017/2018)
    - Veilig Genkt: Ongevallenanalyse (academic year 2017/2018)

- Supervision of several master dissertations:
    - De invloed van de wisselwerking tussen weggebruiker, voertuig en omgeving op het gedrag van bestuurders: naturalistic driving (academic year 2014/2015)
    - Mobiliteit op scholencampussen (academic year 2017/2018)

“We can’t solve problems by using the same kind of thinking we used when we created them.”

Albert Einstein